BOL/QMW/M/0027.10

From : Matt Griffin

Subject : Report on Workshop on Bolometer Array Technology for FIRST

Date : 4 November 1997

Distribution: BOL Institutes (for internal distribution)
Göran Pilbratt
FIRST SAG
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Thijs de Graauw
Nick Whyborn

Dear Colleagues,

The Workshop on Bolometer Array Technology for FIRST took place at QMW on 29 and 30 October. As expected, it proved to be extremely interesting and significant for the BOL instrument. This note summarises the main conclusions and decisions. A copy of the viewgraph package will be distributed to each BOL institute. If anyone else wants one, please ask Judy Long at RAL (j.a.long@rl.ac.uk).

As you will see, we have decided to adopt a less conservative approach in defining the base-line instrument: large-format arrays providing full sampling of the image will now be proposed. This change poses new technical challenges in developing the technology in time and implementing it in FIRST and in coping with the increased on-board data processing requirements; but it is motivated by the facts that bolometer array technology is maturing very rapidly and that there are now good reasons to believe that it can be developed in time for incorporation in our instrument, thereby giving us a substantial improvement in performance.

Best regards,

Matt

Workshop on Bolometer Array Technology for FIRST

QMW, London

29, 30 October 1997

1. Workshop attendance

Peter Ade	QMW
Patrick Agnese	CEA/LETI
Ravinder Bhatia	QMW
Jamie Bock	Caltech
Colin Cunningham	ROE
William Duncan	Oxford. Insts.
Roger Emery	RAL
Walter Gear	ROE/MSSL
Kent Irwin	NIST
Andrew Lange	Caltech
Bruno Maffei	QMW
Harvey Moseley	NASA, Goddard
Göran Pilbratt	ESA
Louis Rodriguez	CEA, Saclay
Bruce Swinyard	RAL
Jean-Louis Augueres	CEA, Saclay
Laurent Vigroux	CEA, Saclay

2. Aims of the workshop

a. To review the scientific requirements of the FIRST Bolometer Instrument(BOL), and the technical constraints on its implementation.

b. To assess the current status and future plans of relevant bolometer array programmes.

c. To establish
- agreed criteria for technology selection;
- an inter-laboratory test programme for comparing the options;
- a schedule for the evaluation and selection programme.

Presentations were made by the various groups working on bolometer array development programmes (Caltech/JPL, CEA Saclay, Goddard/NIST) followed by in-depth discussion of the criteria for array technology selection, the essential tests needed for evaluation of options, the schedule for evaluation, and the question of what should be proposed in the AO response.

3. Conclusions of the workshop

3.1 Change in the base-line BOL detector array technology

The base-line detector array technology for the BOL is to be changed to filled array absorbers with 0.5Fλ pixels instead of feed-horn arrays with 2Fλ pixels.

3.1.1 The previous base-line (now the fall-back option)

- Hexagonally close-packed arrays of $2F\lambda$ circular feedhorns
- Spider-web bolometers
- Dual JFET readout (JFETs at 120 K in a module outside the BOL FPU)
  Note: It was also decided that, for this option, there are compelling technical reasons (related to microphonics and EMC) for putting the JFET module *within* the cold FPU enclosure rather than outside.
- Numbers of detectors:

Photometer	250 µm	61		
	350 µm	37		
	500 µm	19	Total = 117	
Spectrometer	Approx. 40 for either FTS or grating options			

Total no. of detectors in instrument:Approx. 160

3.1.2 The new base-line

- Filled absorber arrays of square $0.5F\lambda$ pixels
- Imaging FTS spectrometer if feasible (still to be confirmed as base-line)
- Bolometer array technology: to be determined (see below)
- Readout electronics: depends on chosen bolometer technology
- Optical design of photometer: Essentially as before, but the requirements for baffling and stray light rejection will be much more stringent.
- Numbers of detectors:

Photometer	250 µm	32 x 32	= 1024	
	350 µm	24 x 24	= 576	
	500 µm	16 x 16	= 256	Total = 185
Spectrometer	25-38 cm^{-1}	16 x 16	= 256	
	38-50 cm^{-1}	16 x 16	= 256	Total = 512

Total no. of detectors in instrument: 2368

3.1.3 Reasons for changing the base-line

(a) The main science driver for the BOL design is the need to have the best possible sensitivity for deep imaging surveys for high-z galaxies. This means having as many detectors as possible. The feed-horn arrays which have been the base-line so far use up all of the available space in the focal plane without producing a fully sampled image of the field of view.

(b) Filled absorber arrays can potentially make use of all of the radiation from the field of view, offering increased sensitivity and a number of other advantages for the BOL:

- Improvement in mapping speed by an order of magnitude or more
- Simplified observing modes (no need for movement of telescope or internal mirror to produce a fully-sampled image)

- Reduced susceptibility to pointing and tracking errors
- Easier imaging spectroscopy with an FTS
- Easier compatibility with simultaneous mappingwith the PHOC

(c) The feed-horn array option is well understood experimentally and there is a good deal of experience with similar systems on ground-based telescopes. It is a reliable conservative design in which we can have full confidence; but by the time the BOL flies (at least eight years from now), it will probably have been superseded by large-format arrays with many more detectors.

(d) The new bolometer array technology is progressing rapidly. A number of development programmes are underway specifically directed at producing large-format arrays suitable for the BOL instrument. The workshop examined the progress and plans of the groups responsible for these various development programmes and concluded that there was good reason to believe that one or more of these technologies could be developed and demonstrated in time for use in the BOL.

(e) Since it is the intention to fly large-format filled arrays if at all possible, it would be more appropriate to incorporate this into the proposal as the base-line when specifying the space-craft interfaces and resource requirements and the internal requirements of our own instrument (e.g., stray light rejection, digital electronics requirements, etc.) and to retain the more conservative feed-horn arrays as a fall-back option.

3.1.4 Technical challenges associated with filled arrays option

- Elimination of stray light within the instrument
- Guaranteeing high per-pixel quantum efficiency
- Coping with the greatly increased data rate and on-board pocessing requirements
- Developing and demonstrating a workable and proven filled array option in time for FIRST

3.2 Change of base-line BOL refrigerator to ^{3}He cooler

The workshop concludes that for the feed-horn and for any of the filled array options, a detector operating temperature of 0.3 K will be sufficient (the only doubt is in the case of the grating spectrometer if the speed of response is as fast as is currently specified, a problem which may be solved if we either fly an FTS or if we relax the speed requirement). Given the much greater simplicity (internal and external) and the higher cooling power of a ^{3}He refrigerator compared with the alternative dilution system, it was decided that the base-line refrigerator for the BOL should be changed to a ^{3}He sorption cooler.

3.3 Plans for the AO proposal

3.3.1 BOL sensitivity estimates to be quoted in the AO proposal

The sensitivity figures already derived for the BOL, based on the feed-horn array option, could be greatly improved upon by using filled arrays. However, the AO response constitutes a promise to ESA and to the scientific community as to the scientific capabilities of the proposed instrument, and it would be unwise to quote numbers which are not yet justified experimentally. It was agreed that it is not appropriate to *guarantee* any level of performance better than that of the feed-horn option until the new technology is proven in practice. The AO response will therefore:

- propose to used filled absorber arrays as described above;
- describe the feed-horn array option as a back-up;

- quote guaranteed sensitivity figures based on our analysis of the feed-horn array option;
- quote much improved*sensitivity goals* based on the envisaged performance of the filled array option.

3.3.2 Description of base-line filled array technology

The exact technology to be flown cannot be decided at present. In the proposal, we will therefore need to describe the array option in generic terms, and the various options (CEA arrays, pop-up or spider-web detectors with TES sensors) will also be briefly described.

There are major differences in the nature and power dissipation of the readout electronics for the various options. We will have to establish an envelope of resource requirements and system parameters (numbers of wires, power dissipation, etc.) compatible with any of the technologies currently under development.

One array option which may be ruled out on technical grounds is the use of JFET readout with large arrays with Ge sensors. This would pose severe problems with the JFET power dissipation in the focal plane unit.

There is very little time between now and the deadline for the first draft of the proposal (mid-December). As a first step in putting together the case to go in the AO, the array groups will provide as much detailed information as possible on the resource requirements of the various options before the Nov. 12 Technical Team meeting.

3.4 Schedule and criteria for array technology selection

3.4.1 Schedule

In the proposal, we must present a plan and schedule for development and evaluation of the various array options and for the final selection. The latest possible date for selection is determined by the deadline for delivery of the Qualification Model of the instrument (QM) to ESA, which is January 2002 in the current schedule. Allowing one year for QM testing prior to delivery, and one year for building and assembly of the QM, this dictates a decision before early 2000. What we put in the AO has to be compatible with this schedule, and it was agreed that January 2000 should be the firm deadline, with mid-1999 as a goal.

A first-cut schedule for the array development programmes and testing was formulated, which covers essentially the next year. More work on this, to formulate a detailed development schedule for the AO response, is needed soon.

3.4.2 Selection criteria

The following criteria for array selection were agreed:

1. To justify the more exacting requirements on the instrument (e.g., stray light and data rate), the array option must be superior to the feed-horn option in mapping speed by a significant factor (say, a factor of 2).

2. If a European option is equivalent or nearly equivalent in mapping speed (within a factor of 50%) to a US option, the European option shall be chosen.

3. A US option, if chosen, shall be fully funded by NASA - no additional effort shall be required from Europe (but the readout electronics and/or warm analogue electronics could

be built in Europe by CEA).

4. The chosen option shall be compatible with available spacecraft resources (especially thermal and telemetry rate restrictions). Some negotiation with ESA on the budgets may be possible, but the figures specified in the IID-A are not likely to change by large factors.

5. The array technology shall be space qualifiable, with a credible process and schedule for qualification being identified.

6. Array prototypes (or at least single-pixel systems) shall have (at the very least) undergone full testing in the laboratory to determine performance parameters. The detailed testing programme and schedule is to be agreed.

7. If necessary, a formal array selection review shall take place prior to the selection deadline, which will select the best option for the BOL based on experimental evaluation:

   - Conformance to the operating and performance requirements
     - Sensitivity; speed
     - Yield
     - Uniformity
     - Crosstalk
     - Ionising radiation susceptibility
     - Etc.
     - Power dissipation
     - Reqd. operating temp.
     - Telemetry rate
     - Redundancy
     - Etc.
   - Instrument optical/thermal/mechanical modelling
   - Accurate estimates of BOL electronics and spacecraft requirements
   - Credible schedule and cost estimates for QM and FM manufacture and delivery, including readout electronics

8. Selection team:

   The array selection shall be based on consensus, with a selection team comprising at least the following: Griffin (PI), Swinyard (Instrument Scientist), Vigroux (Co-PI; CEA group), Lange or Bock (Caltech group), Moseley (Goddard group). The selection process shall be open: external experts and ESA personnel (e.g., Pilbratt, the FIRST Project Scientist; the FIRST Payload Manager) will be invited to observe and advise.

9. Regardless of which technology is flown, all of the participating array groups will wish to maintain a strong interest and involvement in the BOL instrument design, optimisation and scientific exploitation.

FIRST

BOL/QMW/M/0027.10 (VIEWGRAPHS ONLY)

Bolometer Array Workshop · QMW 29 Oct. 97

Attendance

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MATT GRIFFIN

FIRST Bolometer Array Workshop
QMW 29, 30 Oct. 1997

Agenda 29 October

1. FIRST status and schedule	Griffin	09.30
2. The FIRST Bolometer Instrument: scientific requirements; base-line design; technical constraints	Griffin	09:45
Coffee		10.30
3. Filled arrays as alternative to feed-horn arrays for the BOL	Griffin	10.45
4. Overview of the US array development programme	Lange	11.15
5. Spider-web bolometer programme	Bock	11.30
Lunch		12.45
6. CEA planar array programme	Rodriguez	14.00
Coffee		15.15
6. Pop-up detector programme	Moseley	15.30
7. Discussion + Agenda for Day 2	All	16.45
End Day 1		17.30

Agenda 30 October: to be arranged

1. Criteria for array technology selection
2. Essential tests needed for
   (i) AO response
   (ii) Final evaluation of options
3. Schedule for evaluation
4. Agreement on content of AO response
5. Visit to QMW lab.

Aims of the meeting

1. To review the scientific requirements of the FIRST Bolometer Instrument (BOL), and the technical constraints on its implementation.

   Note:
   - The dilution cooler is still the base-line for the BOL, but there are strong reasons for changing to a ^{3}He cooler if we can meet the performance requirements and it is a workable solution in practice.

2. To assess the current status and future plans of relevant bolometer array programmes.

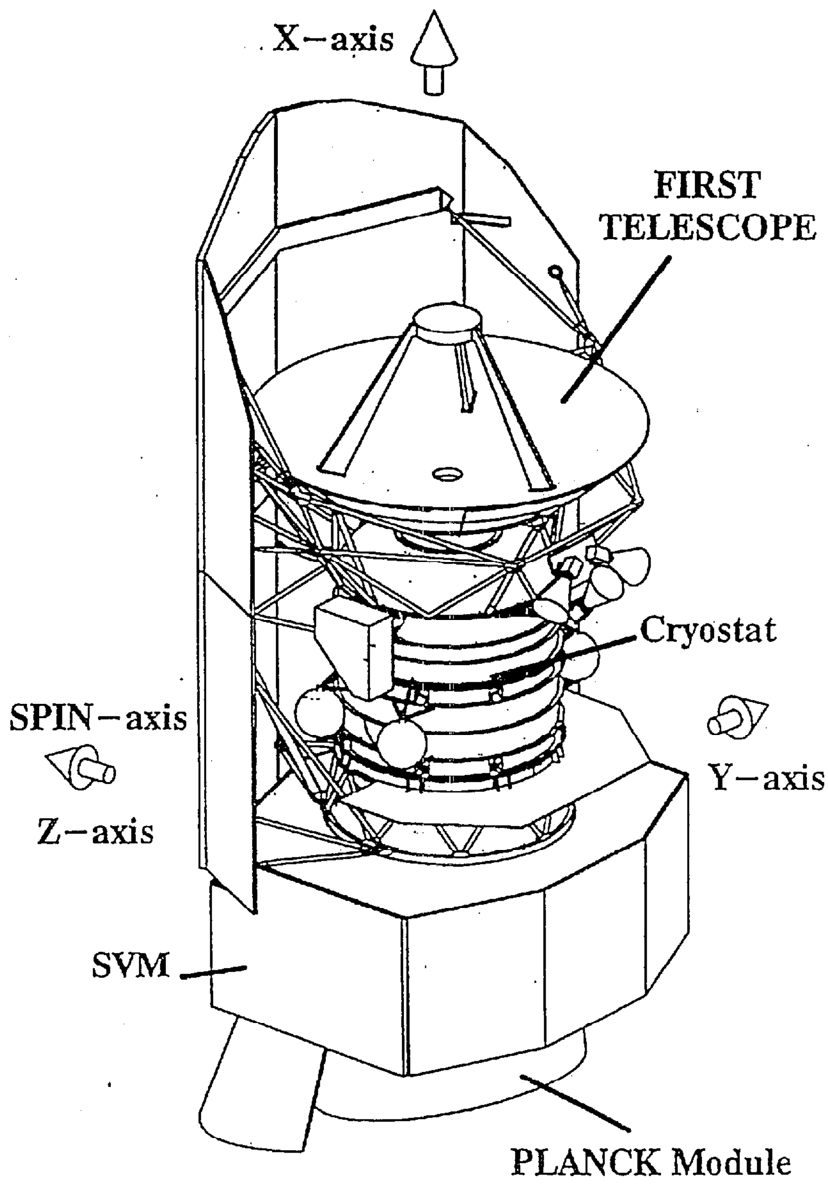
3. To establish
   - agreed criteria for technology selection;
   - an inter-laboratory test programme for comparing the options;
   - a schedule for the evaluation and selection programme.

Where possible, those making presentations describing the various array options should try to address the following:

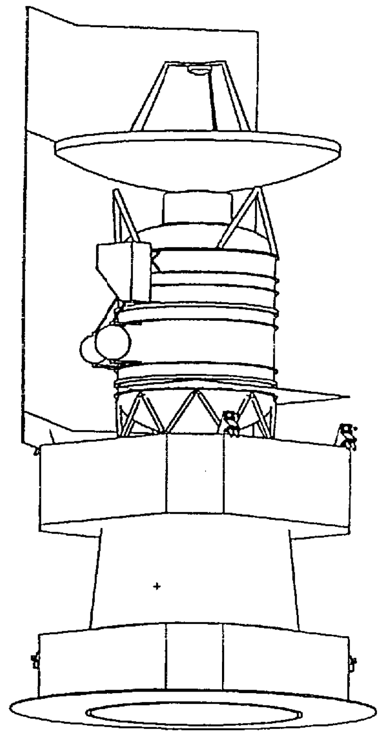
- Scientific performance and compatibility with BOL sensitivity/speed requirements
- Operating temperature (and temperature stability) requirements
- Heat-loads on low temperature stage due to dissipation and wiring
- Power dissipation at 2 K and/or 4 K
- Ionising radiation effects and how to identify them and correct for them
- Pixel angular response and susceptibility to stray light
- Cross-talk
- Achievable array size
- Read-out electronics and multiplexing
- Warm analogue electronics requirements
- On-board processing and telemetry rate requirements
- Space qualifiability

FIRST schedule: From AO to Launch

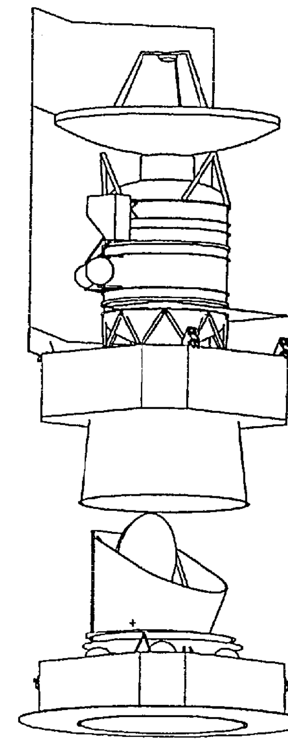
ESA briefing preparation	Nov. 7
ESA AO briefing meeting	Dec. 3
First draft of proposal ready	Mid Dec.
Full BOL consortium meeting in Florence (proposal review)	Jan. 8/9
Proposal submission deadline	Feb. 16
Proposal evaluation by ESA	Feb. - May 98
Clarification meetings	Mar. - Apr. 98
Recommendation by Evaluation Committee	End Apr. 98
AWG/SSAC review	May 98
PI pre-selection by SPC	End May 98
Payload confirmation by SPC	Feb 99
Instrument EM delivery	July 2001
Instrument QM delivery	Jan. 2002
Instrument FM delivery	Jan. 2004
ICC readiness	Dec. 2004
Instrument FS delivery	Jan. 2005
Launch	Dec. 2005


X−axis
FIRST
TELESCOPE
Cryostat
SPIN−axis
Z−axis
Y−axis
SVM
PLANCK Module

SATELLITES DURING TRANSFER PHASE



SATELLITES AFTER SEPARATION



MASS BUDGET COMPARISON (2/2)

	FIRST/PLANCK (Baseline)	**FIRST and PLANCK (Alternative concept)**
TOTAL DRY MASS	3911	3928
FUEL MASS	629	591 + 20 (N2)
ADAPTOR	190	98
TOTAL LAUNCH MASS (incl. ESA reserve + system margin)	**4730 kg**	**4637 kg**
ARIANE 5 MARGIN	**18 kg**	**111 kg (TBC)**

BOL science drivers

- Deep photometric surveys
  - high-z galaxies
  - protostars

- Follow-up spectroscopy + higher S/N photometry
  - using BOL itself
  - using other FIRST instruments

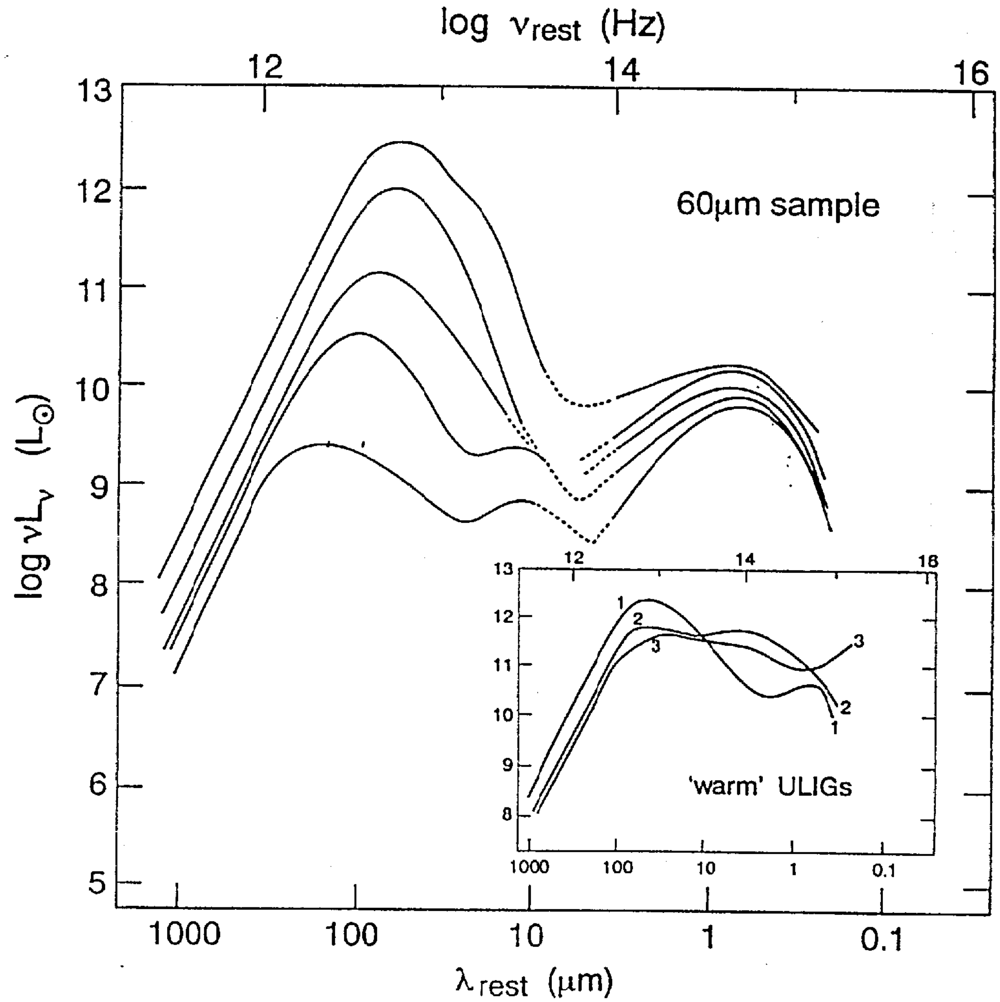
- Telescope background limited
  - Increasing mapping speed means increasing number of detectors

- BOL multi-band imager must be optimised for deep survey project

Galaxy formation and evolution in the early universe

- Systematic study of high-z universe
- Starburst thermal peak redshifted from ~ 50 μm to a few 100 μm
- BOL is the primary instrument for this major survey project
- Many thousands of galaxies will be detected, most at $z > 1$
- Test models of galaxy spectra and evolution, luminosity function, star-formation history
- Follow up with spectroscopic observations → physics and chemical evolution

Sanders & Mirabel
Ann. Rev. Astron. Astrophys.
Vol. 34, 1996



BOL extragalactic survey

- Red Book (1993) proposed shallow, intermediate, deep surveys
- PLANCK HFI survey 5-σ sensitivities:
  - 850 μm: 100 mJy
  - 550 μm: 120 mJy
  - 350 μm: 950 mJy
- BOL capabilities enhanced compared to Red Book (more detectors; simultaneous multi-band imaging)
- Revised survey plan: Deep survey of ~ 60 sq. deg. area (approx. 5 months)
- Predicted counts (based on models of Pearson & Rowan-Robinson, 1996 and Franceschini et al., 1994):

λ (μm)	250	350	500
1-σ per pixel (mJy)	4.0	3.6	3.0
5-σ per pixel (mJy)	20	18	15
Sources/sq. deg.	370	400	140
Source density for 5-σ confusion	1300	660	320
No. of sources in 60 sq. deg.	22500	24000	8500
Fraction with z >1	30%	60%	90%

- Cirrus confusion limit:
  - 5-σ limit < 1 mJy for $I_{100\,\mu m}$ < 2 MJy Sr^{-1} (based on Gautier et al., A. J. 103, 1313, 1992)

The BOL Instrument

- **Three-band imaging photometer**

  - λ = 250, 350, 500 μm

  - $\lambda/\Delta\lambda \sim 3$

  - Sensitivity limited by telescope thermal emission

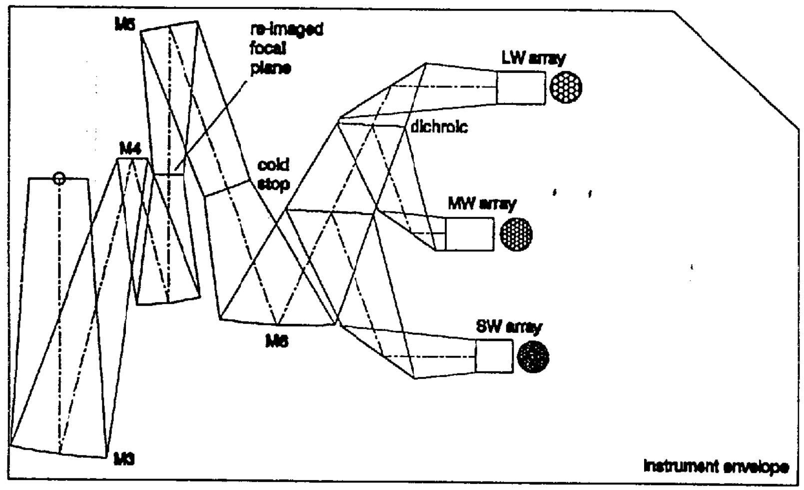
  - Three hexagonally close-packed bolometer arrays

