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THE DESIGN OF A BOLOMETER INSTRUMENT FOR FIRST

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ABSTRACT

The model payload for the FIRST satellite includes an submillimetre direct detection instrument using bolometric detectors, known as the BOL. The scientific drivers for this instrument are discussed and the essential features of the current instrument design are described. The BOL comprises a three-band imaging photometer covering the 200-500μm range and a grating spectrometer with a resolution of order 10^3 covering wavelengths between 200 and 350 μm. The detectors are bolometers cooled to 300 mK or less. The photometer is optimised for deep photometric surveys, and can observe simultaneously the same field of view in all three bands. The grating spectrometer is optimised for spectral rather than spatial multiplexing, the aim being to measure the complete spectrum as rapidly and sensitively as possible.

1. INTRODUCTION

One of the most important scientific projects for the FIRST mission is to investigate the statistics and physics of galaxy formation at high redshift [Refs. 1, 2]. This requires the ability to carry out deep photometric imaging at far-infrared and submillimetre wavelengths (1-500 μm) to discover objects, and the ability to follow up the survey observations with spectroscopy of selected sources. The FIRST bolometer instrument is essential for this programme, and is being designed so as to be optimised for these extragalactic imaging and spectral surveys. In addition, there are many other scientific projects which will be addressed by the BOL, including an unbiased search for protostellar objects within our own galaxy [Ref. 3].

2. THE "RED BOOK" INSTRUMENT

In the FIRST "Red Book" [Ref. 1], a bolometer instrument was described based on a tandem Fabry-Perot spectrometer with a resolution of around 3 x 10^3 and a filter-wheel imaging photometer covering the 200 - 900 μm range. The current design is a departure from this concept for both scientific and technical reasons. Following the recent review of the key science goals for FIRST in the light of the capabilities of currently existing and planned facilities such as SOFIA, large-aperture single-dish mm/submm telescopes and millimetre arrays, it became clear that the Red Book design should be modified and tailored for the high priority science goals of the mission.

With the launch of FIRST now within sight, it is also essential to consider a realistic instrument design involving proven technology, simplicity of operation, low technical risk and affordability. In the context of these requirements a design based on a grating spectrometer and a photometer without a filter wheel has been adopted. This has a number of advantages over the original tandem Fabry-Perot design:

(i) simpler instrument construction and operation;

(ii) higher reliability (the Fabry Perot option included three wheel mechanisms in series);

(iii) less development effort: the revised instrument is based on proven technology (but will be designed so as to take advantage of possible improvements in bolometer array technology);

(iv) higher overall transmission efficiency;

(v) better spectral response function: for a given resolution, the grating response function (roughly Gaussian) is much more well-defined spectrally than the F-P response function (Airy profile) which contains significant amounts of power outside the nominal spectral resolution element.

(vi) the spectral multiplex advantage of the grating over the F-P makes it more suitable for spectral survey work;

(vii) with the grating instrument, it is easier to separate the functions of spectroscopy and photometry and thus to optimise each separately;

(viii) in the original design, the bandpass filters needed to be in the filter wheel at 4 K, posing problems with the temperature stability of the filter wheel and with the significant photon noise emitted from the 4-K filters: without the filter wheel, it is now possible to put the band-pass filters at 2 K or less, eliminating these problems.

The main disadvantages of the grating option are that the instrument is not well optimised for imaging spectroscopy and that it is difficult to achieve a high spectral resolution (> 1000) without having a very large instrument. However, in the light of the main science goals for the mission, and for the BOL in particular, these are not seen as serious drawbacks.

3. THE REVISED BOLOMETER INSTRUMENT

The imaging photometer

The BOL instrument now being studied contains a three band imaging photometer with nominal wavelengths of 250, 350 and 500 µm and a spectral resolution $\lambda/\Delta\lambda \approx 3$. Three detector arrays observe the same approximately 5-arcminute field of view simultaneously, with dichroic beam dividers separating the bands. The photometer is shown schematically in Fig. 1.

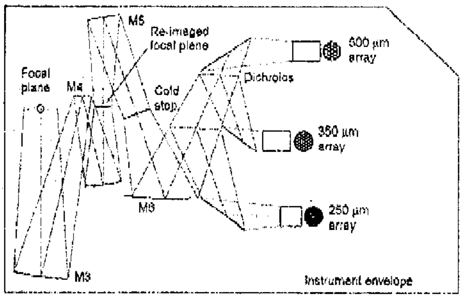

Figure 1: Schematic optical layout of the imaging photometer

The telescope focal plane lies above the input mirror of the instrument (M3). An image of the telescope pupil (secondary mirror) is formed at the chopping mirror M4. This pupil image is then re-imaged by M5 onto the cold stop after the folding flat M6. Mirror M7 produces an image of the focal plane at the detector arrays. Mirrors M3-M6 are at 15 K, the temperature of the BOL instrument outer case. The aperture stop marks the boundary between the 15-K and 4-K stages. The two dichroics and final folding mirror for the long-wavelength detector array are at a temperature of 1.7 K, cooled by a direct thermal strap to the FIRST helium tank. For efficient performance, the angle of incidence of the beam on the dichroics must be less than about 25°.

