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BOL/RAL/N/0002.1

FIRST - BOL

Technical Note

Discussion note on the Grating Spectrometer Option

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Note: F/N/008.01

29 January 1997

Introduction

With possibility of FIRST being brought forward and the re-evaluation of the science goals of the mission. It is now possible that the BOL PDD instrument concept will be modified to use a grating instead of the tandem Fabry-Perot arrangement. This note is intended to promote discussion of what arrangement might be used for grating instrument and highlights some areas that look promising and warrant further study.

Separation of the Photometer and Spectrometer

As the instrument is currently conceived a compromise is made in the detector array between spectroscopy and photometry which leads to the field of view being undersampled unecessarily. Large filters are needed for the order sorting of the FP's and these are of necessity placed well away from the detectors. The use of bolometers means that the straylight control and out of band rejection in the instrument is going to be of paramount importance in determining the final performance of the BOL instrument in both photometric and spectroscopy modes; this looks difficult to achieve with the current design. In a grating instrument the spectroscopic imaging will be one dimensional in nature - i.e. in the cross dispersion direction only, and the full imaging will be achieved either by nodding the spacecraft or by using a scan mirror. In either case it will be difficult to have the same array, or even a split array, used for both spectroscopy and photometry.

For all these reasons it make sense to think in terms of splitting the focal plane into two arrays fed by separate optical trains. In fact the BOL intrument essentially could become two sub-instruments. One suggestion for doing this is sketched out in figure 1.

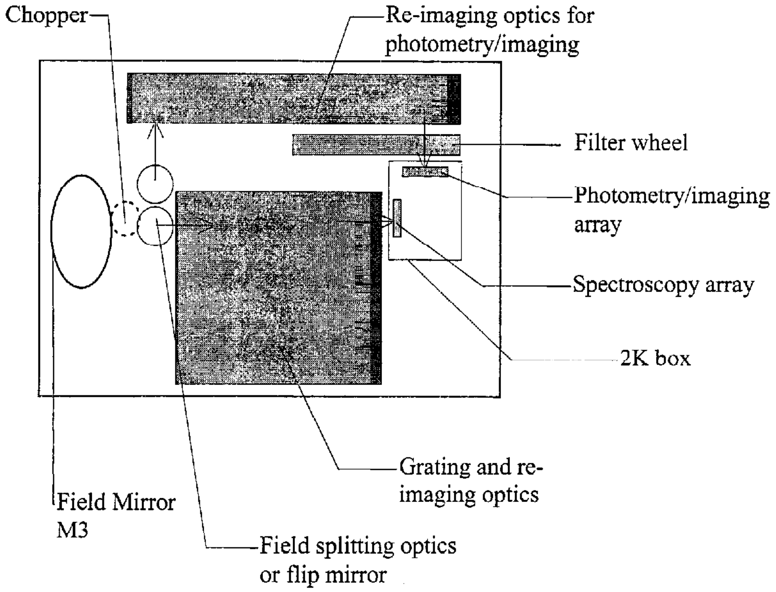

Figure 1: Outline concept for the Bolometer Grating Option.

The basic concept is to split the field of view into two parts: one is fed directly to an imaging bolometer array via re-imaging optics and a dedicated filter wheel; the other is fed via a grating onto a bolometer array that provides imaging across the entrance slit and is filtered to order sort the grating in the dispersion direction (see below). How the field should be split is debatable - in the concept shown in figure 1 one could imagine that the chopper and field mirror are so arranged that while the spectrometer recieves the on axis protion of the field the photometer an off axis portion and vice versa. However this may not be acheivable owing to vignetting of the field as the splitting of the field is well away from the focus of the telescope. Another (simpler?) option would be to place a flip mirror to direct the whole field either into the spectrometer channnel or the photometer channel - this has the disadvantage of a loss of parallel observations in the two modes.

The photometer channel now becomes extremely simple and the filters (and the wheel) can be much smaller with many more dedicated filters and the posibility of using part of it as a CVF. The motor for the wheel can also be placed outside the instrument enclosure completely and the optical path can be highly baffled to control any straylight.