  - Simultaneous observation of same ~ 5 arcmin. field of view

  - Total of 117 detectors

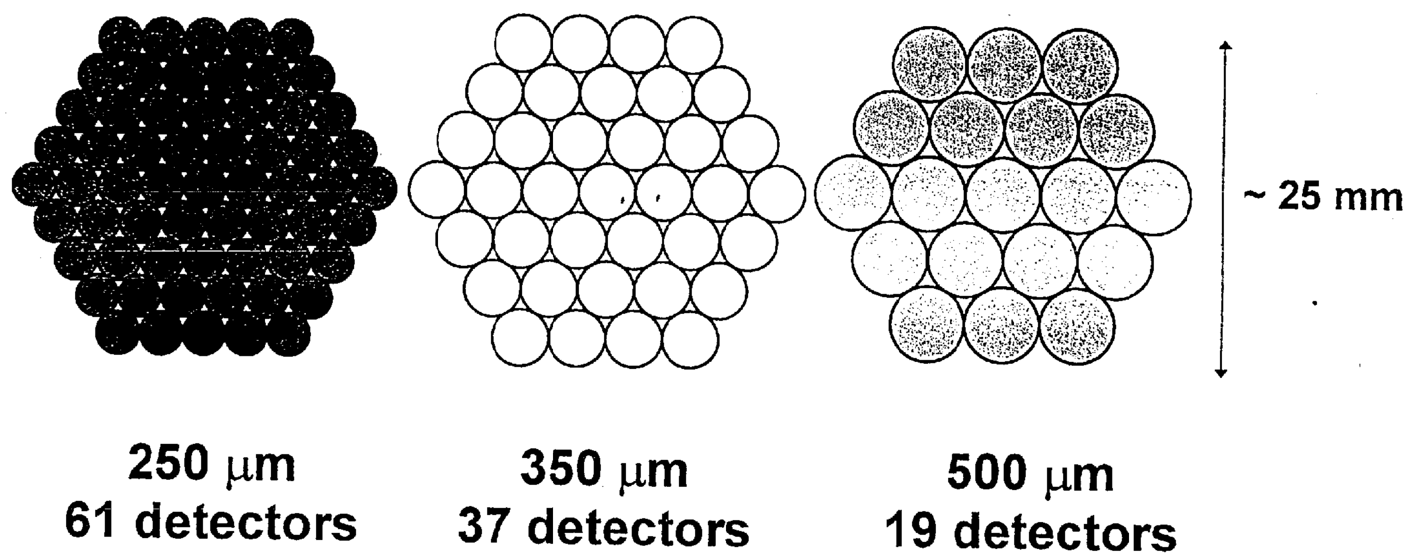
λ_o (μm)	No. of pixels	Beam width (arcsec.)
250	61	18
350	37	25
500	19	36

PHOTOMETER OPTICAL LAYOUT

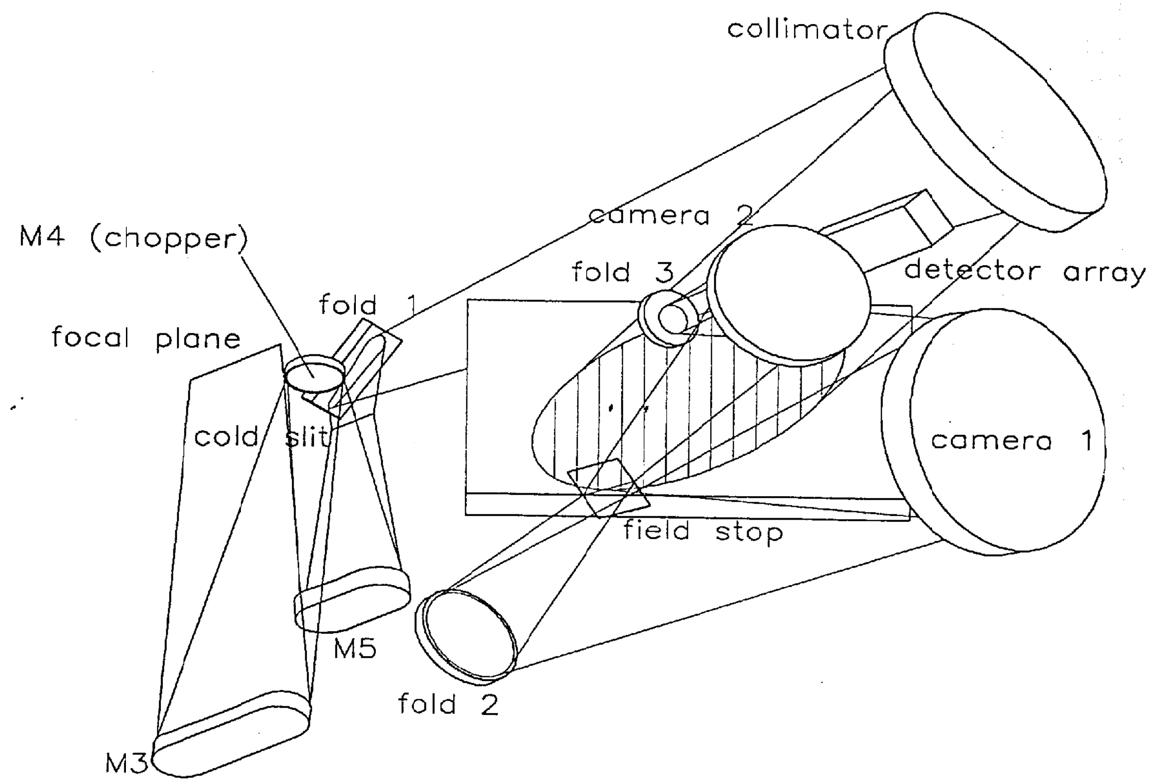


BOL photometer
f/5 final beam size
dichroic angle - 22.5 degrees

BOL hexagonally close-packed arrays
(simultaneous observation of same field of view)



SPECTROMETER OPTICAL LAYOUT



BOL FTS spectrometer option

- Wavelength range : 200 - 400 μm (25 - 50 cm^{-1})
- Minimum resolution: 400
- FTS type : Polarising Martin-Puplett (TBC)
- Rapid scanning (OPD_{max} = TBD cm)
- Output ports:

Port	Spectral range	P_{tel} (pW)	NEP_{ph} (W $Hz^{-1/2}$ x 10^{-17}	Audio freq. range (Hz)
1	25-38 cm^{-1} (263-400 μm)	2.1	6.7	10 - 15
2	38-50 cm^{-1} (200-263 μm)	2.7	6.4	15 - 20

- Base-line imaging capability:

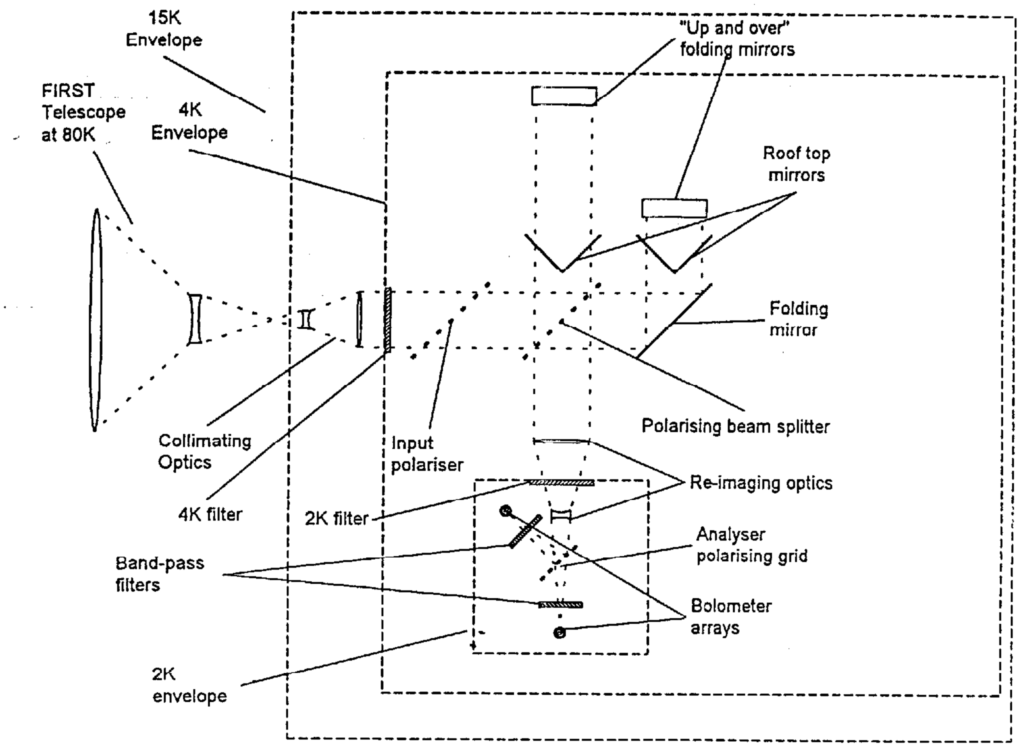
  Compact (e.g. 19-element HCP) feedhorn arrays for each band
  ⇒ Jiggle pattern needed for full spatial sampling
  ⇒ Complex observing mode and data analysis

Advantages of FTS option:
- Flexible spectral resolution
- Immunity to out-of-band leaks
- Immunity to non-modulated stray light
- Higher background on detectors
  → NEP/speed requirements can be met at 0.3 K ?

- Filled absorber arrays could be well adapted to use with FTS

  (Assumption: Filled arrays not suitable for the grating option)

- **BOL FTS option**



DETECTOR OPERATING TEMPERATURE REQUIREMENTS

- Photometer (photon noise limited):

NEP_{PH} x 10^{-17} ($W\ Hz^{-1/2}$)		
250 μm	350 μm	500 μm
12	9	7

  - Speed of response: Ideally 5 Hz ($\tau \approx$ 30 ms)
    Could live with 3 Hz ($\tau \approx$ 50 ms)
  - This performance should be easily achievable at 300 mK

- Grating spectrometer (detector noise limited):
  - Detector NEP target = 1 x 10^{-17} W $Hz^{-1/2}$
  - Speed of response: as for photometer
  - Should be achievable at 200 mK
  - Not clear whether it is feasible at 300 mK (but close)

- FTS spectrometer (photon noise limited):
  - $NEP_{ph} \approx$ 5 x 10^{-17} W $Hz^{-1/2}$
  - Speed of response: Ideally > 20 Hz (τ > 8 ms)
    Could probably live with 15 Hz
    (τ = 11 ms)
  - Should be achievable at 300 mK (but needs to be demonstrated).

- Cooling power: Dilution system (200 mK) : Est. 0.4 μW
  ^{3}He system (300 mK) : Est. 20 μW

- Conclusions:
  1. Detector T_{op} > 200 mK
  2. T_{op} = 300 mK probably adequate
  3. Additional cooling power of ^{3}He may allow bigger arrays to be used

Filled absorber arrays vs. feedhorn arrays

Feed-horn arrays

- Base-line design uses as many detectors as possible given limited field of view available
- Hexagonaly close-packed arrays (as in SCUBA)
- Final optics focal ratio: F = 5
- Single mode ($A\Omega = \lambda^2$)
- Pixel diameter $p \approx 2F\lambda \Rightarrow p = 10\lambda$

λ (μm)	N_{dets}	Max array dimension (Pixels)	(arcmin)	(mm)
250	61	9	4.7	22.5
350	37	7	5.1	24.5
500	19	5	5.2	25.0

Filled arrays

- Pixel size and final optics focal ratio:

  - $p \leq 0.5F\lambda$ for adequate spatial sampling

  - $p \geq 5\lambda$ for efficient absorption **?**

  $\Rightarrow F \geq 10$

- Assume - square pixels
  - $p = 0.5F\lambda$
  - $F = 10$

- Using ~ the same field of view, we could fit :

  250 μm: $(9 \times 4)^2 = 36^2$ dets → 32 x 32 = 1024
  350 μm: $(7 \times 4)^2 = 28^2$ → 24 X 24 = 576
  500 μm: $(5 \times 4)^2 = 20^2$ → 16 X 16 = 256

- Total of 1856 dets vs. 117 (factor of 16)

λ (μm)	N_{dets}	Array size (Pixels)	Array size (arcmin)	Array size (mm)
250	61	32 x 32	4.2 x 4.2	40 x 40
350	37	24 x 24	4.4 x 4.4	42 x 42
500	19	16 x 16	4.2 x 4.2	40 x 40

- Array physical size larger by factor of ~ 2

- But no feedhorns needed → lower mass

- Could fit in ~ 16 times as many detectors with filled arrays.

What improvement in performance will this produce?

- Assume no problems with data rate, power dissipation, no. of wires, etc.

- Answer depends on:

  1. Relative absorption efficiency of bare absorber pixel compared to feed-horn pixel

  2. Relative susceptibility to stray light of the two pixel types

  3. Other factors (cosmic ray susceptibility, crosstalk, observing efficiency, etc.)

- Assumptions/guesses:

  - Effective quantum efficiency per pixel will be ~ factor of two lower for filled absorber ?

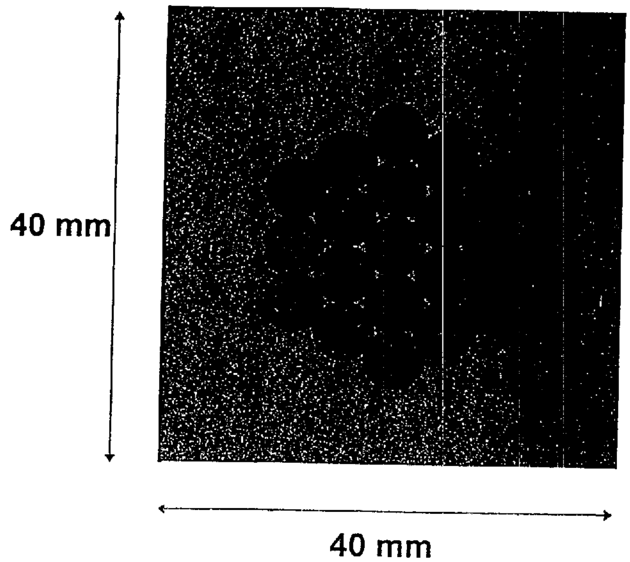
  - Stray light can be successfully suppressed ?

⇒ Need to have at least twice as many detectors to break even

⇒ Potential gain in mapping speed by factor of ~ 8.

Relative physical sizes of feedhorn and filled absorber arrays

- 500 μm 16 x 16 array of $0.5F\lambda$ pixels (F = 10)
- 19-element HCP array of $2F\lambda$ pixels (F = 5)



Background power from the array environment

- Assumptions:
- T_{tel} = 80 K • ε_{tel} = 0.04 • $\lambda/\Delta\lambda$ = 3
- Overall optical transmission = 0.3
  - Feedhorn array: $A\Omega = \lambda^2$
  - Filled array: 5λ pixels
    f/10 final optics

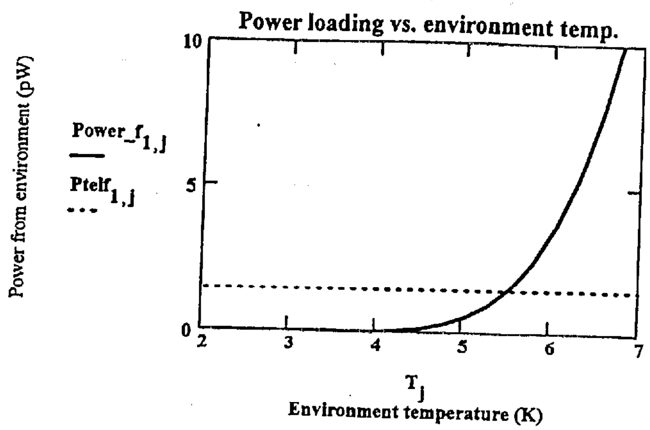
$$\Rightarrow \quad A\Omega_{tel} = \frac{\pi(5\lambda)^2}{4(10)^2} = 0.2\lambda^2 \quad \text{per pixel}$$

$A\Omega$ for array environment = π Sr

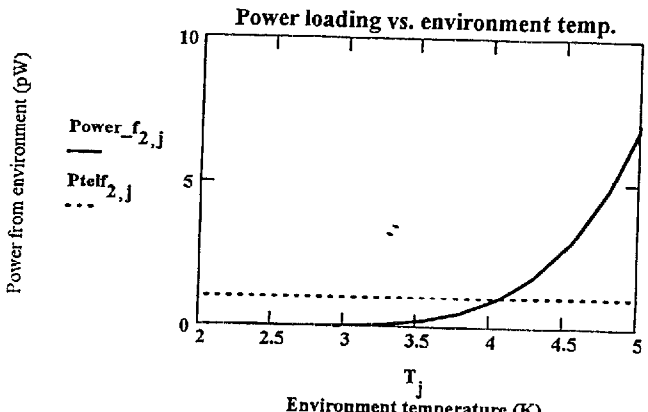
Photometer

	λ (μm)	250	350	500
Feedhorn Array	Ptel (pW)	7.4	5.3	4.8
	NEPph (W $Hz^{-1/2}$x10^{-17})	12	8.7	7.0
Filled absorber Array	Ptel (pW)	1.5	1.0	0.9
	NEPph (W $Hz^{-1/2}$x10^{-17})	5.4	4.0	3.2

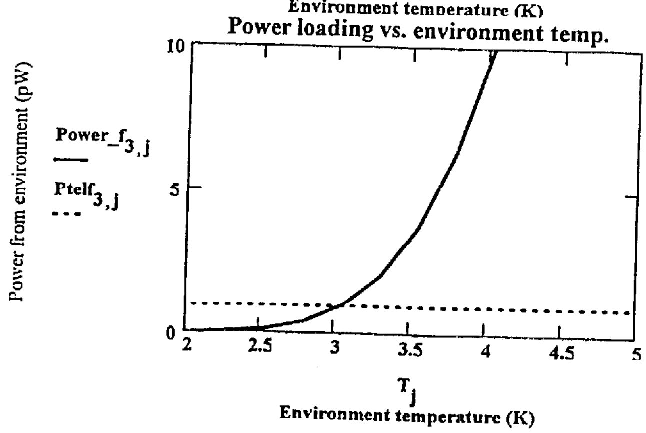
Filled array: Cold stop at < 3 K needed to prevent background power from environment domintating over that from the telescope.



250 μm



350 μm



500 μm

Conclusions

1. Filled array absorbers are potentially attractive for the BOL photometer and FTS spectrometer option

   - Increase of up to an order of magnitude in mapping speed
   - Simplified operating modes
   - Elimination of sensitivity to pointing errors (especially for point source observations)

2. Critical technology issues

a) Pixel quantum efficiency ?

b) Stray light susceptibility ?

- In-band stray light:
  - f/5 vs. π Sr $\Rightarrow$ factor of 100 in solid angle
- Out-of-band straylight:
  - Same problem as above, compounded by:
    - Degraded off-axis performance of filters
    - No long-wavelength waveguide cutoff

$\Rightarrow$ Potentially much more difficult to suppress stray light for pixels with wide field of view

$\Rightarrow$ Instrument optical and thermal design must be optimised for minimum stray light

c) Can the required detector performance be achieved at 0.3 K ?

d) Maturity of technology

- Deadline for choice is tight (≥ 2 years before QM delivery)

- Laboratory demonstration of sensitivity and technical feasibility (esp. stray light rejection) is essential

- Demonstration in working system on a telescope desirable (but may not be time for this)

e) Space qualification/lifetime/reliability

f) Space-craft resource issues

- Resource budgets cannot be changed significantly

- Data rate/data compression/on-board processing
- Power dissipation
  - Focal plane unit
  - Warm electronics
- No. of wires from FPU - warm electronics

g) Hybrid option: ?

- Planar array coupled to multi-mode feed-horns over-illuminating cold stop

LAURENT VIGROUX

Performances required for BOL

Laurent Vigroux, Alberto Franceschini
27 octobre 1997

Main scientitic driver :

detection of dust shrouded starburst galaxies at high z

measurement of their bolometric luminosity

study of the star formation rate in galaxies vs redshift

which z ? :	QSO distribution	peaks at	$z \approx 2.5$
		cut off	$z \approx 5$
	starburts emission peaks at		$\lambda \approx 100 - 200\ \mu m$

conclusion : peak emisssion of starburts galaxy in the wavelength domain of BOL

BOL is THE instrument to achieve these goals

requirement :

BOL must be able to detect a starburst galaxy at z ≈ 5

must be optimized for imaging surveys

sensitivity limits

z	starburst galaxy flux density at 300 μm
0	10 Jy
0.1	0.15 Jy
1	6 mJy
2	2 mJy
4.5	0.5 mJy

predicted fluxes for M82 like starburst ($M = 5\ 10^{10}\ M_0$ SFR 10 M_0/Year)
(Franceschini models)

confusion limit : ≈ 1 mJy

imaging surveys:

get **the largest number of detectors**

the best coverage of focal plane

Baseline design performances

sensitivity limits (from MG, BS mail of Oct 13)

for full sky sampling image in one array field of view

λ	250 µm	350 µm	500 µm
FOV	3.7′	3.9′	3.7′
flux density 1 h - 1σ	1.3 mJy	1.3 mJy	1.5 mJy

For comparison: 10 m South Pole at 300 µm :

- limit ≈ 2 mJy
- field of view : ≈ 1 arcmin.

conclusions : baseline design marginally adequate

no margin on sensitivity

weak gain compared to ground

need to improve performances by ≈ 10 !

