BOL/QMW/M/0014.1 M

FIRST Bolometer Instrument Grating Workshop

ROE, April 3 1997

Agenda

Topic		**Chairman**
9:00	Update on mission status and report from FIRST SAG meeting	Griffin
9:30	Scientific priorities and implications for the BOL requirements	Baluteau
10:00	Spectrometer design - Optical design options (LAS, RAL, ROE) - Detector array	Swinyard
11:30	Photometer design - Focal plane configuration - Optical design and detector arrays	Griffin
12:30	Lunch	
13:30	Mechanical/thermal design - First estimates of sizes and masses of 20-K, 4-K, 2-K and 100 mK boxes - Estimates of dissipation and conduction by wires	Hastings
15:30	Systems aspects - Observing modes and parameters - Data rate - Readout electronics	King
16:30	Conclusions and preparatory work for Grenoble	Griffin
17:30	Meeting ends	

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FIRST BOL Grating Workshop ROE April 3 1997 Attendance

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FIRST STATUS AND GOALS OF THE MEETING

[GRIFFIN]

FIRST BOL Grating Workshop, ROE April 3 1997

1. FIRST/PLANCK merger schedule

- Tiger team study to has not identified any "show-stoppers" (yet)
- ESA are intent on launch in 2005/6
- Accelerated phase-A study June 97 - early 98
- AO issue ~ Sept. 1997 (during phase A)
- EID Part A definition to begin ~ late 97 (during phase A)
- Proposal submission February 98
- Confirmation of new mission at June 98 SPC meeting
- (Formal) instrument selection by ESA ~ June 98.

2. Implications of merger for BOL

- Pressure to simplify instruments to reduce cost and risk - we are doing this already

  Still pressure to simplify cryogenics (higher operating temperature)
- Instrument consortium must be clearly defined soon (this summer)
- Reduction in telescope focal ratio to around f/7 - should be a relatively minor change
- Existing thermal and mass budgets not likely to be relaxed

3. SAG recommendations for BOL

- SAG supports the current re-design work on the BOL (and the PHOC) to simplify and optimise for key science goals

- PHOC will have imaging spectroscopy with ≥ 5 x 5 array up to ~ 220 μm

- PHOC also working on developing GaAs photoconductors (possible extension to 300 μm)

- SAG endorses the emphasis on imaging photometry and point-source spectroscopy for the BOL

  More detectors if possible - esp. to measure the spectrum more rapidly

4. Main goals of this meeting

- Assume f/9.6 optics for now, but look at any important implications of change to f/7.5

- Base-line optical designs for PHOT-BOL and SPEC-BOL

- Focal plane designs for PHOT and SPEC
  - Numbers of pixels and feed-horn dia.
  - Final optics
  - Filtering scheme
  - Feasibility of close-packed absorber array (naked bolometers)

  → Update photometric model

- First estimates of mass, power (conducted + dissipated), and volume requirements at 2, 4 and 15 K

  → Update to figures in PDD (which ESA require urgently)

- Define information needed for more detailed thermal/mechanical study

- Examine basic operating modes

- Identify preparatory work for Grenoble meeting

BOL/FIRST ROE meeting (April 4th,, 1997)

LWS DATA

main cooling lines	M 82 line fluxes	M 82 line to continuum	NGC 4038/39 line fluxes	NGC 4038/39 line to continuum	R (LWS)
[CII] 158um	150	1.9	3.7	1.6	263
[OI] 145um	18	0.18			242
[NII] 122um	22	0.11			203
[OIII] 88um	100	0.19	4.7	0.42	147
[OI] 63um	180	0.43	5.2	0.17	210
[NIII] 57um	45	0.10	1.6	0.22	190
[OIII] 52um	100	0.20	4.9	0.60	173

line fluxes in 10(-19) W/cm2

BOL/FIRST ROE meeting (April 4th,, 1997)

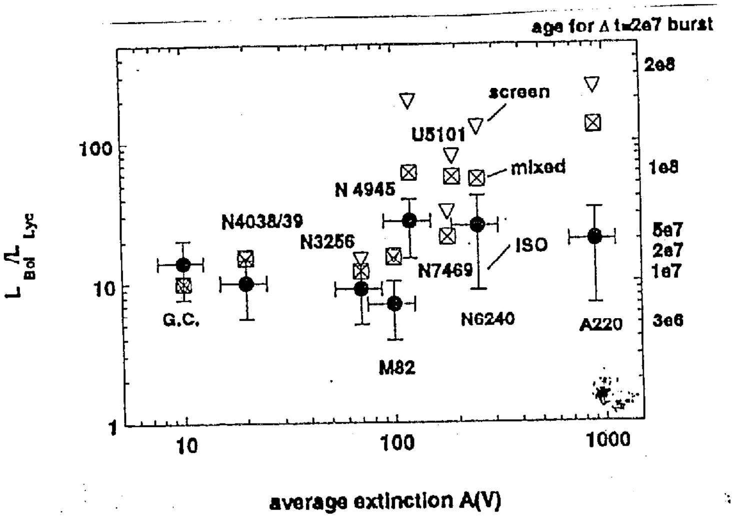
line to continuum ratios

lines	R(LWS)	measur.	R=300 expect.	R=1000 expect.	Z (200-350u
[CII] 158um	263	1.5/2.0	1.7/2.3	5.7/7.6	.27 - 1.2
[OI] 145um	242	0.1/0.2	.12/.24	.41/.82	.38 - 1.4
[NII] 122um	203	.06/.12	.09/.17	.30/.59	.64 - 1.8
[OIII] 88um	147	0.2/0.4	0.4/0.8	1.3/2.5	1.27 - 2.9
[OI] 63um	210	0.2/0.4	.29/.57	.95/1.9	2.16 - 4.5
[NIII] 57um	190	0.1/0.2	.15/.30	.53/1.0	2.49 - 5.1
[OIII] 52um	173	0.2/0.6	.35/1.0	1.2/2.3	2.86 - 5.7

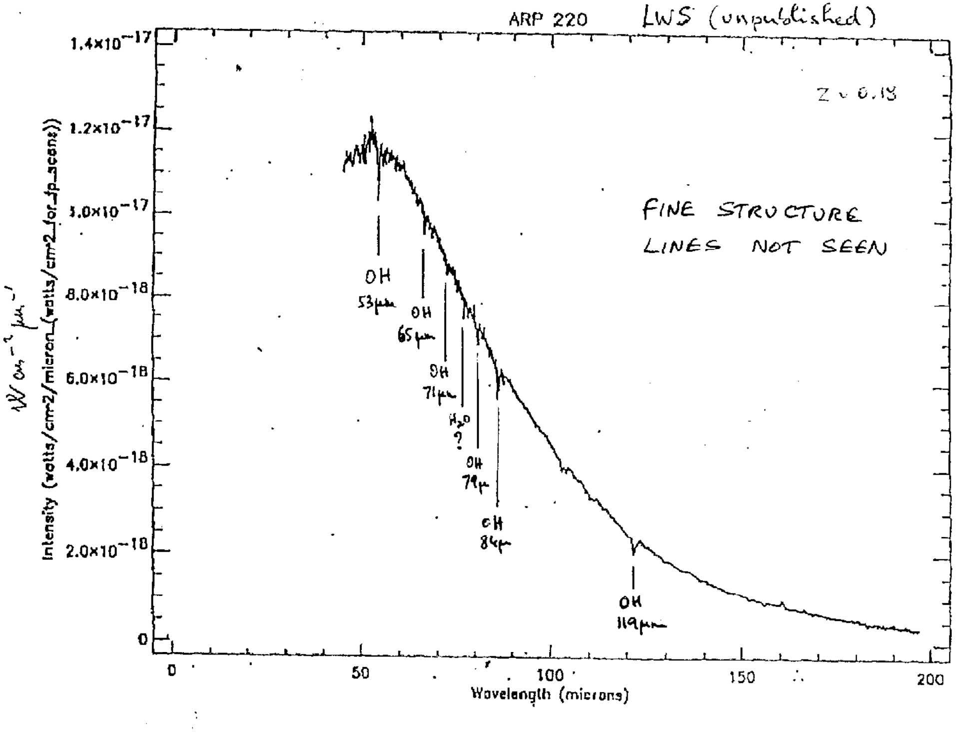
SCIENTIFIC REQUIREMENTS FOR SPECTROSCOPY OF HIGH-Z GALAXIES

[BALUTEAU]

Lutz et al. A&A 315, L.37 (1996)



▽ L_{Lyc} from Brγ line (extinction from Hα / Brγ in foreground cloud)
☒ " (" : dust and gas mixed)
● new SWS data ([NeII]) [⇒ SAME (STARBURST) MECHANISM FOR ALL]



FINE STRUCTURE LINES NOT SEEN

BOL/FIRST

ROE meeting (April 4th,, 1997)

LWS DATA ON ARP 220

line to continuum ratios

main absorption lines	measured	R(LWS)	R=300	R=1000	Z(200-350)
OH 119um	0.15	199	0.23	0.75	0.68 - 1.93
OH 84um	0.13	296	0.13	0.44	1.37 - 3.14
OH 79um	0.06	279	0.06	0.21	1.53 - 3.42
OH 71um	0.02	248	.025	0.08	1.81 - 3.91
OH 65um	0.04	229	0.05	0.17	2.07 - 4.36
OH 53um	0.10	186	0.16	0.53	2.76 - 5.57
[CII] 158um	0.16	263	0.18	0.60	0.27 - 1.21

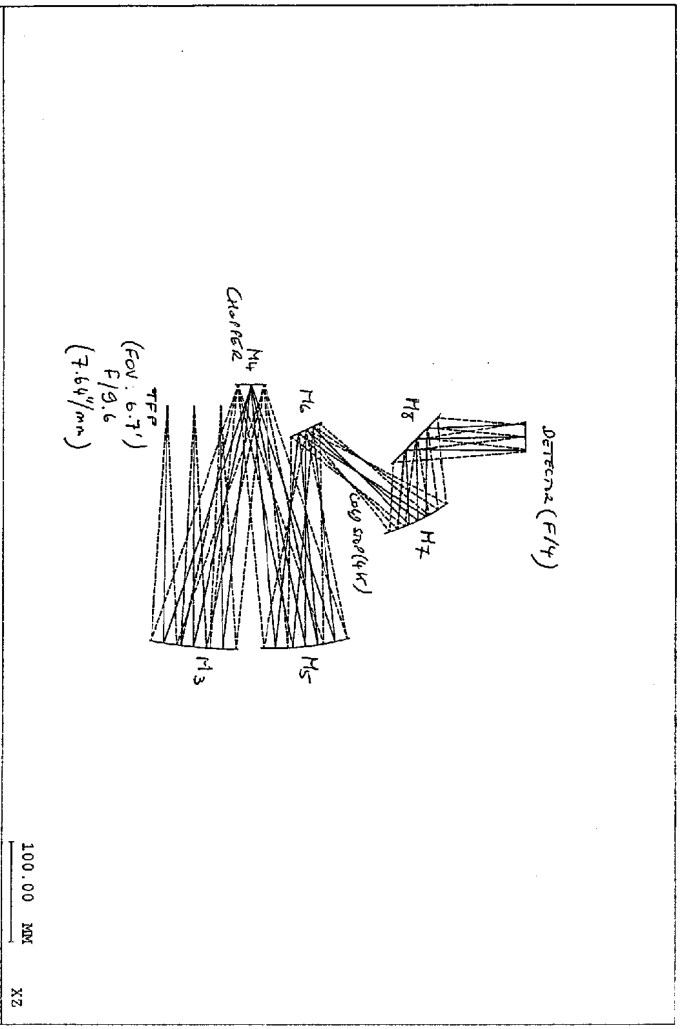
BOL OPTICAL DESIGN

[ATAD]

Preliminary Optical Design of BOL
Eli Atad , ROE , April 1997

Photometer / Imager

- Working wavelengths: 200-600 microns
- Fnumber: F/4
- Field of View: 6.7 arcmin
- Chopper in the instrument and placed at the image of FIRST secondary mirror which is the stop of the telescope.
- Has to fit with the spectrometer in the 700*300*300 mm space enveloppe.
- A physical cold stop at 4K to reduce background radiation.
- The photometer will be completely separated from the spectrometer from the start to reduce stray-light (appropriate baffling).
- 3 arrays of detectors optimized for 3 separate wavelengths: 250, 350,480 microns .
- No Filter wheel .