The Grating Spectrometer

The basic consideration for the design of a grating spectrometer is the size of the grating needed for a given resolving power. Standard texts give the resolving power of a grating as:

$$R_g = \frac{W_g(\sin\beta - \sin\alpha)}{\lambda}, \qquad (1)$$

where W_g is the width of the grating, α and β are the input and exit angles of the difracted beam and λ the wavelength. The resolving power given by this formula is that for the Rayliegh criterieon - i.e. the maximum of one resolution element placed at the first minimum of another. If a resolving power of 1000 is required at around 300 μm then clearly a grating of order 300 mm is necessary.

Several options present thamselves for the mounting of the grating - the most likely are as follows:

i) Littrow:

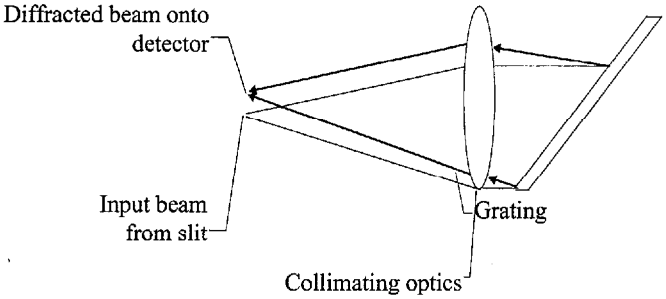

Figure 2: The Littrow mount.

Here the same optics are used both for the input beam and the diffracted beam and input and diffracted beams are on the same side of the grating normal, which gives maximum resolving power. Using the same optics is not always an advantage however as both the input and difracted beams will have to have the same speed and this may lead to compromises in straylight baffling and could make the instrument too big.

ii) The "LWS" Configuration:

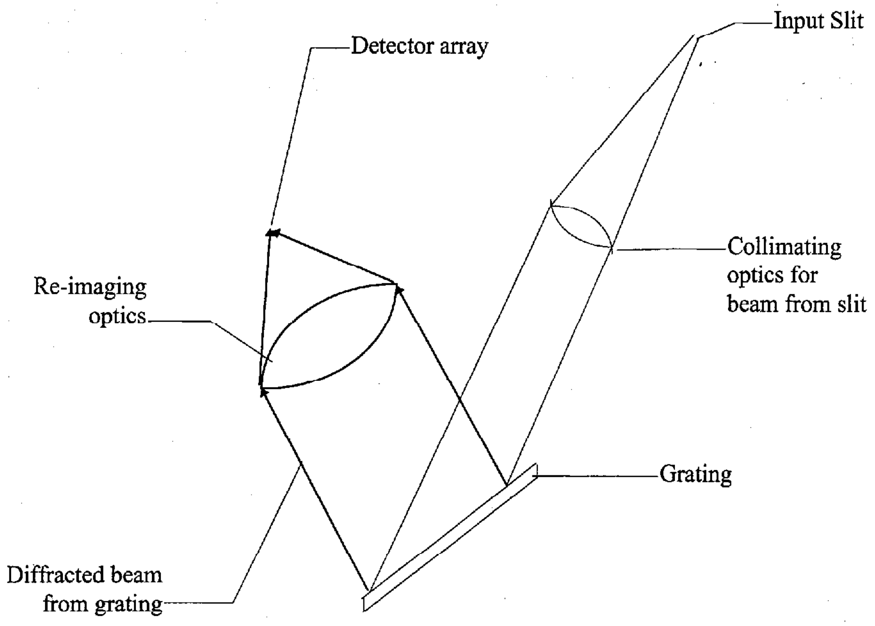

Figure 3: The configuration used in the LWS.