>>>> increase field of view 5′

>>>> increase image sampling 100 %

BOLOMETER array definition

Constraints: **minimize cost developments**

limit the number of different arrays

>>>> 2 array types only

1 for 250 and 350 µm

1 for 480 µm and (?) spectro

Geometrical characteristics

assuming a FIRST telescope

Φ = 3.5 m at f/9

BOL photometer at f/5

Wavelength (µm)	250	350	480
FWHM (arcsec.)	18	25	36
number of resolution élement in 5arcmin.	17	12	8.5
number of px to achieve PSF sampling (FWHM/2.5)	42.5	30	21.2
PX size (mm) (= FWHM)	1.5	2.1	3
PX size (mm) (=FWHM/2.5)	0.6	0.84	1.2
overall size of the bol array	26	26	26

possible array definitions

1) PX ≈ FWHM

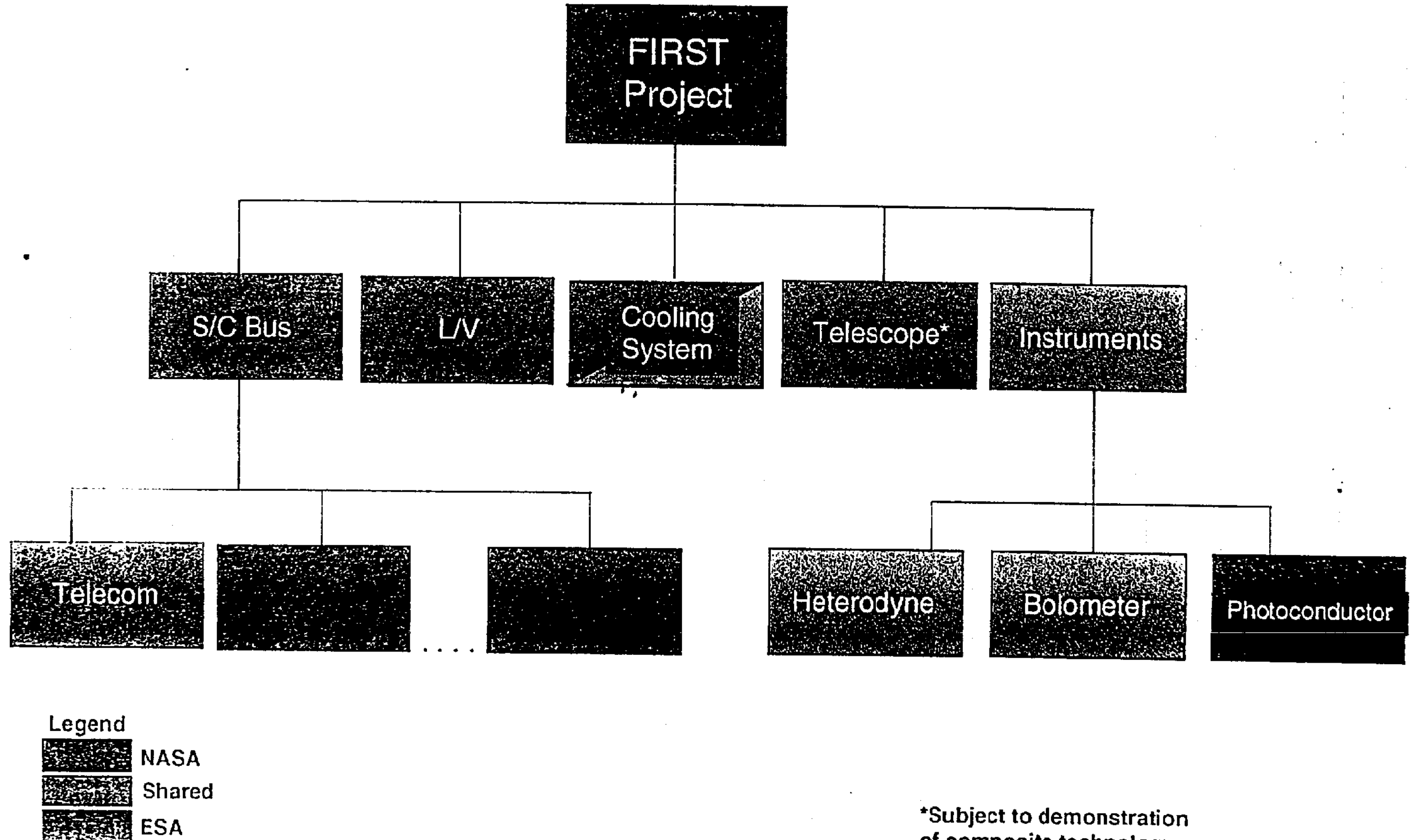
Wavelength (μm)	250	350	480
number of PX	16 x 16	16 x 16	8 x 8
PFOV (arcsec)	18.7	18.7	37.5
FWHM / PFOV	0.96	1.34	0.96
PX size (mm)	1.57	1.57	3.15
detector size (mm)	25.5	25.5	25.5

2) PX ≈ FWHM / 2.5

Wavelength (μm)	250	350	480
number of PX	32 x 32	32 x 32	16 x 16
PFOV (arcsec)	9.4	9.4	18.7
FWHM / PFOV	1.92	2.66	1.92
PX size (mm)	0.78	0.78	1.57
detector size (mm)	25.5	25.5	25.5

ANDREW LANGE

NASA - ESA Collaboration



*Subject to demonstration of composite technology

Key Science Programs

- **Origin of Galaxies**
  - Ang resolution @80 µm <5"
  - Imaging: $\lambda/\Delta\lambda \sim 3$, 80–900 µm
  - Spectroscopy: $\lambda/\Delta\lambda \sim 3x10^4$, 85–300 µm
- **Evolution of Stars and Galaxies**
  - Ang resolution @80 µm <5"
  - Imaging: $\lambda/\Delta\lambda \sim 3$, 80–900 µm
  - Spectroscopy: $\lambda/\Delta\lambda > 10^5$, 150–600 µm
- **Origin of Stars and Planets**
  - Ang resolution @80 µm <5"
  - Imaging: $\lambda/\Delta\lambda \sim 3$, 80–900 µm
  - Spectroscopy: $\lambda/\Delta\lambda > 3x10^5$, 150–600 µm

Engineering Implications

- **Telescope**
  - > 3.5m, diffraction-limited at 80 µm.
- **Heterodyne Instrument**
  - 0.5–2 THz
  - $\lambda/\Delta\lambda > 3x10^6$
  - Physical temp ~ 4K
- **Bolometer Instrument**
  - >1000 pixels
  - Physical temp ~ 0.1-0.3K
  - **Grating Spectrometer**
    - 200–350 µm
    - $\lambda/\Delta\lambda > 3x10^4$
  - **Imaging Photometer**
    - 80–900 µm
    - $\lambda/\Delta\lambda \sim 3$
- **Photoconductor Instrument**
  - European instrument

Key Technologies

- **Composite mirrors**
  - 1.5 µm rms warm
  - 2 µm rms cold
- **Photomixer, multiplier LO Sources**
  - P > 50 µW, ν < 1.2 THz
  - P > 5 µW for ν > 1.2 THz
  - Tuning range > 10%
- **SIS, HEB Mixers**
  - $T_{noise} < 5\ h\nu/k$
  - 0.5–2 THz
- **Spider or Pop-up Bolometer Arrays**
  - 30 x 30
  - Response > 10 Hz
  - NEP < 10^{-17} W/√Hz
  - TES sensors, SQUID readouts
- **Cooling systems?**

FIRST

Budget

Real year $$

FIRST Mission	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
Tech Development	1.40	6.46	7.13	3.63										18.62
Pre-Phase A	0.47													0.47
Phase A		1.55	1.29											2.84
Phase B			1.61	3.35										4.96
Project (C/D)				6.70	19.72	20.49	20.03	10.41						77.35
Total	1.87	8.01	10.03	13.68	19.72	20.49	20.03	10.41						104.24

- FIRST is an ESA Cornerstone Mission ~ $900M
- Launch on Ariane 5
- Instruments, telescope, and mission all start Phase C/D in 2000
- Technology budgets assume that core technology funding (Code SM) continues for instrument development (heterodyne and bolometer) and cryocoolers
- ESA will handle MO; DSN may be part of telecommunications package
- DA will start in 2006, at about $10 M/year

U.S. Bolometer Development for FIRST

Jamie Bock, Jason Glenn, Andrew Lange, Rick Leduc
Caltech and JPL

Harvey Moseley
Goddard Space Flight Center

Eric Grossman, Kent Irwin
NIST

> Consortium formed

> Parallel development of 3 technologies

> Down-select in mid-2000 (?)

> Funding in hand (FY98 = $1.0 million)

U.S. Bolometer Development for FIRST: Technical Approach

Three options :

1) "Spider-web" + Ge thermistor

2) "Spider-web" + TES

3) "Si Pop-up" + TES

Plan:

Develop full arrays of (1) (CIT/JPL)

Develop full arrays of (3) (GSFC/NIST)

Develop single pixels of (2) (CIT/JPL)

Develop SQUID MUX (NIST)

NEP

optical efficiency (including feed optics and filters)

time constant

array format (number and size of pixels)

uniformity and stability of responsivity

yield

cross-talk

1/f noise

cosmic-ray cross-section and response

required heat sink temperature

heat load at sub-K (lead conduction and dissipation)

susceptibility to stray-light and RFI

susceptibility to microphonics

requirements on ambient E and B fields

required readout electronics and space-qualification thereof

on-board processing and TM requirements

maturity / experience in other instruments

350 μm camera for CSO

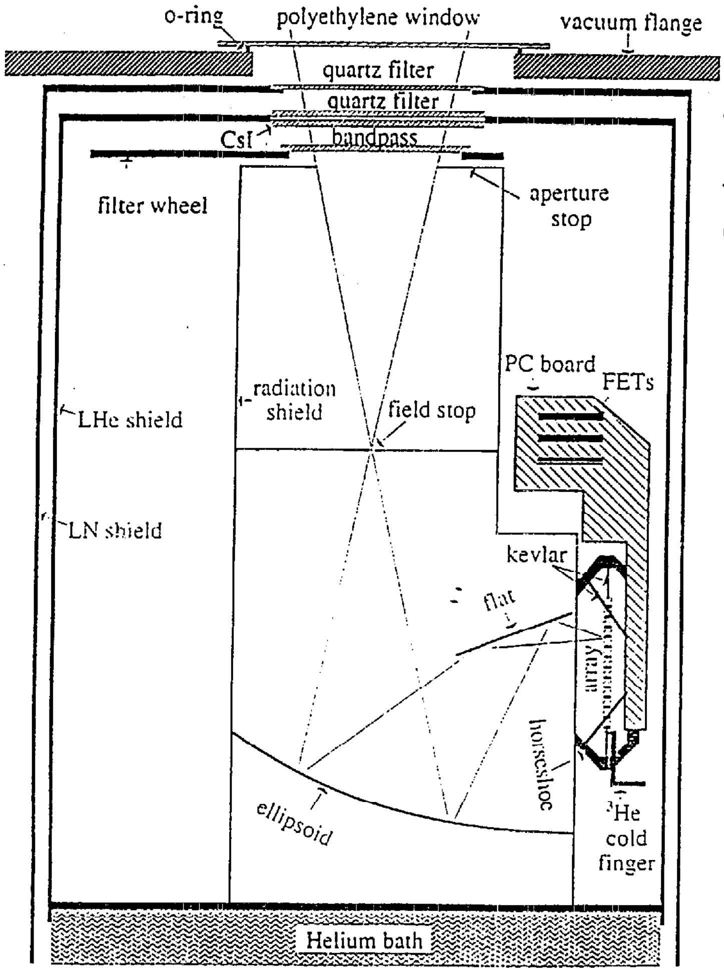
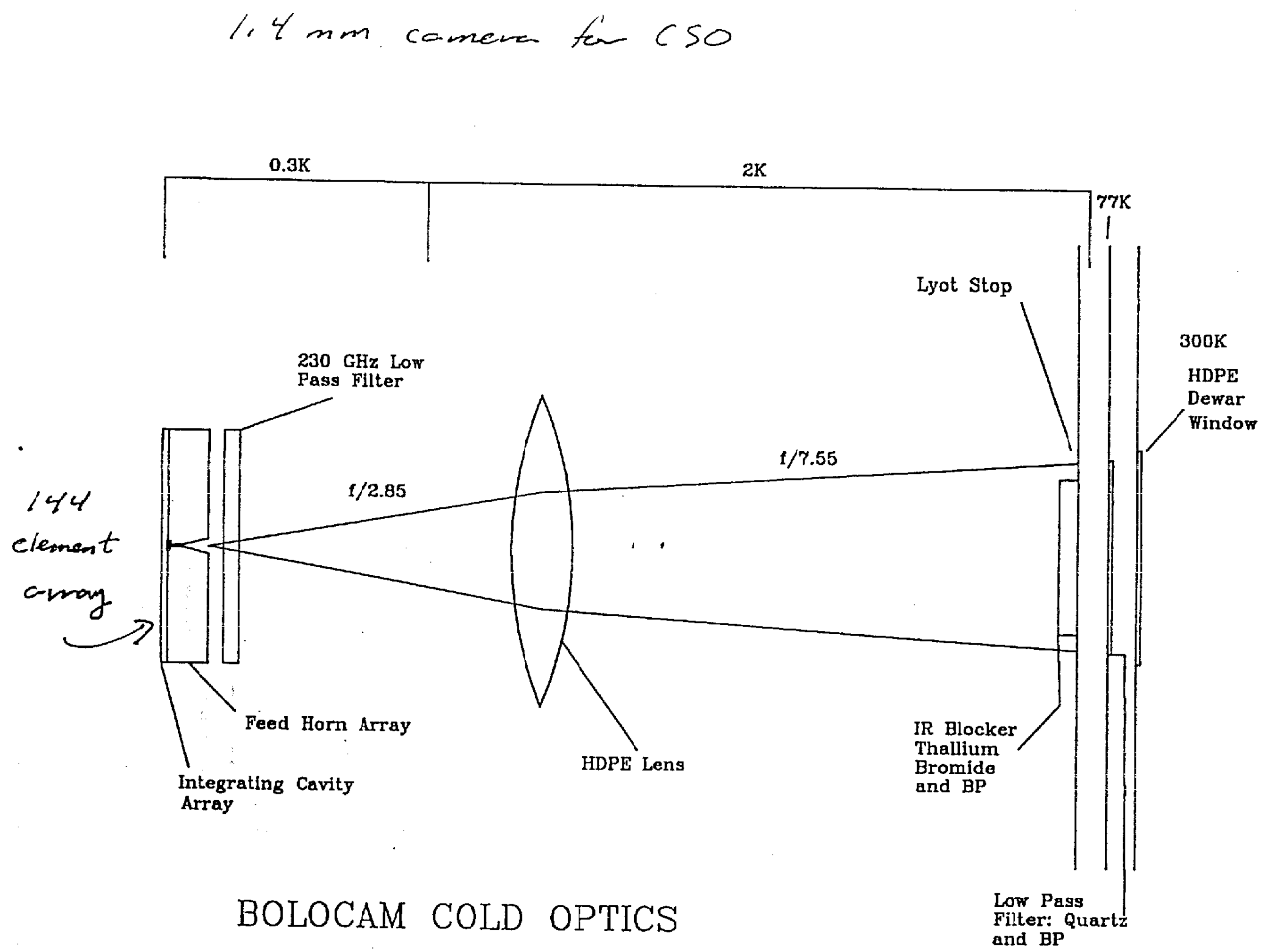


Fig. 1. Schematic diagram of the CSO submillimeter camera. PC, printed circuit.

SHARC

from Wang et al. 1996 Appl. Opt. 35 6629



BOLOCAM COLD OPTICS

JAMIE BOCK

Silicon Nitride Micromesh Bolometers for Infrared and Mm-Wave Astrophysics

Andrew Lange
Jonas Zmuidzinas
California Institute of Technology

Phil Mauskopf
University of Massachusetts

James Bock
Rick Leduc
Jet Propulsion Laboratory

Tom Kenny
Stanford University

Jeff Beeman
Lawrence Berkeley Laboratory

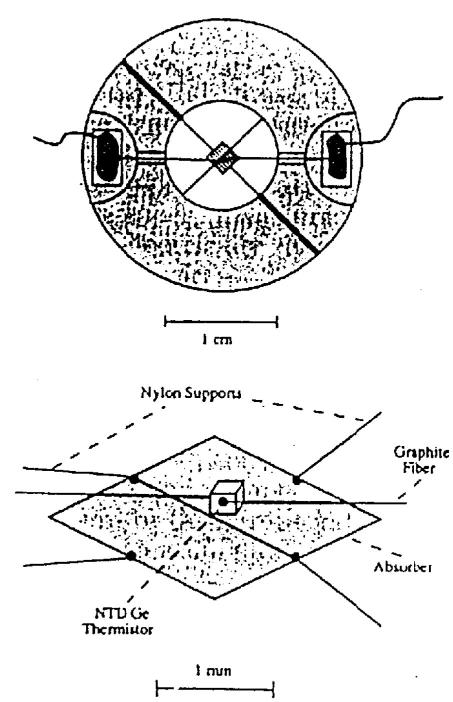
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology

Jointly supported by CSMT Code X funding
and NASA Innovative Research
We gratefully acknowledge support of V. Sarohia in the program office at CSMT.

CSMT

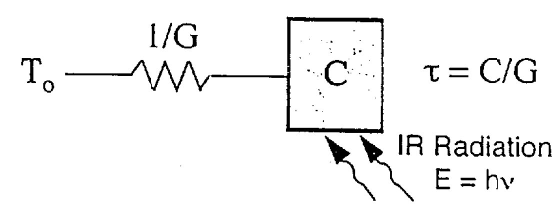
JPL

Conventional Composite Bolometer



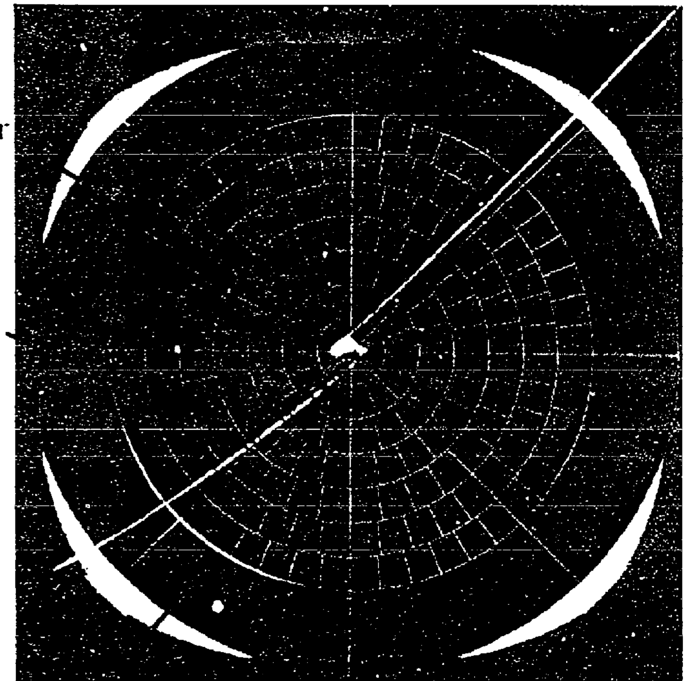
Principle of operation

- Infrared radiation is absorbed by lossy metal film on dielectric substrate
- Temperature change detected by semiconductor thermistor.
- NEP α $\sqrt{4kT^2G}$



JPL

Silicon Nitride Micromesh Bolometer Structure



Absorbing mesh dimensions:
Legs 1 mm x 5 μm wide
Active diameter 5.3 mm
Grid spacing 200 μm
Fill factor 3%

Advantages

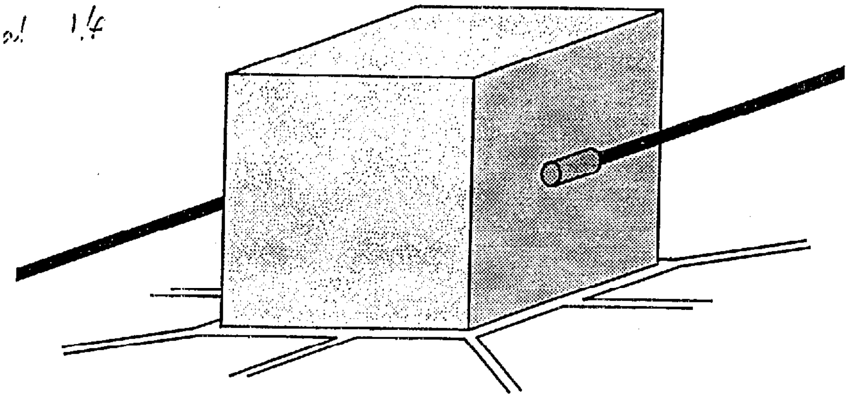
- Low heat capacity
- Low thermal conductance
- Small cosmic ray cross section
- Reduced susceptibility to microphonics
- Reduced response to out-of-band signal
- Excellent DC stability
- Easy to manufacture, array compatible

IMPROVEMENTS IN THERMISTORS

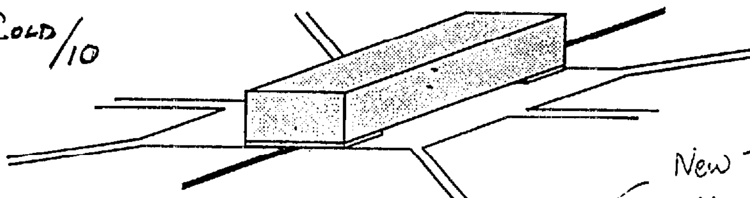
NTD Germanium

+ Reproducible
+ Minimal 1/f

C_{OLD}

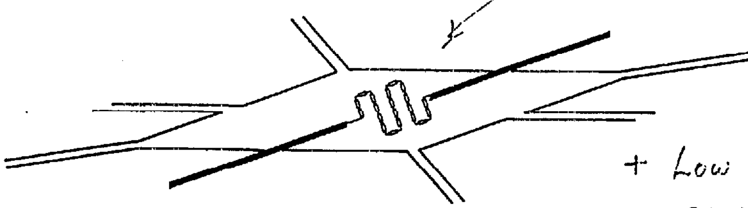


$C_{NOW} = C_{OLD}/10$

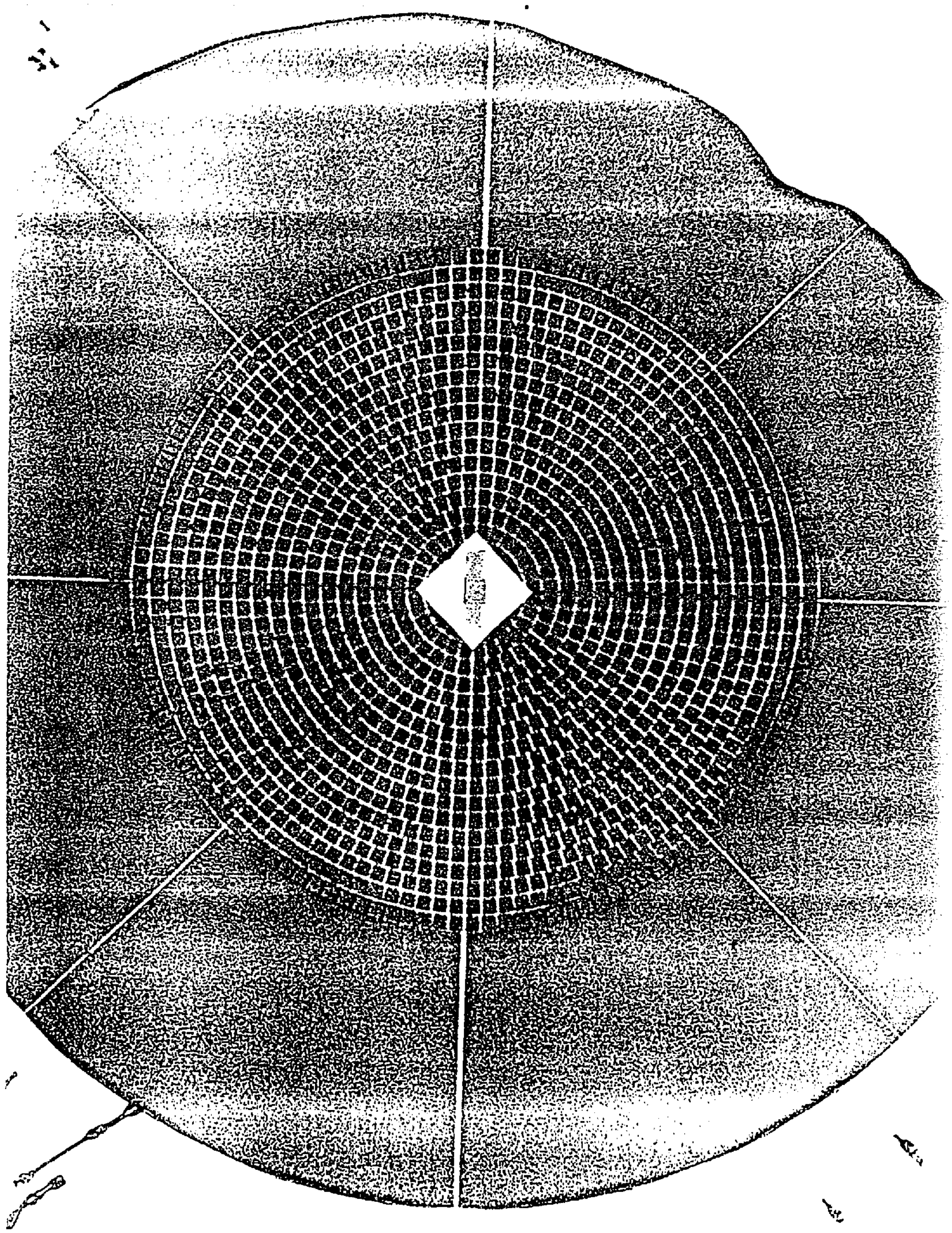


New Thermistors
+ Voltage-biased TES
SIN junctions
Au-Ge, Nb-Si . . .

$C_{NOW}/10$

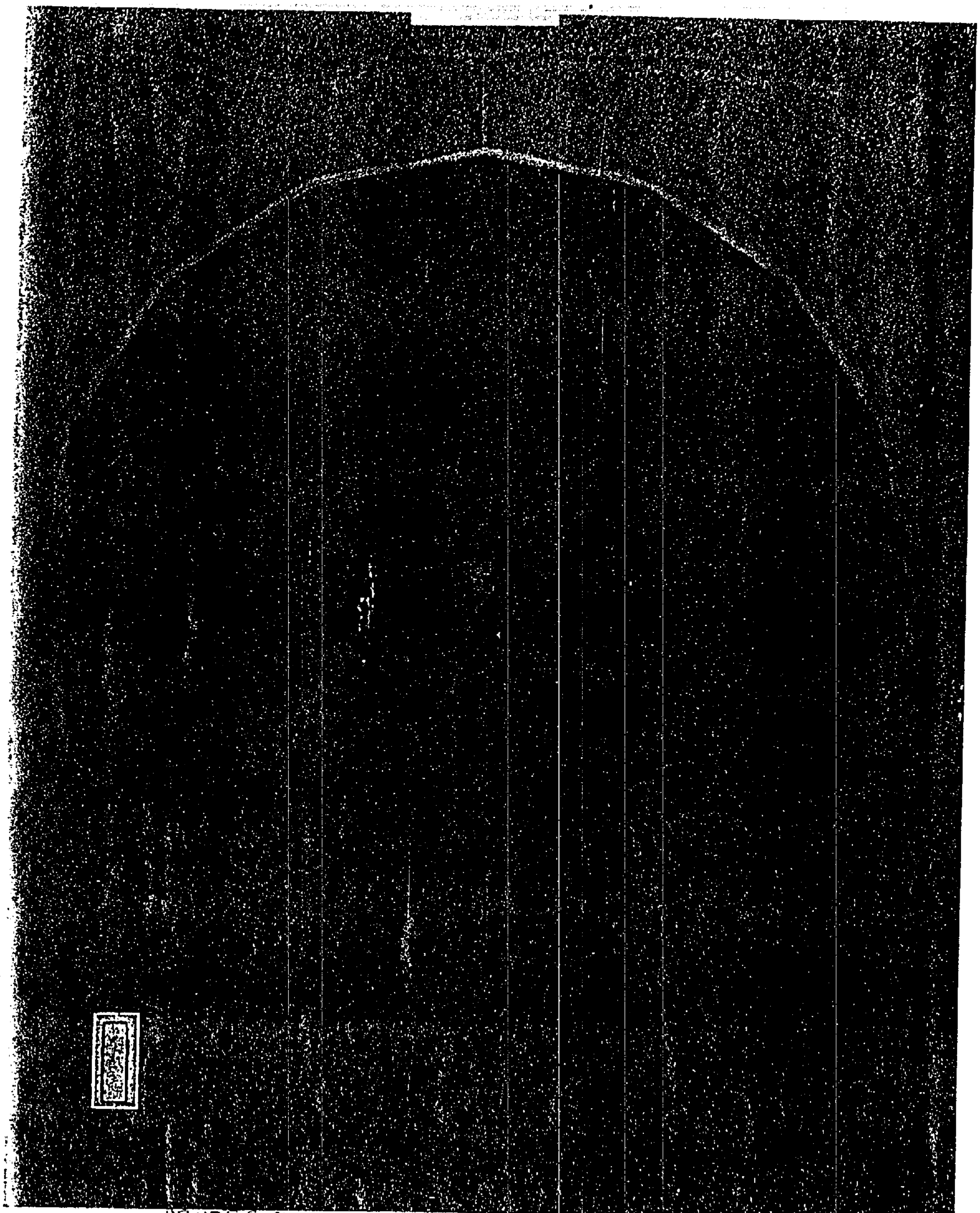


+ Low C or
+ Strong ETF
+ Photolithography



ACHIEVED DEVICE PERFORMANCE

	Tc = 300mK	Tc = 100mK
NEPe ($W/\sqrt{Hz}$)	1.2×10^{-17}	2.0×10^{-18}
τ (ms)	100	75
NEP$\sqrt{\tau}$ (J)	4×10^{-18}	5×10^{-19}
diameter (mm)	2.5	2.5
τ_{min} (ms)	30	5



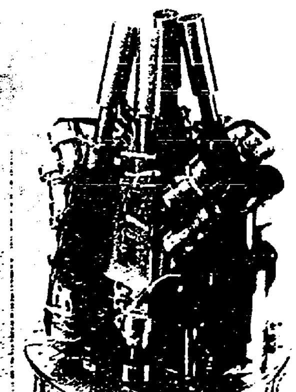
Silicon Nitride Micromesh Bolometer

Missions

SNM bolometers will be used in the following missions:

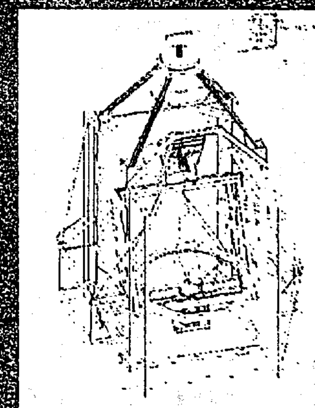
- COBRAS/SAMBA
- SuZIE (ground-based)
- BOOMERanG (balloon-borne)
- MAXIMA (balloon-borne)

COBRAS/SAMBA is an ESA M3 mission to be launched in 2004. It will image the Cosmic Microwave Background (CMB) over the entire sky with < 10 μK/pixel sensitivity at 10 arcminute angular resolution. The broad frequency coverage and high sensitivity provided by the SNM bolometers give COBRAS/SAMBA almost two orders of magnitude greater capability than MAP, which is scheduled to fly in 2000.



