SPIRE Beam Steering Mirror Design Description

v 4.0

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Update:

Date	Index	Remarks
5 Jun 2000	1	Creation of the document
28 Aug 2000	2	Revision of the document, internal to ATC
	3.1, 3.2.	Revision of the document, internal to ATC
12 Oct 2000	3.3	Revision – adding significant mechanical, electronics & controls content. Produced summary description for verbatim release in SPIRE-ATC-PRJ-001 and -003
02 Feb 01	3.4	Updated update table to include unreleased versions. Amended images to latest mechanical design state. Included flex pivot call out. Note electronics section requires substantial update to reflect progress.
20.Jul.01	4.0	Updated substantially for DDR

1. Table of Contents

1.1 Table of figures

1.2 Tables

2. Scope of the Document

This document describes the design Herschel-SPIRE Beam Steering Mirror mechanism subsystem. The intent of the document is to incorporate all design information available at a given release date, and it is expected that the document will be updated, on approximately a quarterly basis, as aspects of the design undergo changes under configuration control.

Section 5 of this document provides a summary design description that is referenced complete into AD1 and RD5.

3. Document List

3.1 Applicable Documents

	Title	Author	Reference	Date
AD1	SPIRE Beam Steering Mirror Mechanism Subsystem Specification	D.Henry	SPIRE-ATC-PRJ-000460 v 3.2	Jul.01
AD2	SPIRE Project Development plan	K.J.King	SPIRE-RAL-PRJ-000035	latest
AD3	Herschel-SPIRE BSM PA Plan	I.Pain	SPIRE-ATC-PRJ-000711 v1.0	26.Jun.01
AD4	Optical System Design Description	K.Dohlen, B.Swinyard	SPIRE-LAM-PRJ-000447 Draft 1	18.Dec.00
AD5	Spire Harness Definitions	D.K.Griffin	SPIRE-RAL-PRJ-000608 iss 0.3	30.May.01
AD6	ICD Structure - Mechanical I/F	B.Winters	SPIRE-MSS-PRJ-000xxx v1.0	April 2001

3.2 Reference Documents

	Title	Author	Reference	Date
RD1	Instrument Requirements Document	B.M.Swinyard	SPIRE-RAL-PRJ-000034 Iss .30	May 2000
RD2	Instrument Development Plan	K.King	SPIRE WE Review viewgraphs	6 Dec 1999
RD3	Proposal for Beam Steering Mirror	R.Sidey	ATC contract no. 017693	undated
RD4	Assessment of System Level Failure Effects for SPIRE	B.M.Swinyard	SPIRE-RAL-NOT-000319 v 4	4-APR-2001
RD5	BSM Development Plan	I.Pain	SPIRE-ATC-PRJ-000466	17.Jul.01
RD6	Space Engineering, Mechanical Part 3 - Mechanism Design	ESA	ECSS-E30(a)-part3	25 Apr 00
RD7	Optical design. Diffraction analysis & design.	M.Caldwell	SPIRE-RAL-DOC-000441 ISSUE: 1.0	14 Jun 00
RD8	Mirror Thermal Cycling Procedure	I.Pain	SPIRE-ATC-Internal-NOT-003 V 1.0	12.Jun.01
RD9	CM4 Hole Size Considerations and stray light control	T.Richards	SPIRE-RAL-NOT-000576 ISS 1.0	23 Jan 01
RD10	Spectrometer and photometer pupil imagery and CM4 SIZE CONSIDERATIONS	T.Richards	BSMSIZE_MEMO.DOC	21.Sep.00
RD11	SPIRE Optical Alignment Verification plan	A.Origne, K.Dohlen	SPIRE-LAM-PRJ-000445	10.Apr.01
RD12	SPIRE AIV plan	B.Swinyard	SPIRE-RAL-DOC-000410 issue 2.0	23.Feb.01
RD13	A cold Focal Plane Chopper for Herschel-PACS - Critical Components and Reliability	R.Hofferbert, D.Lemke et al	paper	undated

4. Glossary

Abbr.	Meaning	Abbr.	Meaning
AD	Applicable Document	LAT	Lot Acceptance Tests
ADP	Acceptance Data Package	MAC	Multi Axis Controller
ATC	United Kingdom Astronomy Technology Centre	MAPTIS	Materials and Processes Technical Information Service
BSM	Beam Steering Mirror	MSFC	Marshall Space Flight Centre
BSM	Beam Steering Mirror dummy	MCU	Mechanism Control Unit
BSMe	Beam Steering Mirror electronics	MIP	Mandatory Inspection Point
BSMm	Beam Steering Mirror mechanism	MGSE	Mechanical Ground Support Equipment
BSMs	Beam Steering Mirror structure	MPIA	Max Planck Institute for Astronomy
CAE	Computer Aided Engineering	MSSL	Mullard Space Science Laboratory
CDR	Critical Design Review	NASA	National Aeronautical Space Agency
CoG	Centre of Gravity	NA	Not Applicable
CIL	Critical Items List	NCR	Non Conformance Report
CQM	Cryogenic Qualification Model	NCRP	Non Conformance Review Panel
CTD	Change to Drawing/Document	OGSE	Optical Ground Support Equipment
DCL	Declared Components List	PA	Product Assurance
DDR	Detailed Design Review	PAD	Part Approval Document
DM	Development Model	PFM	Proto Flight Model
DML	Declared Materials List	PPARC	Particle Physics and Astronomy Research Council
DPA	Destructive Physical Analysis	PI	Principal Investigator
DSP	Digital Signal Processor	PID	Proportional – Integral - Derivative
ECSS	European Co-operation for Space Standardisation	QA	Quality Assurance
EGSE	Electrical Ground Support Equipment	RAL	Rutherford Appleton Laboratory
ESA	European Space Agency	RAL SSD	RAL Space Science Department
FMEA	Failure Modes and Effects Analysis	RD	Reference Document
FMECA	Failure Modes, Effects and Criticality Analysis	rms	Root mean square
FPGA	Field Programmable Gate Array	SDOF	Single Degree of Freedom
FPU	Focal Plane Unit	SMEC	Spectrometer Mechanism
FS	Flight Spare	SPIRE	Spectral and Photometric Imaging Receiver
FSM	Flight Spare model	TBC	To Be Confirmed
GDFC	Goddard Flight Centre	TBD	To Be Defined
GSE	Ground Support Equipment	TBW	To Be Written
HoS	Head of Specialism	UK ATC	United Kingdom Astronomy Technology Centre
Herschel	ESA Mission name (formerly FIRST)	UK SPO	UK SPIRE Project Office
ICD	Interface Control Document	WE	Warm Electronics
IBDR	Instrument Baseline Design Review		
KIP	Key Inspection Point		
LAM	Laboratoire d'Astrophysique de Marseilles		

5. Outline Description of the Beam Steering Mirror mechanism subsystem.

5.1 Overview

The Beam Steering Mirror mechanism subsystem (BSM) is a critical part of the SPIRE Instrument. It is used to steer the beam of the telescope on the photometer and spectrometer arrays in 2 orthogonal directions, for purposes of fully sampling the image, fine pointing and signal modulation.