FIRST BOL PHOTOMETER/IMAGER Scale: 0.25 27-Mar-97

Photometer/Imager Optical Data:

Component	Radius of Curv (mm)	Thickness (mm)	y- Tilt (degrees)	CA Diameter (mm)
telescope FP f/9.5915 (7.64"/mm)	plano	240		53.0
M3	480.00	266.42	6.0	85.0
M4 (chopper)	plano	266.42	12.0	28.0
M5	277.24	216.0	6.0	86.0
M6	plano	68.0	25.39	30.0
cold stop	plano	76.0		28.0
M7	Ry= 185.64 Rx=226.70	82.0	25.0	72.0
M8 (dichroic)	plano	108.54	45.0	66/45
detector/f/4				25
(18.32"/mm)				

IMAGE QUALITY

Encircled Energy Diameters (mm) and Strehl ratios:

Wavelength (µm)	250	350	480
Airy disk (80%) (mm)	2.0	2.8	3.84
Geometrical spots (mm)			
80% on-axis	0.20	0.20	0.20
off-axis	2.0	2.0	2.0
Strehl ratios			
on-axis	0.98	0.99	1.0
off-axis	0.60	0.76	0.87

THROUGPUT : 0.89 (without filters)

(assuming 0.98 reflectivity per mirror)

Optical Design of BOL Spectrometer

- FOREOPTICS

The spherical collimator mirror M3 reimages the telescope pupil onto the chopper M4. A spherical concave mirror M5 reimages the slit focal plane onto a cold slit (4K) at ~f/4.5 (16.28 "/mm).

The diffraction (80%) of the telescope is 2*λ/D where D=2815 mm ; so for λ=200 µm , the Airy disk for the telescope is 29.3"/mm.The width of the slit , matching the diffraction of the telescope is about 1.8 mm.

The 3 mirrors in the foreoptics are at 20K. The input slit to the spectrometer is at 4K.

- COLLIMATOR:

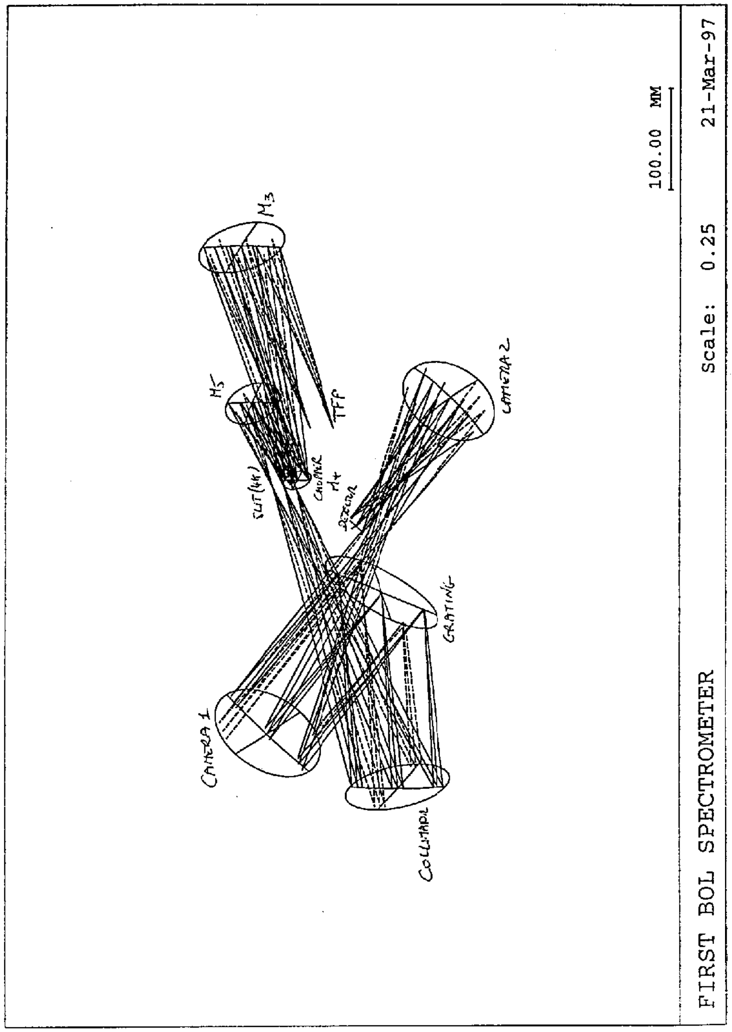
A spherical concave mirror sends a 89 mm collimated beam to the grating and also reimages the pupil onto the grating to avoid changes in scattering by the grating along the slit.

- GRATING:

Quasi-Littrow configuration. Blaze angle: 40 degrees,
order 5 ; groove spacing: 1.017 mm
off-axis angle: 44 degrees
Size: 150 mm

- CAMERA (F/3):

2 tilted concave mirrors . An intermediate physical image of the slit spectrum will allow the insertion of a cold mask at 4K, to stop straylight and diffraction effects from the grating



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BOL SPECTROMETER OPTICAL DATA

Component	Radius of Curv (mm)	Thickness (mm)	y- Tilt (degrees)	CA Diameter (mm)
telescope FP f/9.5915 (7.64"/mm)	plano	240		53.0
M3	480	266.42	6.0	85.0/25.0
M4 (chopper)	plano	128.83	12.0	28.0
M5	224.0	112.0	6.0	56.0/25.0
slit at ~f/4.5 (16.28"/mm)	plano	400.0		25.0
M6 Collimator	800.0	200	15.0	100.0
Grating (40 deg./5th order/)	plano	200	40.0 x-tilt: 22 deg.	150.0/120.0
Cam1	Ry=784.71 k=-0.407	392.355	15.0	150.0
slit image	plano	257.645		52 .0/27.0
Cam2	Ry = 209.17 Rx= 235.08	193.46	10.0	140.0
detector/horn f/3 (24"/mm)				25.0

SPECTRAL RESOLUTION

Grating tilt θ (degrees)	40			50			60		
λ (microns)	200	250	350	200	250	350	200	250	350
R= 178* tgθ/λ (theoretical limit)	747	597	427	1061	849	606	1542	1233	881
R=2* tgθ* Fcam/a a=pixel size=2mm Fcam=267 mm	224	224	224	318	318	318	462	462	462

IMAGE QUALITY

Encircled Energy Diameters (mm) and Strehl ratios:

Dispersion (mm)	-10	0	10
Wavelength (μm)	235	243	250
Airy disk (80%) (mm)	1.41	1.46	1.50
Geometrical spots (mm)			
80% on-axis	1.34	0.91	2.41
off-axis	2.13	2.05	3.18
Strehl ratios			
on-axis	0.86	0.93	0.68
off-axis	0.54	0.52	0.46

througput: 0.67 (including 0.80 for grating and 0.98 for mirrors)

BOL ISSUES (3/4/97):

1. DISTORTION:

How 20% distortion affects the process of data reduction ?

2. STRAY-LIGHT:

How scattering of mirrors surfaces and particularly of grating affects performance ?

3. SLIT IMAGE IS TILTED:

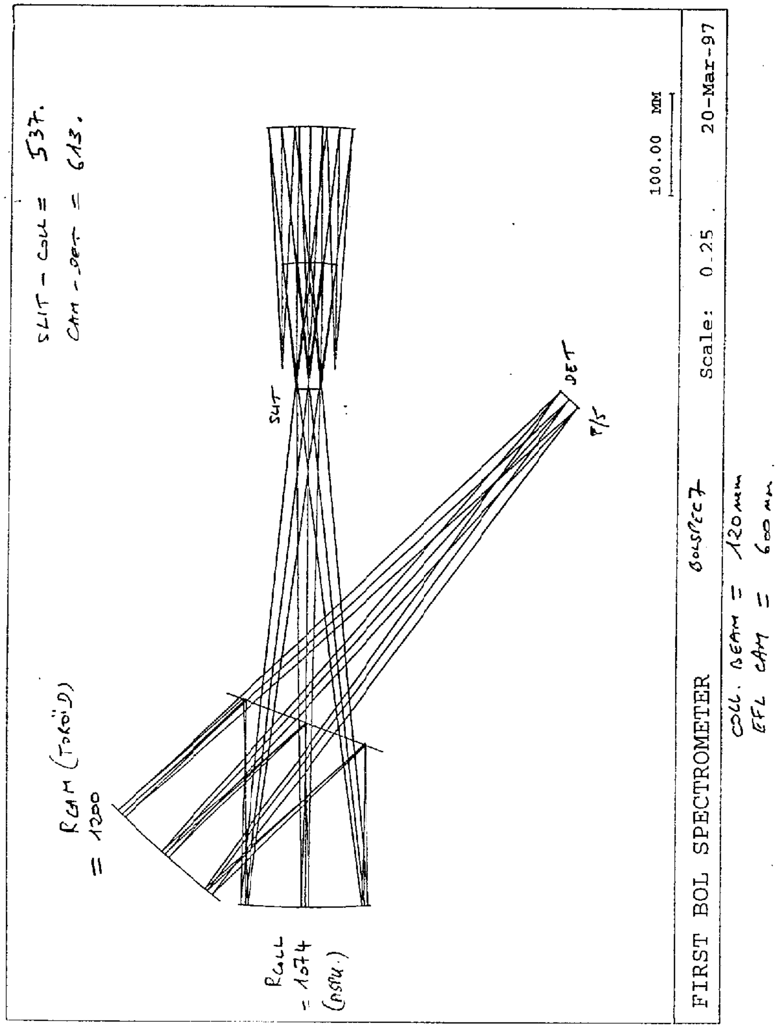
A tilt in the slit image at the detector plane is expected to be about 40 degrees and vary with grating scan. A solution is to counteract this rotation by rotating the entrance slit by the same amount in opposite direction.

4. THERMAL EFFECTS:

All the mirrors will be in Al-Alloy (previously thermally cycled to increase stability). The optical chassis will also be made in Al-Alloy so that at 20K or 4K the materials involved contract at the same rate resulting in a small change of scale.