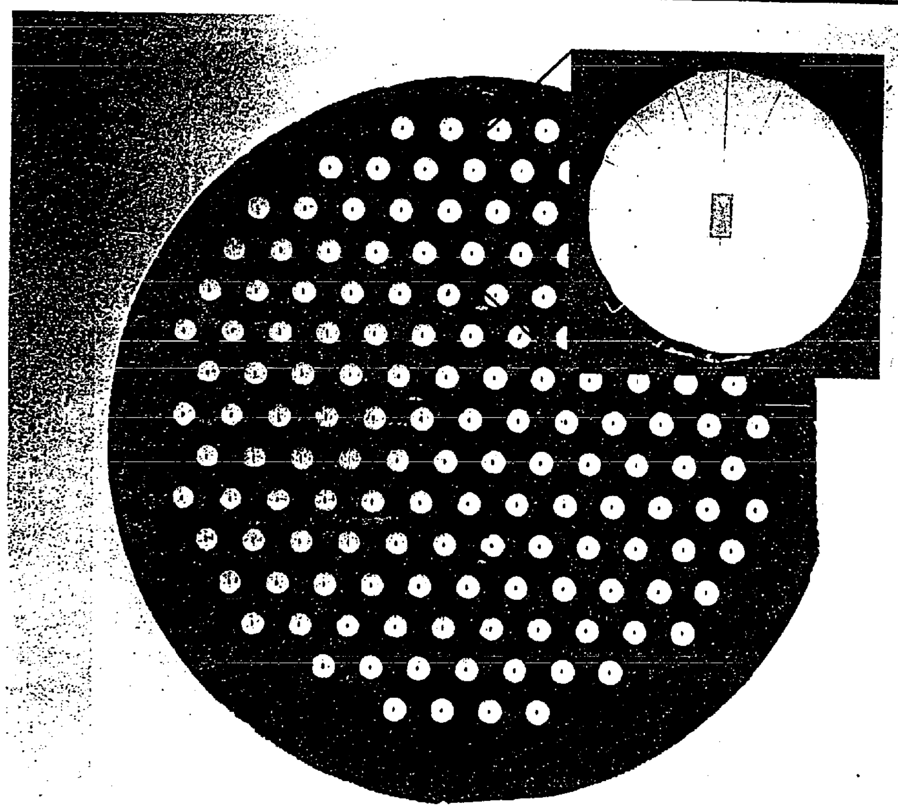
SuZIE is a bolometric instrument designed to measure fluctuations in the Cosmic Microwave Background (CMB). Instrument contains four three-channel photometers.

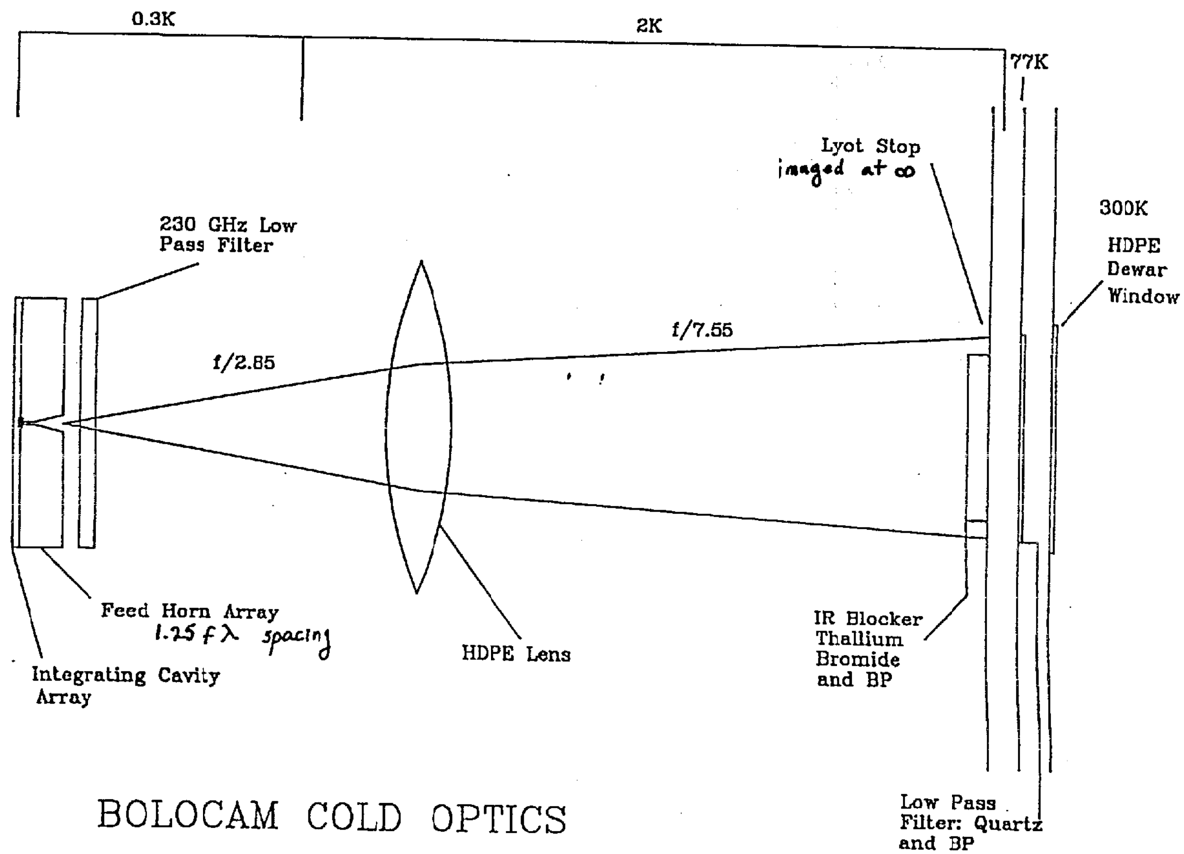
BOOMERanG is a long duration balloon experiment which aims to map the CMB with 12' resolution and a sensitivity of ~ 20 μK/pixel over 10% of the sky.



MAXIMA is a balloon-borne experiment designed to map CMB anisotropies with an angular resolution of [illegible]

JPL Silicon Nitride Micromesh Bolometer Array





BOLOCAM COLD OPTICS

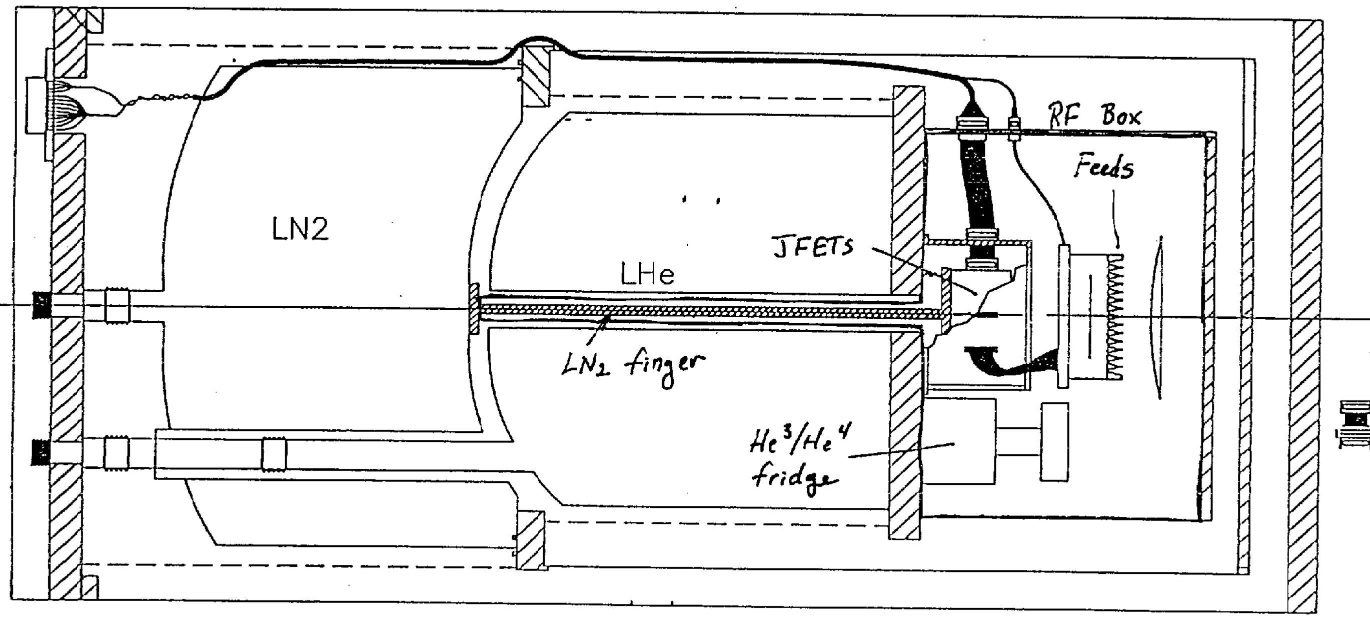
TOLERANCES UNLESS OTHERWISE NOTED	
.XX	±.03
.XXX	±.005
.XXXX	±.0005

BOLOCAM

Wiring: 0.002" manganin (Oxford)

JFET's → 4K Heat load ≃ 72 μW / detector, 4" wires 4/det.

WIRING 4K → 300 mK Heat load ≃ 115 nW / detector, 5" wires 2/det.

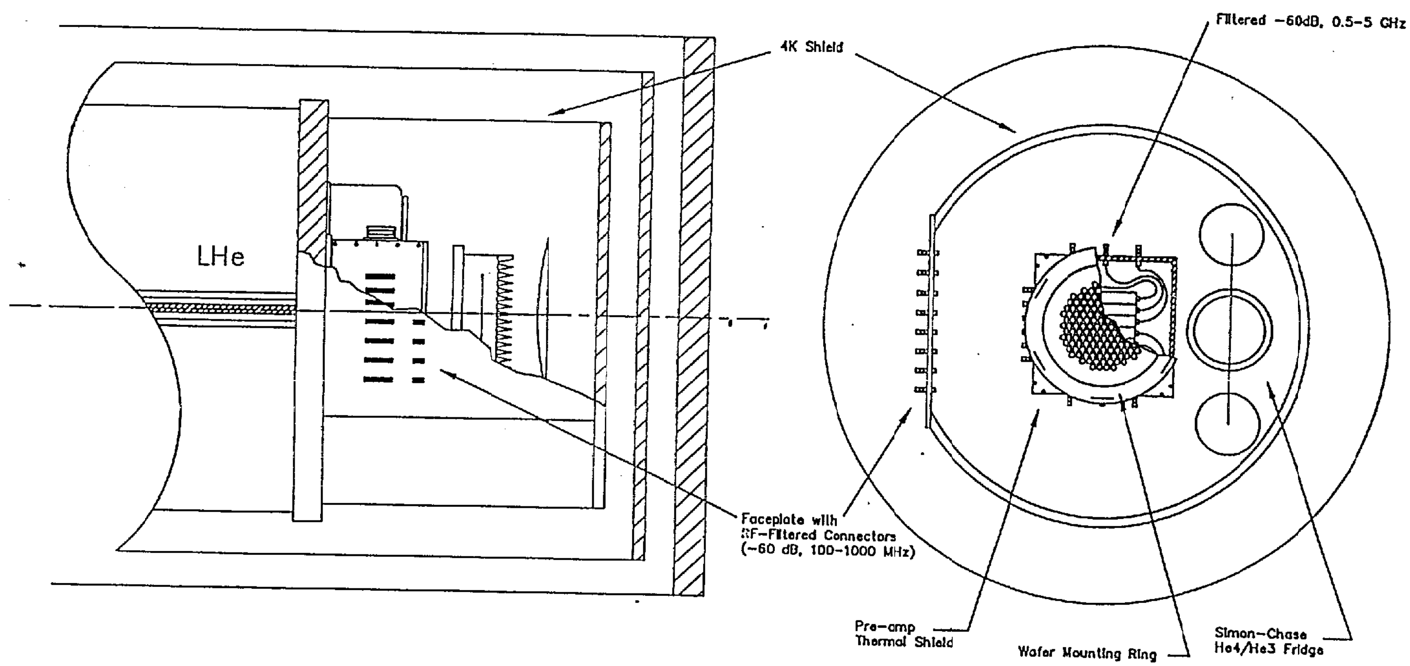


NOTES
Modified from Precision Cryogenic

FCRAO — FIVE COLLEGE RADIO ASTRONOMY OBSERVATORY, UNIVERSITY OF MASSACHUSETTS AT AMHERST

TITLE: Bolocam Dewar Layout | DWG NO: 1 | REV

TOLERANCES UNLESS OTHERWISE NOTED	
.XX	±.03
.XXX	±.005
.XXXX	±.0005



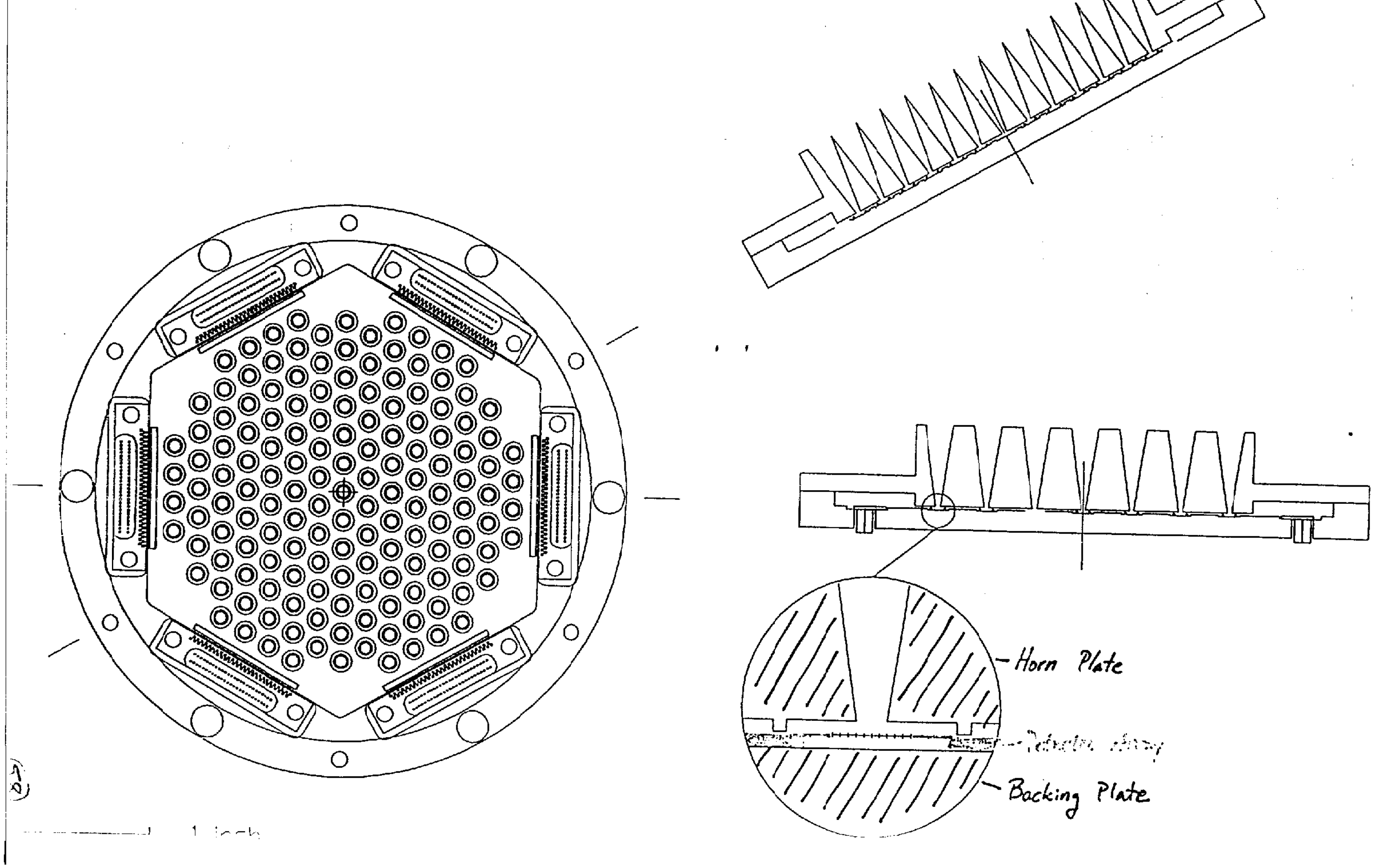
"FIGURE 4"

NOTES

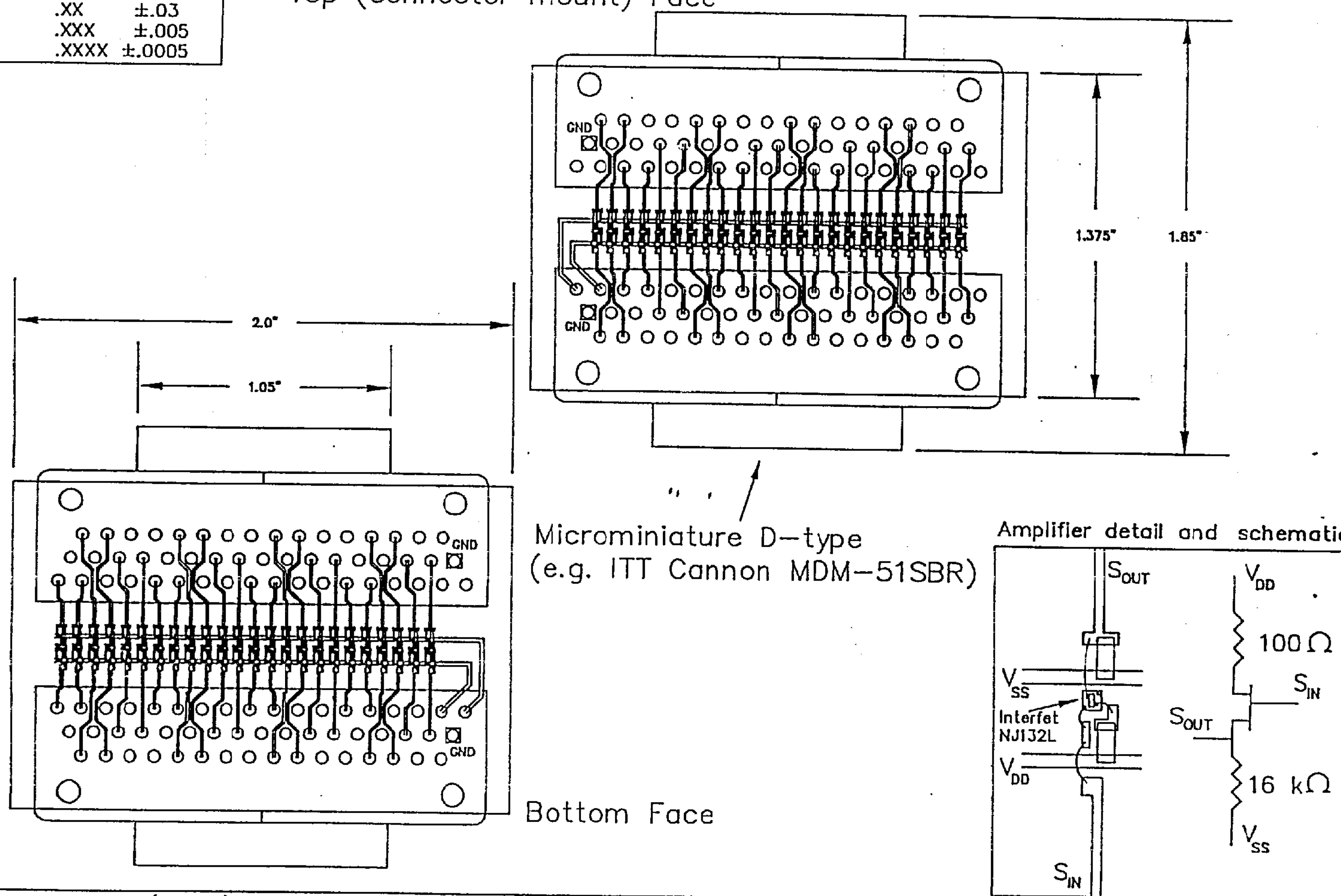
Example cold plate layout and
4K shield connector faceplate cutaway

FCRAO FIVE COLLEGE RADIO ASTRONOMY OBSERVATORY UNIVERSITY OF MASSACHUSETTS AT AMHERST		
TITLE: Bolocam Dewar 4K layout	DWG NO: 2	REV
DRAWN: B. Pownd DATE: 6/97	SCALE: NTS	SHEET 1 OF 1

BOLOCAM FOCAL PLANE



TOLERANCES UNLESS OTHERWISE NOTED	
.XX	±.03
.XXX	±.005
.XXXX	±.0005

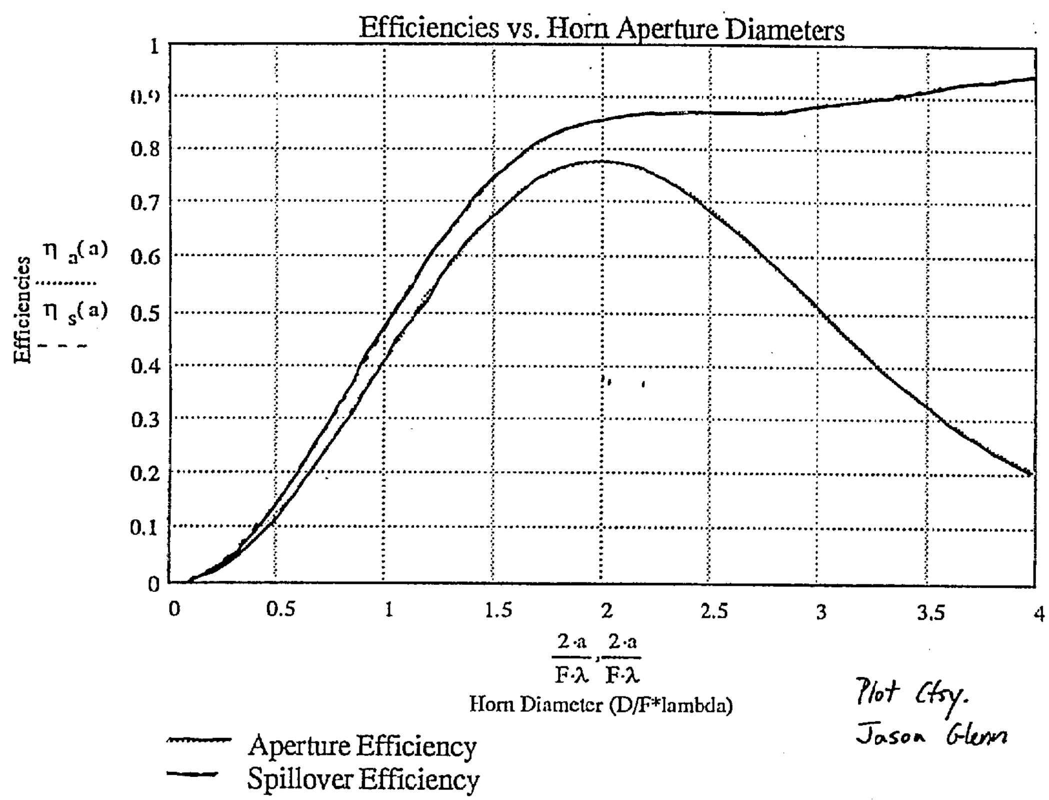


NOTES Cold (100K) pre-amp board.