In the LWS a different set of optics are used for the input collimator and for the re-imaging of the diffracted beam from the grating. This has the advantage that the two beams can have different speeds which can be used to make a more compact instrument. In the LWS the re-imaging mirror and grating make up a Schmidt camera with the corrector plate being a figure applied to the grating itself. A Schmidt camera has the advantage of having aberration free imaging but the size of the instrument may be unacceptable because the mirrors will have to be large. To make the instrument more compact a shallow diffraction angle can be used with the orders overlapping, however the corrollary of this is that, in order to maintain the resolving power, a large input angle must be used. Whether this will affect the overall efficiency of the grating remains a subject for further study; in the case of the LWS it does not seem to have been a problem when working in first and second order.

iii)Wadsworth:

This is a variation on the Rowland circle configuration using a concave grating. It has the advantage of being extremely simple as it only requires two optical elements; a collimating mirror and the concave grating. However in practice the size of both the mirror and the grating are limited if the best imaging and resolving power are to be achieved with an instrument of reasonable size. Also the width of the rulings have, in practice, to be variable across the grating to maintain the resolving power and image quality for all diffraction angles.

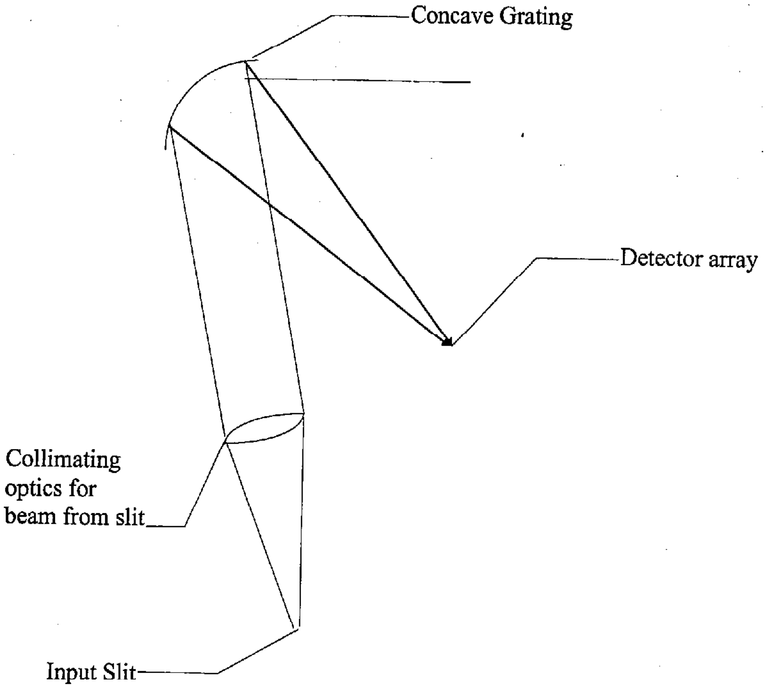

Figure 4: The Wadsworth mount.

The Use of Overlapping Orders

Apart from the resolving power and wavelength, another critical design driver for the BOL instrument is the necessity to keep the detector arrays as compact as possible to prevent excessive heat load on the 100mK stage. This means both keeping the focal length of the re-imaging optics as short as possible and keeping the angular separation of the detectors as small as possible. One way to do this is to overlap several orders and use filters on the detector arrays for order sorting - the grating can then be moved to effectively change both the input and output angles for a given detector array thus scanning the spectrum.

The angular dispersion of a grating is given by:

$$D = \frac{d\beta}{d\lambda} = \frac{1}{\lambda}(\sin\beta - \sin\alpha)\cos\beta. \quad (2)$$

This increases with increasing input angle and is a complicated function of both input and output angle. In the Littrow mount it increases non-linearily with increasing angle and to keep the instrument as compact as possible one would minimise the input angle. However (1) shows that this will be at the expense of resolution. From (1) it can be seen that $\beta=-\alpha=30$ would give a resolution of 1000 at 300 μm for a 300mm grating. Figure 5 shows the range of wavelengths covered for this situation for a grating working in 3,4,5 and 6 orders.

