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Introduction

There is a pressing need to improve the sensitivity of the BOL spectrometer design in order to take full advantage of the opportunities for follow up spectroscopy on the high redshift galaxies that will be discovered in the photometer survey. In fact the BOL spectrometer will be the only instrument optimised for high red shift object spectroscopy and it is critical to the success of the FIRST mission. It is difficult to envisage substantial improvements being made to the detector NEP's via technological development in time for inclusion in the FIRST payload. It may be possible, however, to change the design of the spectrometer in order to take full advantage of the multiplex advantage offered by multiple order grating spectroscopy.

The current designs for the spectrometer for the FIRST-BOL instrument employ a linear array of detectors with order sorting filters to cover the wavelength range from 200 to 400 μm. These detectors of necessity will have a finite size and, given the constraints of the cold focal plane, will only be able to cover a limited range of angles. Each detector will therefore be used over a large number of resolution elements by scanning the grating or a scan mirror. This is the method of operation successfully demonstrated on the spectrometers on ISO. It does however suffer from the drawback that the spectrum is gathered serially, i.e. some of the multiplex advantage of the grating is lost.

In this note a possible design of the BOL spectrometer is discussed which uses a second grating to perform the order sorting rather than filters. This cross dispersion technique allows more detectors to be fitted into the focal plane and thus reduces the wavelength coverage of each detector, and, in turn, the scan range required from the grating.

Nominal Spectrometer Design - linear array

To illustrate the possible advantages of using a cross dispersion grating I will use a nominal design of a spectrometer based loosely on the ISO LWS. The important elements are shown in figure 1. The design is shown for illustration only and may not be the optimum from the point of view of aberration control, stray light or, even, fitting into the box! It does have the essential elements, however, and could be optimised to provide a real design for the spectrometer. The optical parameters are given in table 1.

Groove Spacing	1767.67 μm
Incident Angle	-45°
Diffraction angle range	28 to 37°
Focal length/ratio of collimator	300mm; f/3
Number of detectors	10
Spacing of detectors	1° (≅ 5mm)
Grating Scan Range	-3 to +3.5° for full λ coverage

Table 1: Parameters for "high resolution" planar grating

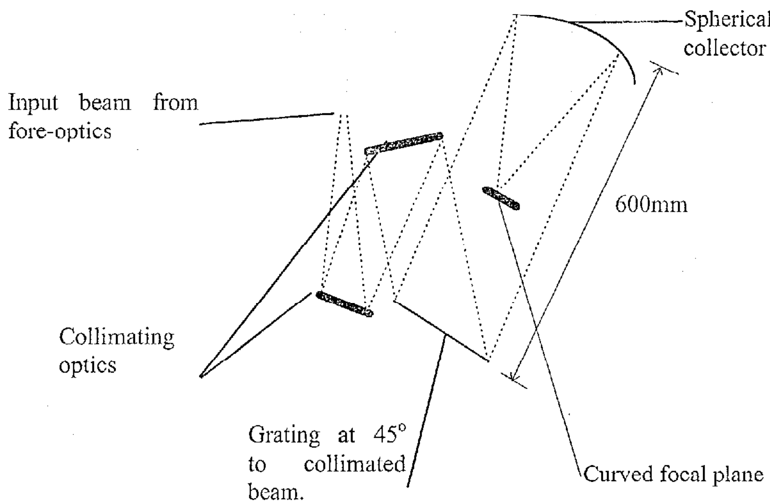

Figure 1: Nominal optical layout. The grating and spherical collector form a Schmidt camera with the off axis correction provided by profiling on the grating as in the ISO-LWS.

The coverage of each detector is shown in figure 2 and given explicitly in table 2.

Detector Order	Detector Angle w.r.t. to 33°	Wavelength at grating angle +3.5°	Wavelength at grating angle +1°	Wavelength at grating angle -3°
10	1	201.5	213.8	231.8
10	-4	214.7	226.7	245.0
9	2	220.8	234.6	255.8
9	-3	235.7	249.1	269.6
8	3	245.0	260.6	284.6
8	-2	261.9	277.0	300.2
7	4	276.0	294.0	321.5
7	-1	295.5	313.0	339.6
6	5	317.4	338.4	370.7
6	0	340.3	360.8	392.1

Table 2: Position and wavelength coverage of each detector in nominal design.