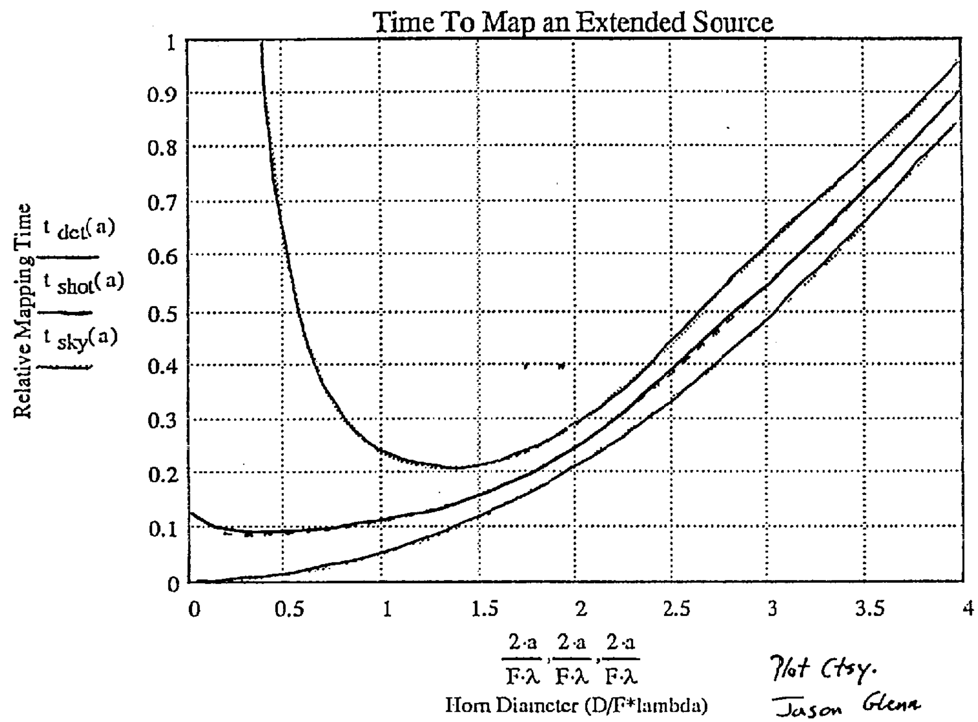
FCRAO	FIVE COLLEGE RADIO ASTRONOMY OBSERVATORY UNIVERSITY OF MASSACHUSETTS AT AMHERST		
TITLE: Cold FET Module		DWG NO: 2	REV M2
DRAWN: Rownd	DATE: 7/97	SCALE: NTS	SH! 1 OF 1

RELATIVE ADVANTAGES OF FEEDS AND BARE ARRAYS

	FEEDS		BARE ARRAYS
Sampling Efficiency			+
Optical Efficiency	+		
Aperture Efficiency			+
Detector Size	+		
Straylight	+		
Focal Ratio		?	

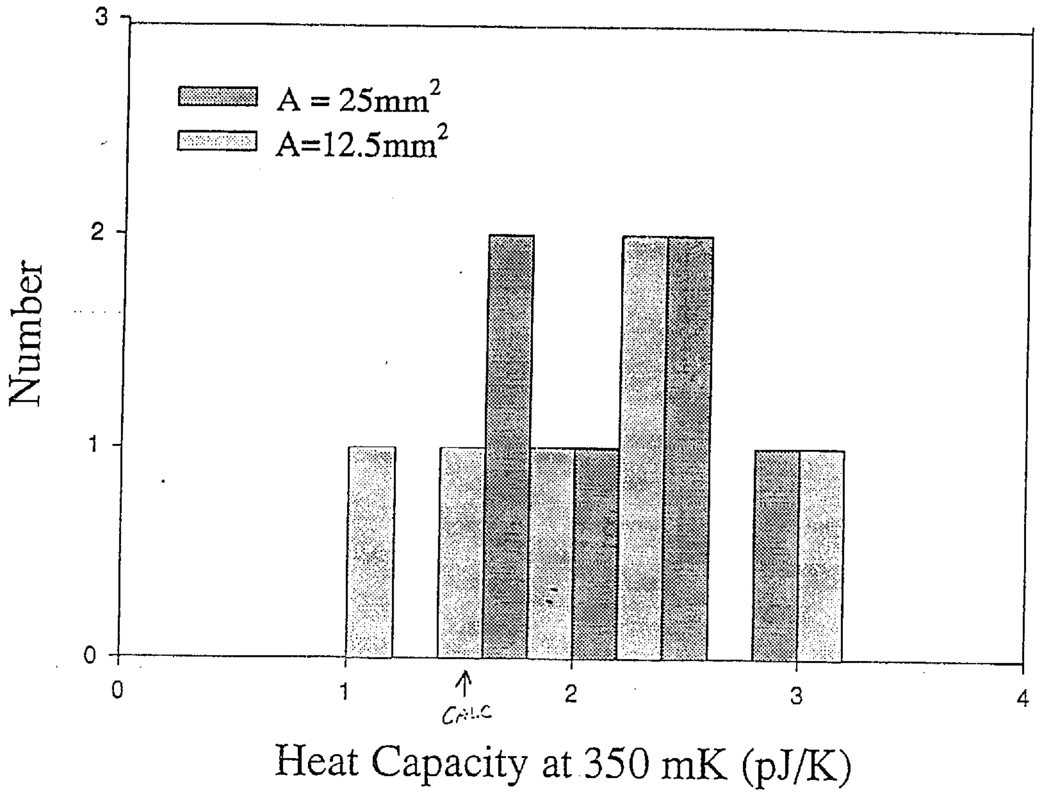


Plot Ctsy. Jason Glenn



Plot Ctsy.
Jason Glenn

MEASURED HEAT CAPACITY OF 12 BOLOMETERS



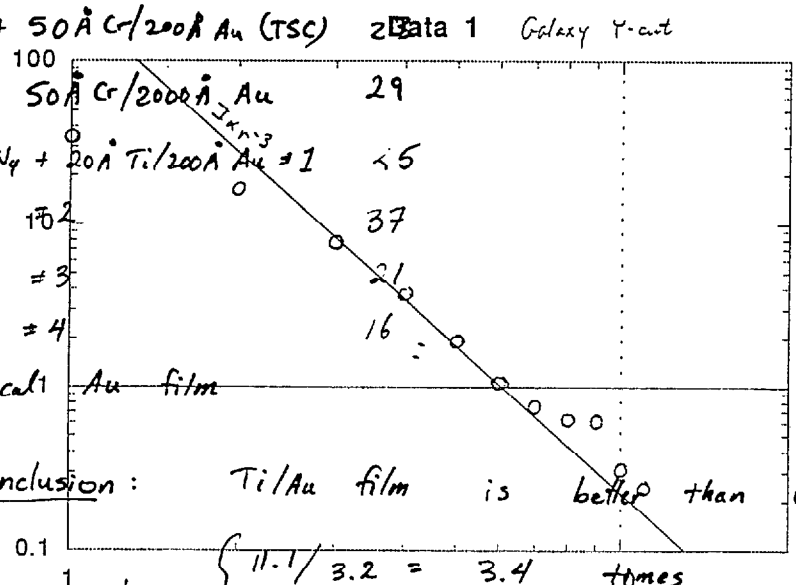
$\bar{C} = 2.3$ pJ/K

$\Delta C < 1.0$ pJ/K $\rightarrow$ $C/A < 8 \times 10^{-14}$ J/K mm²

Recall $\frac{C_V}{\sigma} \cdot \frac{2}{R_\square} \simeq 3 \times 10^{-14}$ J/K mm² for Cr-Au.

HEAT CAPACITY STUDY

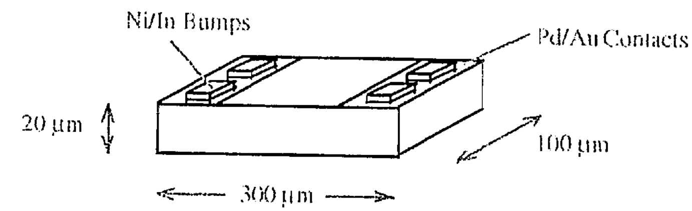
Sample	ΔC (pJ/K) @430mK	ΔC/A (pJ/K mm²)
Berkeley Si_3N_4	32	6.4
Stanford Si_3N_4	7	≲ 2.2
St. Si_3N_4 + 50Å Cr	70	12.3
" " + 50Å Cr/200Å Au (Veeco)	50	9.9
" " + 50Å Cr/200Å Au (TSC)	2[illegible]	10.4
" " + 50Å Cr/2000Å Au	29	16.6
St. Si_3N_4 + 20Å Ti/200Å Au #1	< 5	< 5
#2	37	2.5
#3	21	3.8
#4	16	3.4
Theoretical Au film		0.7



Conclusion: Ti/Au film is better than Cr/Au,

by { 11.1/3.2 = 3.4 times
[11.1 − 2.2]/[3.2 − 2.2] = 8.9 times

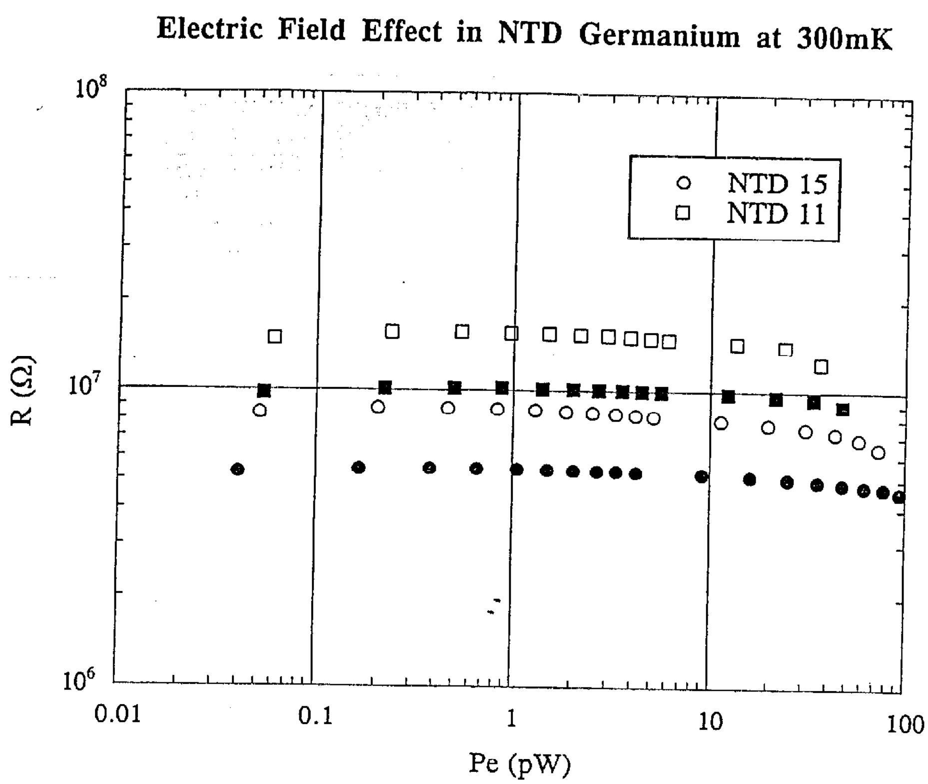
PROPERTIES OF NTD GERMANIUM THERMISTORS



Heat Capacity Budget

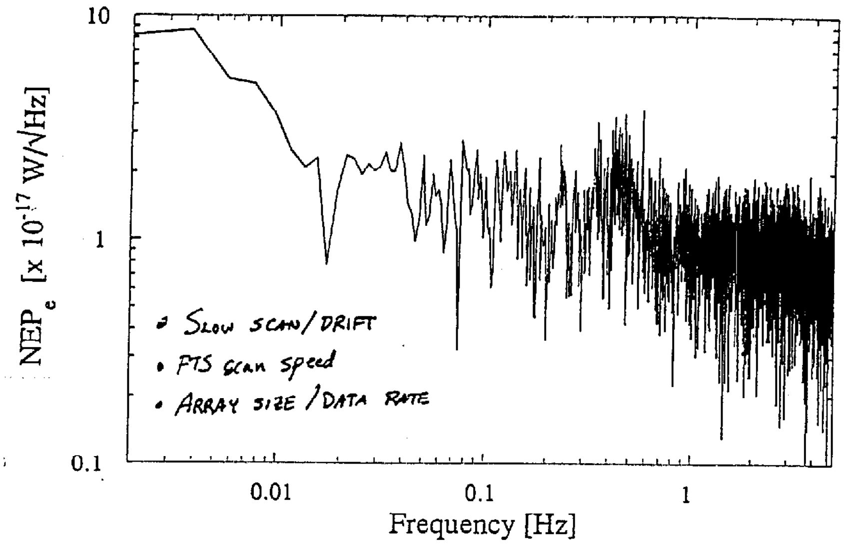
Material	Ce (J/ccK^2)	Cl (J/ccK^4)	V (cc)	C (pJ/K)
Au	7.30E-05	4.30E-05	4.20E-09	0.13
Pd	1.20E-03	1.10E-05	2.10E-10	0.10
Ge	1.90E-07	3.00E-06	6.00E-07	0.16
Ni	1.10E-03	3.30E-06	1.71E-10	0.08
In	0.00E+00	9.60E-05	1.14E-08	0.07
			Total:	0.54
Leads +Abs.				0.04

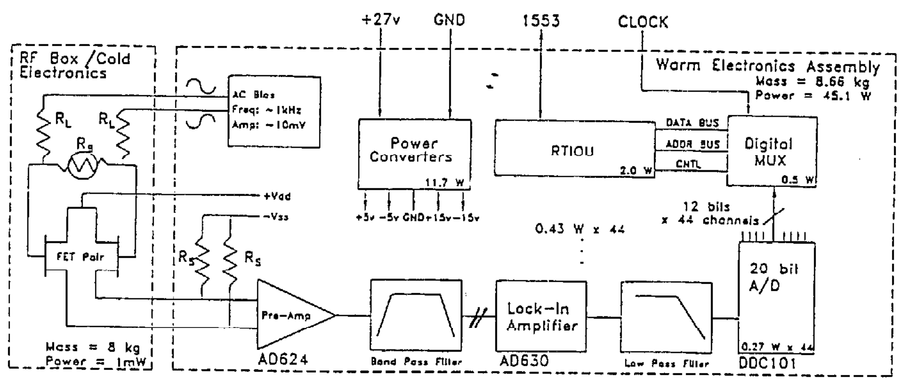
- R = Ro exp((Δ/T)^0.5) --> α = dlnR/dlnT ~ 5
- R = 5 MΩ --> Vn ~ 10 nV/rtHz
- Ro matched to ~ 20%
- E-field effects negligible at 300 mK for Pe < 10 pW
- No 1/f noise to 20 mHz



Electric Field Effect in NTD Germanium at 300mK
NTD 15
NTD 11
R (Ω)
10^8
10^7
10^6
0.01
0.1
1
10
100
Pe (pW)

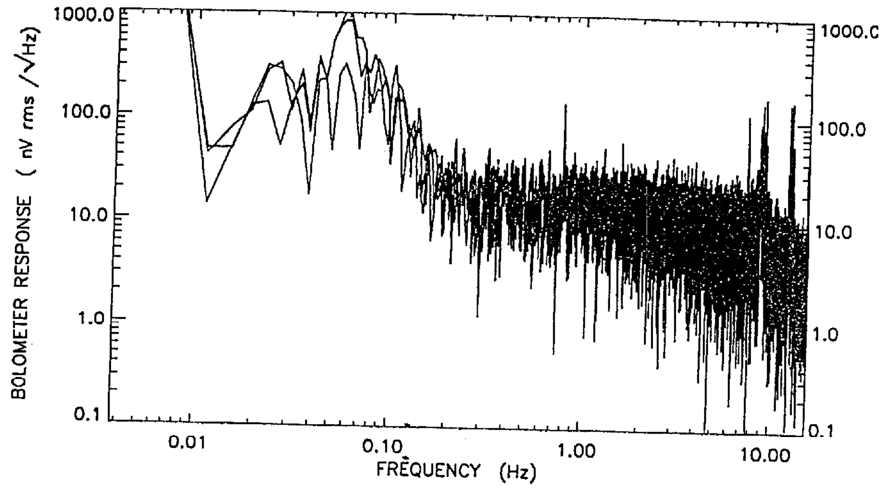
DC- STABLE READOUT





Measured noise spectrum of a micromesh bolometer operating from a 300 mK cold stage using a DC-stable total-power readout circuit. Low frequency noise stability is required to produce accurate maps using the slow-scanning strategy employed in many space-borne observations (e.g. COBRAS/SAMBA). The slow rise in the noise spectrum at low frequencies is caused by drifts in the voltage reference in the 20-bit A/D converter: the feature at 0.5 Hz is due to the response time of the thermally regulated cold stage.

SPIDER BOLOMETER MICROPHONIC RESPONSE
YOGI DILUTION REFRIGERATOR AT 0.1K , INPUT AT 37Hz

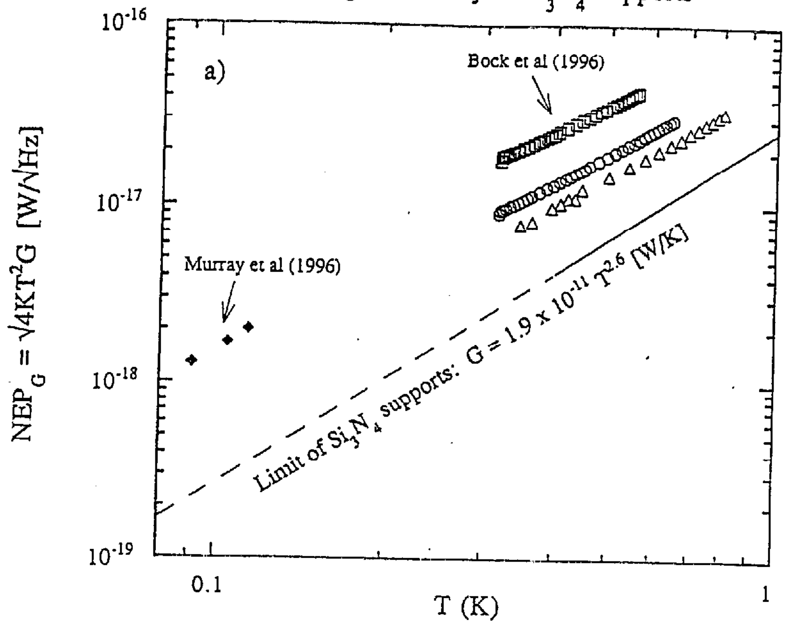


BLANKED BOLOMETER AND CRYOSTAT WINDOW
CALTECH AMP , 7.04mV pk AC BIAS , TEMP CONTROL ON
JFET AT 115K , PLOT YBOL37.PS , 27 JUNE 1997

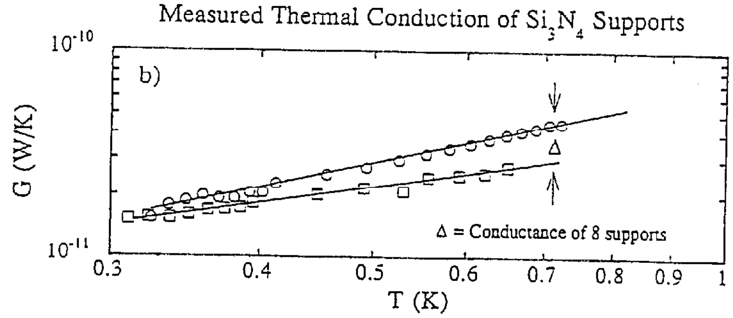
FILE 1 : APR1811.FFT , QUIESCENT RESPONSE
FILE 2 : APR1821.FFT , ACCN 20.6 mg rms AT BOL , 13.7 mg rms AT 2K PLATE
FILE 3 : APR1822.FFT , ACCN 37.1 mg rms AT BOL , 22.5 mg rms AT 2K PLATE

Ctsy. Ravinder Bhatia

Limiting Sensitivity of Si_3N_4 Supports



Measured Thermal Conduction of Si_3N_4 Supports



The excellent thermal isolation of silicon nitride enables the production of extremely sensitive infrared bolometers. The fundamental noise limit, set by phonon shot noise in the supports, varies as $NEP = \sqrt{4kT^2G} = 3.2 \times 10^{-17}\ T^{2.3}$ W/√Hz (see panel a). Including Johnson noise in NTD Ge thermistors, bolometers may be fabricated with NEP's of 2.5×10^{-19}, 3×10^{-18}, 1×10^{-16}, and 1×10^{-15} W/√Hz from a 0.1, 0.3, 1.5, and 4.2 K cold stage, respectively. The thermal isolation of current silicon nitride bolometers at 300 mK (Bock *et al.* 1996) and 100 mK (Murray *et al.* 1996) is quite low and may be still further reduced by minimizing the conductance of the electrical leads. The conductance of the silicon nitride supports was measured by removing 8 legs from a Si_3N_4 bolometer (see panel b).

Limiting NEP of Si_3N_4 Bolometers with Ge Thermistors

T [K]	NEP [W/√Hz]
0.1	3×10^{-19}
0.3	3×10^{-18}
1.5	1×10^{-16}
4.2	1×10^{-15}

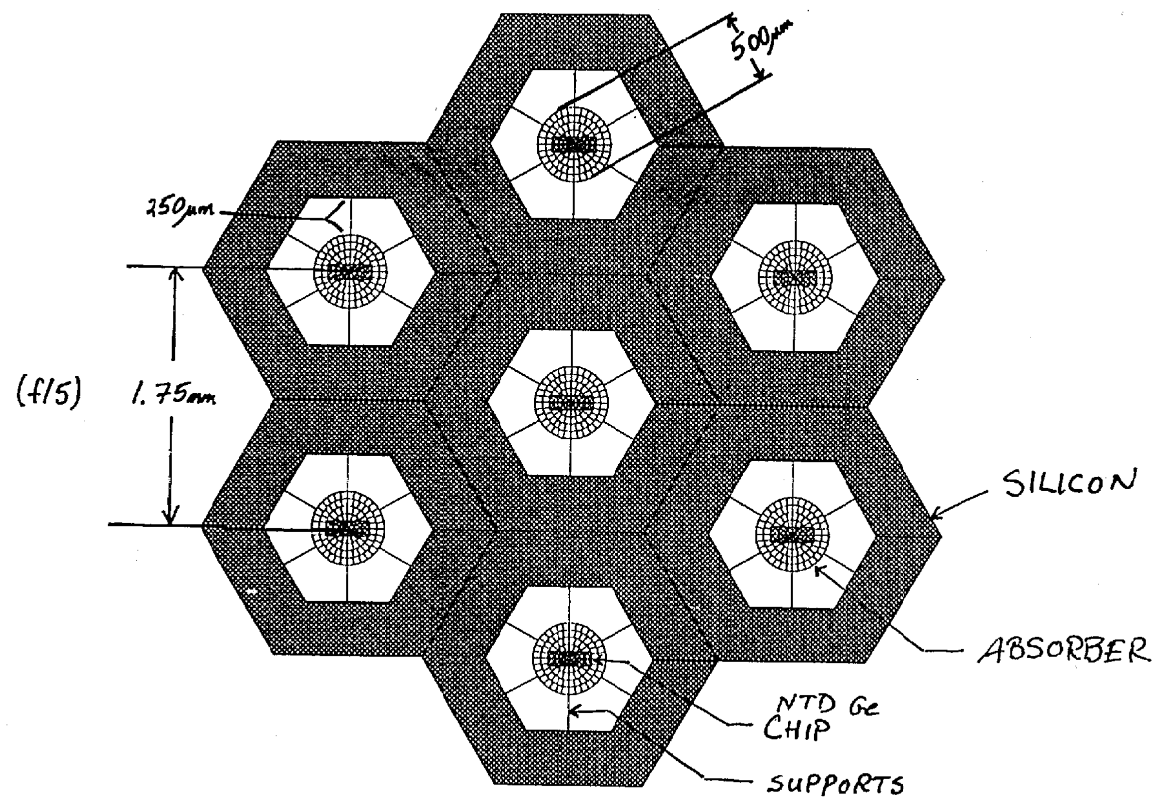
FIRST BOLOMETER SPECIFICATIONS

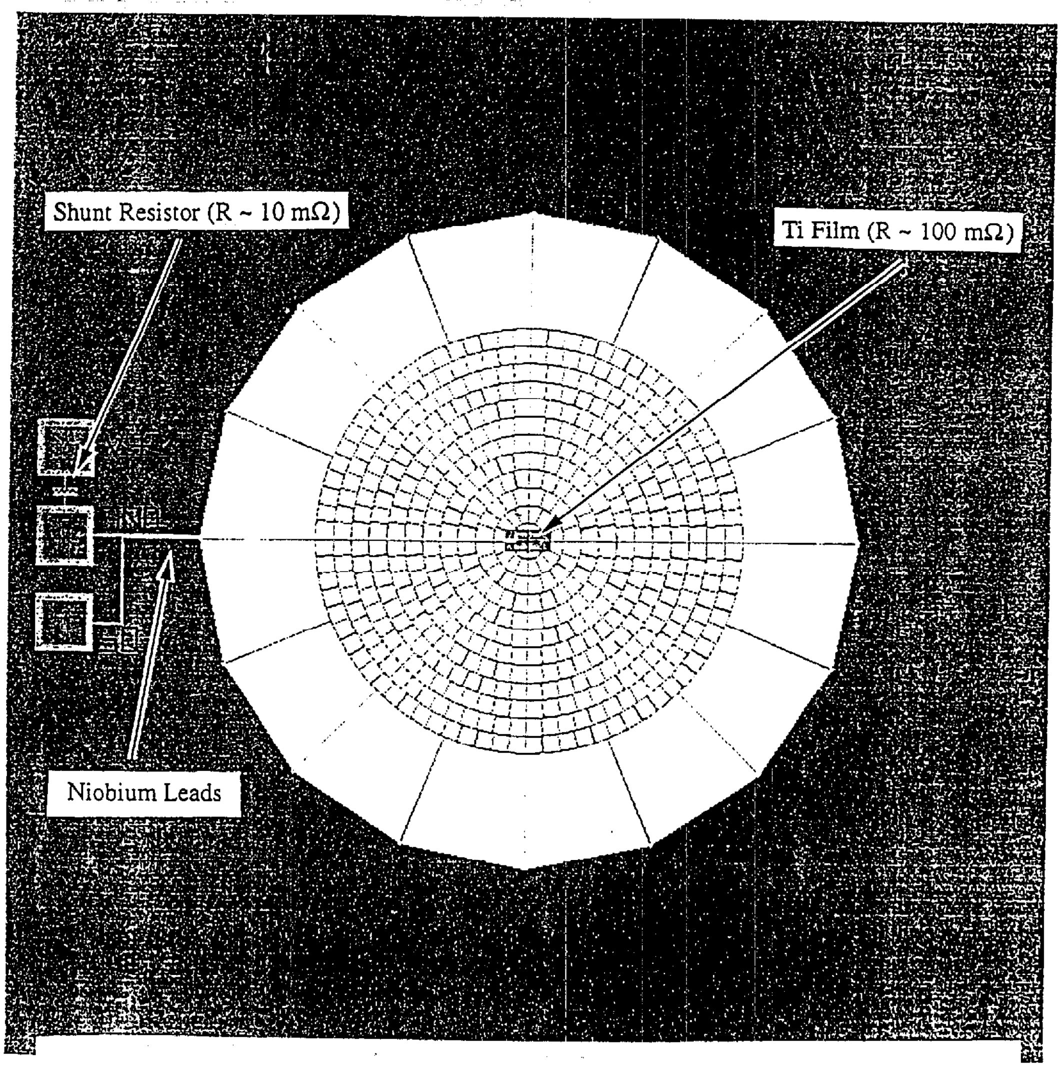
Channel	Q(pW)	G(pW/K)	τ(ms)	NEPd(x 1e-17)	NEPblip	NEPtot/NEPblip
P500	4.8	160	3.5	4.2	7	1.17
P350	5.3	175	3.2	4.4	9	1.11
P250	7.4	250	2.2	5.2	12	1.09
FTS	3.2	105	8	3.3	7	1.10
GS	0.02	18	30	1.4	0.5	3