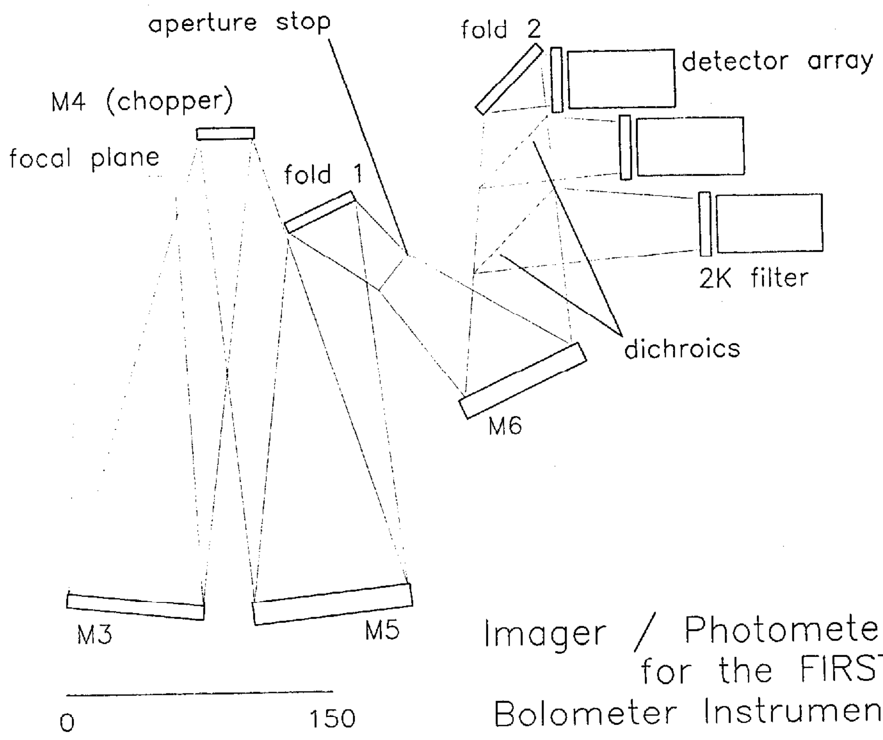
5. OPTICAL IRREGULARITY REQUIRED FOR MIRRORS:

If we assume that the P-V wavefront error introduced by these errors should be smaller than 0.1*λ/4 where λ =200μm , we get a budget error smaller than 5 μm. Taking into account that there are 9 mirrors in the spectrometer ,we get 5/3=1.7 μm. For surface errors we get 1/2 of this value which means that the surface P-V irregularities shall be smaller than 0.8μm. This should be easily achieved by diamond turning Al-Alloy.

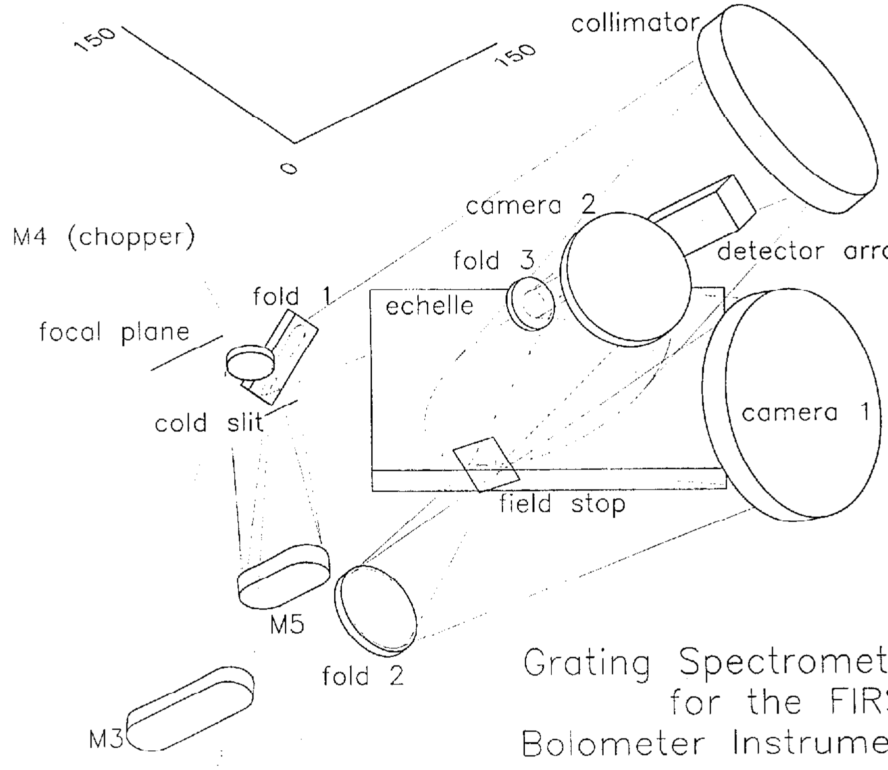


BOL LAYOUT

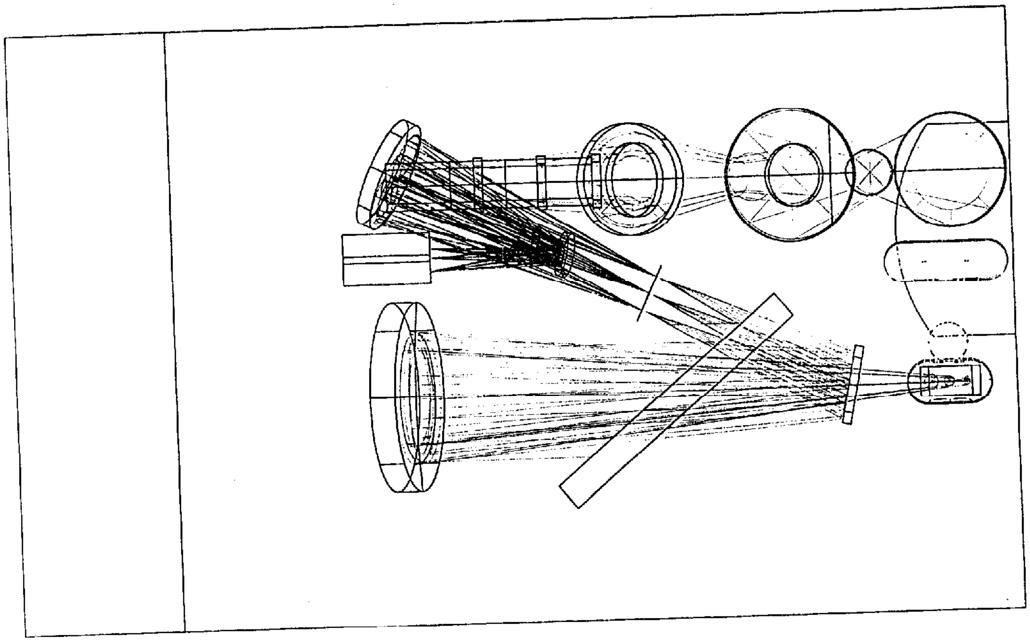
[HASTINGS]

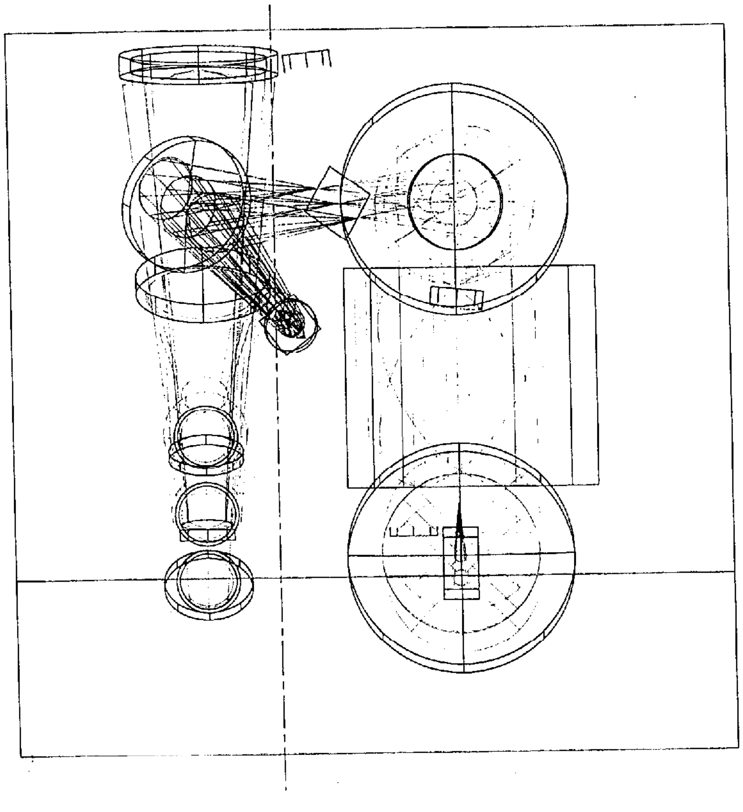


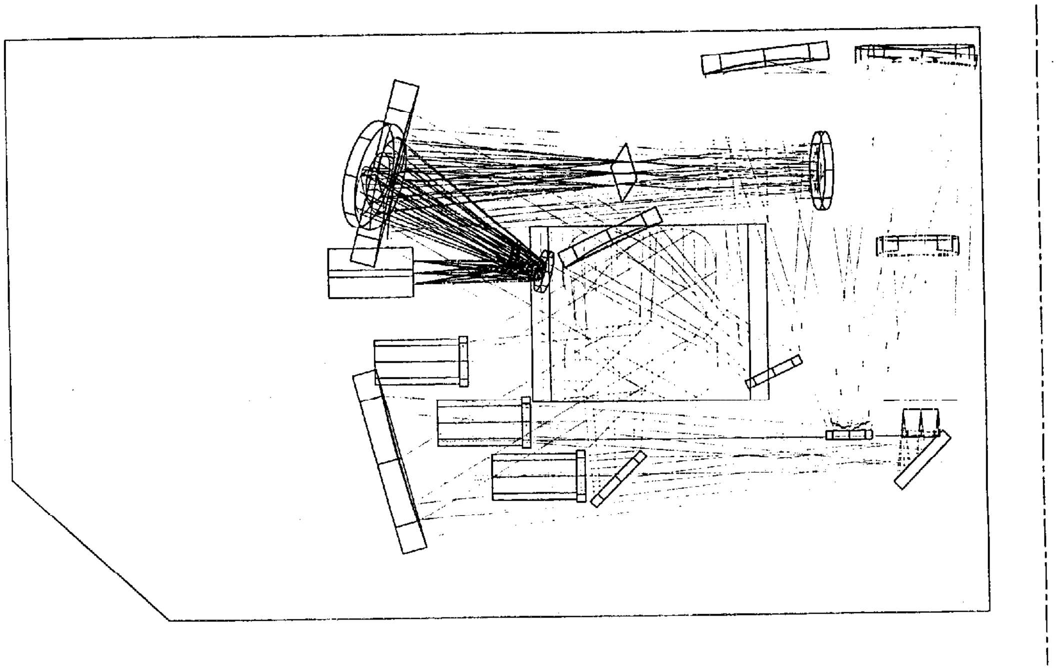
Imager / Photometer
for the FIRST
Bolometer Instrument



Grating Spectrometer
for the FIRST
Bolometer Instrument







BOL OPTICAL DESIGN

[DOHLEN]

Proposal for dual-channel Bolometer for FIRST

Kjetil Dohlen

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2 Place Le Verrier, 13248 Marseille Cedex 4, France

1. INTRODUCTION

Following the work-group meeting at RAL 10-11 February 1997, this note describes a proposal for a dual channel bolometer. The FIRST telescope focus is taken to be F/10. Both channels have separate sky-chopping mirrors: M3 forms for each channel a pupil onto wobbling M4 of Dia. 30mm. The photometer channel (PHOT-BOL) produces an F/4 beam onto three arrays separated by dichroics. The spectrometer channel (SPEC-BOL) produces a spectrum of a slit in a F/3 focus. 5 orders are measured simultaneously to cover the range from 200µm to 350µm with a grating movement of ±6.2°.

Fig 1 shows a view of the entire instrument within its envelope, looking down along the telescope axis.