Two grating positions are given in table 2 - one to give the extreme wavelength coverage (i.e. the grating needs to move to +3.5 degrees in order to get to ~200 μm) and the other the minimum scan angle required in order for there to be no gaps in the spectral coverage. This of course implies a lower limit to the wavelength coverage in total, but does represent the minimum scan range required of the grating to cover the nominal wavelength range.

The number of grating steps required to cover the minimum scan range at a resolving power of 500 at the minimum wavelength and 1/4 resolution element sampling, is:

$$N_{steps} = FIX\left(\frac{4x500x(231.8\text{-}213.8)}{201}+0.5\right) = 180 \qquad (1)$$

Likewise the number of steps required to cover the whole wavelength range with the same sampling is:

$$N_{steps} = FIX\left(\frac{4x500x(231.8\text{-}201.5)}{201}+0.5\right) = 302 \qquad (2)$$

Cross Dispersion and 2-D Array

If the spherical collection mirror in the nominal design is replaced with concave grating with the grooves orthogonal to those on the main grating, the light will be diffracted out of the plane of the diagram in figure 1 at the same time as being focused onto the detectors. The cross-dispersion grating then begins to look like a Wadsworth mount and, with judicious choice of grating groove spacing (see for instance Onaka, *Applied Optics* **34** pp659-666, 1995) the aberrations will not be too bad and the necessity for a focal plane curved in to directions should be avoidable.

Assuming that the details of cross-dispersion grating can be arranged to give reasonable image quality then a grating with the parameters given in table 3 will give wavelength positions in the focal plane shown in figure 3.

Groove Spacing	1000 μm
Incident Angle	3°
Diffraction angle range	14 to 27° - only first order used
Radius of curvature/aperture	600mm; ~100mm
Number of detectors	~65
Spacing of detectors	1° (≅ 5mm)
Grating Scan Range	-0.3° to +0.3° for full λ coverage

Table 3: Parameters for the cross-dispersion concave grating.

If the final focal length is to be 300 mm then the detector spacing is as shown in figure 4. Here a nominal detector outside diameter set at ~5mm is shown to indicate the final spacing of the detectors. If the detectors can be spaced at one degree of arc then each detector will be centred on a wavelength given in table 4. A total of 65 detectors would be required for contiguous wavelength coverage for the spacing given here, although with small shifts in the detector positions it should be possible to reduce this slightly.

Diffraction Angle (deg)	10th Order	9th Order	8th Order	7th Order	6th Order
25	199.708	221.898	249.635	285.298	332.847
26	202.493	224.992	253.116	289.276	337.488
27	205.254	228.060	256.568	293.220	342.090
28	207.991	231.101	259.989	297.130	346.651
29	210.702	234.114	263.378	301.003	351.170
30	213.388	237.097	266.734	304.839	355.646
31	216.046	240.051	270.057	308.637	360.076
32	218.676	242.974	273.346	312.395	364.461
33	221.279	245.865	276.598	316.112	368.798
34	*223.851*	248.724	279.814	319.788	373.086
35	*226.394*	251.549	282.993	323.420	377.323
36	*228.906*	*254.340*	286.132	327.008	381.510
37	*231.386*	*257.096*	*289.232*	330.551	385.643
38	*233.834*	*259.815*	*292.292*	334.048	389.723
39	*236.248*	*262.498*	*295.310*	*337.497*	393.747
40	*238.629*	*265.143*	*298.286*	*340.898*	397.715
Number of Detectors	9	11	13	15	17

Table 4: Wavelengths at centre of detectors placed at intervals of one degree at each of the five cross dispersed orders. Where the figures are in italics a detector is unnecessary as that wavelength is covered in the next order.

