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INTRODUCTION

At the FIRST Bolometer instrument consortium meeting at Marseilles on the 22/23 September 1997, a baseline design for a single grating spectrometer utilising a concave grating was presented by Kjetil Dohlen (BOL/QMW/M/0024.10). The design is compact, uses few optical elements and scans the grating over a small angular range; however, concerns have been expressed about the efficiency of a concave grating in this waveband. This note attempts to address those concerns by evaluating the grating efficiency using the PC GRATE 1E software developed by Leonid Goray of INTEGRATE in St. Petersburg. This calculates the grating efficiency for the case of an infinitely conducting surface as a function of wavelength, grating ruling shape and groove spacing and angle of incidence. A check of the results of this software against the calculations by Petit's group at Marseilles for the ISO LWS grating showed good agreement.

SPEC BOL BASELINE GRATING DESIGN

Figure 1 shows the essential elements of Kjetil's design for the SPEC BOL laid out in two dimensions - in reality it is a three dimensional design with the beams tilted to avoid clashes. The schematic layout shows clearly that the effective angle between any input ray and the local grating normal changes across the grating. It is this feature of the system that causes concern over the overall efficiency of the grating. The diffracted spectrum is detected in orders -5 through -9 with a central diffraction angle of about -16°; a grating groove spacing of about 1.7 mm is required to achieve this.

GRATING EFFICIENCY MODEL

To maximise the diffraction efficiency in each order from all parts of the grating it will be necessary to have a varying blaze angle across the grating. The PC Grate software does not explicitly deal with concave gratings but one can be modelled as a series of flat gratings with different blaze angles and input angles. The first problem is to identify what the input angle is as a function of distance across the grating and, then, to determine the optimum blaze angle for each segment of the grating. Figure 2 shows the calculated input angle with respect to the local grating normal for the configuration described at Marseilles as a function of angle of the local grating normal from the centre (θ in figure 1). As a first cut model I have taken three grating segments with approximately even distributions of input angle as shown in figure two. Each segment is represented by a single input angle - these are 60°, 53° (the nominal angle) and 47° respectively. For each segment I have run an analysis of the grating efficiency as a function of wavelength and blaze angle in each order from -5 to -9 for a triangular groove shape. The wavelength at which the maximum efficiency is found and the maximum efficiency itself can then be plotted as function of blaze angle for each segment - figures 3 through 5.

The efficiency curve tends to become narrower with increasing order (and decreasing wavelength). The critical point in selecting blaze angle for each segment is therefore to ensure that the peak of the efficiency is at the same wavelength in order -9 at each input angle - in this case I have chosen 200 μm as the blaze wavelength. As can be seen from the plots in figures 3-5 this does not necessarily coincide with the peak efficiency for each input angle.