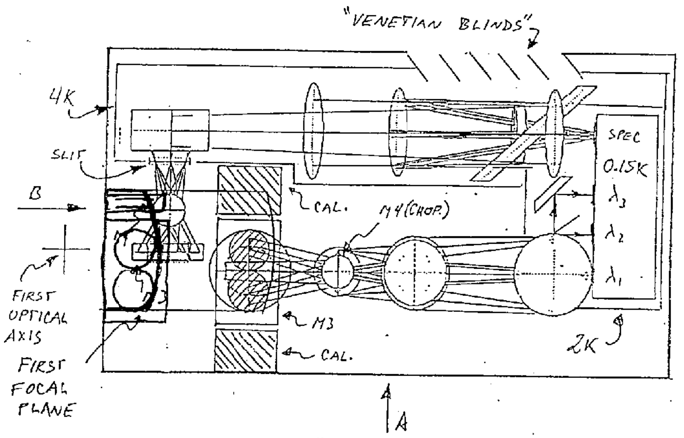


Figure 1.

2. PHOT-BOL

The photometer channel consists of 6 mirrors (M3 to M8) outside of the 2K box, with a pupil on M4 (chopper) and M8 (Lyot). The 2K box has an entrance window and contains two dichroics and three folding flats, directing the F/4 beam onto three separate arrays (cf. Fax from Griffin, 18/02/97). The arrays are co-planar amongst themselves as well as with the spectro array (see Sec. 4). The Lyot stop may possibly moved to the 2K box entrance window if a transmission stop is preferred. Fig. 2 shows a side-view of the PHOT channel.

All mirrors are flat or spherical, except M8 which is toroidal. A spherical M8 may be acceptable but the geometrical spots are then slightly larger than the smallest detectors due to astigmatism. With a toroidal M8, the spots are within Ø1.5mm over the entire FOV.

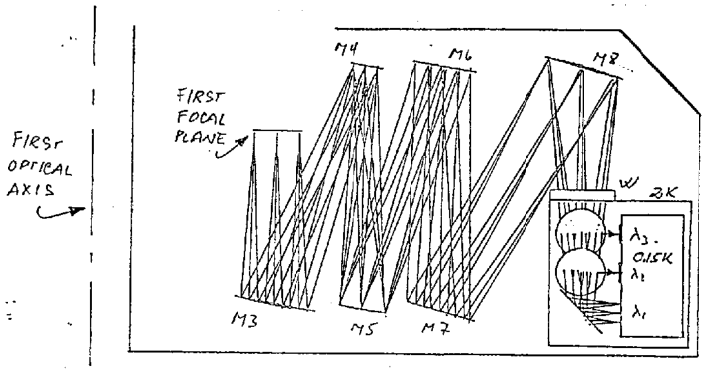


Figure 2.

3. SPEC-BOL

The spectrometer channel consists of 7 mirrors (M3 to M9) and an off-plane Littrow grating (G) outside of the 2K box. The F/3 beam enters the 2K box through a window directly onto the detector array (see Sec 4). A slit is placed between M4 (chopper) and M5. The slit is physically a slot in the 4K enclosure, everything following is thus at 4K. A pupil image is placed close to the grating, but it has been found impractical to produce another pupil image within the 4K enclosure. (Note added in proof: A possibility for a pupil on M7 and on the grating appears to exist, but with very steep beam-angles between M7 and M8 (the collimator). To be looked into.)

The channel is very crowded and it is not entirely clear if all fits in, particularly a collision between grating and 2K box is a worry. A 3D CAD study is required to figure this out.

The spectral range is divided into five orders as shown in Table 1. The resolving power (given by order times number of rulings, nN) is optimized for $R = 1000$ at 250 µm. The resulting grating measures about 85mm by 175mm and tilts through ±6.2° from 48.56° to 61°.

Figure 3 shows two views of the grating instrument, one (a) from the direction marked A in Fig. 1 and one (b) from the direction marked B in Fig.1.

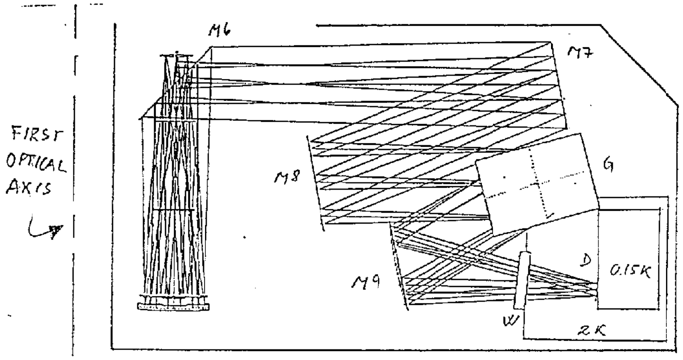
FIRST, SPEC-BOL, grating calculations

K. D., LOOM 6/3/97

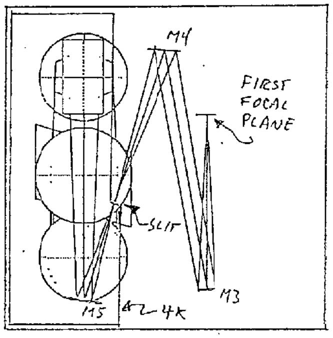
Assumptions:			*At lambda = 250 um:*	
lamMax	350.00	um	n_250	8.00
thMax	61.00	deg	th_250	56.41
nMin	6.00	no unit	R_250	1000.02
Diam	83.04	mm		
d	1.20	mm		
Wgr	171.27	mm		

Order	*Wavelength range*		*Angular range*		*Resolving powers*	
n	lamMax	lamMin	thMax	thMin	Rmax	Rmin
6.00	350.00	300.00	61.00	48.56	855.99	627.06
7.00	300.00	262.50	61.00	49.93	998.66	752.17
8.00	262.50	233.33	61.00	51.03	1141.33	879.75
9.00	233.33	210.00	61.00	51.92	1283.99	1009.31
10.00	210.00	190.91	61.00	52.67	1426.66	1140.47

Table 1.



(a)



(b)

Figure 3.

All mirrors are flat or spherical except M9 (camera) which is toroidal. The resulting geometrical spots are within Ø3mm. There is certainly room for improvement by deforming other mirrors.

Due to the off-plane arrangement of the Littrow grating, the slit image is tilted by about 30° in the focal plane. The 5x5 detector array should therefore be laid out as shown in Fig. 4.

Stray light rejection has not been treated in detail, but it seems that the major problem is to eliminate the parts of the spectrum diffracted off the grating which is not imaged onto the detector array. One solution may be to place Venetian blinds in the side wall of the instrument as indicated in Fig. 1, allowing unwanted flux to exit from the instrument altogether, possibly into free space...

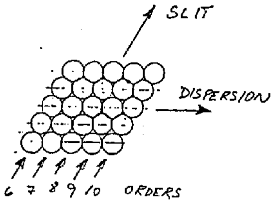


Figure 4.

4. COLD (2K) BOX

The 2K box has two entrance windows allowing the two beams to enter. The PHOT beam enters in a direction parallel to the FIRST optical axis, the SPEC beam enters perpendicular to this axis. The detectors are mounted on the face of the 0.15K box, enclosed within the 2K box. The detector plane is perpendicular to the SPEC beam. The PHOT beam is initially parallel to the detector plane. Two successive dichroics split the beam into three beams which are directed onto the detector arrays via folding flats. Fig. 5 shows a view of the 2K box from the direction marked A in Fig. 1.

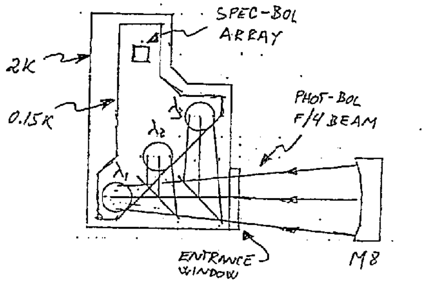


Figure 5. View of the cold box looking down at the detectors. The three PHOT arrays are hidden below the folding flats.

ROWLAND CIRCLE OPTION

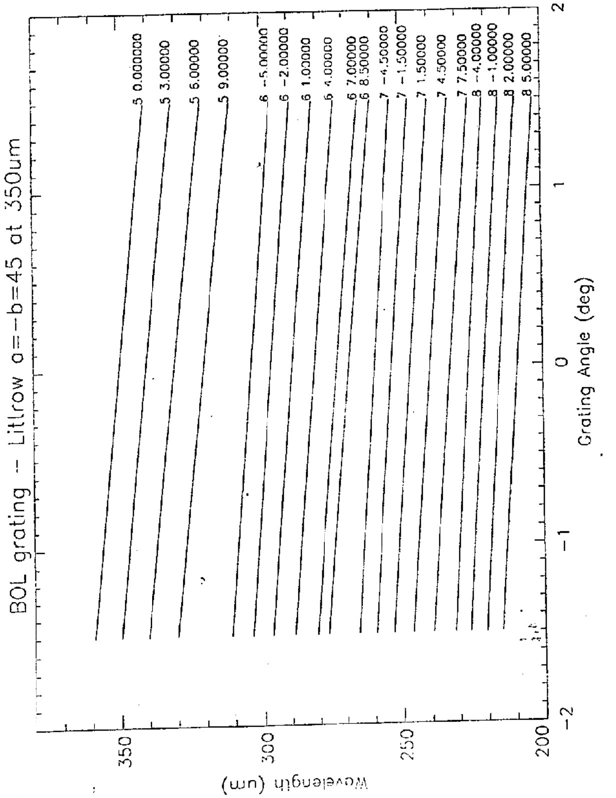
[SWINYARD]

BOL grating - Littrow with $\alpha=-\beta_o=45$.

Table of detector central wavelengths, angles and filter requirements (assuming triangular filter function)

Central Wavelength	Wavelength at m-1	Wavelength at m+1	Central Order	Resolving power required for filter	Angle of Detector centre w.r.t. β_o
350.000	437.500	291.667	5	4.80000	0.000000
340.601	425.752	283.834	5	4.80000	3.00000
330.749	413.436	275.624	5	4.80000	6.00000
320.469	400.587	267.058	5	4.80000	9.00000
303.822	364.586	260.419	6	5.83333	-5.00000
296.667	356.001	254.286	6	5.83333	-2.00000
289.099	346.919	247.799	6	5.83333	1.00000
281.139	337.366	240.976	6	5.83333	4.00000
272.807	327.368	233.835	6	5.83333	7.00000
268.509	322.211	230.151	6	5.83333	8.50000
259.422	302.659	226.994	7	6.85714	-4.50000
253.229	295.434	221.576	7	6.85714	-1.50000
246.685	287.799	215.849	7	6.85714	1.50000
239.807	279.775	209.831	7	6.85714	4.50000
232.615	271.384	203.538	7	6.85714	7.50000
226.113	258.415	200.989	8	7.87500	-4.00000
220.642	252.163	196.126	8	7.87500	-1.00000
214.866	245.561	190.992	8	7.87500	2.00000
208.801	238.630	185.601	8	7.87500	5.00000

$a = 1237 \mu m$.



SLIT WIDTH AND ACHIEVABLE RESOLUTION

[SWINYARD]

SLIT WIDTH

GIVEN APPROXIMATELY BY:

$$W_S = \frac{m R_{GD}}{a} \times \frac{\lambda}{R}$$

R_{GD} = distance from grating to detector or entrance slit

R = resolving power.