The BSM comprises 4 main deliverables:

1. **The cryogenic <u>mechanism</u>** (BSMm).
2. **The <u>structural</u> interface** (BSMs).
3. **The warm <u>electronics</u>** (BSMe)
4. **Mass and optical alignment <u>dummies</u> as required for SPIRE system level integration,** (BSMd)

The position of the BSMm & BSMs are indicated in Figure: 1

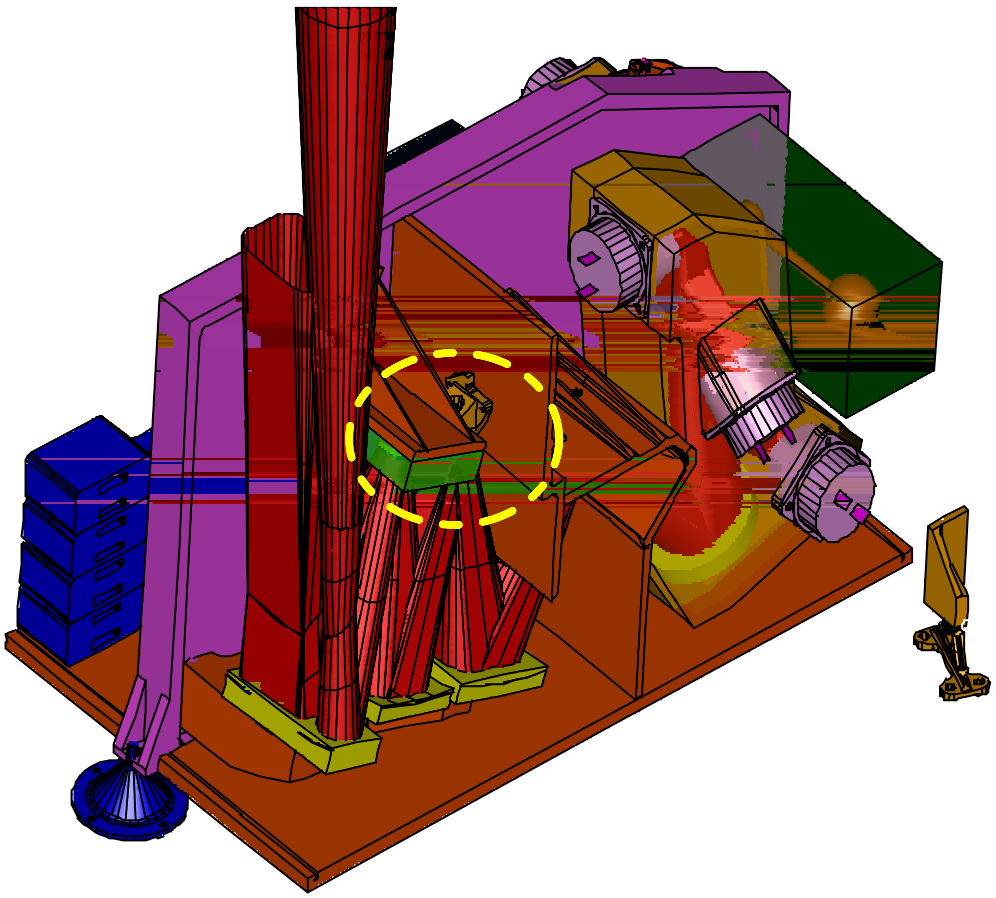


Figure: 1 Photometer Layout, BSM in green, highlighted with yellow oval

The <u>BSMm</u> consists of an aluminium alloy mirror, nominal diameter 32mm, machined as part of the chop axis. This is mounted orthogonally within a gimbal-type frame which provides for jiggle axis motion. The axes are suspended by flex-pivot mounts. The BSMm is a cryogenic device with nominal temperature 4-6K. Nominally, the chop axis provides 2.4 ° of mirror motion at 2 Hz and the jiggle axis provides 0.6° of motion at 1 Hz. The mirror also provides an aperture through which the Photometer Calibration Source is directed towards the detector arrays

The BSMs provides location of the BSMm on the SPIRE optical bench, and will also provide for a light tight enclosure and structural support for harnessing and thermometry. The BSMs integrates to the SPIRE Photometer Calibration Source (PCAL), supplied by the University of Cardiff, a baffle (supplied by RAL or ATC…TBC) and the SPIRE optical bench (MSSL). The BSMs is a cryogenic structure with nominal temperature 4-6K.

The BSMe provides electrical actuators which are used to provide motion of the mirror. Electrical transducers are used to measure the mirror position to allow control of the mirror position. The BSMe baseline design makes use of cryogenic motors used in PACS and magneto-resistive sensors used in ISOPhot. Each axis houses a rare-earth (NdFeB VacoDym 344) permanent magnet moving pole piece and is driven by a motor coil fixed to the mechanism housing/structure.

The cryogenic electronics are connected to the analogue power and amplifier electronics on the Warm Electronics (WE) by a cryogenic harness which will also feed out signal cables from thermocouples on the BSMs. The BSM operates under control of the Detector Readout and Control (HSDRC) sub-system's Mechanism Control Unit (MCU) supplied by LAM. The BSMe will be specified and designed by the UK ATC, then manufactured by LAM in conjunction with the SMEC electronics. Integration and test will be at LAM, with support from ATC.

The BSMd may comprise several actual dummies, with at least (1) an optical dummy for initial alignment work and (2) a mass-representative model for structural vibration tests. Designs for mass and optical alignment dummies will not be specified in detail until the BSMs/BSMm design is complete.

5.2 Mission profile

The BSM is developed as a sub-system and then integrated to the SPIRE FPU. The SPIRE instrument is subsequently integrated to Herschel. The instrument is to be cryogenically cooled, and will be cold during launch. Launch is scheduled for 2007 to an L2 orbit. The mission duration is a minimum of 4.25 years.

Per RD1, in normal operations the satellite is expected to have a 24-hour operational cycle with data being collected autonomously for 21 hours and a 3 hour ground contact period – the Data Transfer and Commanding Period (DTCP). During the DTCP the data will be telemetered to the ground and the commands for the next 24-hour period will be uplinked.

6. BSM Block Diagram

The block diagram below is adopted from RD1 Fig 3.1-1 and shows the relationships between the sub-systems of the SPIRE instrument.