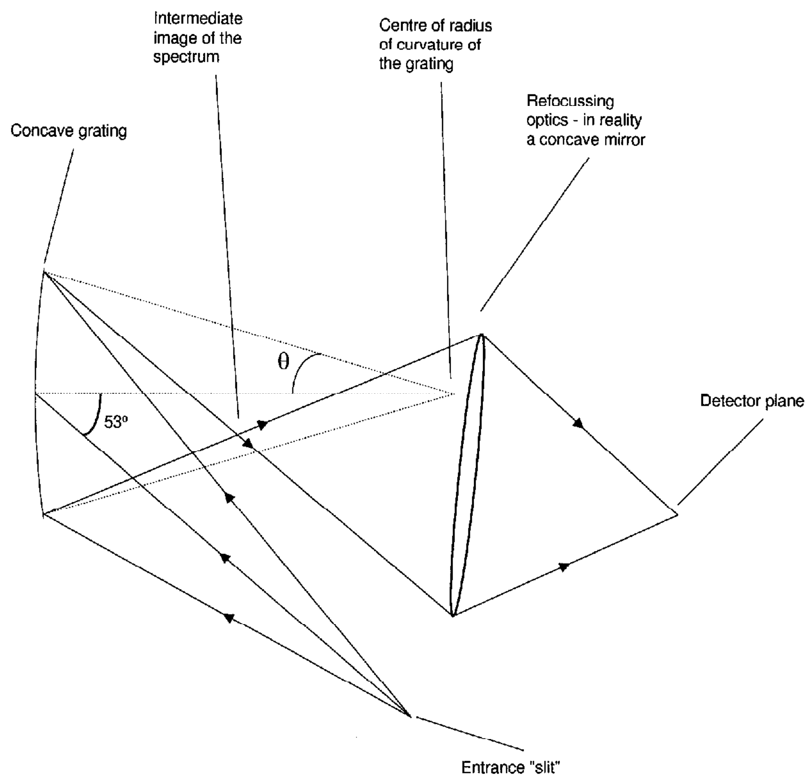


Figure 1: Schematic layout of the SPEC BOL single grating design. In reality the design has no entrance slit as such - the resolution being determined by the size of the diffraction spot size at the detector plane. Rather, there is a defining aperture at the entrance to the spectrometer that will determine the FOV of the instrument.

The efficiency vs. wavelength for each order for each segment with the optimum blaze angle is plotted in figure 6 together with the average efficiency over all three segments.

It can be seen that the average efficiency is very nearly identical to that of the central segment of the "model" grating. To a first approximation then we can treat the concave grating as a single flat grating with its blaze angle optimised for 200 μm in order -9. The average efficiency

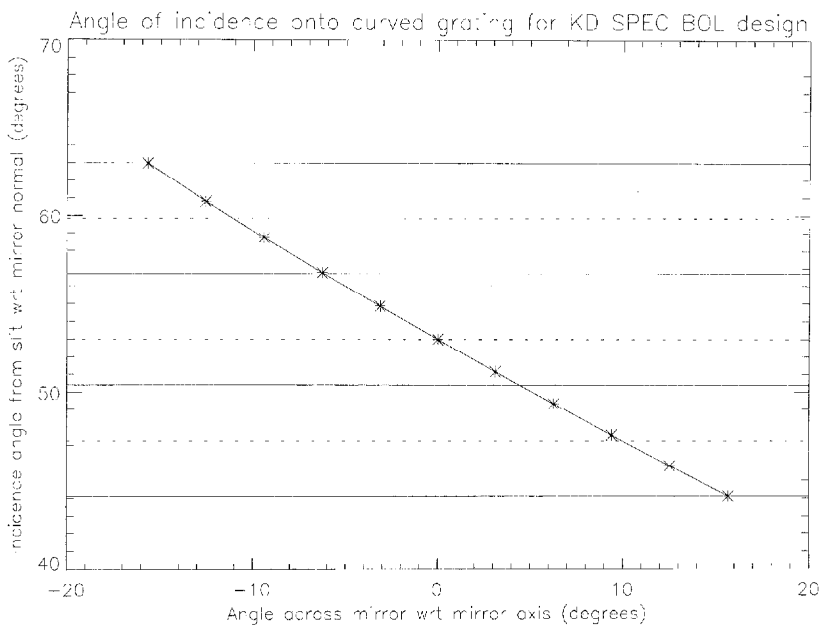


Figure 2: Calculated angle of incidence with respect to the local grating normal for the baseline SPEC BOL design. The solid lines represent the division of the grating into three segments of equal distribution of incidence angle. The dotted lines are the angles chosen as representative of the these segments as flat gratings with a single incidence angle. Note that the central segment is not quite symmetrical about the chosen angle - this is because the chosen angle is the nominal angle of incidence.

over all orders and wavelengths for such a grating is 54% - figure 7. The blaze angle (defined here as the angle of the grating facet from the grating normal) is 56.11°.

WAVELENGTH COVERAGE OF THE DETECTORS

Kjetil has calculated a nominal central angle for each detector which equates to an angular difference of about 0.5° between detectors. In figure 8 I show the wavelength coverage for each detector as a function of grating rotation angle. Here I have used 19 detectors with approximately the same angles and orders as Kjetil, but not exactly the same, to illustrate one possible configuration for the detector array and to highlight the critical points in calculating the required number of steps of the grating to cover the complete wavelength band.