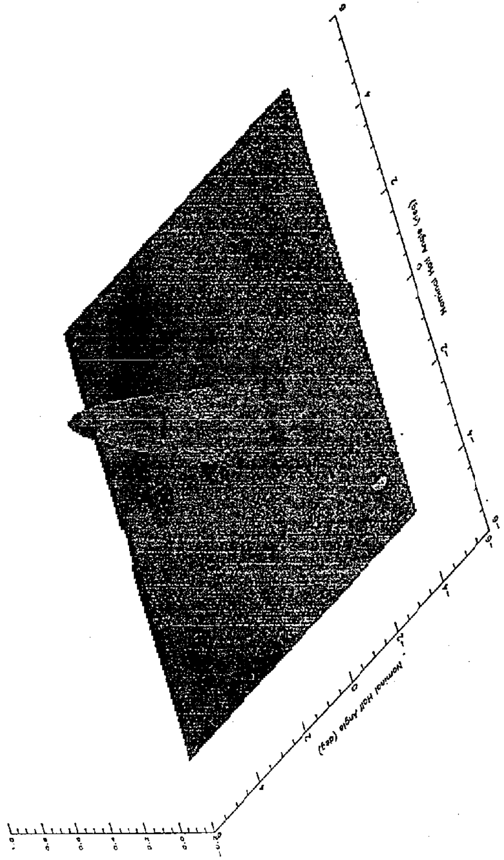
FOR $R = 1000$ @ 250μm

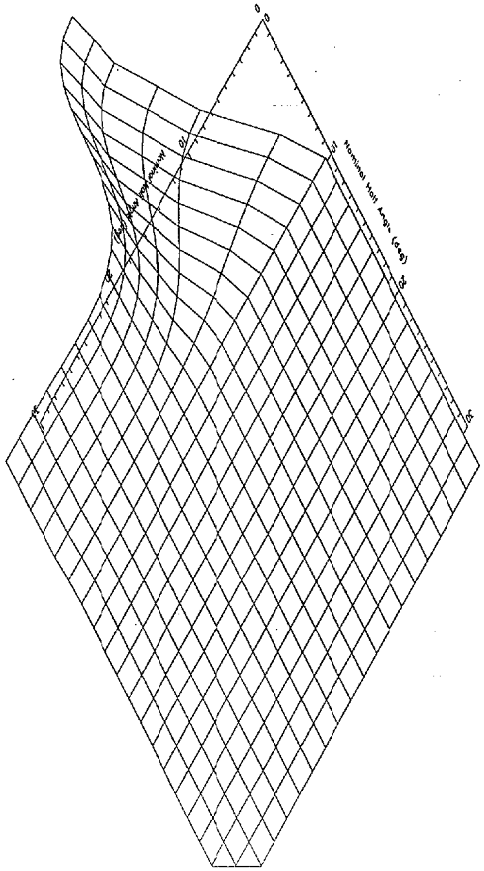
$R_{GD} \approx 900$ mm $W_S \sim 1.5$ mm

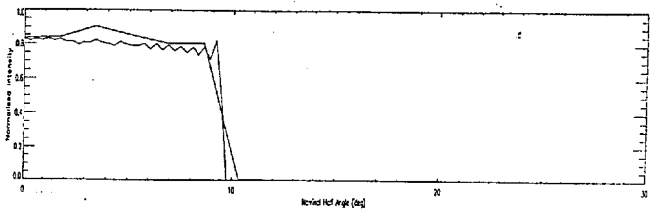
$R_{GD} \sim 620$ mm $W_S \sim 0.6$ mm.

Throughput : 1.5 ~ 0.9
0.6 ~ 0.6

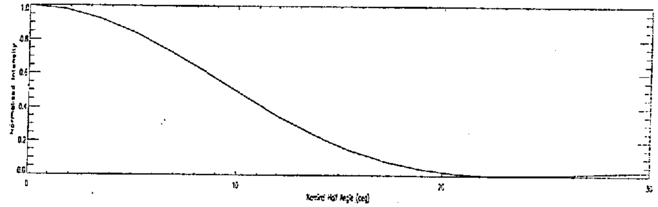
This does not include diffraction



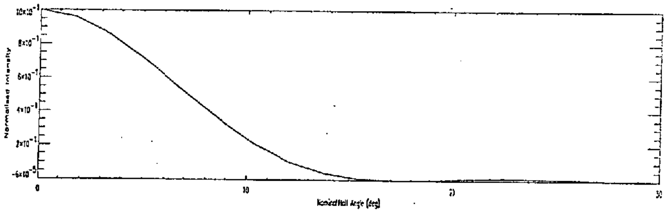




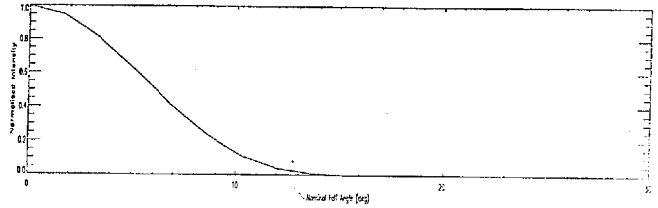
300μm
$S_\omega = 0.8$



$S_\omega = 1.2$



$S_\omega = 1.6.$



SUMMARY OF OPTICAL DESIGN DISCUSSION

[SWINYARD]

SUMMARY OF OPTICAL DESIGN DISCUSSION

- SPECTRAL MULTIPLEXING IS NEEDED ($\Delta\theta_g < \pm 3°$)
- WHAT IS THE AVAILABLE RESOLUTION?
- CONTINUE STUDY OF PLANAR + CONCAVE GRATINGS
- STRAYLIGHT STILL AN IMPORTANT DESIGN DRIVER
- POINT SOURCE SPECTROSCOPY ONLY 2 PIXELS (ON AND OFF SOURCE))
- [illegible]

(FURTHER) DESIGN CRITERIA

- DETECTOR SPACING 4–4.5MM (MINIMUM). [ACTUAL PIXEL ~2.5–3MM].
- KEEP F9.6
- WAVELENGTH CAN GO TO >350μm IF "FREE"
- PIXEL SIZE SHOULD INCREASE WITH λ (IMPLICATIONS FOR FOV AND RESOLVING POWER?).
- DISTORTION OF IMAGE SHOULD BE MINIMIZED OR STRATEGIES FOR CORRECTION ADOPTED
- CALIBRATION SOURCE MUST BE IN (BOTH FLUX AND λ).
- MOVE M3 CLOSER TO IMAGE PLANE.

PHOTOMETER FOCAL PLANE ARRAYS

[GRIFFIN]

AT
TELESCOPE
FOCUS

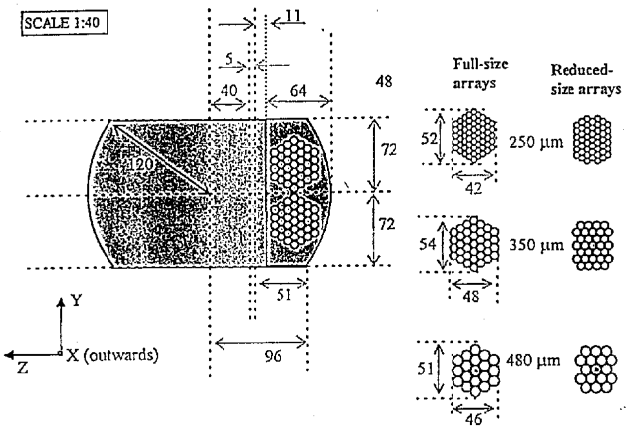


Figure 3 Available area (unvignetted field of view) and array sizes at the telescope focal plane (all dimensions in mm). The shaded area is the part of the focal plane which is effectively available to the BOL. The largest (350-µm) array is superimposed. Possible reduced size arrays are also shown to scale.

ON
M3

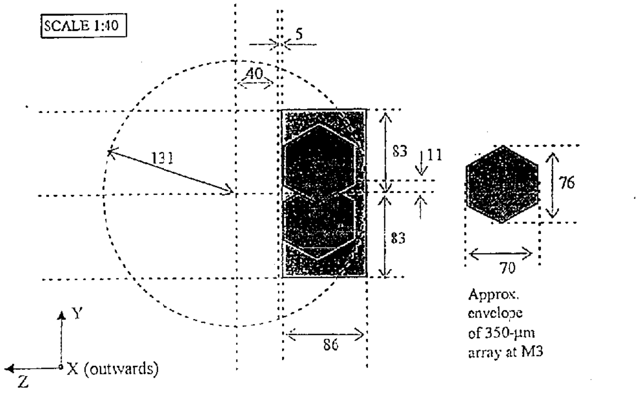
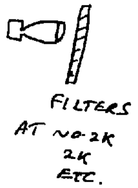


Figure 4 Available area and array sizes at the M3 mirror focal (all dimensions in mm). The shaded area shows the size of a practical M3 mirror. The size needed for the 350-µm array is shown superimposed on the mirror.

PHOTOMETER ARRAYS

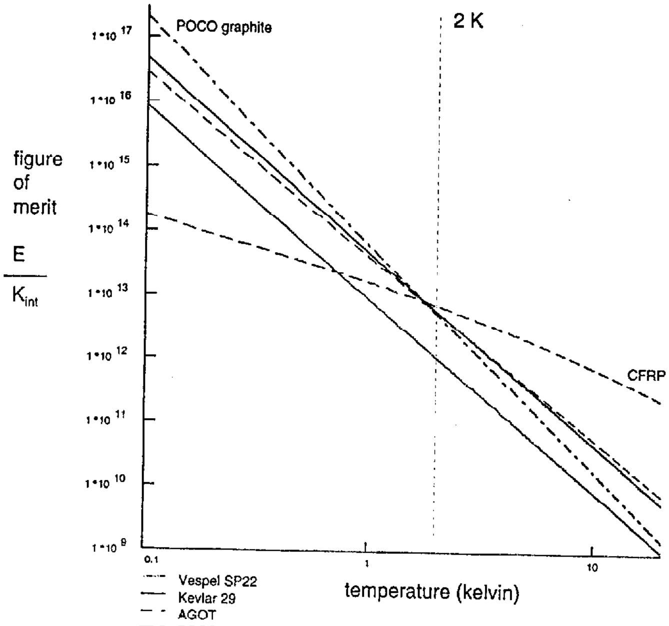
- f/5 INSTEAD OF f/4 FINAL OPTICS
- DIFFRACTION → REDUCED NO OF DETECTORS ? [NOT BY MUCH.]
- BASELINE = SINGLE FEED HORN [STRAIGHT-WALLED HORN OR WINSTON CONE]



QMW TO DEFINE FILTERING SCHEME

MECHANICAL SUPPORT OF THE BOL

[HASTINGS]



Comparison of Structural Materials for the FIRST bolometer array support structure(s)

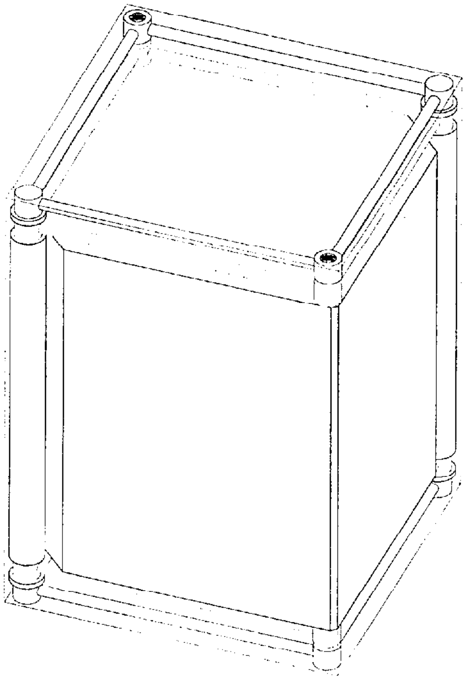
Comparison of candidate materials for the structures in the BOL instrument

