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**From** : Matt Griffin and Peter Ade  
**Date** : 17 June 1997  
**Subject** : Workshop on Bolometer Array technology for FIRST

Dear Colleagues,

As you know, ESA will issue an announcement of opportunity for the FIRST payload instruments at the end of September, with a response due in February 1998. The current schedule for the mission is as follows:

AO issue	:	End September 1997
AO response due	:	February 1998
Instrument selection by ESA	:	June 1998
QM delivery	:	June 2002
FM delivery	:	January 2004
FS delivery	:	January 2005
Launch	:	Late 2005 or early 2006

The Bolometer Instrument Working Group continues to study and define the design of an instrument (currently known as the BOI) which we intend to propose in response to the AO, and the essential features of which were described at the Grenoble symposium (see attached write-up).

One of the most important issues in the design and performance of the instrument is the choice of bolometer array technology. The proposal which we submit in February 1998 must adopt as a base-line a mature and proven technology. The best option at the moment is the Caltech/JPL spider-web bolometer coupled to the telescope beam by a feed-horn. Bolometer technology is a rapidly evolving field, and several groups are currently working on the development of bolometer arrays geared towards the requirement of FIRST. Clearly, the goal must be to fly the best available technology consistent with the schedule and with FIRST technical constraints, in order to maximise the scientific return from the mission; this is something which is agreed by all the groups involved.

It is intended that the proposal will describe an instrument based on the base-line technology, while pointing out that further advances in array and readout technology may be forthcoming over the next couple of years and that it may be possible to take advantage of these to build a more powerful instrument; this is already understood by ESA and is acceptable to them. The detailed design of the instrument must proceed during this intervening period, but be kept as flexible as possible. It will also be important that we are able to describe some of the systems implications of alternative technologies in the proposal; and ESA will naturally want to be convinced that the development programme for improved arrays is well organised and co-ordinated within the instrument schedule.

If the 2005/6 launch date is maintained, then the schedule for QM delivery means that the flight technology will need to be frozen by early 2000. It is clearly important to monitor and review the progress of the array development programmes and to co-

ordinate development and evaluation of the possible options. In order to initiate this process, we propose to hold a two-day working meeting at QMW later this year on bolometer array technology, bringing together the main groups whose array technologies are of potential interest. The main aims will be

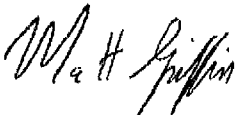
1. To review the scientific requirements of the FIRST instrument.
2. To assess the current status and future plans of the various array programmes.
3. To establish
  - agreed criteria for technology selection;
  - an inter-laboratory test programme for comparing the options;
  - a schedule for the evaluation and selection programme.

Important topics to be addressed include:

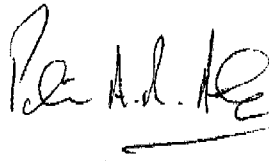
- Review of the FIRST BOL scientific requirements and base-line design.
- Technical constraints for FIRST (stray light, thermal budget, data rate, etc.).
- Relative merits of filled arrays vs. feed-horn arrays.
- Sensor/absorber technology: silicon nitride/NTD germanium/TES/CLA devices.
- Operating temperature requirements.
- Readout electronics and multiplexing.
- Identifying/removing particle hits.
- Status and future plans of various array development programmes.
- Evaluation criteria, test programme, and schedule for assessing the various options and selecting technology to be flown on FIRST.

A suitable time for such a meeting would be some time during September. Please let us know (a) if you agree to participate in this meeting and (b) your availability during this period.

Best regards,



Matt Griffin



Peter Ade

# THE DESIGN OF A BOLOMETER INSTRUMENT FOR FIRST

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## ABSTRACT

The model payload for the FIRST satellite includes a 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 200-500  $\mu\text{m}$  range and a grating spectrometer with a resolution of order  $10^3$  covering wavelengths between 200 and 350  $\mu\text{m}$ . 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 abilities to carry out deep photometric imaging at far-infrared and submillimetre wavelengths (100-500  $\mu\text{m}$ ) to discover objects, and the 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  $3 \times 10^3$  and a filter-wheel imaging photometer covering the 200 - 900  $\mu\text{m}$  range. Since the Red Book was written, the instrument design has evolved away 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 advances 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  $\mu\text{m}$  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.

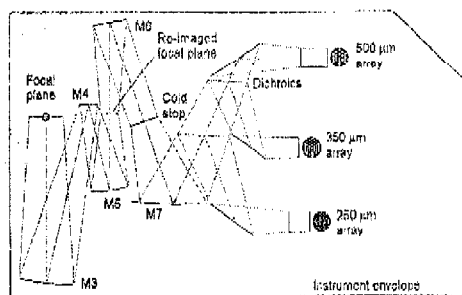


Figure 1: Schematic optical layout of the imaging photometer

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 and M7 are at 4 K, and the two dichroics and final folding mirrors are cooled to 1.8 K 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  $25^\circ$ .

In the base-line design, the focal plane arrays incorporate spider-web absorbers using NTD germanium thermistors [Refs. 4, 5]. The bolometer

sensitivity ( $\text{NEP} \sim 6 \times 10^{-17} \text{ W Hz}^{-1/2}$ ) and speed of response (time constant  $\sim 30 \text{ ms}$ ) requirements for the BOL can easily be met by spider-web bolometers operating at  $^3\text{He}$  temperature. The spectrometer needs a detector NEP of  $1 \times 10^{-17} \text{ W Hz}^{-1/2}$  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  $2F\lambda$ , 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 30-m telescope [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.