The first point to note is that the dispersion increases with decreasing order - therefore, the overlap between orders for the same maximum rotation angle gradually decreases. This becomes critical for the overlap between -6 and -5 - as shown in figure 8. The grating must be rotated far enough in each direction to give a reasonable amount of wavelength coverage in each order to allow the full spectrum to be stitched together without any holes and to allow the proper calibration of each detector band. This is illustrated in figure 9 where the wavelength coverage for each detector is superimposed on the calculated grating efficiency in each order. At the critical overlap region between -6 and -5 it can be seen that the grating efficiency is at the minimum and that this amount of overlap is really only just sufficient. Even so it does not give full redundancy as the loss of either the first order -5 detector or the last order -6 detector will leave a sizeable hole in the spectral coverage.

To calculate the number of steps I take the wavelength coverage in the order spanning 200 μm for the rotation of the grating required to give overlap between -6 and -5, and divide by the resolution element at 200 μm. The wavelength coverage is 195.7 to 211.1 μm and Kjetil gives the resolution as ~400 - for an oversampling of 4 the numbers of steps is then:

$$N_{STEPS} = \mathrm{FIX}\left(4 \times \left(\frac{211.1-195.7}{0.5}\right)\right) = 123$$

AFFECT ON SENSITIVITY

Matt has put the two relevant numbers (overall efficiency = 0.54 and number of steps 123) into his grating model. Whilst it has relatively little impact of the sensitivity to a known line - increasing the minimum detectable flux from 48.9 mJy to 54 mJy (1.2 to 1.3×10^{-18} W m^{-2}) - the minimum detectable flux for a full spectral survey rises from 84.6 mJy to 133 mJy (2.1 to 3.3×10^{-18} W m^{-2}). This increase is due almost entirely to the more realistic calculation of the number of steps required to fully cover the spectral range (123 as opposed to 60 in the original calculations).

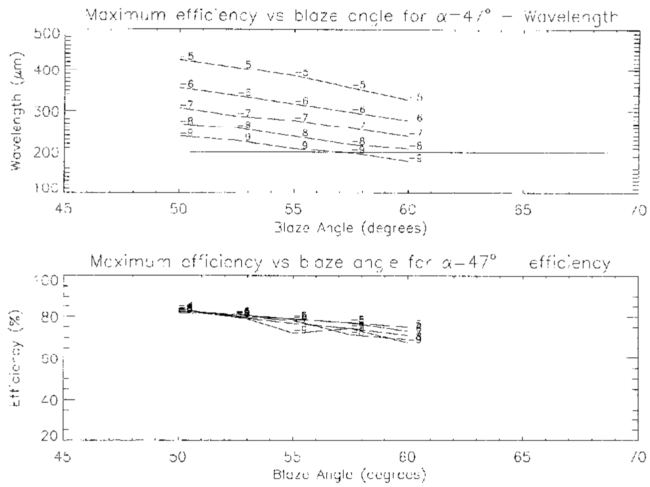


Figure 3: Results of PC GRATE calculations of blaze angle required for maximum efficiency at 200 μm and efficiency vs. blaze angle for an input angle of 47°.

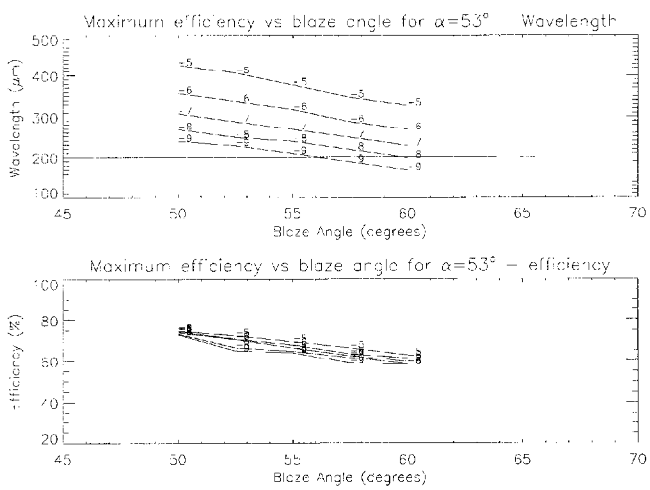


Figure 4: Results of PC GRATE calculations of blaze angle required for maximum efficiency at 200 μm and efficiency vs. blaze angle for an input angle of 53° - this is the nominal input angle.