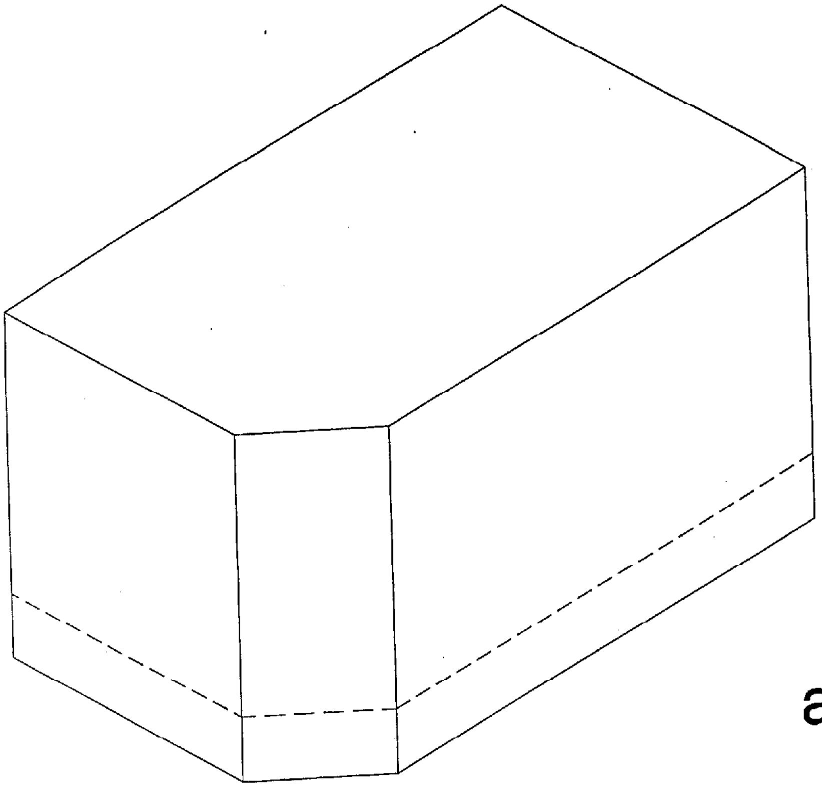
mass at a given temperature which can be supported without exceeding the heat budget

material	4 K	2 K	0.1 K
Kevlar 29 cord	12.8 kg	877 kg	175 gm
graphite (pre-stressed)	1.5 kg	330 kg	104 gm
high-modulus CFRP	208 kg	2039 kg	94 gm
graphite (plain)	1.5 kg	185 kg	58 gm

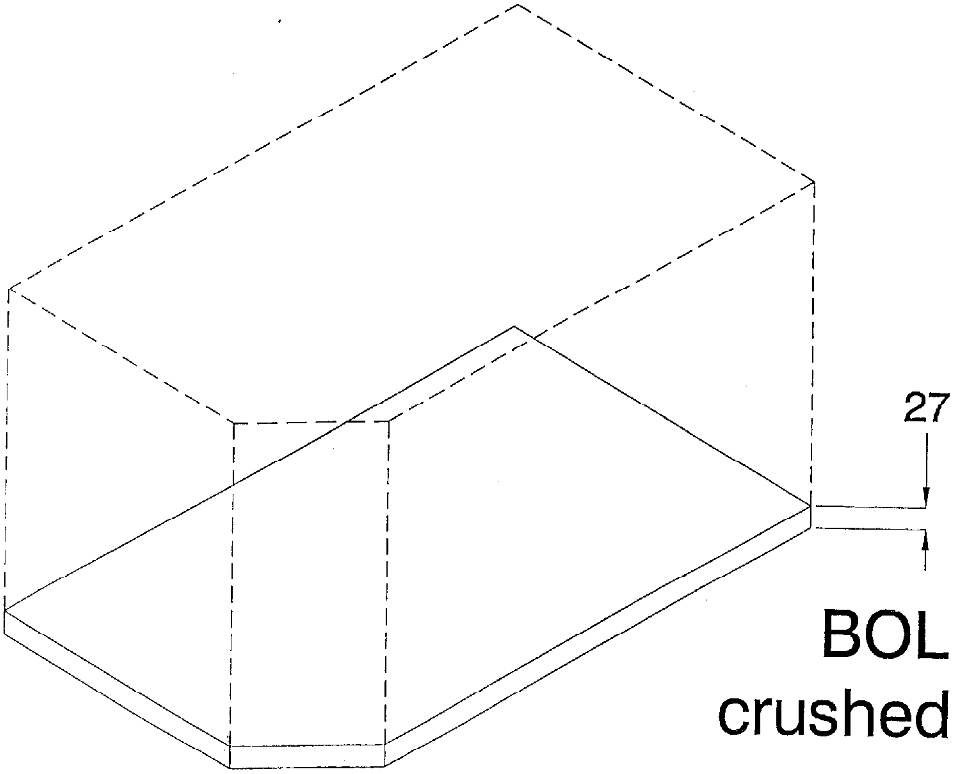
BOL Instrument
Mass Budget

20 K	outer casing, fore-optics (two sets), choppers (two)
4K	inner enclosure, photometer optics, spectrograph optics, grating mechanism, filter wheel (order sorting)
2K	photometer dichroics (?), filters, array enclosure, outer feedhorns
0.1K	feedhorns & arrays, dilution refrigerator
20K	8 kg
4K	10.5 kg
2K	1 kg
0.1K	0.5 kg
wiring	1 kg
TOTAL	21 kg





BOL
afloat



BOL
crushed

CONDUCTION & DISSIPATION BY THE WIRING HARNESS

[MAFFEI]

THERMAL MODEL

Estimates of dissipation and conduction by wires

Assumptions

- * Stainless steel wires ⌀ 100 μm
- \+ Brass wires for Grating drive coils ⌀ 100 μm
- * Length of wires between stages: 20 cm.
- * Temperature of stages: 0.1, 2, 4, 15, 50, 80 and 300 K.

* Dissipation in wires → Lowest temperature (worst case)

Results

ool. power	Stage Temp.	Conduction (wires)	Dissipation. (wires)	Total (wires)
2 mW	2 K	32 μW	0.04 μW	32 μW
.8 mW	4 K	0.7 mW	0.35 mW	1 mW
	15 K	8.4 mW	0.9 mW	9.3 mW
	50 K	13 mW	1.3 mW	14.3 mW

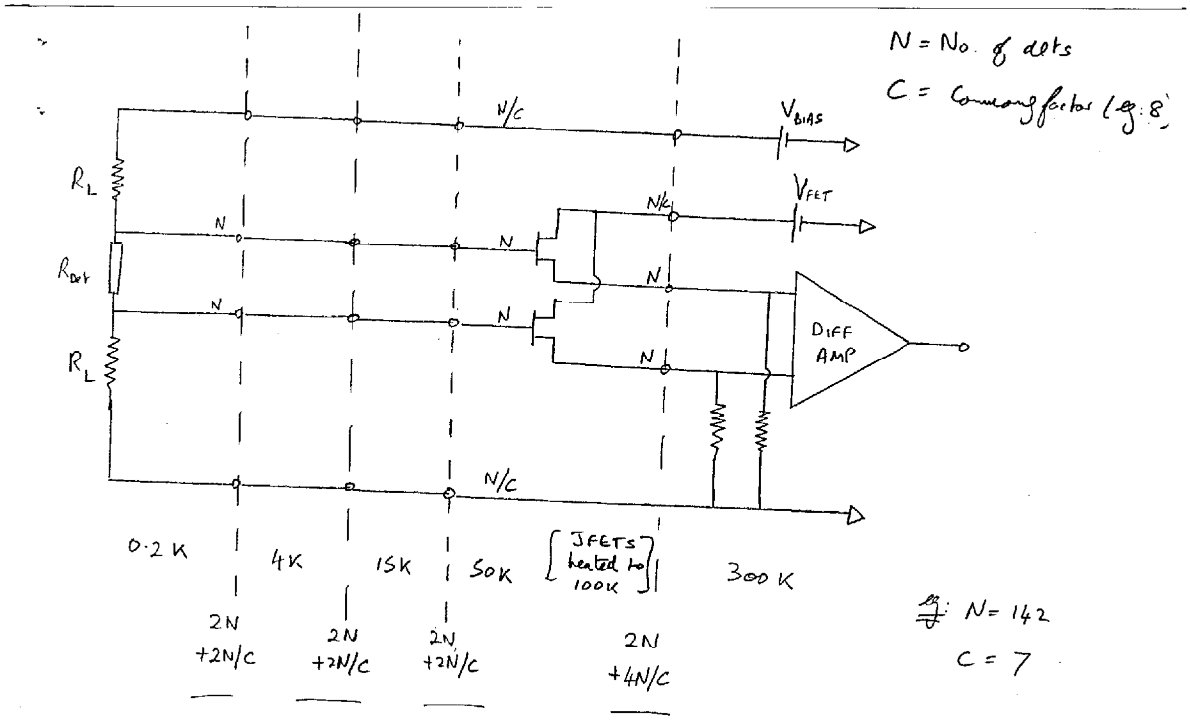
Need of a complete model

- Conducted power [Harness
Mech. supports
- Dissipated power [Harness
Devices (Grating, JFET...)
- Radiation.

To go on, we need:

- * Mechanical support design
- * Estimates of masses on the stages
- * Power dissipated in devices
  - JFET
  - Grating (assumed 5 mA max current for wire dissipation)
  - Chopper : drive coil current (2 mA ?)
    pick-up coil current (1 mA ?)
- * Temperature of the 4th stage (15-20K)

N = No. of dets
C = Commoning factor (eg: 8)



eg: N = 142
C = 7

SUMMARY OF OBSERVING MODES

[GRIFFIN]

- **SPECTRAL:** ≡ LO1 (COMPLETE SCAN)
- POINTING ERROR IMPLICATIONS:
  ~8" UNCERTAINTY (⇒ 25% SIGNAL LOSS FOR FWHM = 25")
- ⇒ JIGGLE PATTERN NEEDED ?
- ⇒ PEAK UP WITH CHOPPER ?
- WE NEED ~3" FOR ~ 95% OF FLUX
- MUST PUSH ESA ON POINTING PERFORMANCE
- USE PHOTOMETER JUST BEFORE EVERY SPECTRUM OBSERVATION?
- CHOPPING :
  - ① SAY 2-3 Hz ; STEP & INTEGRATE
  - ② CHOPPER OFF ; FREQUENCY SCAN
  - ③ DIFFERENCE 2 ROWS OF DETS
  - ④ FIXED GRATING MODE FOR BRIGHT SOURCES OR SLEWING
  - ⑤ SHORT SCANS OF LINES OF KNOWN λ
  - ⑥ SPECTRAL MAPPING : POINT, TAKE SPECTRUM, REPOINT, ETC.

PARALLEL & SERENDIPITY

① PHOC MAPPING — BOL MAPPING
② BOL MEASURING SPECTRUM — ~~SER~~ PARALLEL UNDER SAMPLED MAPPING
— PHOC ?
③ BOL MAPPING — BOL DOING FIXED GR. SPECTRUM
— PHOC DOING SOMETHING

PHOTOMETRY MAPS

- FULLY SAMPLED IMAGE
  ⇒ 16 POINT TELESCOPE JIGGLE WITH CHOPPER ON, CHOPPING WHOLE ARRAY
- ON THE FLY MAPPING :
  CHOOSE SUITABLE SCAN DIRECTION (SHOULD BE SAME FOR ALL 3 ARRAYS)
  CHOPPER ON, SLOW SCANNING TELESCOPE
- MUST SELECT STEP FOR SHORTEST λ ARR

POINT SOURCES

- 8" POINTING ERROR ⇒ MUST DO LITTL
  5 OR 9 PT MAP
  ⇒ TAKES LONGE
- <3" " " ⇒ POINT AND CHOP BETWEEN 2 PIXELS
  [CAN WE DO THIS WITH REASONABLE ARRAY LAYOUT]

SUMMARY OF ACTIONS / FUTURE WORK

[GRIFFIN]

ACTIONS

- QMW +CALTECH — WHAT'S REQUIRED DET. OPERATING TEMP (CAN WE PUSH IT TO 300 mK)
- ROE/LAS/RAL : REFINE SPEC OPTICAL DESIGN
- QMW [BM] — BRING TOGETHER ALL THERMAL /MASS DATA FOR PDD REVISION
- QMW — ESTABLISH BASELINE FILTERING SCHEME FOR PHOT → PHOTOMETRIC MODEL
- MJG + PARA +RAL — INVENT FIRST CUT CHOPPER + SPECTRAL SOURCE SPECS
- QMW/RAL INVESTIGATE WAYS OF LIVING WITHOUT CHOPPER
- MJG — SUMMARISE TELESCOPE POINTING SPEC AND DISTRIBUTE
- MJG/KJK/ROE — SUMMARISE BASELINE OPERATING MODES
- ROE : — FOLDING OF PHOT FINAL OPTICS WITH F/S
- IDH : — ADR PARAMETERS FOR $T_0 \geq 250$ mK

EXTRACT FROM FIRST
POINTING SPEC.