Notes:

Tc = 300 mK
C = 1 pJ/K
NEPd^2 = NEPjohnson^2 + NEPphonon^2 + NEPamp^2
Vn(amp) = 5 nV/rtHz; Rbol = 5 MΩ
G = max[10Q/Tc, C/1.8]

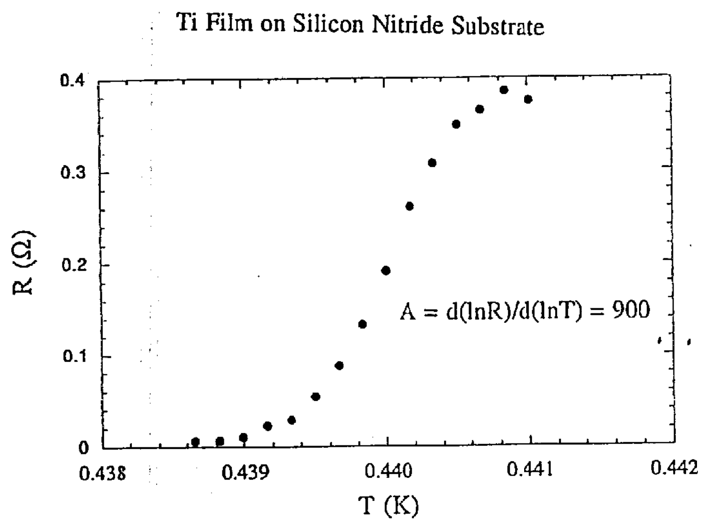
FIRST 350μm ARRAY LAYOUT

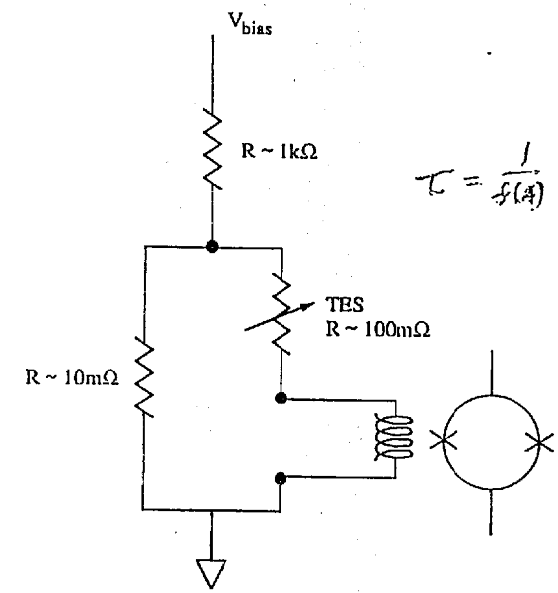




Mask for prototype TES/micromesh bolometer under development at JPL. The Ti sensor, located at the center of the device, is read out with lithographed Nb leads. The device is voltage-biased via a lithographed shunt resistor.

New Thermistor Technology: Transition-Edge Superconductor

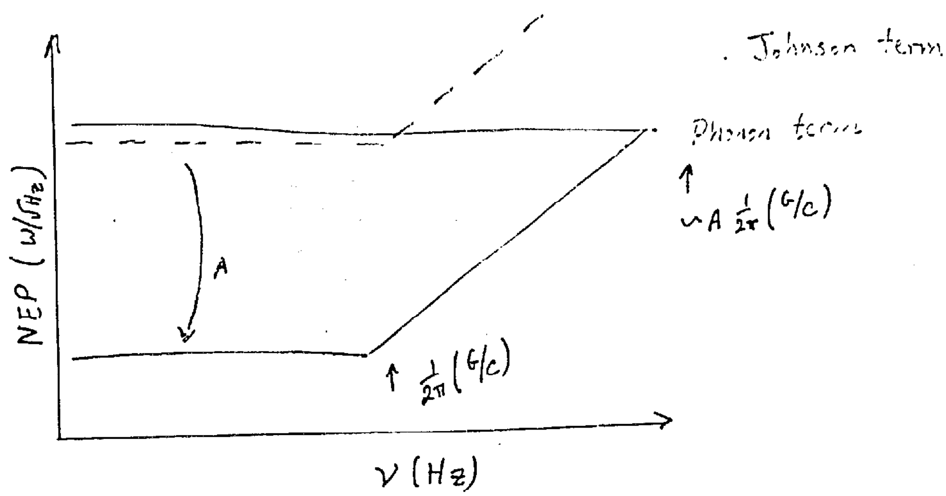




$\tau = \frac{1}{f(A)} \, C/G$

The large A = d(lnR)/d(lnT) of a voltage-biased transition-edge superconductor (TES) dramatically reduces the effective time constant and surpresses low frequency noise via electrothermal feedback. For a micromesh bolometer, the limiting time constant is the thermalization time of the absorber ~ 1 ms. The combination of TES and silicon nitride technology promises devices with high sensitivity, due to the low thermal conduction of the silicon nitride, and fast speed of response, due to the strong electrothermal feedback. Measured performance of (a) Ti film sputtered on silicon nitride gives a transition temperature of 440 mK and A = 900 (compare with A ~ 5 for NTD Ge). The detector is (b) AC-biased and read out with a SQUID current amplifier placed directly on the sub-K cooler.

Transition - Edge Superconductors



- Johnson noise surpressed by $f(A) \sim A$ for large A.

$$A = \frac{d\ln(R)}{d\ln(T)} \doteq \begin{cases} \sim 1000 & \text{TES} \\ 5 & \text{NTD Ge} \end{cases}$$

→ 1/f noise in film reduced

→ Response time reduced by $\sim A$

Advantages	Potential Problems
300mK bolometers for Planck/FIRST	1/f noise stability
SQUID readout at 300mK?!	magnetic fields
Can AC-bias	new readout electronics

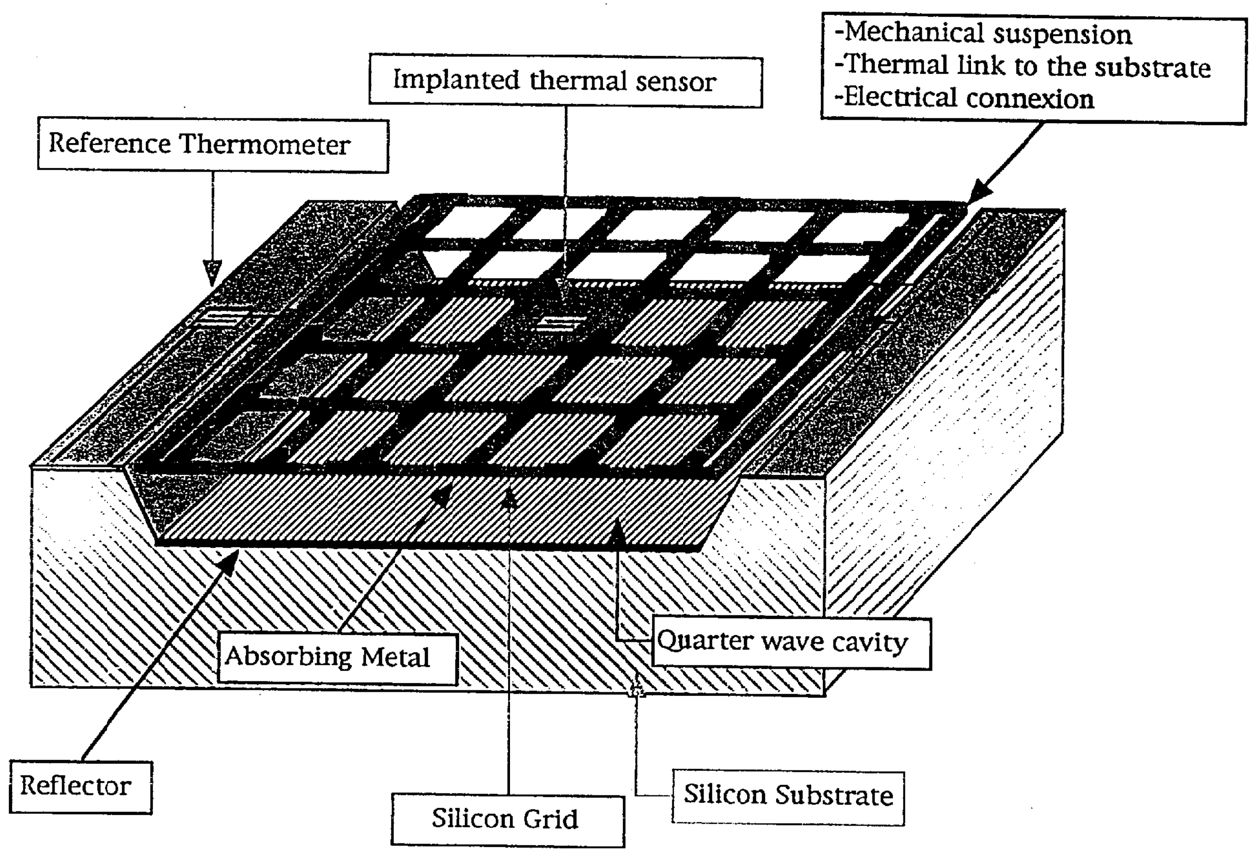
BOLOMETER ISSUES	STATUS / TEST APPROACH
NEP and time constant	Phot and FTS OK, [illegible]
Optical efficiency / sampling efficiency / aperture efficiency	BOLOCAM
Heat Sink Temperature	300 mK
Heat Load	set by scaling
Energetic Particles	OK
Pixel Angular Response	OK with Lyot stop
RFI	approaches known
Straylight	approaches known
Microphonics	[illegible]
Cross-talk	BOLOCAM
Yield / Uniformity	BOLOCAM
l/f knee	30 mHz
Readout electronics	IRTS, PLANCK
[illegible]	BOLOCAM [illegible]

LOUIS RODRIGUEZ

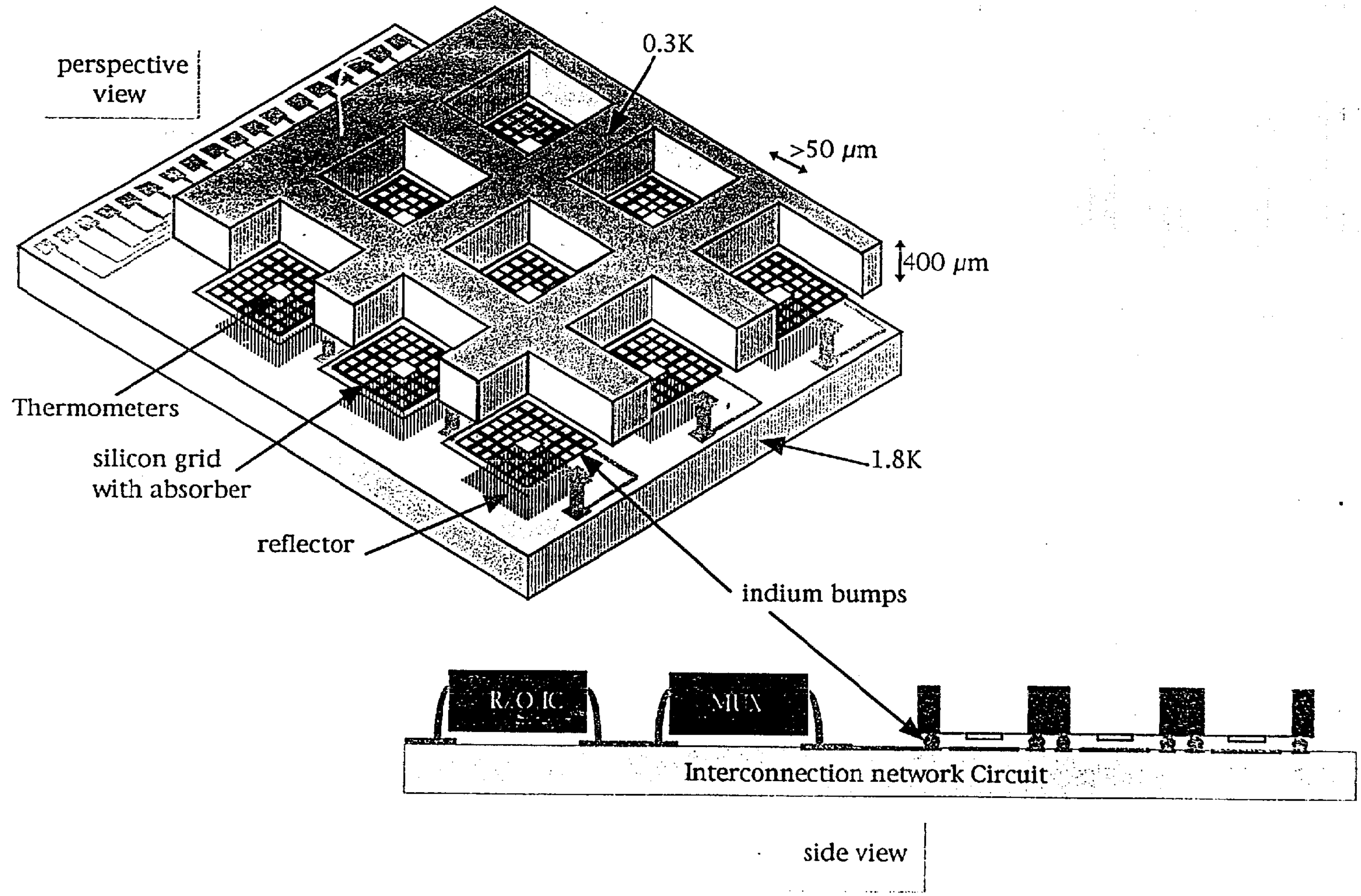
PLANAR BOLOMETER ARRAYS DEVELOPMENT AT CEA FOR THE BOL INSTRUMENT OF FIRST

P. AGNESE L. RODRIGUEZ L. VIGROUX

THE DETECTOR PRINCIPLE

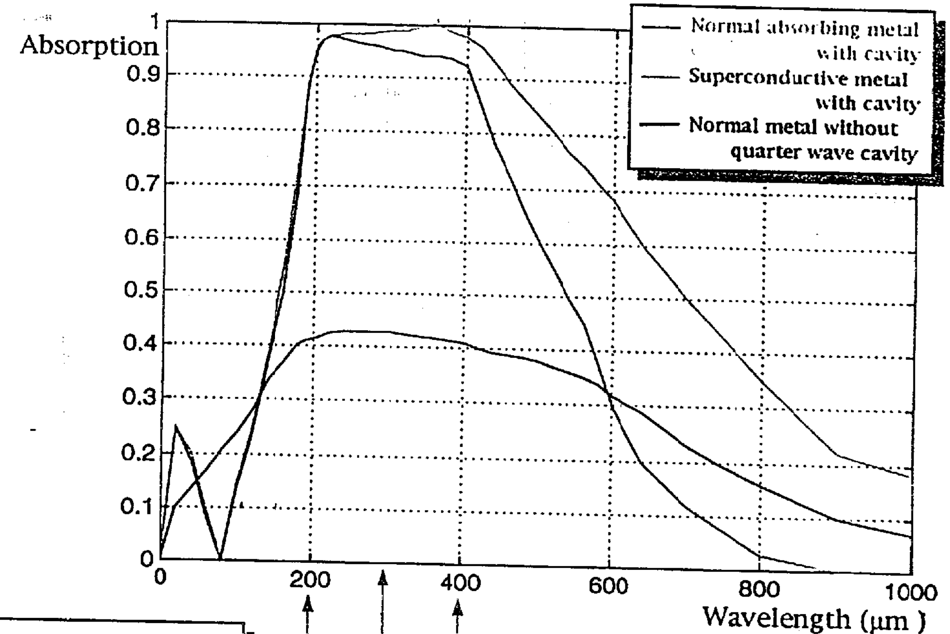


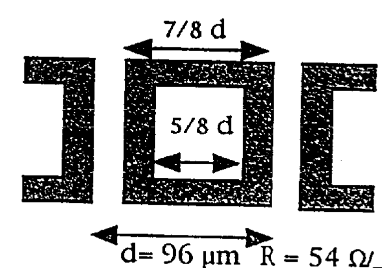
THE DETECTOR ARRAY CONFIGURATION



THE DETECTOR ABSORPTION

Resonant absorption mechanism

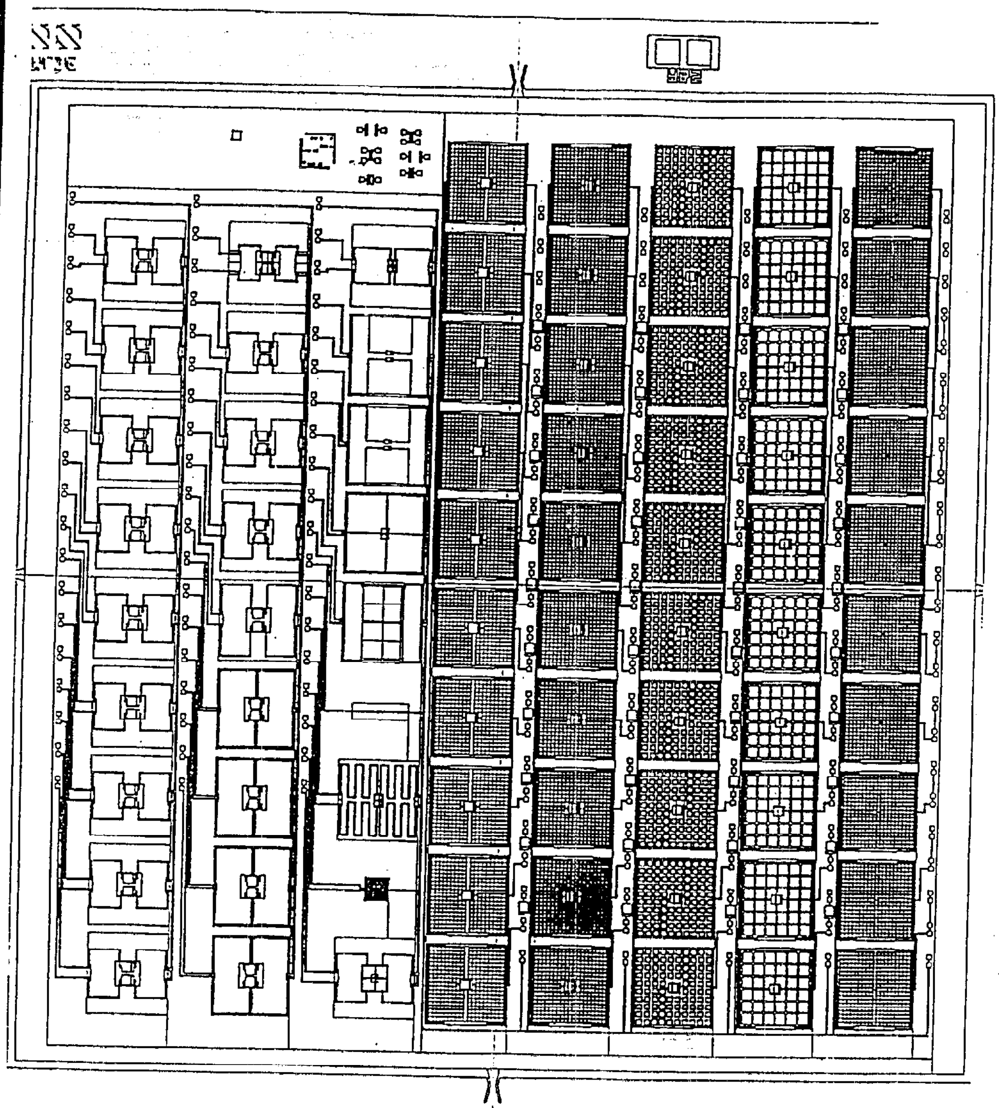




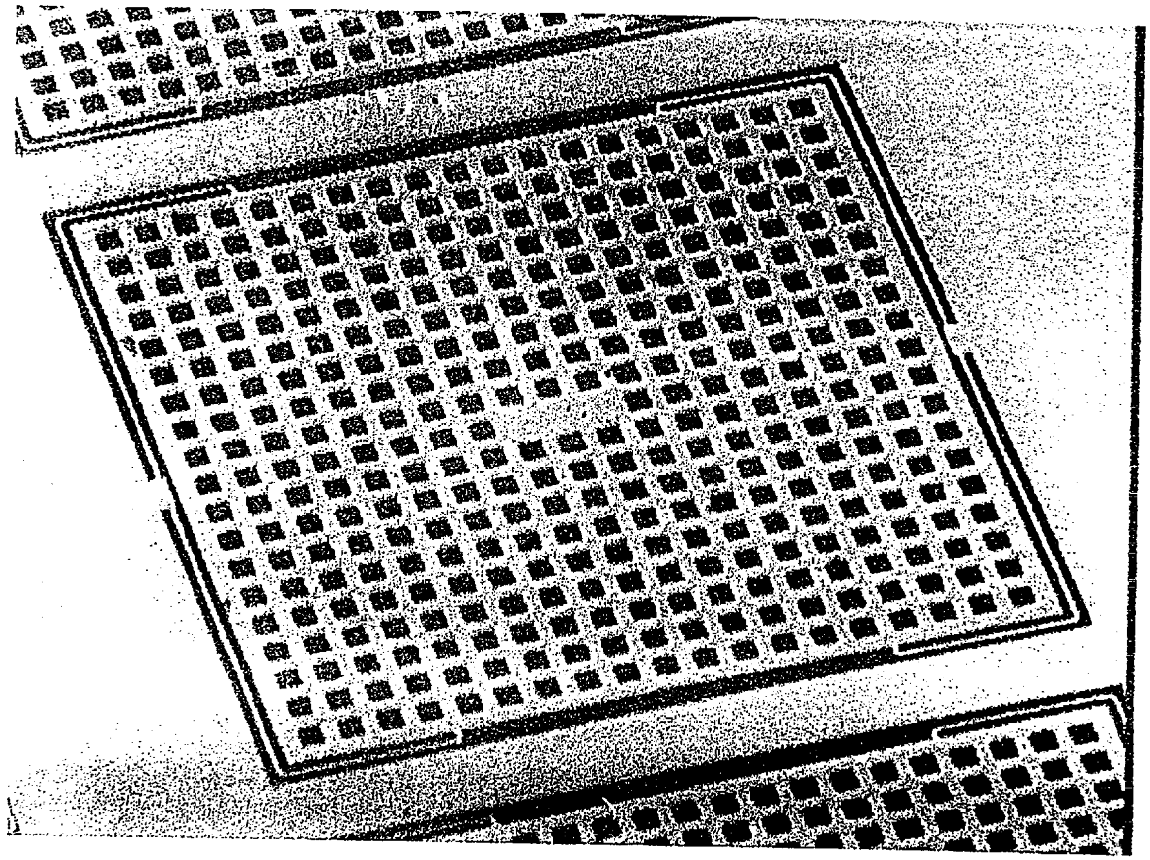
HORIZONTAL PATTERN

ABSORPTION MODELISATION:
Calculations for the 200 -> 400 μm electromagnetic band:
-capacitive absorbing metal loops,
-cavity 75 μm (center wavelenght : 300 μm).
Comparison of normal and superconductive metallic absorber, here well below Tc to ensure at the time a significant decrease of heat capacity and ($h\nu >> 2\Delta$) to ensure the vacuum impedance matching.