In the base-line design, the focal plane arrays incorporate spider-web absorbers using NTD germanium thermistors [Refs. 4, 5]. The bolometer sensitivity (NEP ~ 6 x 10^{-17} W $Hz^{-1/2}$) and speed of response (time constant ~ 30 ms) requirements for the BOL can easily be met by spider-web bolometers operating at ^{3}He temperature. The spectrometer needs a detector NEP of 1 x 10^{-17} W $Hz^{-1/2}$ or less with a similar time constant, which may also be achievable at a temperature close to 300 mK.

The bolometers are fed by single or few-moded feed-horns of entrance aperture roughly 2Fλ, where F is the focal ratio of the final optics. Signal readout is via cold JFETs located on the 50-K shield of the cryostat, but heated to a temperature of around 100 K. This array design is similar to that of ground-based bolometer array receivers such as the SCUBA instrument on the JCMT [Ref. 6] and the 19-channel bolometer array on IRAM [Ref. 7]. The BOL array parameters are summarised in Table 1, and the three arrays are illustrated to scale in Fig. 2. The array diameter in the focal plane is around 25 mm, and he three arrays observe simultaneously the same roughly 5-arcminute field of view.

λ_0 (µm)	No. of pixels	FWHM (arcsec.)
250	61	18
350	37	25
500	19	36

Table 1: Photometer array parameters

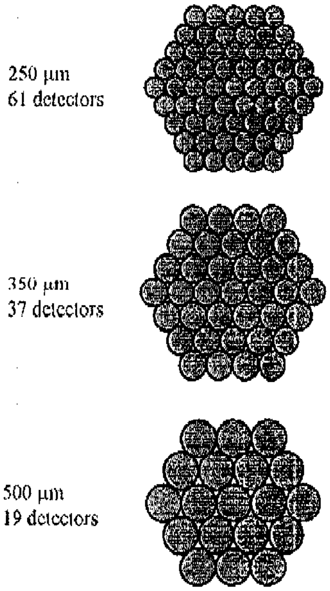

Figure 2: Hexagonally close-packed detector arrays (to scale). Each array is approximately 25 mm in diameter and has a field of view of approximately 5 arcminutes.

The arrays contain as many detectors as can be accommodated within the field of view available to the BOL. While the feed-horns are close-packed in the focal plane, the beams on the sky are separated by twice the diffraction-limited FWHM for 2Fλ horns: thus the array does not fully sample the field of view. In order to make a fully-sampled map (half-beam spacing), it is therefore necessary to perform at least 4 x 4 = 16 separate pointings of the array. When mapping simultaneously with the three arrays, a pointing step of 9 arcsec. is needed to sample fully the image at 250 μm. Since the beam separation at 500 μm is twice that at 250 μm, an 8 x 8 = 64-point map will need to be made. The maps made at 350 and 500 μm will then be comfortaly over-sampled.

An alternative approach to the array implementation is to use pixels of size ≤0.5Fλ which fully sample the image in the focal plane. For a given number of detectors of the same sensitivity, it takes the same length of time to make a fully-sampled map of a given area of sky to a given noise level, regardless of the pixel size. In principle, therefore, the two schemes are equivalent. However, the filled-array option offers the prospect of having a much larger number of detectors thereby improving the sensitivity for deep surveys. Other advantages would be the reduction of observing overheads associated with telescope motion, less susceptibility to pointing inaccuracy, and a smaller instantaneous field of view resulting in lower aberrations at the edge of the field.

It is not feasible to use feed-horns to implement pixels much smaller then 2Fλ because the horn aperture efficiency decreases rapidly as the diameter is reduced [Ref. 6]. Over-sampling of the image in the focal plane thus requires the elimination of detector feed optics and the use of an array of bare bixels (as is done at shorter wavelengths with CCDs and infrared arrays). Such filled bolometer arrays are in development [Ref. 8] but have yet to be demonstrated. The filled array is therefore an option for the photometer which can be adopted if the technology is proven in time for FIRST and if their greater susceptibility to stray light does not prove to be a problem.

The grating spectrometer

The photometer and grating spectrometer will have common input optics and use the same cryogenic system to cool the detectors, but their optical chains will be otherwise entirely independent, and will occupy separate compartments within the instrument. The spectrometer will cover the wavelength range from 200 - 350 μm. There will thus be some overlap with the PHOC instrument at short wavelengths and with the HET instrument at longer wavelengths. It will be designed for maximum spectral multiplexing, with a minimal capability for imaging along the slit. One or two linear arrays of around 20 detectors will sample the spectrum produced by the grating. Several designs are being studied, which fall into two basic categories: either a concave grating or a Littrow design with a planar grating. Figure 3 shows the essential features of an optical scheme for a Littrow design. The fore-optics are shared with the photometer part of the instrument. The collimated beam is dispersed by the grating (length ~ 200 mm) and enters a two-mirror Gregorian camera. The first mirror creates an image of the sky where a field stop is placed to control stray light. The second camera mirror focuses the spectrum onto one or two linear arrays of bolometers. The grating and camera mirrors are at 4 K and the field stop and subsequent mirrors are at 1.7 K. The photon noise limited NEP will be around 5×10^{-18} W $Hz^{-1/2}$. A practical target for the detector NEP is around 1×10^{-17} W $Hz^{-1/2}$. The spectrometer will therefore be detector-noise limited.