4.2.2 Initial Acquisition

MOOM-020 *After satellite separation from the launcher the ACMS shall perform the initial attitude acquisition. The purpose of this shall be to reduce to near-zero the satellite rotation rates induced by the separation and to bring and maintain the satellite Z-axis within a half cone angle of 5° from the Sun vector.*

MOOM-025 *The duration of the initial sun acquisition phase shall not exceed 15 min. (TBC)*

MOOM-030 *If separation occurs during eclipse, or if eclipse occurs during this phase, the Sun acquisition may be delayed until sunrise.*

4.2.3 Star Acquisition Mode

MOOM-035 *After the initial acquisition has been performed, the star acquisition shall be initiated by ground command to get a known inertial attitude.*

4.2.4 Fine Pointing Mode

The fine pointing mode consists of observation pointings, followed/preceded by slew(s).

This is one of the modes used for science observation.

MOOM-040 *During the observation pointings, the pointing requirements of Section 5.3.2 shall be met. The pointing requirements do not apply:*

- *when any of the guide stars is in a cone around Jupiter centre with a half cone angle of 0.3° (TBC).*

MOOM-045 *It shall be possible to maintain this mode during the science observations phase for periods not less than 20 hours, during which momentum unloading and wheel speed reversal shall not occur.*

4.2.5 ΔV Manoeuvres

MOOM-050 *The spacecraft shall be able to provide all ΔV manoeuvres required to attain and maintain the operational orbit (FMMD-075, FMMD-105).*

MOOM-055 *The system shall provide for a controlled inertial attitude according to the requirements in Section 5.3.2 during thruster firing for ΔV manoeuvres.*

MOOF-020 Off-loading, as well as up-loading, of each reaction wheel shall be possible to a ground-commanded value.

The value for each wheel will be transformed on ground to a total bias angular momentum (satellite and wheels) which will be commanded to the satellite.

MOOF-025 There shall be a one to one correspondence between the bias momentum and the angular velocity of each wheel.

MOOF-030 Bias commanding will be initiated by the ground segment and will be normally executed outside the DPOP.

4.3.2 Slews

A slew is used to change the satellite pointing direction from the current set-point to the next set-point.

MOOF-035 It shall be possible to execute slews during all modes.

MOOF-040 Slews shall nominally not use the Reaction Control Subsystem (RCS).

MOOF-045 The maximum slew speed shall be at least 7°/min when the slew angle is large enough to permit full angular velocity.

MOOF-050 After a slew larger than 6 degrees, the satellite shall be able to acquire a new guide star in less than 30 seconds.

MOOF-055 For slews smaller than 10 arcmin, during observational modes, the total time between initiation of the slew and the moment when the telescope axis is on the new target shall be less than 30 s to achieve the fine pointing accuracy as defined in Section 5.3.2.

MOOF-060 The system design shall be dimensioned for operational slews of at least 90°, executed twice per day. Such a slew shall be completed within 15 min, including settling. The total number of these operational slews over the nominal 4.25 year lifetime is 3100.

No constraints, other than attitude constraints listed in Section 3.2.7.4 apply to the slewing method.

4.3.3 Raster Pointing

Normal raster pointing

Raster pointing is done during fine pointing mode. It is a series of fine pointing observations of equal duration (*t*), separated by slews, in order that the pointing of the telescope axis moves in a raster pattern as defined in Fig. 4.3-1. In this figure the following notations are used:

- M is the number of pointings per line.
- N is the number of lines.
- d_1 is the angular distance between successive steps.
- d_2 is the angular distance between successive lines.

The pattern axes are defined with respect to local celestial perpendicular axes.

MOOF-065 *The system design shall allow for raster pointing as defined above, where the pattern shall be followed line by line in the way shown by the arrows in Fig. 4.3-1.*

MOOF-070 *The raster parameters, M, N, d_1 and d_2 shall be changeable by ground command within the following range and resolution:*

- *M: 2 - 32*
- *N: 1 - 32*
- *d_1: 2 arcsec - 4 arcmin; resolution: 2 arcsec*
- *d_2: 0 arcsec - 4 arcmin; resolution: 2 arcsec*

Note that the minimum of d_2 being zero, means that it shall be possible to scan N times the points of a single line.

① Could it be < 10 s ?

MOOF-075 *The timing characteristics of raster pattern operation shall be ground commandable; the duration of stable pointing at any position, t, will be between 10 s and 30 minutes. The dwell time between points on a line, t_1, and the dwell time between lines, t_2, shall be separately commandable from ground.*

MOOF-080 *Once the set of parameters defined here above are defined and loaded in the ACMS computer, the succession of fine pointings and slews shall be done autonomously to allow the satellite to follow the required pattern, without further ground commands.*

Raster pointing with OFF-position

Raster pointing with OFF-position is a special form of raster pointing with one position on each line being an "off" position as shown in Fig. 4.3-2.

For the "on" positions, the raster is defined by the parameters M, N, d_1 and d_2 as specified above, with for each position an equal observation time t and dwell times t_1 and t_2.

The "off" position, i.e. the $(M+1)^{st}$ position, is defined by the parameter d_{off}, where:

- d_{off} is the angular distance between the last "on" position and the "off" position. This distance will in general differ from d_1.

MOOF-085 *d_{off} shall be changeable by ground command and will be between 4 arcmin and 1 degree with a resolution of approximately 2 arcmin.*

MOOF-090 *The duration t_{off}, of stable pointing in the "off" position shall be changeable by ground command within the range TBD s to TBD min.*

MOOF-095 *As for normal raster pointing, once the set of parameters defined here above are specified and loaded in the ACMS computer, the succession of fine pointings and slews shall be done autonomously to allow the satellite to follow the required pattern, without further ground commands.*

MOOF-100 *The pointing performance in both raster pointing modes shall be as defined in Section 5.3.2.*

4.3.4 Line Scanning

This is a scanning mode along short parallel lines, such that the telescope axis moves as shown in Fig. 4.3-3 with parameters as defined below:

- N is the number of lines.
- D_1 is the angular extent of the lines.
- d_2 is the angular distance between successive lines.

The pattern axes are defined with respect to local celestial perpendicular axes.

MOOF-105 *The system design shall allow for line scanning as defined above, where the pattern shall be followed line by line in the way shown by the arrows in Fig. 4.3-3.*

MOOF-110 *The scan parameters, N, D_1 and d_2 shall be changeable by ground command within the following range and resolution:*

- *N: 1 - 32*
- *D_1: 10 arcmin - 10 deg; resolution: 2 arcmin*
- *d_2: 0 arcsec - 4 arcmin; resolution: 2 arcsec*

Note that the minimum of d_2 being zero, means that it shall be possible to scan N times the same line.

MOOF-115 *The scan rate, r, shall be changeable by ground command and will be between 0.1 arcsec/s and 7 arcmin/s with a resolution of 0.1 arcsec/s.*

MOOF-120 *Once the set of parameters defined here above are defined and loaded in the ACMS computer, the scanning shall be done autonomously to allow the satellite to follow the required pattern, without further ground commands.*

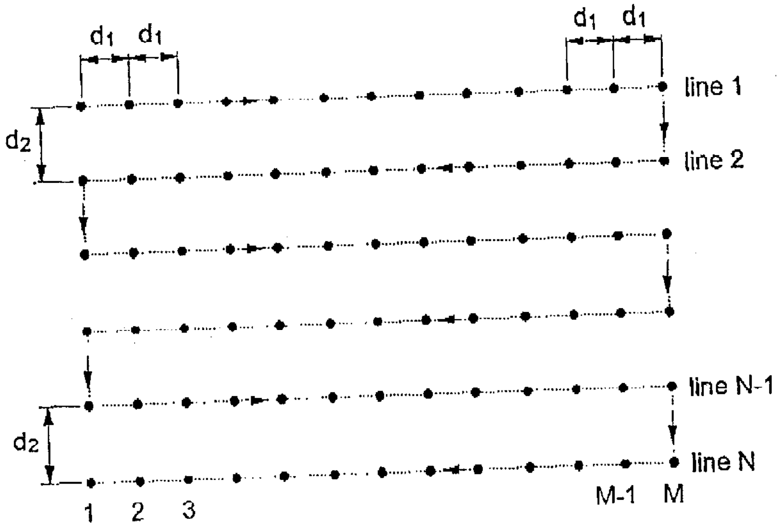


FIGURE 4.3-1 NORMAL RASTER POINTING

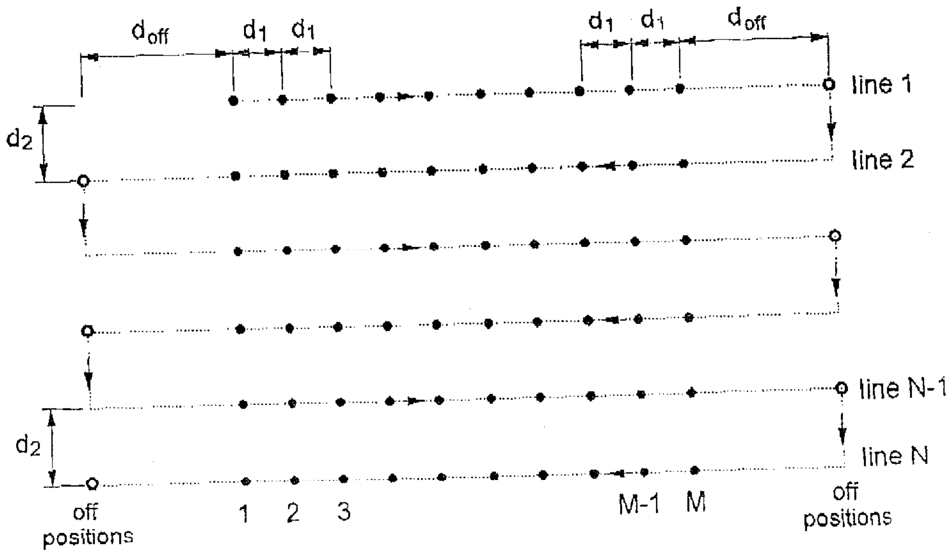


FIGURE 4.3-2 RASTER POINTING WITH OFF-POSITION

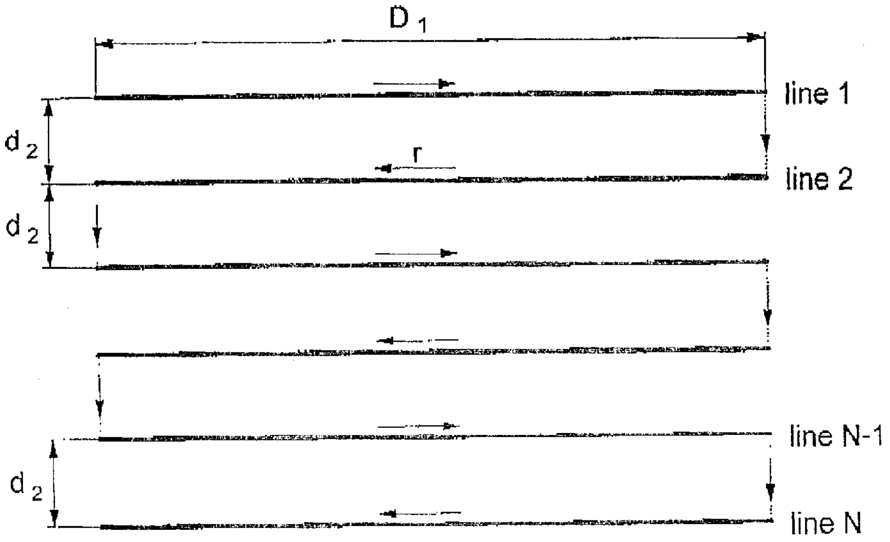


FIGURE 4.3-3 LINE SCANNING

4.3.5 Tracking of Solar System Objects

MOOF-125 *The satellite shall be able to follow, by ground command of a series of fine pointings, objects such as planets, comets, etc. having a maximum speed relative to the tracking star of 10 arcsec/min.*

MOOF-130 *The pointing performances whilst tracking solar system objects shall be as defined in Section 5.3.2.*

4.3.6 Position Switching

Position switching is an observing mode in which the instrument line of sight is periodically changed between a target source and a position off the source.