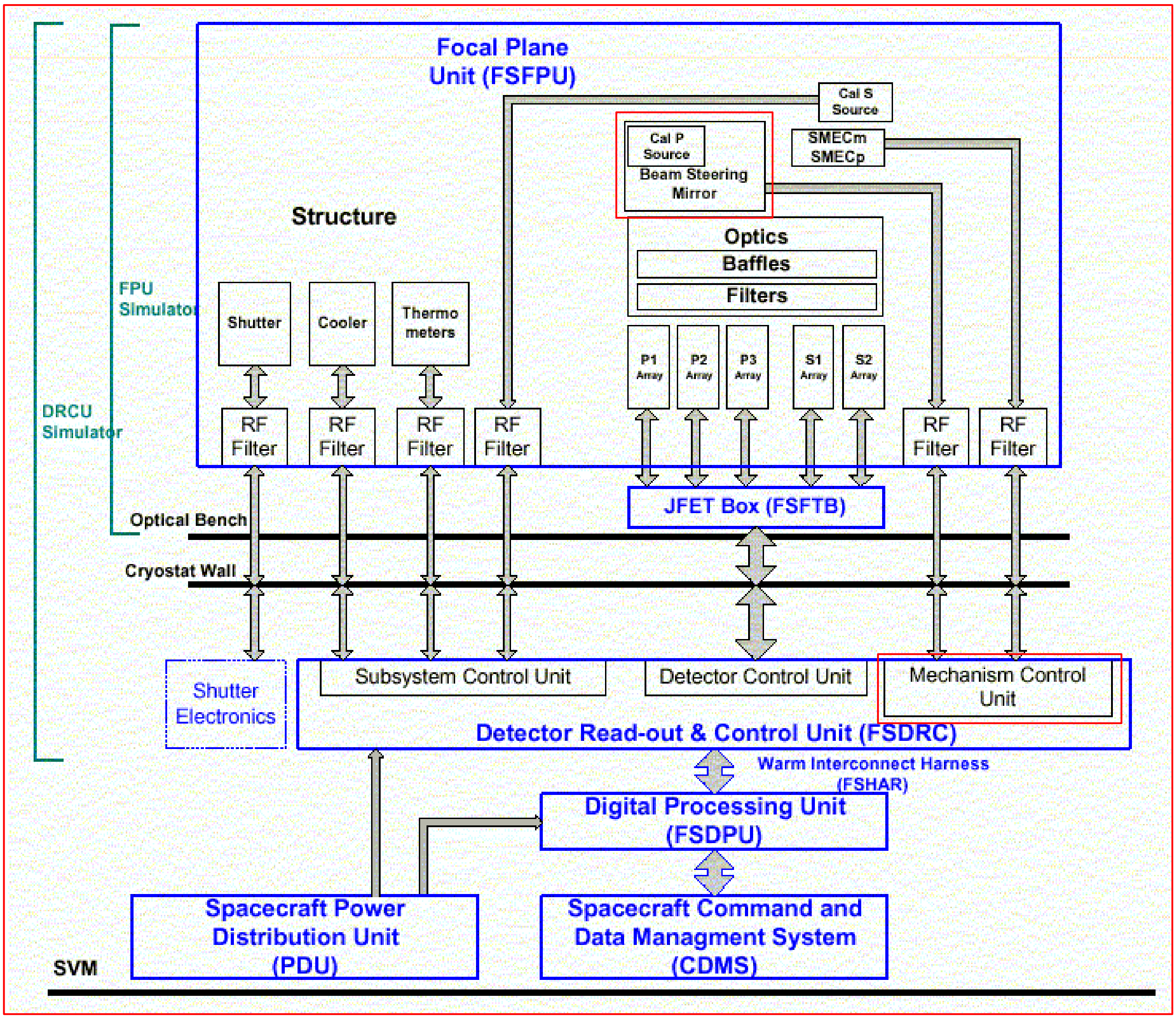


Figure: 2 SPIRE Block Diagram[1] showing BSM, Mechanism Control Unit (MCU).

[1] *Note that the terminology in this figure is in need up an update, as the spacecraft has been re-named Herschel, formerly FIRST. Hence FIRST-SPIRE Focal Plane Unit, or FSDPU should now read HSDPU.*

7. Detailed Description - Mechanical

7.1 Load environment

The BSM is a cryogenic mechanism, attached to the SPIRE Level 1 thermal straps to give a temperature in orbit at 3.5-6K. It is cooled down prior to launch and experiences a vibration load from the spacecraft, potentially amplified buy the SPIRE optical bench structure. On orbit, the mechanism operates in a micro-gravity environment where the principle loads are self-induced fatigue loads during chop and jiggle motion.

During manufacture, qualification and integration the design must survive warm vibration tests (room temperature), bake-out to 80°C, thermal cooldown at a rate of at least 20K/hr (space-craft), life tests of many million cycles at 20K and cold vibrations (at 4K). Not all of the BSM models to be built will experience all of these tests, but the same design must be useable across all environments (i.e. no use of parts only clamped when cold, as they would fail during warm vibration).

The load environment is specified in AD1, as derived from AD6. In summary the maximum quasi-static loads are 25g, sine vibration 40g and random vibration 14g $_{rms}$.

The random vibration environment is summarised graphically as:

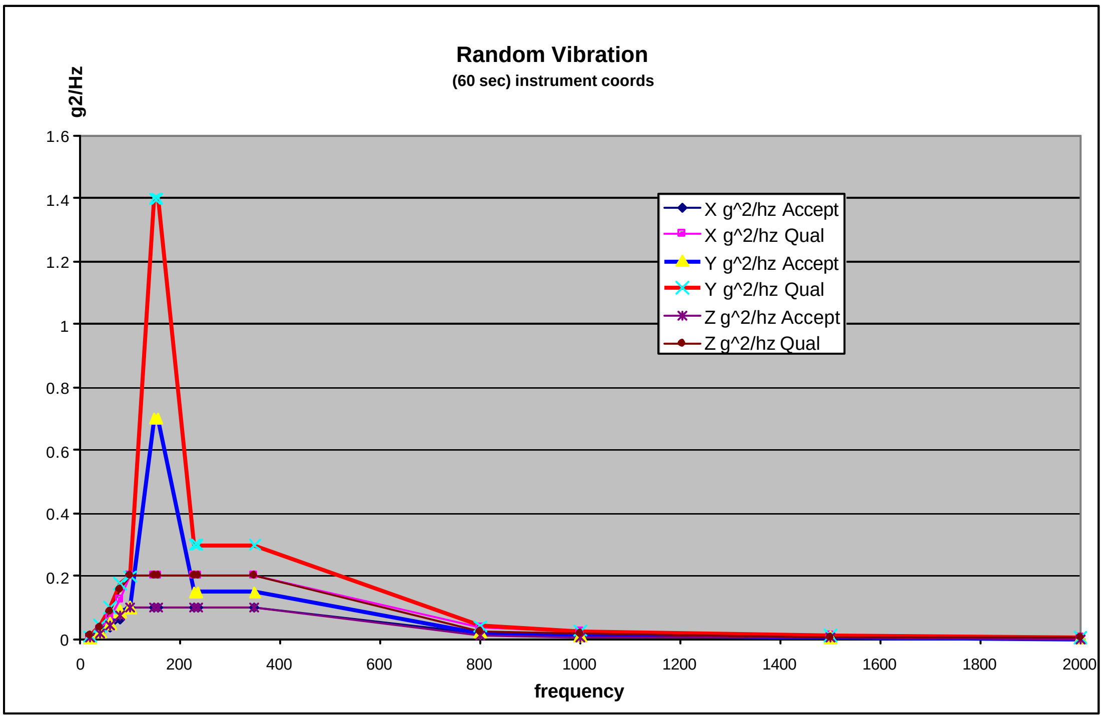


Figure 3 BSM launch load random vibration requirements

7.2 The Cryogenic Mechanism BSMm

7.2.1 General

The BSMm comprises a mirror of diameter 32.5mm, mounted so as to pivot on two axes to provide chop and jiggle motion.

The jiggle axis lies directly coincident with the mirror surface. The chop axis is recessed by 2.25mm from the mirror surface.

Each axis houses a rare-earth magnet moving pole piece and is driven by a motor coil fixed to the mechanism housing/structure. Lucas flex-pivots provide low friction motion and a small restoring torque.