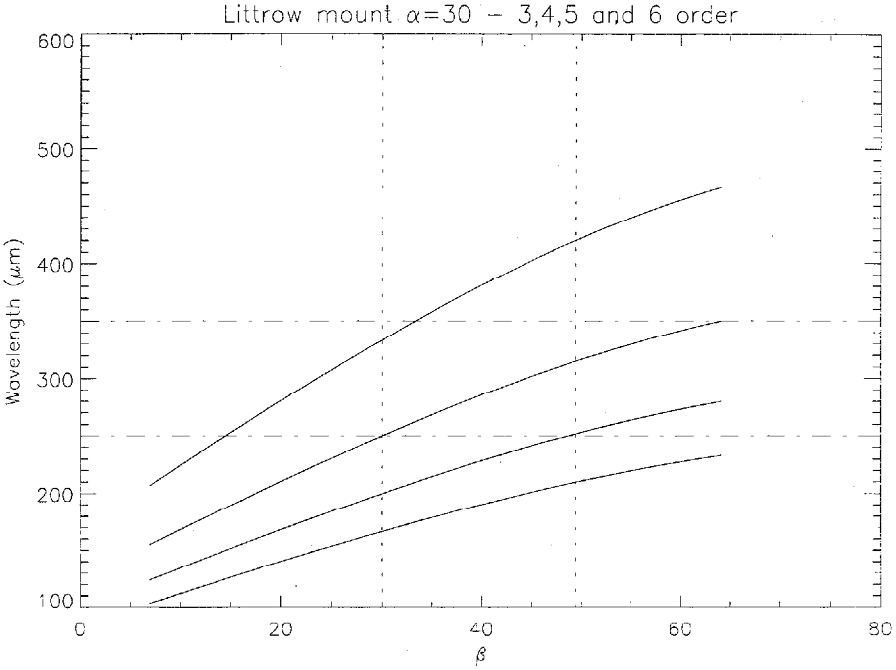

Figure 5: Range of wavelengths covered for a grating in a Littrow mount with $\alpha=-\beta=-30^{\circ}$. The vertical lines show what angular coverage is required for orders 4 and 5 to butt up to each other. The horizontal lines show the nominal 250-350 μm range of the BOL instrument.

For the Littrow configuration to work, the light has to be diffracted to angles beyond the input angle - either higher or lower. To avoid sacrificing resolution a higher output angle is chosen. It can be seen from figure 5 that about 20° are required to give full coverage over the nominal BOL wavelength range. This could be acheived by scanning the grating through about ± 10° or by placing detectors at 3-4° intervals over the focal plane with a total dispersion of, say, 16° and scanning the grating over a smaller range of angles. If the size of the grating is taken as the "aperture" for the re-imaging optics and these have an F number of 2, then the detectors would have to be spread over about 160 mm - this may be too big. On the other hand moving a 300 mm grating through ± 10° could also prove difficult to achieve in practice.

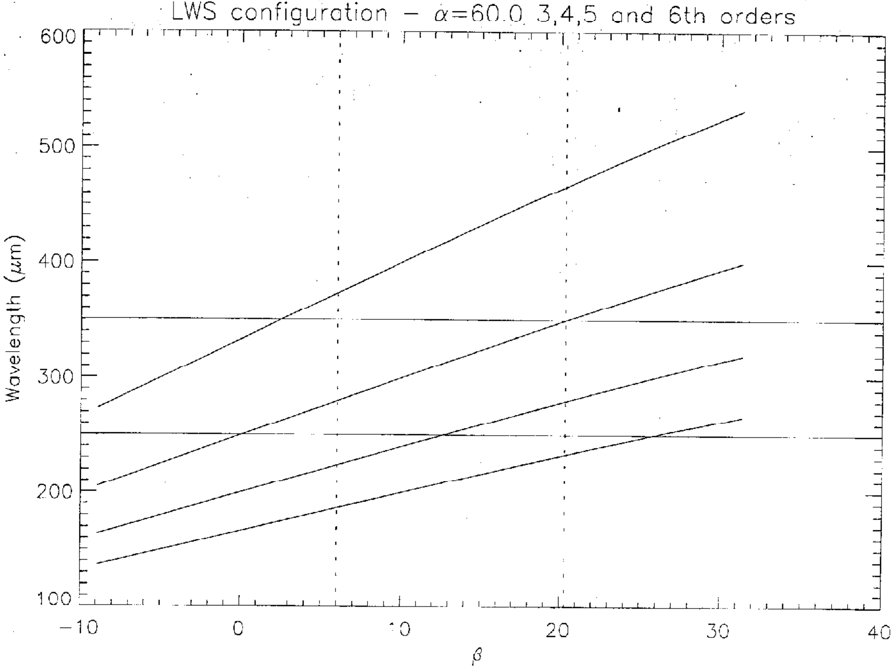

Figure 6: Range of wavelengths covered for a grating in an LWS configuration with α=–60° . The vertical lines show what angular coverage is required for orders 4 and 5 to butt up to each other. The horizontal lines show the nominal 250-350 μm range of the BOL instrument