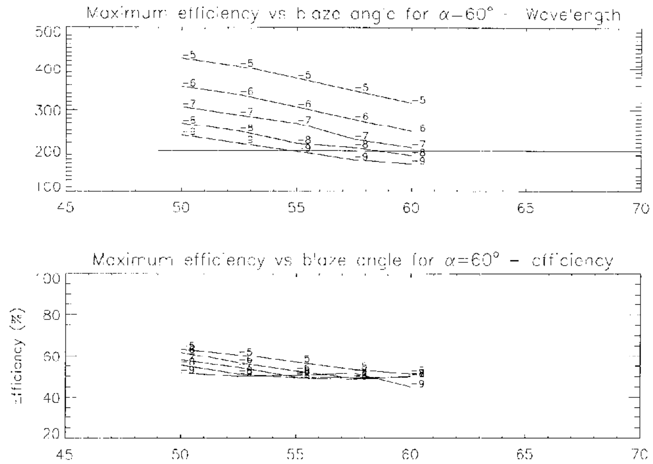


Figure 5: Results of PC GRATE calculations of blaze angle required for maximum efficiency at 200 μm and efficiency vs. blaze angle for an input angle of 60°.

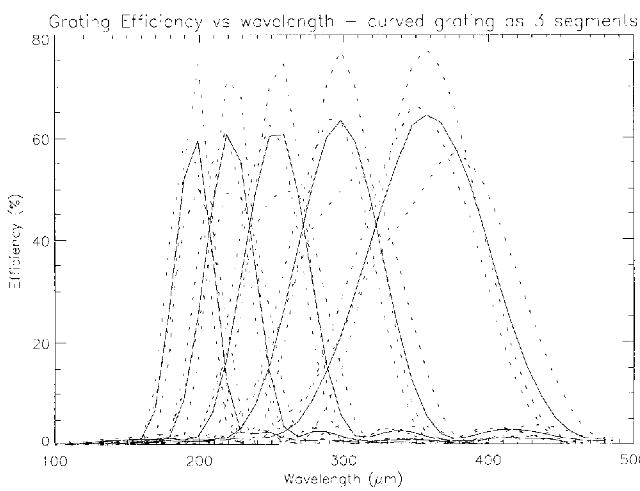


Figure 6: Efficiency vs. wavelength for the three grating segments at the optimum blaze angel at 200 μm - dotted line. The segments are, from bottom to top, α=60, 53 and 47°. The solid line is the average of all three.

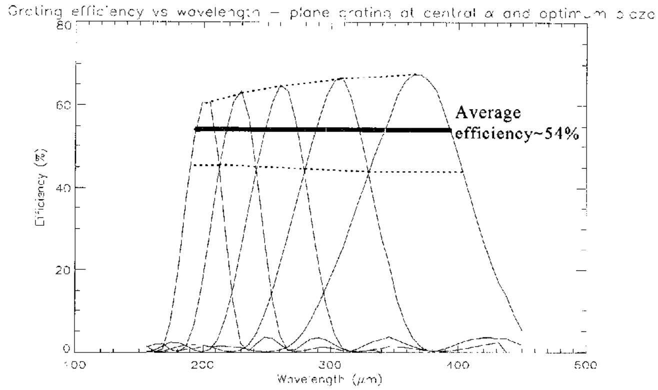


Figure 7: The grating efficiency vs. wavelength for the nominal incidence angle (53°) and the optimum blaze angle for the SPEC BOL grating modelled as a single flat grating. The upper and lower dotted lines are the envelopes for maximum and minimum efficiency in each order respectively. The solid line is the average of these and is taken as the average grating efficiency for all wavelengths in the performance model.