MOOF-135 *The satellite shall be able to periodically change the telescope pointing direction between a target source and some position off the source.*

MOOF-140 *The angular distance between the "off" position, which can be in any specified direction from the source, and the source ("on" position) shall be commandable from ground and shall lie between 0 and 1 degree with a resolution of 2 arcsec.*

MOOF-145 *The integration times in the "on" and "off" positions are equal and shall be changeable by ground command within the range of 30 s to 20 min (depending on the throw).*

MOOF-150 *The time spent observing in the "on" and "off" positions shall be at least 80% of the total cycle time for throws up to 16 arcmin.*

MOOF-155 *In the "on" position the pointing requirements as specified for fine pointing in Section 5.3.2 shall be satisfied. In the "off" position the pointing requirements are TBD.*

MOOF-160 *Once the set of parameters defined here above are defined and loaded in the ACMS computer, the position switching shall be done autonomously to allow the satellite to follow the required pattern, without further ground commands.*

4.3.7 Nodding

Nodding is an observing mode in which the target source is moved from one instrument chop position to the other chop position. In this case the pointing direction will change in the direction of the instrument chopper throw.

MOOF-165 *The satellite shall be able to periodically change the telescope pointing direction such that the source is moved from one instrument chop position to the other position.*

MOOF-170 *The angular distance between the two positions shall be commandable from ground and shall correspond to the instrument chopper throw (between 0 and 16 arcmin with a resolution of 2 arcsec).*

MOOF-175 *The integration times in both positions are equal and shall be changeable by ground command within the range of 30 s to 20 min (depending on the throw).*

MOOF-180 *The time spent observing in both positions shall be at least 80% (TBC) of the total cycle time.*

MOOF-185 *Specifically, for a throw of 5 arcmin, the total cycle time shall not exceed 3 min; i.e. 72 s integration in either position and two 5 arcmin slews lasting 18 s each (including settling time).*

MOOF-190 *In both pointing attitudes the pointing requirements as specified for fine pointing in Section 5.3.2 shall be satisfied.*

MOOF-195 *Once the set of parameters defined here above are defined and loaded in the ACMS computer, the nodding shall be done autonomously to allow the satellite to follow the required pattern, without further ground commands.*

4.4 TELEMETRY AND TELECOMMAND REQUIREMENTS

4.4.1 Telemetry requirements

MOTT-005 *The spacecraft telemetry shall comply with the Packet Telemetry Standards as defined in AD6-6.*

MOTT-010 *Spacecraft and instrument housekeeping data, as well as the scientific data collected by the payload during routine scientific operations or during commissioning and calibration shall be transmitted to the ground using the S-band frequency range in accordance with the requirements of the Ground Segment Interface Specification (AD3-1).*

MOTT-015 *In the Scientific Operations Phase, telemetry transmission will take place during the DTCP. In the other mission phases, transmission will take place according to the nominal ground station visibility schedule. Data collected outside these transmission periods shall be stored on-board for later transmission.*

- *distribution of all electrical signals through an SVM harness.*

Detailed Service Module requirements are defined in Chapter 6.

5.3 PERFORMANCE REQUIREMENTS

5.3.1 Lifetime

SCPE-005 *The complete FIRST spacecraft shall have a nominal operational lifetime of 4 years (TBC). This duration is counted from the start of routine scientific operations and does not include the required time for cool-down, initial calibration and commissioning. Until the time for initial calibration and commissioning is defined, a total duration of three months shall be assumed.*

SCPE-010 *The completely integrated satellite shall permit storage in a controlled facility before launch, prior to start of transport to the launch site of 12 months.*

SCPE-015 *The lifetime of items which degrade with time or usage shall be designed as 1.1 (TBC) times the calculated cryostat lifetime.*

SCPE-020 *Propellant for orbit maintenance, attitude control and momentum management shall be dimensioned for 1.5 times the calculated cryostat lifetime. The 50 % margin that is included in this figure might be revised later depending on the accuracy of predicting orbit maintenance and momentum management requirements.*

5.3.2 Pointing Requirements

The following terminology shall be used:

- **Absolute Pointing Error (APE):** is the angular separation between the commanded direction and the instantaneous actual direction
- **Absolute Pointing Drift (APD):** is the angular separation between the short time average (barycentre of the actual pointing during some time interval) and a similar average pointing at a later time. The drift is given over 20 hours during the same observation period.
- **Relative Pointing Error (RPE):** is the angular separation between the instantaneous orientation of the satellite fixed axis at some time t and a reference axis (average, barycentre) defined over 1 minute. This is also known as the pointing stability.

- **Absolute Measurement Accuracy (AMA):** is the angular separation between the actual and the measured orientation of the satellite fixed axis defined instantaneously or over a time interval. This performance requirement is referred to as "a posteriori knowledge".

The pointing requirements specified below refer to the instruments Line of Sight as defined by external references on the Focal Plane Units. Contributions to the pointing error which are instrument-related shall not be taken into account in establishing the pointing budget.

The pointing error specifications are expressed as half-cone angles of the optical axis and half-angles around the optical axis. They are specified at a probability level of 95%, which implies that the specific constraints shall not be exceeded with a probability in excess of 5 %.

SCPE-025 *During all scientific observation modes requiring periods of stable pointing, the pointing requirements as specified in the table below shall be met with a single calibration once per 24 hours and an offset of up to 2° between the optical axis of the startracker(s) and the reference star(s).*

②
(i) Can it be better?

8" offset =>
25% loss of signal

(ii) Is APE random?

timescale? →

ERROR	*Optical Axis (arcsec)*	*Around Optical Axis (arcsec)*
APE	*8.0*	*TBD*
APD (20 hours)	*3.0*	*TBD*
RPE (1 min)	*1.0*	*TBD*
AMA	*7.0*	*TBD*

Attitude pointing requirements are also defined for orbital manoeuvres, for High Gain Antenna pointing during the DTCP and for Solar Array pointing. The respective requirements are:

SCPE-030 *During ΔV manoeuvres (orbital manoeuvres including orbit maintenance), the absolute pointing error of the thrust vector shall not exceed 0.5° half cone angle at a confidence level of 95 %.*

During ΔV manoeuvres there are no requirements on the other pointing terms, nor on the pointing around the thrust vector. The attitude constraints as defined in Section 3.2.7.4 must however be satisfied.

SCPE-035 *During data transmission between spacecraft and ground station via the spacecraft High Gain Antenna (HGA), the antenna boresight axis shall be pointed towards the Earth with an absolute pointing error not exceeding 0.5° (TBC).*

During the telecommunications phase there are no requirements on the other pointing terms, nor on the pointing around the HGA boresight direction. The attitude constraints as defined in Section 3.2.7.4 must however be satisfied.

SCPE-040 *After initial Sun acquisition and during safe modes, the solar array rotation axis shall be Sun-pointing with an absolute pointing error not exceeding 1.0° (TBC).*

During these phases there are no requirements on the other pointing terms, nor on the pointing around the solar array rotation axis.

SCPE-045 *If, nominally, gyro's are used during stable pointing, alternative methods shall exist to satisfy the pointing requirements defined above.*

SCPE-050 *The pointing budget shall demonstrate compliance of the design with these requirements; it shall be established according to the rules defined in the ESA Pointing Error Handbook (RD-9).*

5.3.3 Orbit Control

For orbit control, i.e. midcourse corrections after insertion into the transfer trajectory and orbit maintenance, the requirements of Section 4.2.5 (ΔV manoeuvres) are applicable.

The actual magnitude and direction of the required manoeuvres will be determined by ESOC after periods of tracking and subsequent orbit determination and the manoeuvre parameters will be uplinked to the spacecraft which will execute the manoeuvres by either time-tagged or ground command.

SCPE-055 *The spacecraft must be able to execute the commanded manoeuvres with an accuracy of the thrust vector direction as specified in Section 5.3.2 (SCPE-030). The magnitude error of the ΔV manoeuvre shall not exceed 1% (TBC) of the commanded magnitude at 95% confidence level.*

5.3.4 Straylight

For FIRST, the straylight coming into the focal plane can have three distinct origins.

The requirements are the following:

a. Sources outside telescope field of view

The far infra-red and sub-millimetre sky is dominated by four extremely bright objects: the Sun, the Earth, the Moon and Jupiter. Off-axis rejection is determined mainly by the quality of the baffling system at small angular distances from these bright sources.

SCPE-060 *The parasitic light in the focal plane shall be below 1% of the background induced by self emission of the optical system for Sun, Earth, Moon and Jupiter at worst case locations corresponding to the aspect angle limits as specified in Section 3.2.7.4.*

b. Sources inside field of view

The diffraction theory shows, that for a telescope of limited size, the energy coming from a monochromatic point source, even if it has a very strong maximum, is distributed across the whole focal plane. Imperfections in the mirror qualities, mainly dirt and small scale irregularities, will amplify this spill-over.

SCPE-065 *Over the entire field of view at an angular distance of 3 ~~arcsec~~ arcmin or more from the peak of the Point Spread Function (PSF) the irradiance shall be less than 10^{-4} of the PSF peak irradiance (in addition to the level given by diffraction).*

c. Thermal self emission

The optical subsystem of FIRST being at a finite temperature will emit far infra-red and sub-millimetre radiation that will fall onto the detectors, introducing spurious signals which are difficult to eliminate.

SCPE-070 *Spurious light issued from the optical subsystem due to thermal self-emission shall be, at the level of the focal plane:*

- *less than 20% of the radiation coming from a 110K blackboy covering the subreflector over the total integrated field of view and*
- *less than 2% of above defined blackboy radiation for a detector element with 10 mm diameter and an acceptance cone being 10% of diameter larger than subtended by the secondary reflector anywhere within the field of view.*

5.3.5 Autonomy

Autonomous operations are those operations that the spacecraft will itself initiate following an on-board event. Autonomous operations may be implemented by hardware or software or a combination of both.

An on-board event is any event not foreseen in the mission timeline, typical events are e.g.:

- Unit, sub-unit or experiment not performing as specified
- LCL tripping
- Loss of Sun pointing