The maximum number of steps required with a resolution of 500 at the minimum wavelength covered and 1/4 resolution element stepsize, will be:

$$N_{steps} = FIX\left(\frac{4x500x(202.493-199.708)}{199.708}+0.5\right) = 28 \quad (3)$$

In fact this number of steps will give **full** wavelength coverage unlike (1).

The transmission efficiency of the system using two gratings will be, at the very worst, a factor of two lower than with the single grating - assuming an efficiency of 50% for the cross-dispersion grating. Therefore the cross-dispersion system, at the very worst, will cover its maximum wavelength range 1.6 times faster than the single grating covers its *minimum* wavelength range and covers *the whole range from 200-400 μm* 2.8 times faster. These really are worst case figures as the grating efficiency is likely to be somewhat higher than this and they do not take into account the fact the cross-dispersion system does not require narrow band order sorting filters.

Conclusions

The cross-dispersing echelle spectrometer appears to offer significant advantages in sensitivity over a single grating echelle with a linear detector array and is the only way open to improving the sensitivity of the BOL grating spectrometer. The speed advantage is at least a factor of two and could be as high as four, depending on the final characteristics of the grating. It also has the advantage that the grating mechanism becomes very much smaller, lighter and will use much less power.

The design illustrated here uses detectors with an external diameter of 5mm. If this could be reduced - for example the need for a filter mount has gone, then the advantage of the cross-dispersion system increases. It would also be possible in these circumstances to reduce the final focal length of the system which would reduce the size of the collimating mirror/cross-dispersion grating. However the focal ratio would also need to be reduced to maintain the correct slit-width for the given resolution, or the resolution would have to be reduced.

Design optimisation remains to be completed, in particular there are the following outstanding issues:

- Control of unwanted orders from the cross-dispersion grating.
- Quality of the final image.
- Avoidance of a focal plane curved in two dimensions.
- Manufacturing tolerances on the cross-dispersion grating (can it be made at all?).
- Efficiency of the gratings.

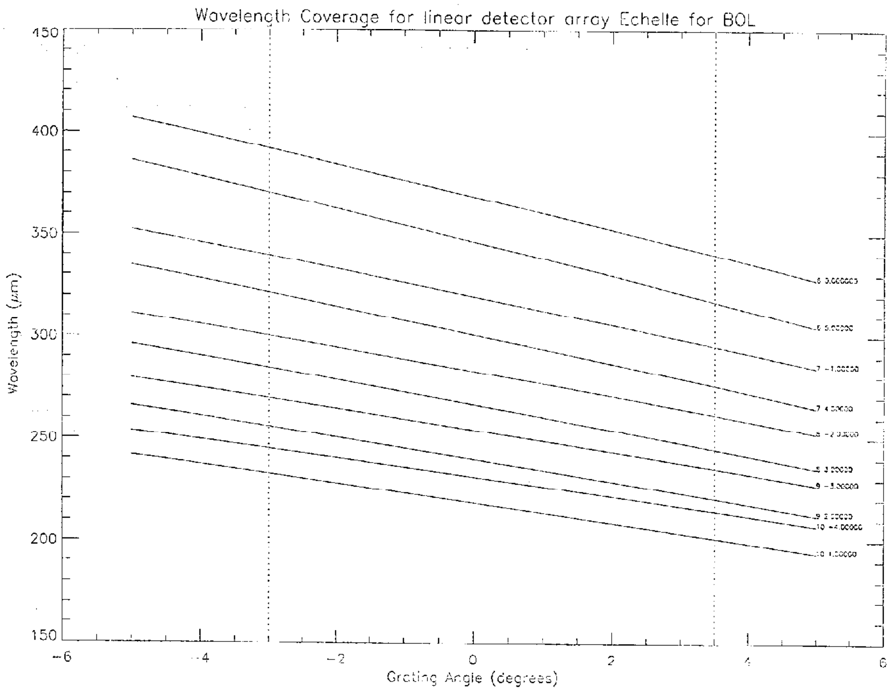

Figure 2: Wavelength coverage of each detector for a single grating echelle spectrometer with a linear detector array covering five orders.