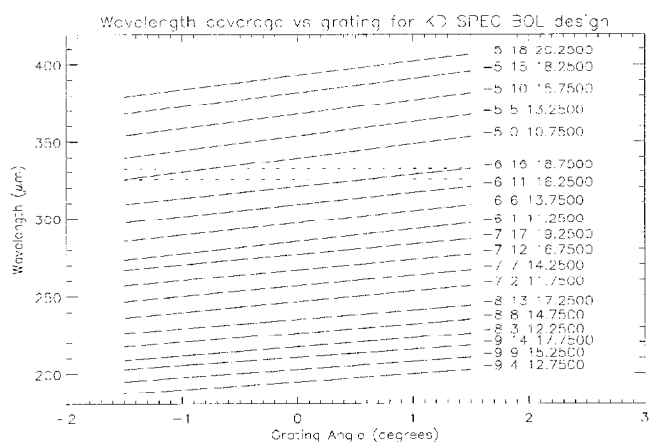


Figure 8: Wavelength coverage, grating order, detector number and central diffraction angle for a possible detector plane configuration in the SPEC BOL grating option. The dotted lines show the maximum wavelength in order -6 and the minimum wavelength in order -5 - it is the need to have overlap between these orders that sets the maximum grating rotation angle.

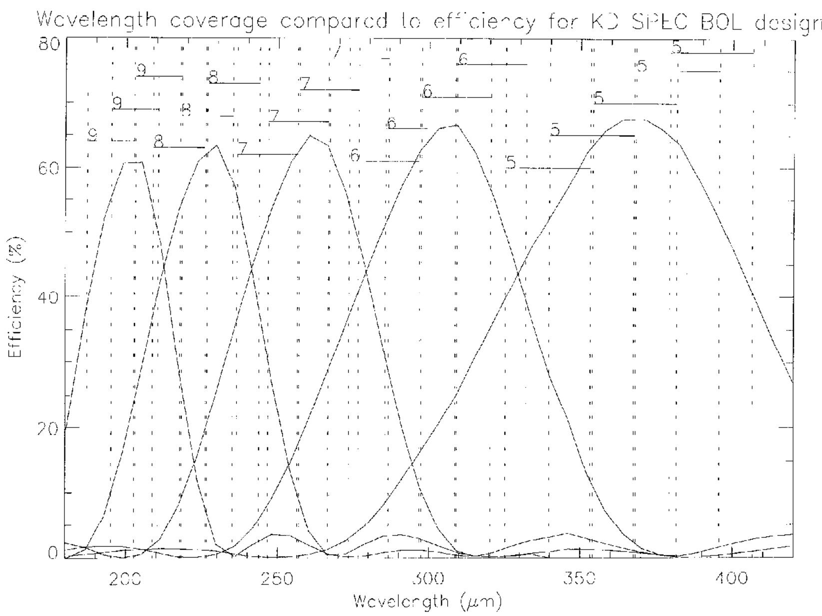
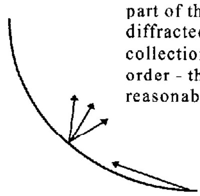


Figure 9: Wavelength coverage for each detector superimposed on the grating efficiency vs. wavelength for the grating modelled as a flat grating with an input angle of 53°. Note the relatively small overlap between order -6 and -5. The difference in efficiency between one detector and the next will, in practice, be rather worse than shown here because of the essentially triangular shape of the filters required for band pass blocking.

OTHER POINTS OF NOTE

A couple of other points of interest to the grating spectrometer design were shown up by this work:

i) In certain circumstances diffraction orders can have small but finite efficiency at very large angles w.r.t. to the local normal (maybe as much as 1-2% at angles close to 90°). In the case of the concave grating this power could be "re-diffracted" from another portion of the grating - the sketch below shows the idea - leading to an increase in the in-band straylight.



ii) Very careful consideration will have to be given to the calculation of the blaze angle. Naively, the blaze angle for any diffraction angle β and incidence angle α is, as defined here, given by:

$$B = 90 - \left(\frac{\alpha - \beta}{2} + \beta\right)$$

So for 200 μm which comes at 15.1° for α=53 at the groove spacing used in PC GRATE (1.7 mm), the blaze angle should be 56°; very close to that given by PC GRATE. When the incidence angle increases to 60°, 200 μm is found at β=11.12°; giving a calculated blaze angle of 54.44. In fact the blaze angle apparently required is rather nearer 55° according to PC GRATE. This discrepancy will have to be closely investigated as will the requirement on the accuracy of the control over the blaze angle across the grating. This is especially important given that the groove spacing - and therefore the diffraction angle - will vary across the grating as well.