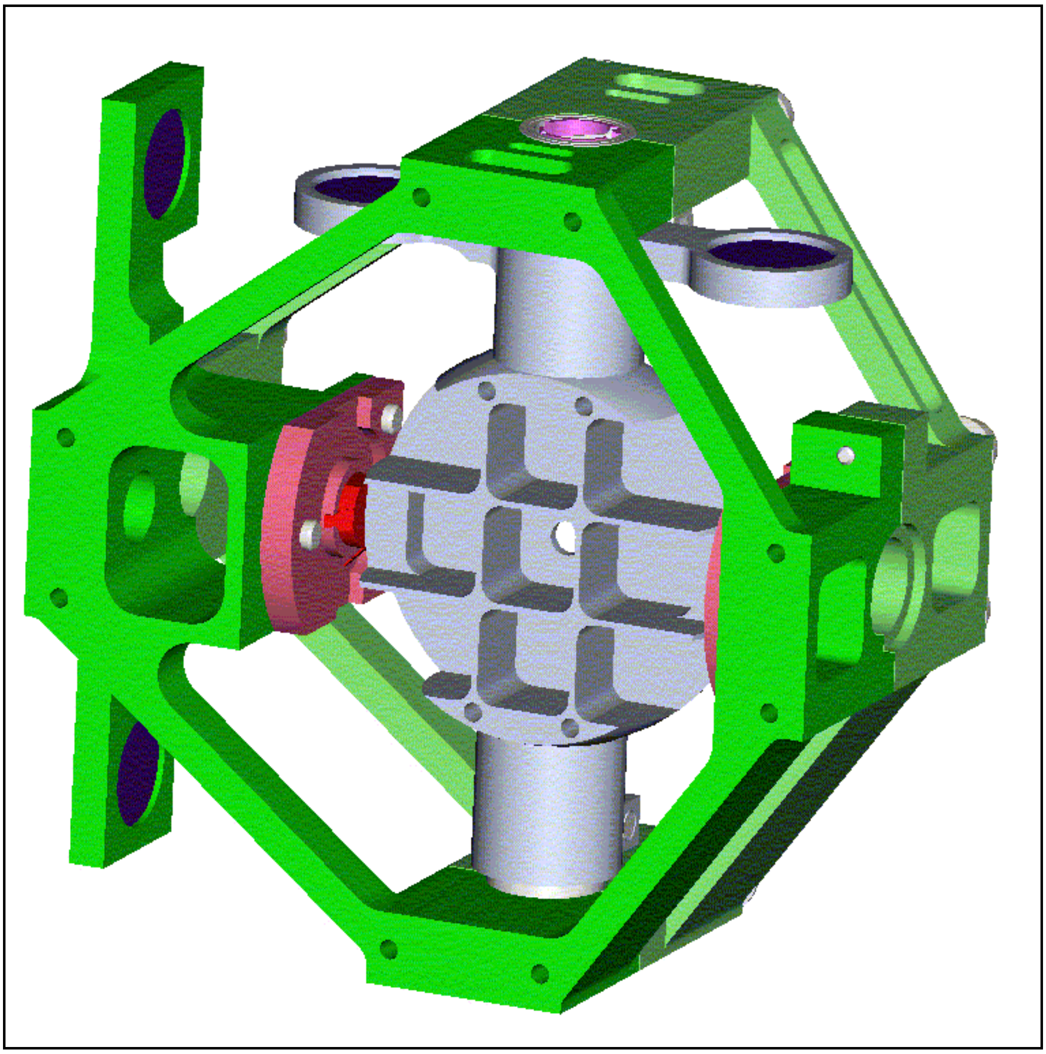


Figure 4: View on underside of mirror - Chop stage grey, jiggle stage green, motor magnets purple and sensor mounts (shown without adhesive) red.

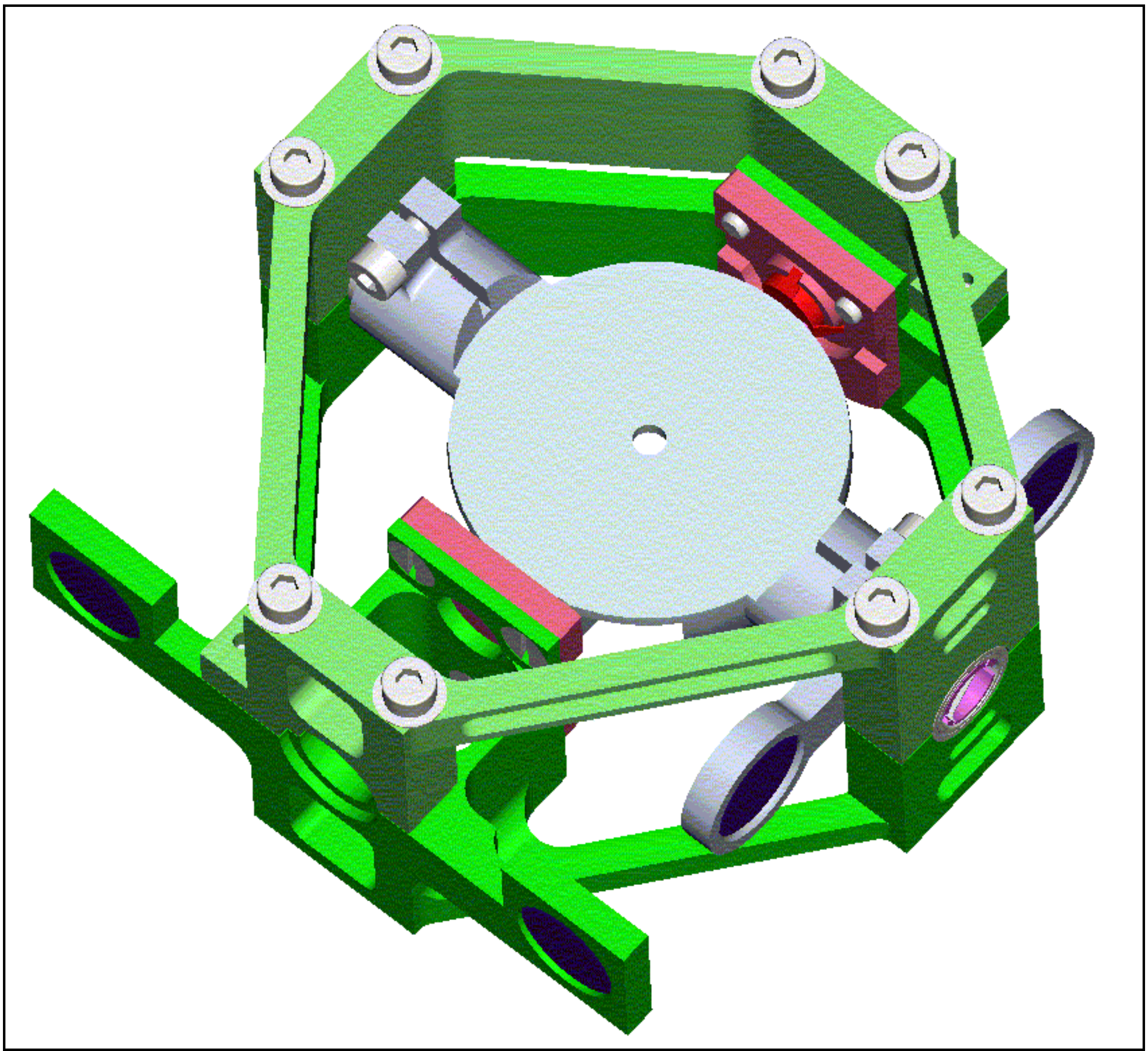


Figure 5 top side of jiggle frame and mirror. All fasteners are M2.5.

The chop and jiggle stages are shown in Figure 4. The chop stage is monolithic with the mirror machined integrally. The underside of the mirror is light-weighted and has pockets for the iron plates for the magneto-resistive position sensors. The chop direction is along the long axis of the array (the spacecraft y-axis). A 2.8mm diameter (TBC) hole in the centre provides an optical path for the calibrator mounted behind the BSMm

The moment of inertia of the chop stage has been minimised to reduce power consumption during chop transitions. At 1.7 kg.mm^2, it is little more than the ISOPhot rotor which was 1.57 Kg.mm^2. Mass, at 16 gm is also minimised to keep loads on the flex pivots down during qualification and launch.