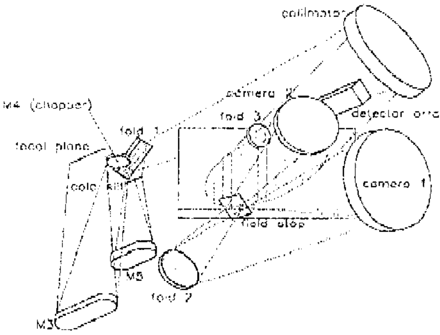

Figure 3: Possible optical layout of the grating spectrometer.

4. SENSITIVITY ESTIMATION

The sensitivity of the BOL instrument has been estimated under the following assumptions:

- Telescope temperature = 80 K
- Telescope diameter = 3.5 m
- Telescope emissivity = 0.04
- Optics efficiency = 30% (photometry)
  = 20% (spectroscopy)
- Spectral resolution = 3 (photometry)
  = 1000 or 400 (spectroscopy)
- Bolometer NEP = 1.0×10^{-17} W $Hz^{-1/2}$
- Bolometer quantum efficiency = 0.8
- Bolometer feed-horn efficiency = 0.7

- Single-mode throughput ($A\Omega$) $= \lambda^2$
- Chopping efficiency factor = 0.45
- Observing efficiency = 70%
- Required step size for imaging = 9 arcsec. (full spatial sampling at 250 μm)
- Spectral sampling interval = ¼ resolution element
- Number of detectors sampling the spectrum = 20
- Number of spectral elements which must be scanned to measure an unresolved line = 5

Table 2 gives the estimated sensitivity limits for photometry and mapping and the sensitivity for spectroscopic observations is summarised in Table 3.

λ_o	(μm)	250	350	500
Photon noise NEP	(W $Hz^{-1/2}$ x 10^{-17})	26	13	5.8
NEFD	(Jy $Hz^{-1/2}$)	58	51	43
Limiting flux density for point source (1 σ; 1 hour)	(mJy)	0.68	0.60	0.51
Limiting flux density for 5' x 5' map (1 σ; 1 hour)	(mJy)	3.3	2.9	2.4

Table 2: Estimated sensitivity of the BOL for photometry and mapping. The three bands are observed simultaneously.

Limiting line flux (Full spectrum) (1 σ; 1 hour)	(W m^{-2} x 10^{-18})	R=1000 : R=400 :	2.4 1.8
Limiting line flux (Known line) (1 σ; 1 hour)	(W m^{-2} x 10^{-18})	R=1000 : R=400 :	1.0 1.1

Table 3: Estimated sensitivity of the BOL grating spectrometer. The figures are largely independent of wavelength.

The photometer is photon noise limited, with the telescope making the dominant contribution. For the spectrometer, figures are given for spectral resolving powers of 400 and 1000. The latter is the design goal for the instrument, but 400 may be closer to what can be achieved in practice given the constraints on the size and mass of the instrument. For measurement of a line of known wavelength, which involves scanning the grating across the line and employing only one detector, the sensitivity is very weakly dependent on the resolving power because the system is close to being detector noise limited. But for a survey of the complete spectrum, the sensitivity is improved at lower resolving power because the number of grating steps needed to measure the full spectrum is reduced. Further study of the scientific and technical trade-offs will be made to optimise the resolving power.

5. TECHNICAL CHALLENGES

Building the bolometer instrument for FIRST will involve considerable technical and engineering ingenuity. Amongst the problems to be solved are:

(i) Thermal mechanical engineering

It will be necessary to support large masses at the 4-K and 2-K levels in a manner which meets the launch vibration specifications and also satisfies the stringent thermal budget for the FIRST instruments.

(iii) Stray light control

The sensitivity and spectral purity of the BOL instrument are critically reliant on the suppression of stray radiation. This is a particular problem at submillimetre wavelengths due to the small size of the optics in relation to the wavelength (an optical instrument made to the same scale would easily fit inside a 1 mm^3 box), and the significant thermal emission from the instrument itself - even from components at 4 K. An excess background power of 0.01 pW will be enough to degrade the performance of the spectrometer detectors.

(iii) Incorporation of planar detector arrays

The use of planar arrays could in principle improve the sensitivity for deep imaging photometry, for the reasons mentioned above. To be incorporated into the BOL instrument, this array technology will need to be developed and demonstrated on a very short time-scale.

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