97 PROTOTYPE ARRAY

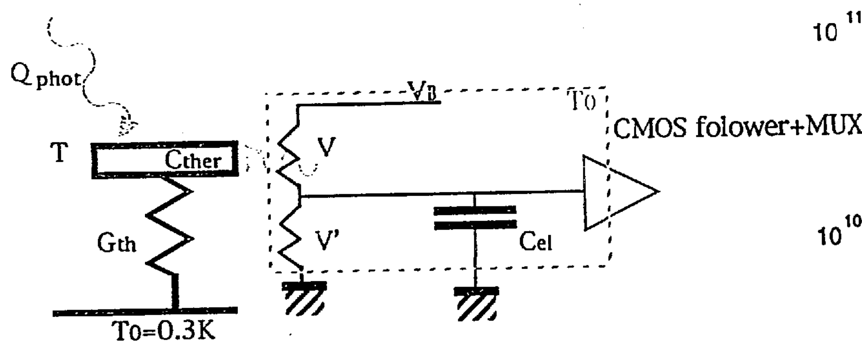


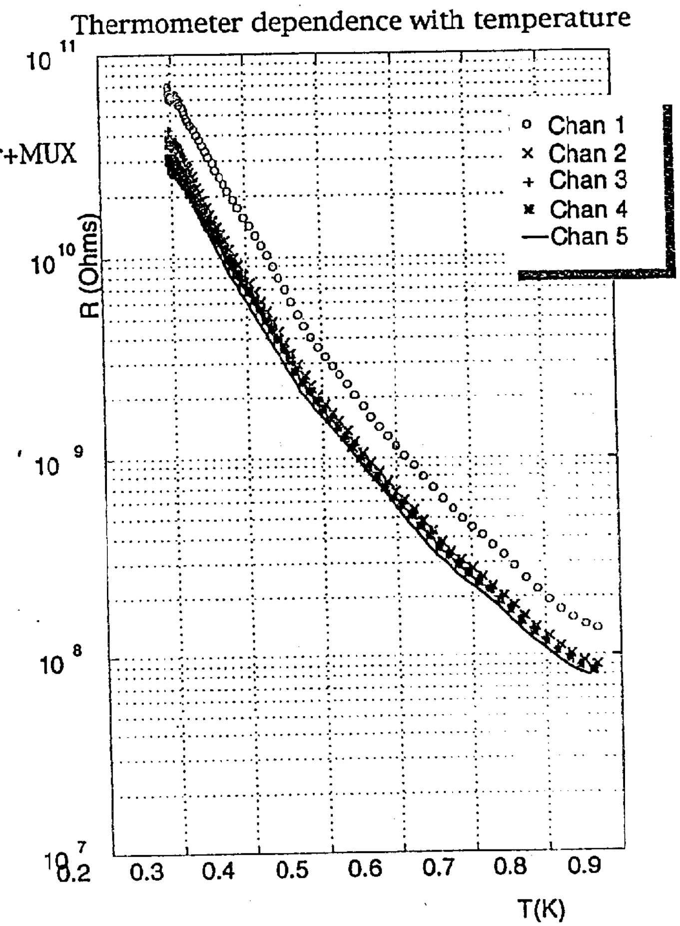
STRUCTURE BOLOMETRIQUE



DETECTOR MODELISATION

THERMAL MODEL





For the 4th type bolometer the thermal characteristics are:

$C_{ther} = 2.2e^{-14}(T/T_0)^3 + 5.36e^{-14}(T/T_0)$ (J/K)

$G_{th} = 5.55e^{-12}(T/T_0)^3 + 7{,}94e^{-13}(T/T_0)$

(silicon beams) (metal strips)

The R $(100\mu m)^2$ thermometer dependence is

$R(E,T) = R_{00} \exp[(T_0/T)^{1/2} + qLE/kT] = V/I(V,T$

Results from massive thermometers:

-measured $\sqrt{T_0} = 12$

- deduced from measurements

$L=0.05\mu$ @ 0.3K

84

DETECTOR MODEL

NOISE

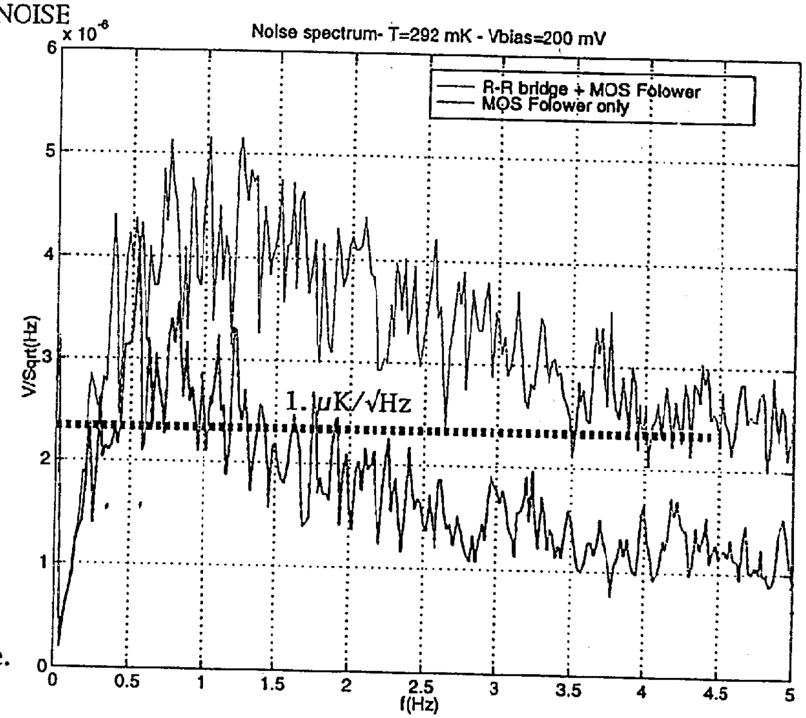
Associated current noises are :

-- Johnson noise = $4\,kT(dI/dV)^{1/2}$

— 1/f noise = $[\alpha_H/(N.f)]^{1/2}\,.\,I$ (A/√Hz)

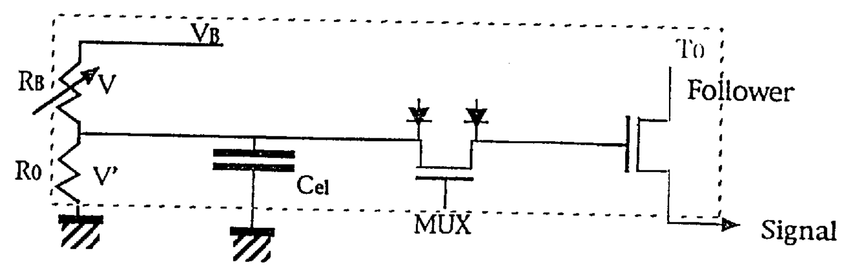
with α_H the Hooge constant and N number of sites in the thermometer volume.

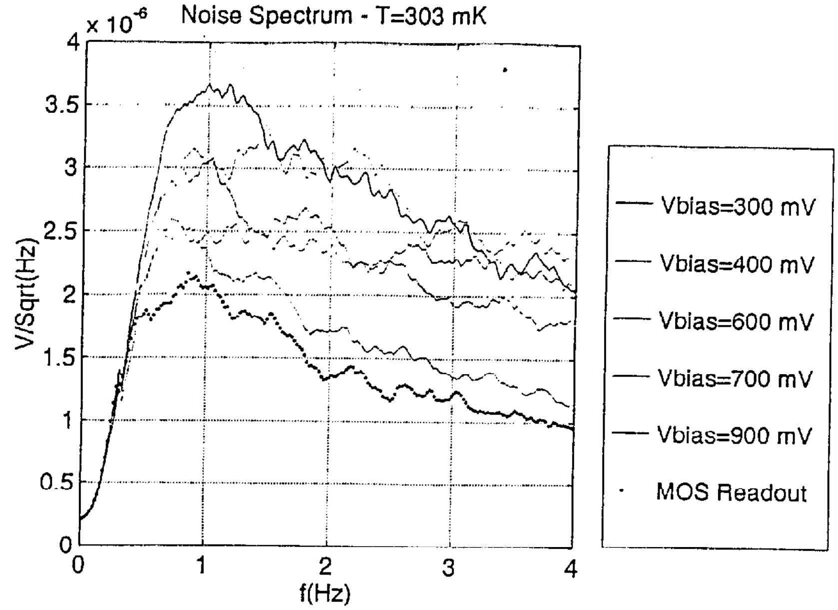
MUST BE COMPARED TO EXPERIMENTAL RESULTS →

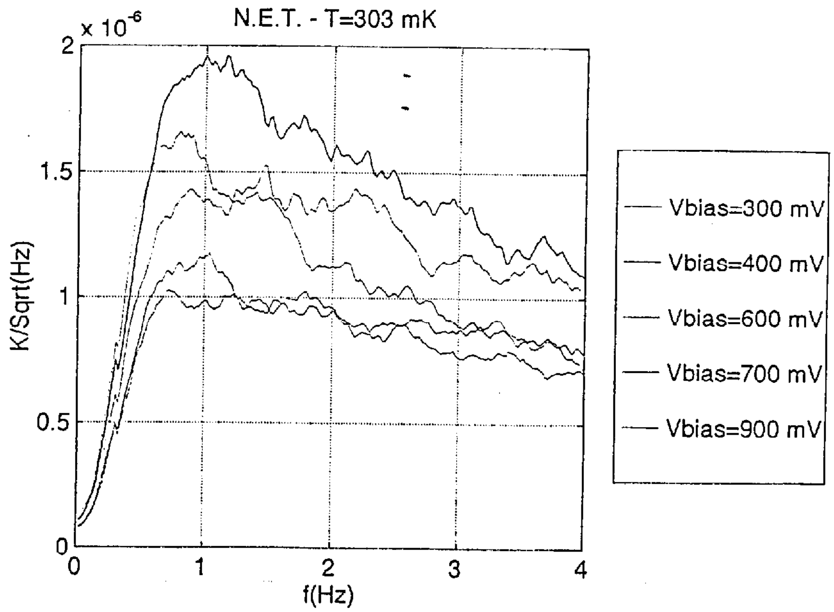


In our measurements, excess noise decreases with bias (not a 1/f standard noise).
-Not a microphonic noise either,
supposed to be a leakage current in the hybridized circuit used for the MUX.
If this is real it should be eliminated in the prototype.

The noise measured is currentely six times the expected johnson noise




Noise Spectrum - T=303 mK
x 10^-6
V/Sqrt(Hz)
f(Hz)
Vbias=300 mV
Vbias=400 mV
Vbias=600 mV
Vbias=700 mV
Vbias=900 mV
MOS Readout


N.E.T. - T=303 mK
x 10^-6
K/Sqrt(Hz)
f(Hz)
Vbias=300 mV
Vbias=400 mV
Vbias=600 mV
Vbias=700 mV
Vbias=900 mV

READ OUT CIRCUIT

2 Options currently evaluated (with A. Benoit):

➡ Square A/C bias @ 10 Hz and multi-sampling.

This option needs low electrical capacity at the detector level: 0.1-0.2 pF.

$f=(2\pi R_{bol} C_{el})^{-1}$ and $4\,kT R_{bol})^{1/2} > e_n/\sqrt{f}$.

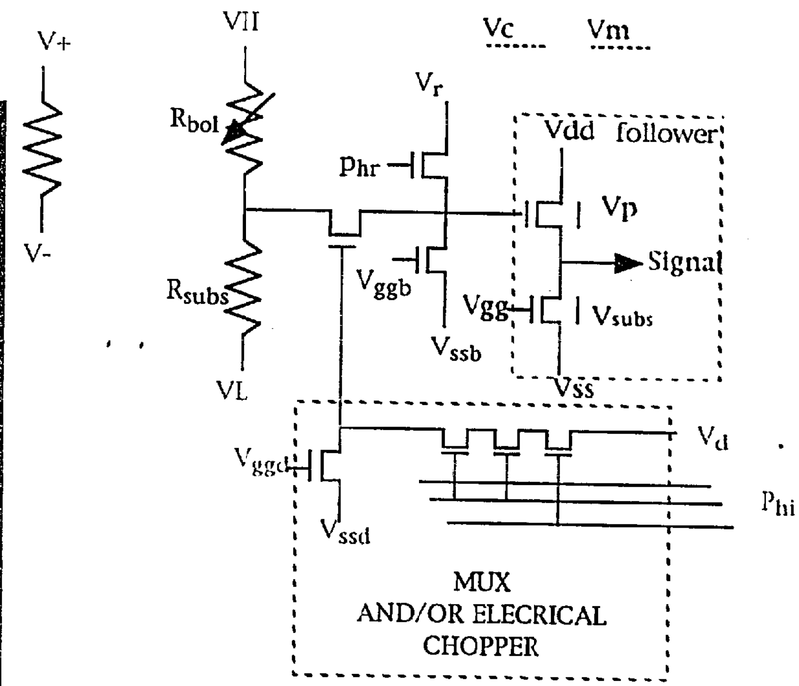
Then $C_{el} < 4\,kT/(2\pi\, e_n^2)$

@ 300mK for a NMOS $C_{el} < 0.16$ pf

➡ Direct Bias and MUX chopping.

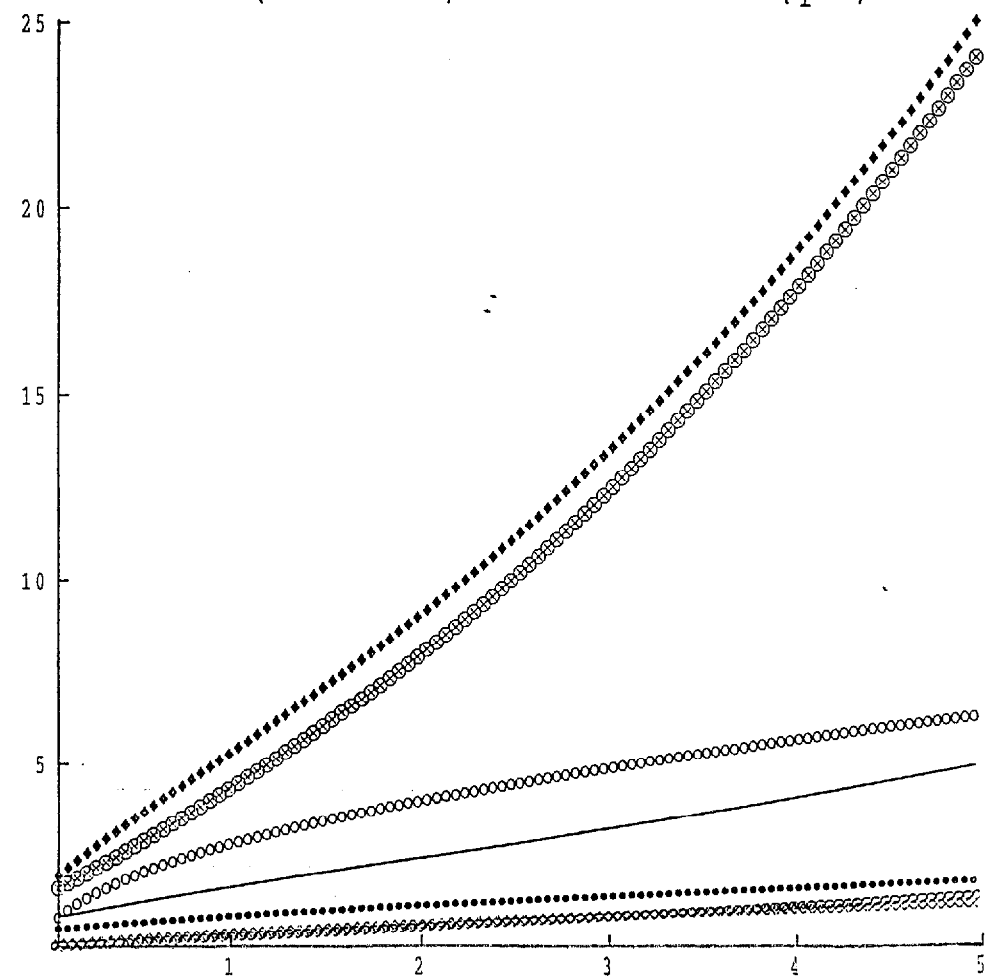
New idea rised when testing low impedance thermometers with A. B.: the MUX can be used to swich from the detector to an internal electrical reference at 10 k Hz. The expected electrical capacity is then around 10 pf.

Voltage measurement



V : Nep total
ⓧ : Nep lecture
ooo : Nep photonique
— : Nep Johnson
••• : Nep phonique
xxx : Nep Joule

NEP(1.D-17) FCT CHARGE(pW)



FROM THERMOMETERS TO BOLOMETERS

To calculate the bolometer properties we have assumed:

THERMOMETER:
Same implantation on thin substrate => same thermometric performances.

THERMAL IMPEDANCES:
Computed from the Casimir law. Valid within a factor of two (LTD 7 conference)

HEAT CAPACITY:
Computed from published data.

ABSORBING METAL:
Two metellic absorbers are currently tested: TiN (350Å) and WN (500 Å)
TiN becomes superconducting @ 2.2 K and WN @ 4.07 K. Both keep their room temperature optical properties at 300 mK 54 $\Omega/\square$.

SELF STANDING GRID MECHANICAL PROERTIES
Measurement from the mechanical prototype.

ABSORPTION OF EM WAVES.
From a 3-D Maxwell code.

INTERCONNECTION NETWORK CIRCUIT:
From LIR data.

INDIUM BUMPS CONDUCTION
From LIR data.

THERMOMETER RESULTS

40 ARRAYS OF 10 THERMOMETER R-R bridges (8000 I/V measurements) tested I(V) between 20 and 1.5 K

I(V,T) and noise measurements from 1K to 0.3 K.

3 splits including boron compensation from 0.1 to 0.5.

Impedance	6 E10 Ω @ 1 pW	Expected value
Sensitivity	~10 V/K	R varies fact. 100 in 350 mK
Dispersion	80% on the wafer few % locally R-R bridge	
N MOS noise	1.5 μV/√Hz @ 2Hz	
Thermometer noise	2,5 μV/√Hz @ 2Hz	x6 Johnson noise
NET (Signal/tot noise)	1.5-2 μK/ √Hz @ 2Hz	

EXPECTED bolometric NEP:

NEPelec NET/Rth -----> few 10^{-17} W/√Hz

LOW IMPEDANCE THERMOMETER

We (A. Benoit) have measured low impedance termometers (10-100 mΩ) at CRTBT Grenoble with a dilution fridge.

<u>Current results are:</u>

Read out through 80K JFET

-> NET identical to the high impedance ~ 3μK/Hz @ 2Hz with a 1/f noise (x5 johnson noise) increasing with bias.

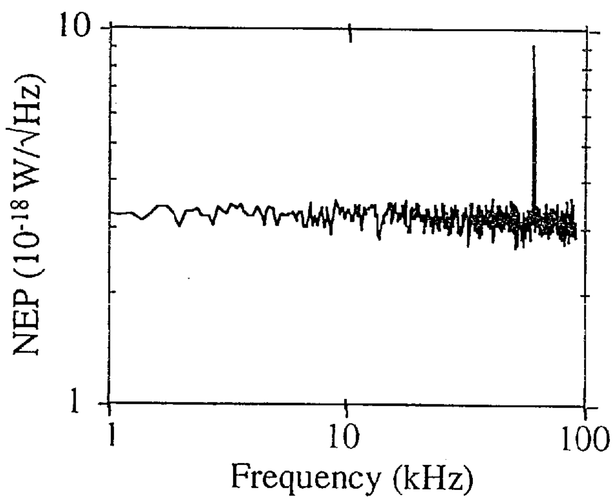
Result: same performance than high impedance in merit but lower signal at output.

TES Advantages

- Significant Speed advantage
  Noise bandwidth nearly 100 times that of semiconductors.
  $\tau_e << 10^{-3}$ s possible at FIRST-BOL NEP's.
  Large Bandwidth offers increased flexibility in choice of signal freqs. and minimizes loss of data due to particle hits.

- Naturally Couple to SQUIDS
  Low power, low noise 2 K amps.
  Multiplexing capability

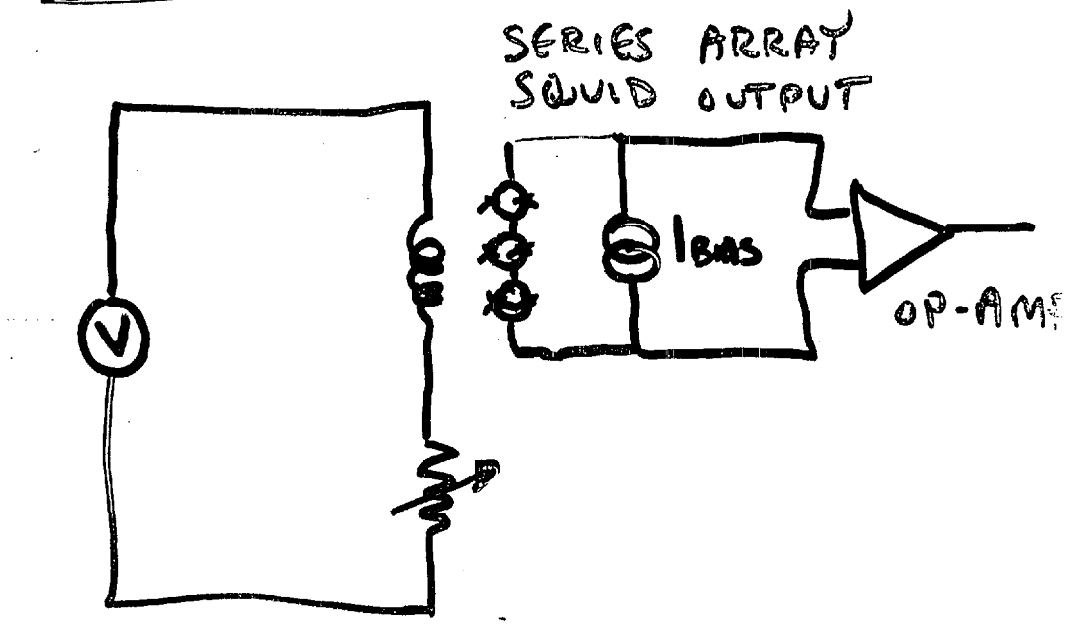
Electrical NEP Measurement of Transition-Edge Bolometer



- **Electrical NEP ~ 3 x 10^{-18} W/√Hz**
- Transition temperature T_c ~ 85 mK
- Thermal conductance G ~ 25 pW / K
- Thermodynamic fluctuation noise limit ~ 2.2 x 10^{-18} W/√H

NIST Boulder

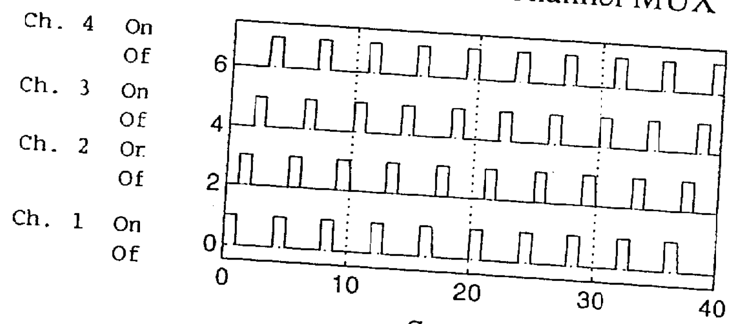
NON-MULTIPLEXED TES w. SQUID READOUT



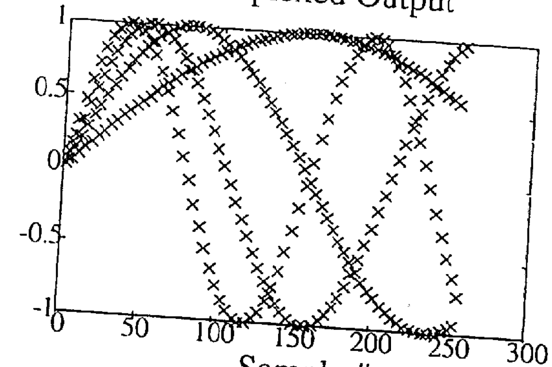
- SQUID TECHNOLOGY IN HAND
- POWER DISSIPATION ~ 100nW

Multiplexing

State Diagram for N=4 Channel MUX



Multiplexed Output



- The bolometer signal is thermally integrated.
- High frequency Johnson noise is rolled off at bandwidth

$$f_{knee} = \frac{R_{dyn}}{2\pi L_{in}}$$

- As long as the amplifier noise is low enough, no information in the Nyquist bandwidth is lost

$$f_{Nyquist} = \frac{1}{2Nt_s}$$

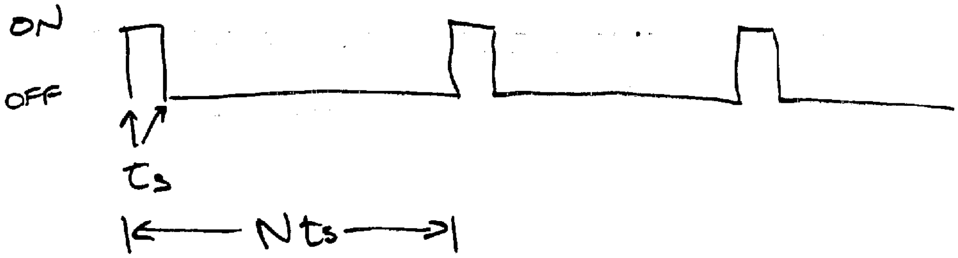
Dynamic Resistance of Sensor

Input Inductance of 1st Stage SQUID

Multiplex N channels, sample each for time t_s

NIST Boulder

NOISE & BANDWIDTH



- BANDWIDTH:

  SIGNAL: NYQUIST $\Delta B_{SIG} = f_{NYQUIST} = \frac{1}{2 N t_s}$

  AMPLIFIER: INTEGRATED OVER t_s: $\Delta B_{AMP} = \frac{1}{2 t_s}$

- "MULTIPLEX DISADVANTAGE"

  SINCE THE AMPLIFIER B.W. IS N× LARGER,

$$S_{I_{AMP}} = \frac{S_{I\,SIGNAL}}{N}$$

- SENSOR NOISE

$$S_{I\,TES} = \frac{8 K_B T}{R}$$

  { TRANSITION-EDGE SENSOR IN EXTREME FEEDBACK LIMIT

- AMPLIFIER NOISE

  SQUID ENERGY SENSITIVITY ξh

$$\tfrac{1}{2} L_{in} S_I = \xi h$$

$$S_{I_{SQUID}} = \frac{2 \xi h}{L_{in}}$$

- POSSIBLE NUMBER OF CHANNELS

$$\boxed{N = \left(\frac{L_{in}}{R}\right) \frac{4 K_B T}{\xi h}}$$

REASONABLE: $N = (200\,\mu s) \frac{4 \cdot K_B \cdot (0.1\,K)}{300\,h} \approx 5500$

MULTIPLEX SPEED

- "DWELL TIME" $t_s = 10\mu s$ IS ATTAINABLE. TIMES AS FAST AS $t_s = 1\mu s$ MAY BE POSSIBLE IN THE FUTURE, WITH SUFFICIENT RESOURCES
- L/R ROLLOFF

THE L/R B.W. LIMITS THE NOISE WITH KNEE

$$f_{L/R} = \frac{R}{2\pi L}$$

ANY NOISE POWER ABOVE THE NYQUIST FREQUENCY IS ALIASED INTO THE SIGNAL B.W. SINCE THE L/R IS A ONE-POLE FILTER, THE DEGRADATION IN NEP IS ~20% IF $f_{L/R} = \frac{f_{NYQ}}{2}$.

$$\frac{R}{2\pi L} = \frac{1}{4Nt_s}$$

$$\frac{L}{R} = \frac{2Nt_s}{\pi}$$

- THERMAL RESPONSE TIME

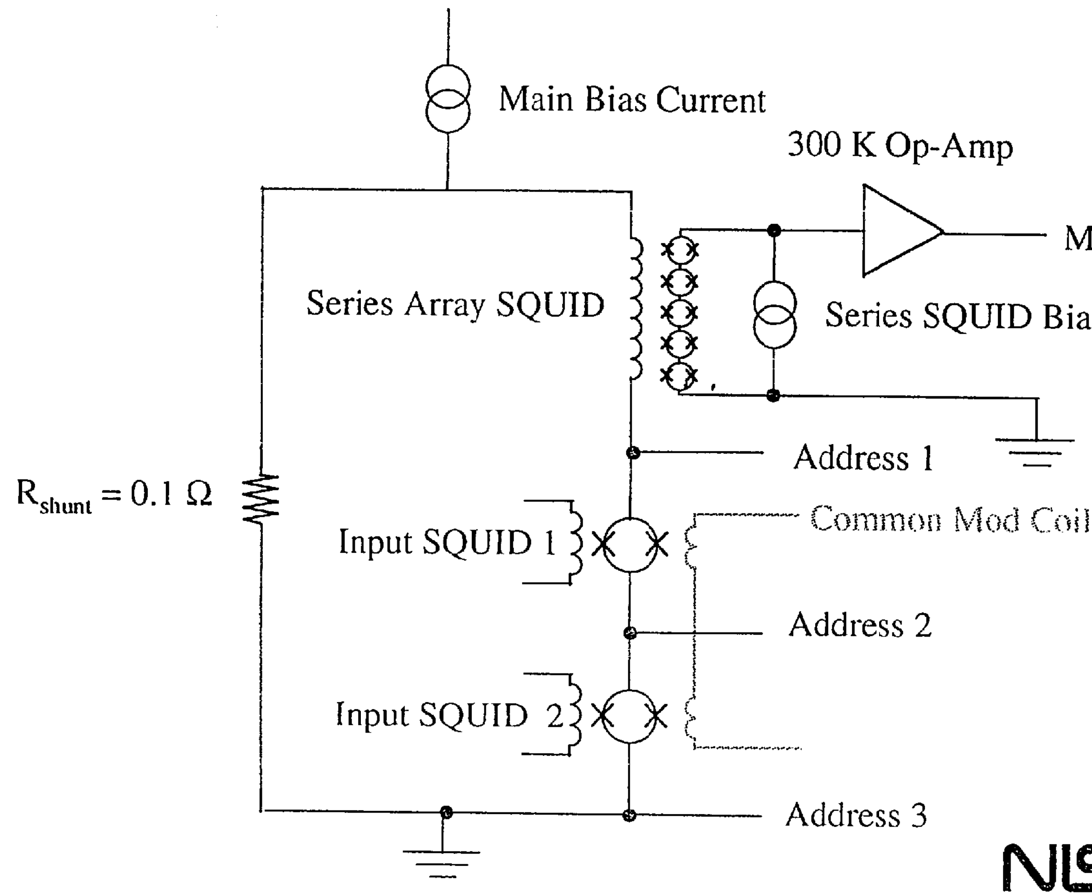
FOR STABLE OPERATION, $\tau_{EFF} \gtrsim 6\, L/R$

$$\tau_{EFF} \gtrsim 4Nt_s$$

$$32 \times 32 \text{ MUX}, \quad t_s = 10\mu s$$

$$\tau_{EFF} \gtrsim 1.3\,ms$$

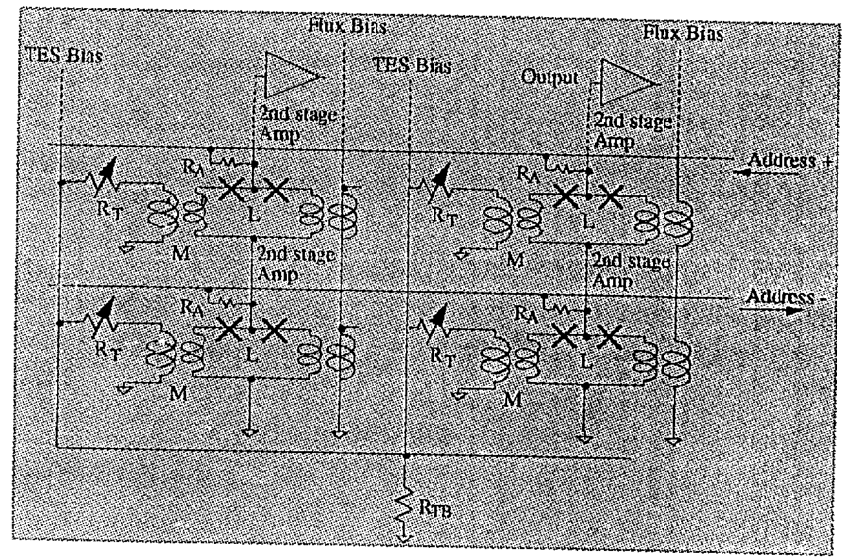
1 x 2 Discrete SQUID MUX Demonstration



NIST Boulder

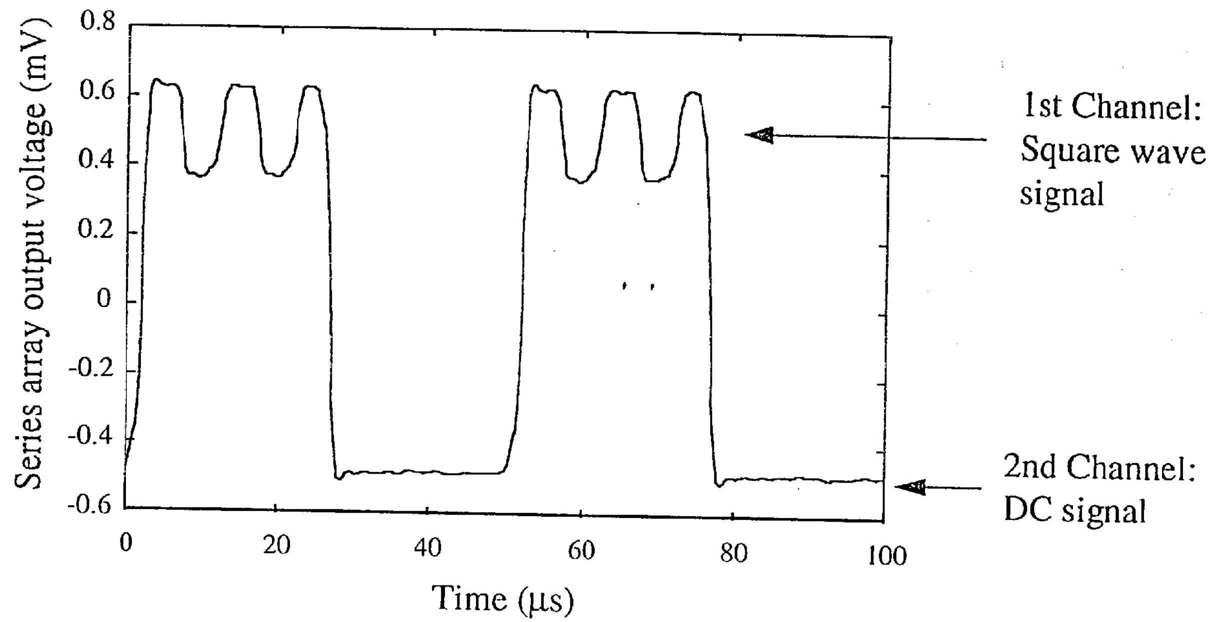
SQUID multiplexer design

- each column is an array of SQUID amplifiers
- voltage of each SQUID read by 2nd stage amplifier (SQUID series array)
- row biasing applied
- unaddressed SQUIDs off (superconducting)
  Does not add signal
  or noise to readout,
  no power dissipation!



NIST Boulder

1 x 2 SQUID MUX Demonstration: 40 kSa/sec



NIST Boulder

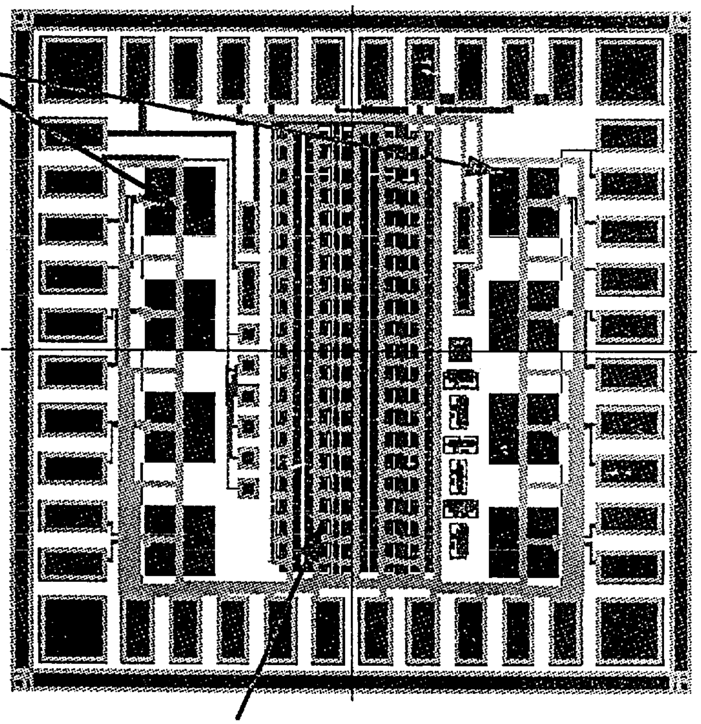
SQUID MUX POWER DISSIPATION

STAGE
(1) FIRST STAGE SQUIDS ~1nW PER
32×32 ARRAY ~ 32nW
(2) SQUID ADDRESS RESISTORS
(10× SQUIDS, DEPENDING ON CROSSTALK)
32×32 ARRAY ~ 320nW
(3) SERIES ARRAY SQUIDS ~ 100nW PER
32×32 ARRAY ~ 3.2μW
(4) SQUID ADDRESS SHUNT RESISTOR
32×32 ARRAY ~ 3.2μW

TOTAL POWER COLD 32×32

AT SQUID STAGE (BASE OR 2K)	~350nW
AT 2K	~ 6.4μW

SQUID multiplexer design & layout



final fabrication
steps underway

NIST Boulder

Spectrometer Applications

$R = 3000 \Rightarrow P \sim 3\times10^{-15}\,W \Rightarrow NEP_B \sim 2.5\times10^{-18}\,W/\sqrt{Hz}$ @ 600 μm

$1.7\times10^{-18}\,W/\sqrt{Hz}$ @ 400 μm

T_B	T_t	P_s	$G^{\neq}$	NEP	τ_e
.10	.15	$3\times10^{-15}\,W$	$3\times10^{-13}\,W/K$	$4\times10^{-19}\,W/\sqrt{Hz}$	1 ms (.1s)
.20	.30	$3\times10^{-15}\,W$	$1\times10^{-12}\,W/K$	$1.6\times10^{-18}\,W/\sqrt{Hz}$	1 ms (.1s)
.30	.45	$3\times10^{-15}\,W$	$1\times10^{-11}\,W/K$	$7.5\times10^{-18}\,W/\sqrt{Hz}$	1 ms (.1s)

$\neq$ Based on achieved conductances

AFTERNOON: " E113

THURSDAY OCT 30:

AGENDA:

1. PLAN FOR AO RESPONSE 09.30
   - BASELINE
   - DESCRIPTION OF OPTIONS

2. CRITERIA FOR ARRAY TECHNOLOGY SELECTION 10.30

3. ARRAY EVALUATION TEST PROGRAMME 11.30

4. SCHEDULE FOR EVALUATION PM
   BY MID. 1999 (Goal): Early 2000 formally.

5. Decide on He-3 as baseline

- JFET MODULE ACCOMMODATION
- IMPLICATIONS OF FILLED ARRAYS FOR OPTICAL DESIGN (STRAYLIGHT)

- standardise on 350 μm as nominal test λ
- $\lambda/\Delta\lambda \sim 3$

Calibration module:

- Speed
- Optical responsivity
- DC power loading
- Optical crosstalk
- Electrical crosstalk
- γ-Ray response
- Uniformity
- VIs
- Linearity
- Dynamic range (Needs Scientific Spec)

AO response

- **Base-line:**

Photometer:
- $2F\lambda$ single•mode feeds
- Spider-web bolometers
- Array sizes as currently defined (or similar)
- JFET readout (T ~ 120 K)
- Bias circuit and readout amplifier TBD

Spectrometer:
- FTS or grating
- Grating : Linear array of $2F\lambda$ pixels
- FTS : TBC
  Possibly 2 x 19 element HCP arrays with $2F\lambda$ pixels

- **Option to be described in proposal:**

- Large-format arrays for photometer (and FTS spectrometer option)
  - Sub-options under study and development
- Benefits to be gained
  - Scientific
  - Operational
- Parallel array development and test programmes
- Technical maturity and space-qualification status
- Selection criteria, schedule and deadline
- Implications for ESA:
  - Spacecraft interfaces
  - Spacecraft resources
    - Power (FPU; warm)
    - Operating modes
    - Telemetry rate

Proposed array technology selection criteria

better to have same type for FIRST + photometer

1. Array option must be superior to base-line in mapping speed by a factor of TBD.

2. If European option is equivalent to a US option to within a factor of TBD in mapping speed, the European option shall be chosen. ~ $\sqrt{2}$ [No need to go below confusion limit]

3. US option, if chosen, shall be fully funded by NASA - no additional effort shall be required from Europe (but readout electronics and/or warm analogue electronics could be built in Europe).

4. Chosen option shall be compatible with spacecraft resources (esp. thermal and telemetry rate restrictions).

5. Array technology shall be space qualifiable, with credible process and schedule for qualification.

6. Array prototypes (or at least single-pixel systems) shall have (at the very least) undergone full testing in the laboratory to determine performance parameters.

   Detailed testing programme and schedule to be agreed.

7. Formal array selection review shall take place on date TBD based on experimental evaluation and conformance to a defined set of operating and performance requirements:
   - Sensitivity; speed
   - Yield
   - Uniformity
   - Cross-talk
   - Ionising radiation susceptibility
   - Etc.
   - Power dissipation
   - Reqd. operating temp.
   - Telemetry rate
   - Redundancy
   - Etc.

   - Instrument optical/thermal/mechanical modelling
   - Accurate estimates of BOL electronics and spacecraft requirements
   - Credible schedule and cost estimates for QM and FM manufacture and delivery, including readout electronics

8. Possible selection team:

   Griffin, Vigroux, Swinyard, Lange/Bock, Moseley, [Pilbratt, agreed external experts (e.g., FIRST Mission Scientists ?)] — in the presence of --

   Payload Manager?

Array evaluation tests

- QMW can provide test facility:
  - Blanked measurements
    - Load curves; noise; speed of response (γ-rays)
  - Photometric measurements
    - Optical responsivity, NEP, speed of response
  - Beam profiles and stray light susceptibility
  - Microphonic susceptibility
  - Crosstalk, uniformity

Test module passed around? with [illegible]

EMC susceptibility?

- What's needed for testing:
  - Single pixel equivalent or small array
  - Appropriate readout electronics (warm and cold)
  - QMW can provide filtering
  - Mechanical, electrical details will vary with array type

Module design? Standard ok.

- Participation in set-up and testing by staff from array-producing groups is highly desirable

Cold Vibration? [standard]

- Test programme can be phased/continuing, with results being fed back to the development programme
- Final evaluation should be based on an agreed set of tests, standardised as much as possible

BASELINE:

- 250 32 x 32 0.5 fλ

  350 24 x 24 "

  500 16 x 16 "

- QUOTE
  - Guaranteed: 10 1hr as for feedhorn array (already calculated)
  - Goal : Improvement by factor of TBD [~ 1 order of magn.]

- Baseline :
  - Readout electronics
  - FPU power dissipation
  - No of wires
  - Data rate

  } Define this this afternoon

This afternoon

2PM

① CEA test programme

② Caltech " "

③ Goddard /NIST " " } ≡ one programme

④ Overall test programme

⑤ Schedule for future ARRAY Workshop Meetings

3PM

Baseline for proposal: • ARRAYS baseline

- Readout electronics
- FPU dissipation
- No of wires
- ~~Dat~~ Telemetry Rate
  - on-board processing

Goal: Finish by 4PM

SPIE 20 - 28 MARCH

⇒ Next ARRAY Meeting JUST BEFORE ~20th MARCH

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TECHNICAL QUESTIONS WE HAVE TO REPLY TO IN AO RESP. / ID PART B.

[~~ANDREAS~~ MARIE ~~LOUGH~~ JEAN-LOUIS AUGUÈRES]

1) BRIEF TECHNICAL DESCRIPTION OF 32×32, 24×24, 16×16

2) SPECS:

READOUT ELECTRONICS: — ON/OFF STANDBY PARALLEL/SERIAL

TOP

POWER COLD/WARM → FOR EACH OPERATING MODE

HARNESS – NUMBER + TYPE WIRES

EMC – FREQUENCY PLAN. (MAGNETISM).

THERMAL MODEL

CONDUCTION / RADIATION / DISSIPATION TO/FROM: EACH TEMP STAGE

DATA RATE *:

READ OUT FREQ.

ADC REQUIREMENTS

ON BOARD PROC / MEMORY REQS

FINAL TELEMETRY RATE.

COMMANDING /

MECHANICAL

OUTLINE MECH INTERFACE *

MASS

HANDLING REQS

THERMAL INTERFACE → COOLING REQUIRE.

EXPECTED PERFORMANCE

NEP

SPEED

NOISE SPECTRUM → CHOPPING?

UNIFORMITY

COSMIC RAY REJECTION

- - - - - - -

DEVELOPMENT SCHEDULE

HERITAGE
OUTLINE DEV PLAN
⇒ MILESTONES
e.g. SMALL ARRAY + CAB. ELECTRONICS

'HARD' BITS
ALL OF SMALL ARRAY
WORKING EGM
COMPATIBLE WITH INSTRUM

→ FLIGHT MODEL DEVELOPMENT SCHEDULE
CONSISTENT WITH TID A

(RISK.).

PRODUCT ASSURANCE
- SPACE QUALIFICATION
- YIELDS / PROCESS
- MATERIALS
- AGING
- ENVIRONMENT SPECIAL HANDLING

SPECIAL SPACECRAFT
e.g. POINTING, THERMAL CONSTRAINTS
STABILITY etc.

GROUND TEST / CALIBRATION PROGRAMME

OPERATING MODES
BEST WAY TO TAKE DATA

S MAXIMUM.

Caltech / JPL

1. Test Ti TES on spiders
   → low freq. stability
   → performance
   ~ 3 months
2. build ^3He test dewar ~ 6 months.
3. feedhorn packing & efficiency ~ 6 months
4. absorber techniques, absorption spectroscopy ~ 6 mon.
   + QMW

NIST / Boulder

1. Test shadowmask TES on popup
   ~ 3 months.
2. Test custom 1x8 MUX chips
   ~ 3 months.
3. Build ADR test ~~facility~~ dewar.
   ~ 3 months
4. Evaluate bilayer TES metal systems
   (Al + Ag, Pd, Cu ...)
   ~ 1 year.
5. Process Integration with popup microfabricatn
   ~ 6 months
6. Test TES's with MUXs
   ~ 1 year

<u>GSFC</u>

1) Electrical tests of semiconductor popups.
   NEP, τ 3 M.
2) Layout of Gen. 2 popups with TES.
   6.5 M.
3) ~~Develop~~ ADR test facility - 6 mo.
4) Complete Warm Elec. for SQUID MUX FIRST GEN. 3 MO.

(140)

3. ... with ... on ... ...
backshort for detectors.

QMW

Produce drawing of calibrator system
Envelope + mating flange. 1m.

CEA

1) → Nov. → December 97 for. El. opt tests
Low. Imp. small. connector.
NEP. + Spectral response (speed)
→ High Imp. (IAS. - orsay)

2) Feb 98 → homogeneous array. 8 x 10 p
⇒ Sept. 98 ←

3) New Int. Circuit → extract all the pixel at the same time → Mux. mid 98

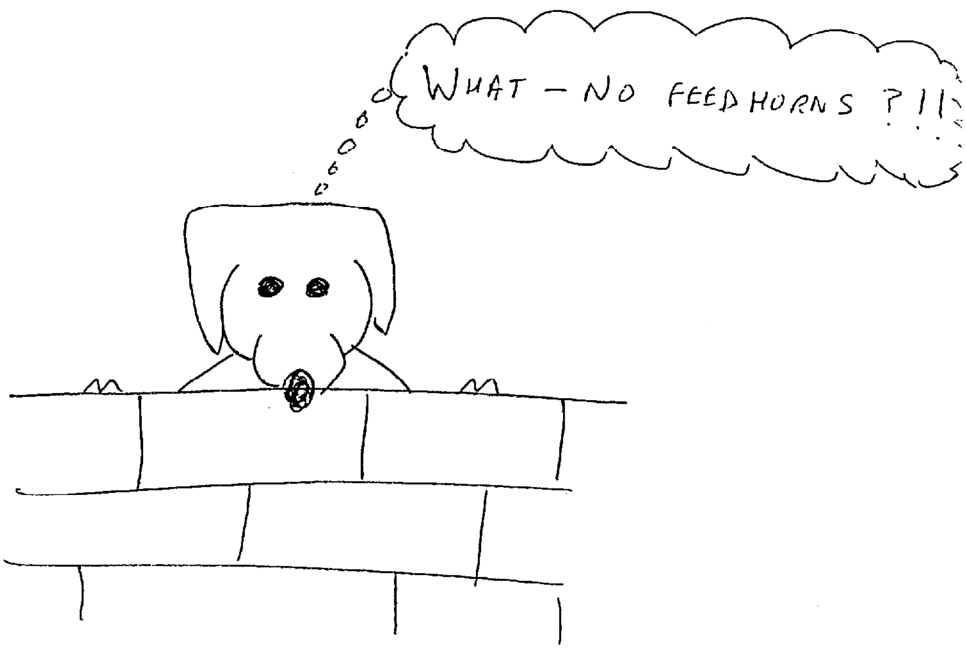
4) Start of a Prototype - 32 x 32
early 98

5) ~~Test~~ Measure The indium. bumbs thermal conductivity?

ADDITIONAL INFORMATION FOR AO:

– SCHEDULE to ~1 MONTH RESOLUTION
(to BE INCLUDED IN RESPONSE TO BRUCE'S EMAIL) UP TO QM DELIVERY ESPECIALLY

- Date of next meeting of Array Team get-together:
  - Just before SPIE KONA meeting in March 98
    ⇒ ~ 18 - 20 March (To be defined).
    [one-day meeting at Caltech]


WHAT – NO FEEDHORNS ?!!