With the LWS configuration there is more freedom to choose the input and diffraction angles. Figure 6 shows the range of diffraction angles required to cover the nominal BOL operating range in 4th and 5th orders together with the wavelength ranges simultaneously available in 3rd and 6th orders. This is for an input angle of 60° . It can be seen that wavlengths from ~180 to ~450 μm can be covered with an angular range of about 14° centred on 13° ;moreover the wavelength coverage is contiguous over this range except a small gap at 350 μm. The wavelength coverage can be achieved either by dispersing the detectors in the focal plane and scanning the grating or a scan mirror over a limited range of angles (± 3°); or by having a more limited dispersion of the detectors in the focal plane and scanning the grating over a wider range. The latter option is attractive given the need to have a compact focal plane and figure 7 shows the wavelength coverage of a single detector placed at a diffraction angle of 13° in each of the four orders while the grating is scanned. It can be seen that scanning the grating through ± 6° is sufficient to give contiguous wavelength coverage, albeit with limited overlap between the orders. This latter could be improved by dispersion of the detectors in the focal plane and/or by scanning the grating slightly further. This scan range is the same as used on the ISO LWS.

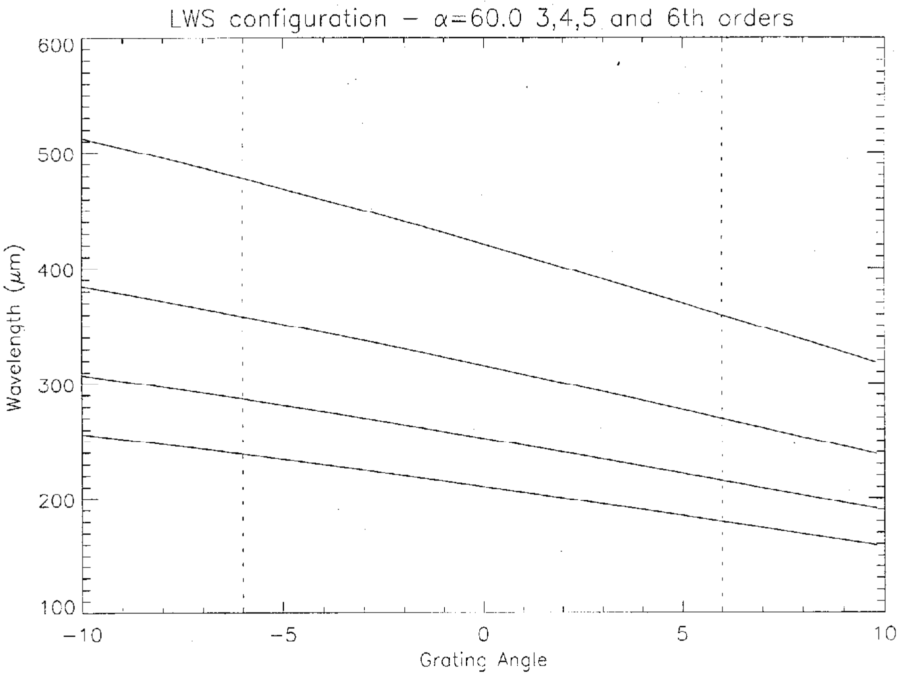

Figure 7: Wavelength coverage for the LWS configuration as the grating is scanned for a detector placed at 13° and an input angle of -60°. The vertical lines indicate a possible scan range for the grating and the commensurate wavelength range in each order.

For this configuration the centre of order wavelengths and resolving powers are as follows:

Order	Wavelength at 13°	Resolving Power
3	420	780
4	315	1039
5	252	1299
6	210	1560