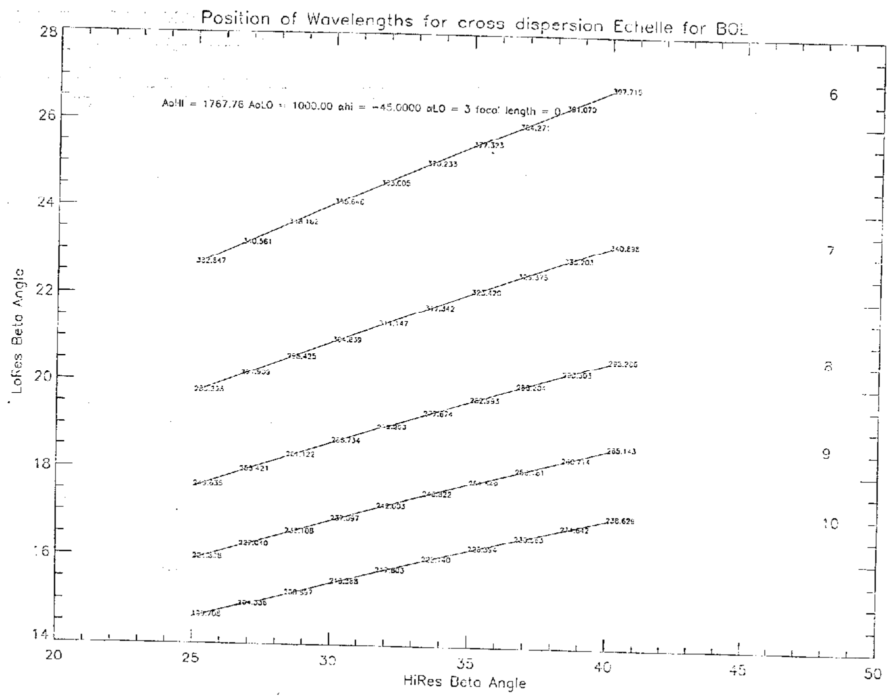

Figure 3: Wavelength as a function of angle in the focal plane for a cross-dispersion echelle spectrometer for five orders of the high resolution grating. The low resolution grating is working in first order only.

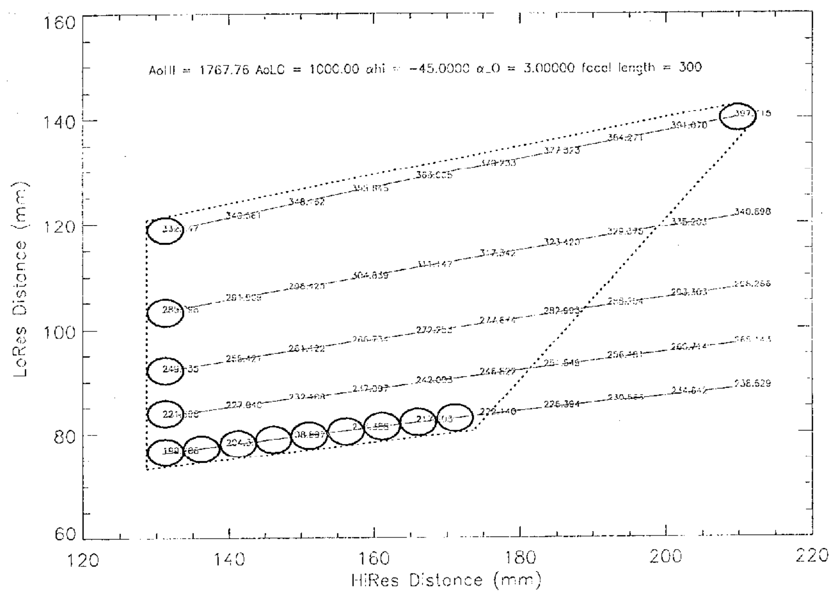

Figure 4: Wavelengths seen in the focal plane for the cross-dispersion system and a focal length of 300mm. The ellipses represent detectors of about 5mm diameter and the dotted lines show the approximate area covered by the focal plane array.