$\lambda_0$ ( $\mu\text{m}$ )	No. of pixels	FWHM (arcsec.)
250	61	18
350	37	25
500	19	36

Table 1: Photometer array parameters

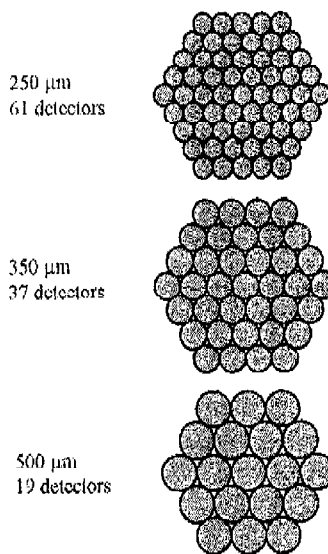


Figure 2: Hexagonally close-packed detector feed-horn arrays (to scale).

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  $2F\lambda$  horns: thus the array does not completely sample the field of view. In order to make a fully-sampled map (half-beam spacing), it is therefore necessary to perform at least  $4 \times 4 = 16$  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  $\mu\text{m}$ . Since the beam separation at 500  $\mu\text{m}$  is twice that at 250  $\mu\text{m}$ , an  $8 \times 8 = 64$ -point map will need to be made. The maps made at 350 and 500  $\mu\text{m}$  will then be comfortably over-sampled.

An alternative approach to the array implementation is to use pixels of size  $\leq 0.5\lambda$ , 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, and would also allow areas smaller than the field of view to be mapped more quickly. 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. Potential difficulties with filled arrays are their much greater susceptibility to stray light and electromagnetic interference, and the need to achieve a high absorption efficiency without an integrating cavity.

It is not feasible to use feed-horns to implement pixels much smaller than  $2F\lambda$  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 pixels (as is done at shorter wavelengths with CCDs and infrared arrays). Such filled bolometer arrays are in development [e.g., Ref. 8] but have yet to be demonstrated. The filled array is therefore regarded as an option for the photometer which can be adopted if the technology is proven in time for FIRST and if its greater susceptibility to stray light does not prove to be a problem.

#### The grating spectrometer

The photometer and grating spectrometer have common input optics and use the same cryogenic system to cool the detectors, but otherwise occupy

separate compartments within the instrument. Their optical chains are separated at the re-imaged focal plane between M6 and M7 shown in Fig. 1. The spectrometer will cover the wavelength range from 200 - 350  $\mu\text{m}$ . 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 an off-axis Littrow design. The fore-optics are shared with the photometer part of the instrument. The collimated beam is dispersed by the grating (length  $\sim 200$  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 1.8 K. The photon noise limited NEP will be around  $5 \times 10^{-18} \text{ W Hz}^{-1/2}$ . A practical target for the detector NEP is around  $1 \times 10^{-17} \text{ W Hz}^{-1/2}$ . The spectrometer will therefore be detector-noise limited.

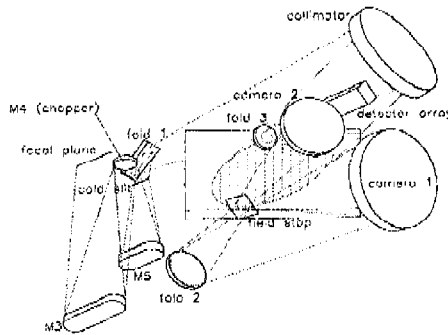


Figure 3: Possible optical layout of the grating spectrometer.

#### 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 =  $1.0 \times 10^{-17} \text{ W Hz}^{-1/2}$
- 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  $\mu\text{m}$ )
- Spectral sampling interval =  $1/4$  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.

$\lambda_c$	( $\mu\text{m}$ )	250	350	500
Photon noise NEP	( $\text{W Hz}^{-1/2} \times 10^{-17}$ )	26	13	5.8
NEFD	( $\text{mJy Hz}^{-1/2}$ )	58	51	43
Limiting flux density for point source (1 $\sigma$ , 1 hour)	( $\text{mJy}$ )	0.68	0.60	0.51
Limiting flux density for 5' x 5' map (1 $\sigma$ , 1 hour)	( $\text{mJy}$ )	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 $\sigma$ , 1 hour)	( $\text{W m}^{-2} \times 10^{-18}$ )	R=1000 : 2.4 R=400 : 1.8
Limiting line flux (Known line) (1 $\sigma$ , 1 hour)	( $\text{W m}^{-2} \times 10^{-18}$ )	R=1000 : 1.0 R=400 : 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 essentially detector noise limited. But for a survey of the complete spectrum, the sensitivity is better for a 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 require 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.

### (ii) 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 fit inside a 1  $\text{mm}^3$  box), and the significant thermal emission from the instrument itself - even from components at 4 K. An excess background power of less than 0.1  $\mu\text{W}$  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. If it is to be incorporated into the BOL instrument, this array technology will need to be developed and demonstrated on a very short time-scale.

#### ACKNOWLEDGEMENTS

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