The jiggle stage is in the form of a split frame split and clamps together around the flex pivots. Stainless steel fasteners (M2.5) are used in self locking inserts, with a stainless steel disc-spring to retain clamping forces during cooldown.

To balance the jiggle stage the framework in the opposite corner to the coils has been made solid. This also increases the stiffness of the structure. This structure carries the chop stage, and is inevitably heavier. The moment of inertia is estimated at 46.5 kg.mm^2 and mass at 88gm. Fortunately, the requirements call for lower amplitude and frequency in this axis, so we can use stiffer flexures.

Both stages are designed to be stiff, so that the first resonant frequencies are high enough (> 700 Hz (TBC) that the system modelling can regard them as rigid bodies.

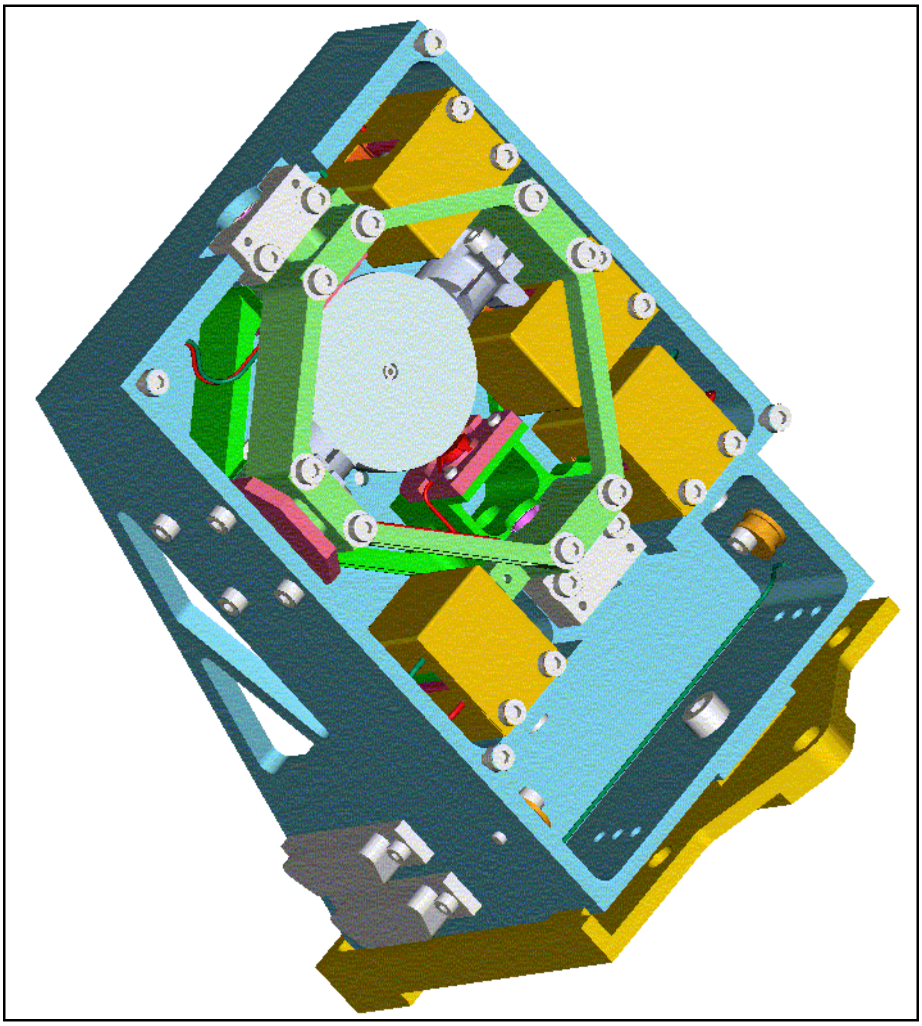


Figure 6 BSMm and BSMs with baffle ommitted. Jiggle frame in green, motor coil assemblies in orange, sensors are red/pink.

Space envelopes for the coils and sensors are shown in Figure 6. There will be a 'primary' and 'cold redundant' motor for each axis. The baseline is that motor for a single axis will have the two prime coils on the outer side of the rocker beam, and the two redundant coils on the inner side of the rocker beam.

The coils are adopted directly from the PACS chopper design, RD 13, as it has been determined to be more cost effective to buy into a well tested coil meeting the SPIRE requirements than to design our own.

All the motor coils mount directly to the BSMs, i.e. the chop stage air gaps must be slightly over-size to accommodate chopping whilst in various jiggle modes. The current magnetic circuit has not been modelled.

Position sensors for the chop axis are mounted on the jiggle stage, which means flexible cable connections are required, unlike the jiggle stage position sensors, which mount directly on the non-moving housing.

7.2.2 Finite Element Analysis FEA

Initial FEA work of the structure and mirror was been performed to calculate approximate strength and resonant frequencies. The full report is found in ATC document, spire-bsm-001-tdn-001.doc, see Appendix 3A.

NB – this analysis needs to be repeated to reflect design changes since this early concept work

This early analysis assumed a slightly lighter structure than implemented in the later stages of design, where manufacturing costs and feasibility were folded in to a greater degree. The results are thus conservative in the sense that stiffness and hence resonant modes will have been increased, but non-conservative where gravity induced loads will have been increased by extra mass (about 88gm compared to 55 gm).

7.2.2.1 Modelling

Modelling was performed using the COSMOS-M FEA package, and was based on the Pro/Engineer design models at the time of the analysis. The jiggle stage structure was been represented by thin shell elements. The chop stage was represented by a tube of solid elements together with lumped masses (shown red in the illustration below) to give the same mass and moments of inertia as the solid model. The flex pivots were modelled using a combination of solid and shell elements.

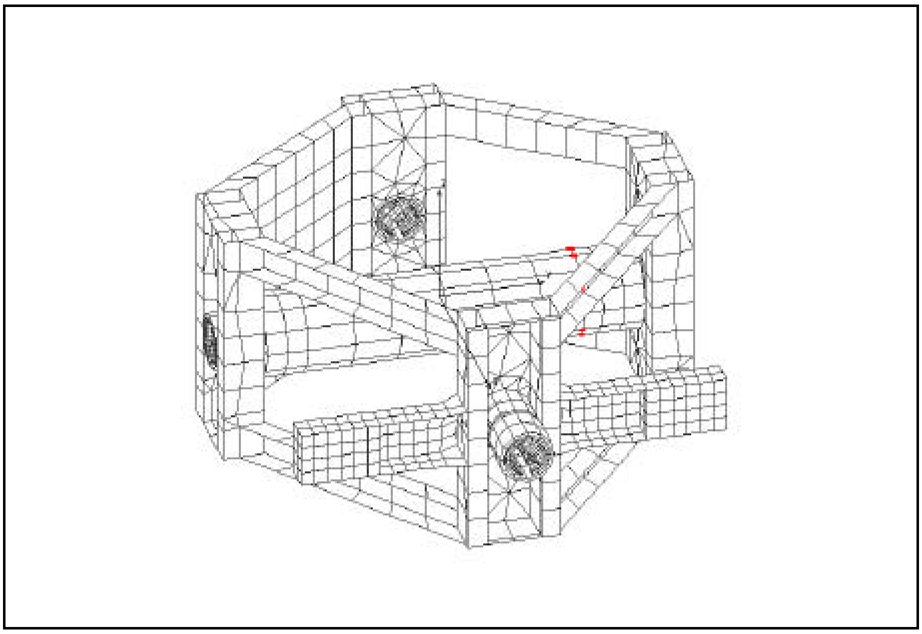


Figure 7 FEA mesh for initial stiffness modelling

The jiggle stage framework between the flex-pivot housings was modelled as 5mm x 5mm x 0.5mm channel section. (the subsequent manufacturability enhancements make this 5mm x 5mm x 1mm channel on the upper arms and 3mm square on the lower arms of the cage). The pivots have been moved as far as reasonably practical towards the mirror to minimise the inertia and maximise the stiffness. To clear the coils this leads to an asymmetric arrangement. To balance the jiggle stage the framework in the opposite corner to the coils has been made solid. This also increases the stiffness of the structure. Due to the use of lumped masses which do not give the correct products of inertia and also because the jiggle stage has not been dynamically balanced there will be some inaccuracy in modelling coupling of the stages.

7.2.2.2 Load cases

The following analyses have been made:

- 50 g static load in X,Y and Z directions
- Frequency response analysis for excitation of the chop and jiggle stages by couples of 1 Newton forces at the centre of the drive magnets (equivalent forces for the chop stage.)

7.2.2.3 Dynamics

The full report is found in Appendix 3A

7.2.2.4 Static stress analysis results

The three load cases (50g in X, Y and Z) lead to stresses in the flexures of similar magnitude,

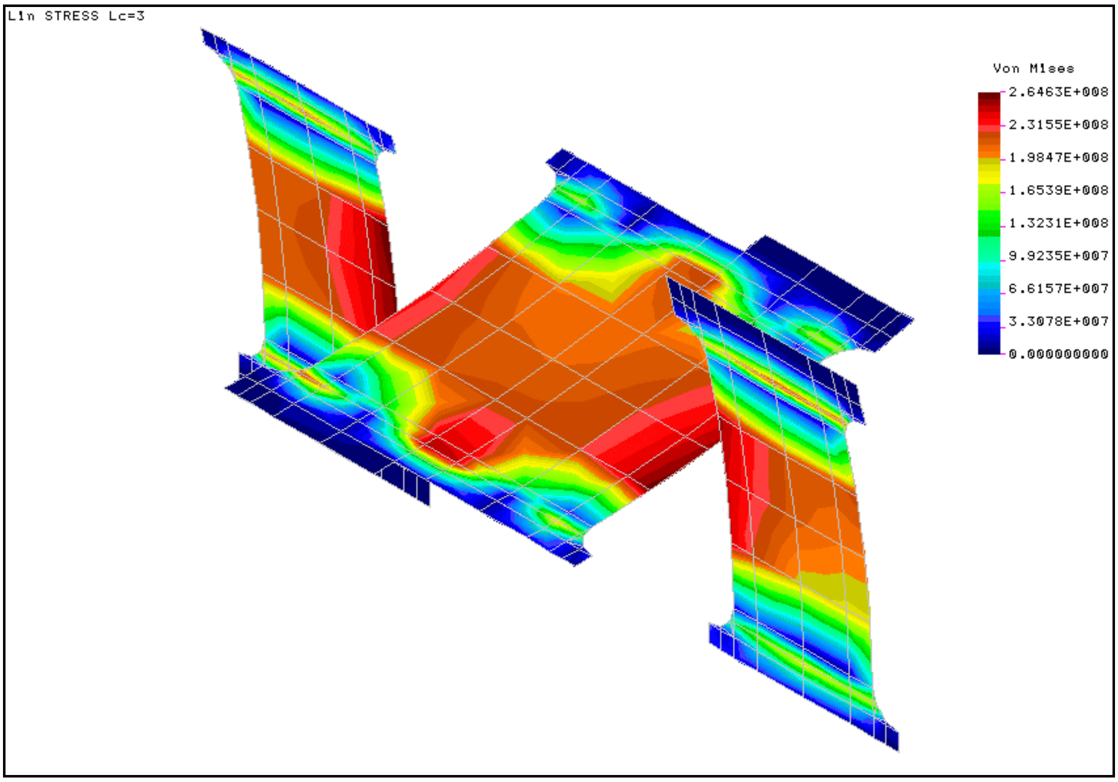


Figure 8: Flex pivot stresses from FEA

The predicted highest stress, 265 MPa, occurs in the jiggle axis flex-pivots. The 0.2% proof and ultimate tensile stresses of 420S29 equivalent to the stainless steel used for these items are 555 MPa and 755 MPa respectively so the design appears relatively safe. <u>It should be noted however that the model is a simplified representation for dynamic analysis and would need refinement for accurate stress calculation.</u> However, as equivalent 3 sigma static loads as high as 258g may occur during this would indicate a safety factor of 0.4. A more accurate appreciation of load capacity is provided by the manufacturer's rated loads, discussed in the following section.

7.2.3 Flex Pivots

Two flex pivot types are envisaged, supplied by Lucas Aerospace TRW (formerly Bendix). The jiggle axis uses type 7010-800 and the chop axis the lighter 7010-600 units.

The baseline material is Inconel grade 718, electron beam welded Inconel flex pivots supplied by Lucas TRW.

This is a special material order, differing from the standard 5010 type Lucas pivots (which are grade 420 and 429 stainless steel). The off-the-shelf grade material suffers from cryogenic embrittlement and will only be used in early test bed models of the BSM whilst longer lead cryogenic components are awaited.

It is noted that programmatic concerns exist with these inconel flex pivots as they have a high cost, and options are being explored to resolve this.

To reduce material and tooling charges it would be desirable to use a common type of pivot in both axes. Note that if the jiggle axis were to employ a lighter type (7010-800) pivot to obtain commonality with the chop axis the survival loading would be 90g (bucking failure): this would be inadequate to meet the 3 sigma peak launch loads from random vibration. Hence commonality would only be obtainable by stiffening the chop axis pivot (and increasing power budget).

7.2.4 Flex Pivot Protection

The flex pivots are the most critical element of the BSM design, and the most vulnerable. Much design effort is thus directed towards their protection.

7.2.4.1 Load control & Margin

As a first approach, the loads on the pivots are controlled as far as possible.

- Mass of the structures carried by the flex pivots (the chop axis and jiggle frame) is kept as low as practical, as this minimises loading during launch. Additional margin could be obtained by further light-weighting of the jiggle frame components, but is currently not required on technical grounds.
- The BSM mounting structure, jiggle frame and chop stage are kept stiff so that that the risk of amplification of the loads transmitted during launch are minimised.

Initial FEA work of the flex pivots has been performed to calculate stresses in flex pivots upon launch.

In addition, a static analysis is presented in Appendix 3C. The quoted catalogue load capacity of each of the standard (420 grade stainless steel) pivots is 245 N (55 lb.) and based on the analysis presented in Appendix 3c, the safety factor for 3-sigma peak response during vibration testing is:

chop axis flex pivots (5010-800)	1.05
jiggle axis flex pivots (5010-600)	1.95

The inconel grade pivots are manufactured in a higher grade material and have additional margin. They do not have an equivalent catalogue rated load, but stress calculations have been performed, summarised below.

The rated life for these flexures, from data supplied by Lucas is given below.

Axis	Mass (gm)	Material	Temperature	Load (lbs.)	spring type	Margin of safety (fatigue)	Approx. max G loading (extrapolated)	FoS on 260G 3-sigma launch load
Jiggle	90	420 SS	77F	3.3	600	7.6	126.7	0.5
		304 SS	77F	no data	600	no data	no data	no data
		Inconel 718	77F	3.3	600	4.6	76.7	0.3
		420 SS	-423F	no data	600	no data	no data	no data
		304 SS	-423F	no data	600	no data	no data	no data
		Inconel 718	-423F	3.3	600	10	166.7	0.6
Chop	20	420 SS	77F	9.9	800	2.5	562.5	2.2
		304 SS	77F	9.9	800	1.1	247.5	1.0
		Inconel 718	77F	9.9	800	1.3	292.5	1.1
		420 SS	-423F	9.9	800	no data	no data	no data
		304 SS	-423F	9.9	800	4.6	1035.0	4.0
		Inconel 718	-423F	9.9	800	3.7	832.5	3.2

Table 1: Rated fatigue loads and margins

Error! Reference source not found. shows margins on fatigue life for loads of 3.3 and 9.9 lbs. on both the jiggle and chop type pivots.

These values are conservative, as they are for infinite fatigue life whereas the vibration test would generate a significantly reduced number of cycles (max 120000 if 2kHz for 60 sec). There is also an apparent discrepancy in that the heavier section type 600 pivots appear to have a reduced ability to cope with higher loads, - this requires resolution with TRW.

The difference between warm and cold fatigue life properties will require careful test design to account for this in performing warm and cold vibration tests.

However, buckling overload of the flexures would place a cap on the survivable load. Based on correspondence with TRW, the highest combined stress in any of the cases in the table above is less than 19,000 psi in the flexures. Critical buckling stress is quoted by TRW as 34,040 psi, i.e. a margin of 1.8 on bucking failure. Based on linear extrapolation the maximum gravity loading with a buckling safety factor of 1.0 would thus be:

chop axis (7010-800) - worst of warm and cold - 405g (buckling)

This would indicate a margin on the 3-sigma peak vibration load of 1.55

Material	Temperature (deg F)	Ultimate Tensile Strngth (psi)	E (psi)	Fatigue Strength (psi)
420 SS	77	230000	29 E^{o}	60000
Inconel 718	77	180000	29.4 E^{o}	40000
304 SS	77	95000	28 E^{o}	35000
304 SS	-423	257000	29 E^{o}	94500
Inconel 718	-423	265000	30.5 E^{o}	80000

Table 2 : Material data for flexures

7.2.4.2 Protection Sleeves

To prevent damage by shear of the mechanism on launch a flex pivot capture sleeve, similar to this used by Goddard on COBE, will be utilised, as sketched below.

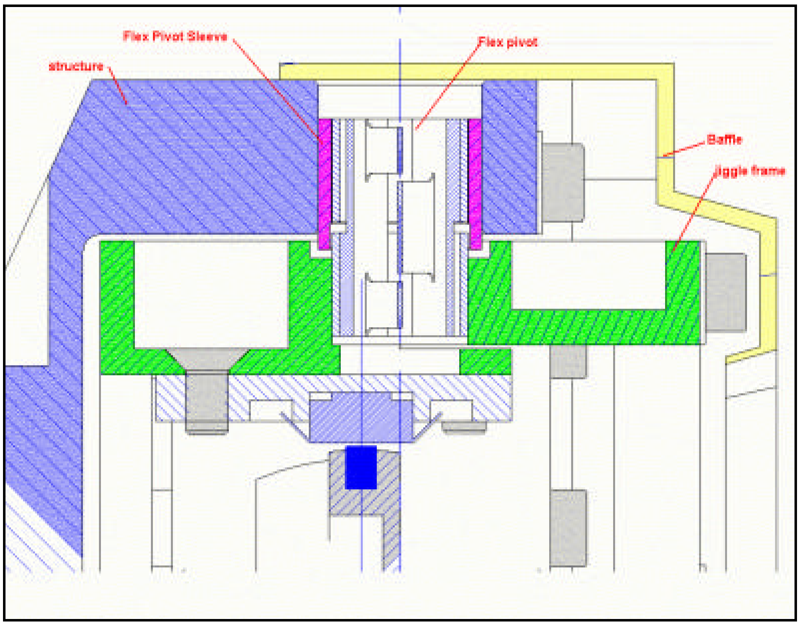


Figure 9 : Flex pivot protection sleeves, á la Goddard

Based on holding the 0.36° requirement on the nominal (0,0) position, in the BSM specification a ~ 200 micron diametral clearance would be required on the approx. 80mm distance between pivots. This would prevent slop in the jiggle pivots producing an apparent chop motion, or vice versa. Without constraint, the standard flex-pivots would produce about +/-200um of slop (though they would fail before this was reached).

A working flex pivot produces some de-centring motion as it twists anyway: about +/-20um of linear motion in our case. We would arrange for this to be in the plane of the mirror (careful of course to install flex pivots in handed pairs, to prevent twist).

The ATC pivot sleeve design provides for 50-75um of clearance, which is sufficient to

- allow normal rotation (and associated de-centre),
- prevent buckling failure of the pivot by shear loading (TBC by load tests)
- provide for capture of any broken pivot with 0.126 degrees of slop, sufficient to meet the fail-safe regime

Assembly of the sleeve to the pivot is by a light push fit, which becomes a close fit on cooldown. As this would be inadequate to survive warm vibration, an adhesive (Eccobond 285 or 286) will be used to ensure the flex pivot is secured. The adhesive will be supplied via radial holes drilled in the sleeve.

7.2.4.3 Flex-pivot failure modes:

Launch loads are a much larger concern than long term fatigue life, which is well characterised and easily tested. Tests performed by LAM suggest that the primary failure mode on launch would be where the flex pivots suffer shear in the radial direction, and the flex pivots fail in a buckling mode.

a) In the event of flex pivot failure, we could control position by motors alone and the random slop of the pivots would remain within spec. Long term chop or jiggle would not be advocated as we presume the capture sleeves would make poor journal bearings and would wear relatively quickly. However, the aim would be to move the mirror to a rest position and then hold it against spacecraft micro vibration.
b) In the event of motor failure (or launch damper failure to disengage), the flex pivots sleeves would provide self-centring (note that alignment of the centred position on integration will thus be critical, unless this is adjustable elsewhere in the optical path).
c) If both motors and pivots fail the position would be completely indeterminate, probably an end-stop out of the spectrometer field of view.
d) One other failure mode could occur - the linear de-centre of the flex pivot is produced by a combination of opposing de-centre of each flex spring. If only one of them fails we assume that the de-centre will include an out-of plane component. e.g. if one chop pivot 'half failed' then a chop demand to the end-stop would also produce a 20um lift of that end of the chop axis (a small jiggle and a mirror translation of 10um upwards). This failure mode would probably only exist for a short while until the second flexure also failed, and would be correctable in software if identified.

7.2.4.4 Launch Latch

The failure mode (c) above advocates for a launch latch. The argument against a launch latch is that the added protection against mission loss from this dual failure could be less than the risk of de-scoping to scan-mode only from a launch latch failure, or the risk that over constraint of the pivots would increase the risk of failure. Only a full program of launch latch and mechanism qualifications sufficient to quantify this trade off statistically would generate a logical decision one way or the other and funds for such a programme do not exist.

The baseline that has been agreed is to provide a compromise ‘deployable end stop’. In this scheme, a launch lock pin is used, but instead of deploying firmly into a detent, it would deploy into a hole with sufficient clearance to allow for +/-1.5° of chop axis motion and unrestricted (0.6°) jiggle motion. In the event of combined motor and flex pivot failure it would limit the wander of the chop stage to within the spectrometer field of view. This baseline design would be included in the early qualification tests, and would be deleted later if proven that it was demonstrated not to be required.

A candidate launch latch has been identified by LAM for the SMEC mechanism and is illustrated below. LAM are undertaking a flight qualification programme for this device. With small modifications (e.g. front mounting, offset latch pin) this device will meet the BSM requirement.

An ATC space envelope drawing has been prepared for exchange of information with LAM, drawing number SPIRE-BSM-020-001-007.

The LAM supplied solenoid lock pin would provide a simple threaded interface, to which the BSM 'kinked' pin would be fitted. Use of a compliant pin (e.g. G10) would be desirable to reduce impact (chattering) between the pin and be mirror on launch.

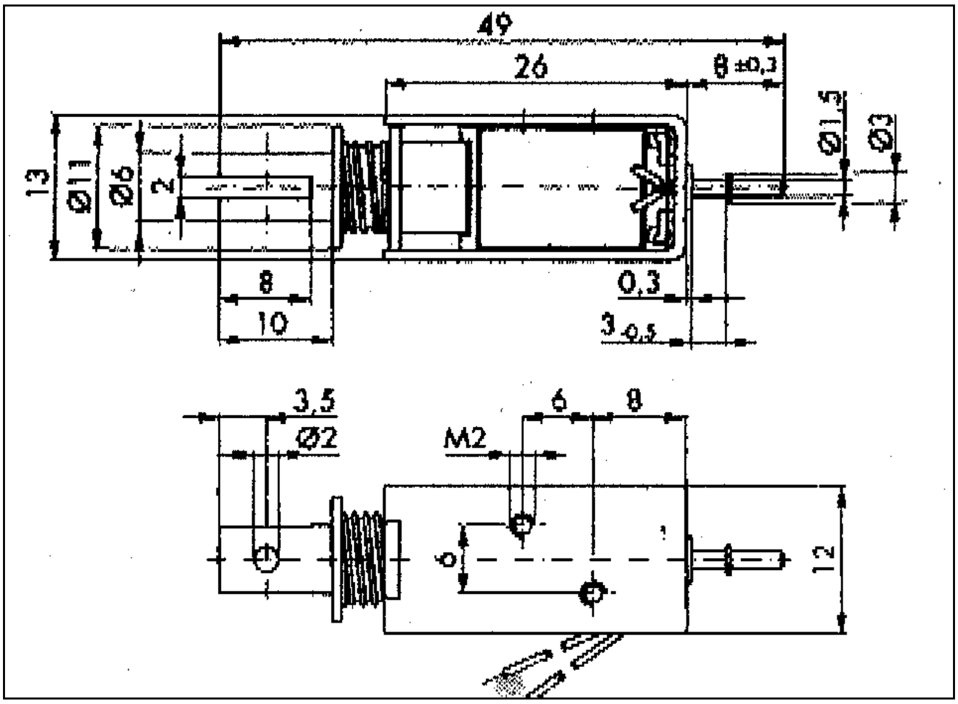


Figure 10 Candidate Launch latch (courtesy LAM)

Another alternative could be to request a reduction of the maximum chop axis throw, such that when its at its end stop half the FTS field of view is available ...This would be based on a trade off decision that there might not be too high a requirement to chop the full distance. G.Wright advises that mostly observers will do pixel-pixel chopping on small sources and scan map with (small) chop on the big ones, and there just aren't that many medium sources in the sky.

7.3 Structural Interface

7.3.1 The Support Structure BSMs Design

The BSM Structure – or BSMs is a machined stiff aluminium alloy mount with a mass of ~ 290 gm, and an associated baseplate (or ‘mounting shoe’) of mass ~ 85gm.

The mounting and alignment functions of the baseplate are described in section 9 (optics)

The BSMs provides for mounting of the:

- jiggle stage flex-pivots,
- jiggle stage sensors
- the jiggle and chop stage motors
- thermometry
- Photometer calibration source (PCAL)
- harness and connector mounts
- baffle

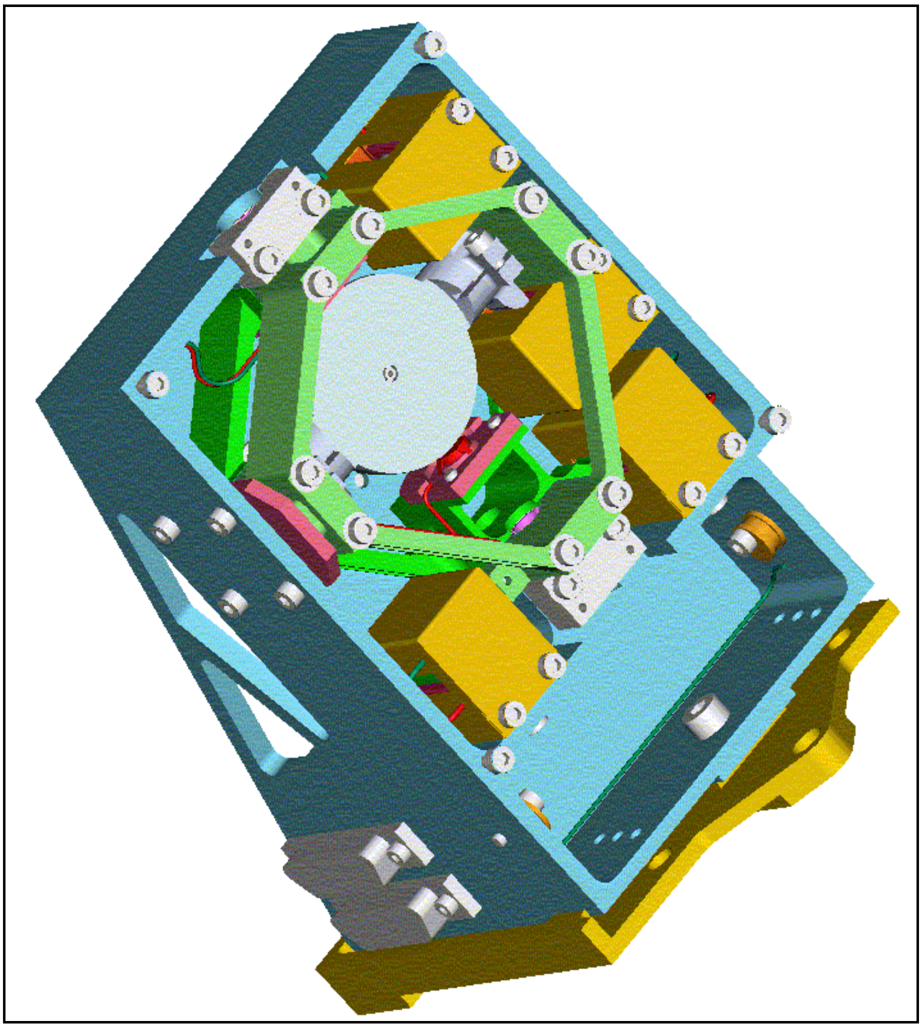


Figure 11 BSMm and BSMs with baffle ommitted. 3D view from Pro/E model looking onto the mirror surface. Jiggle frame in green, motor coil assemblies in orange, sensors are red/pink.

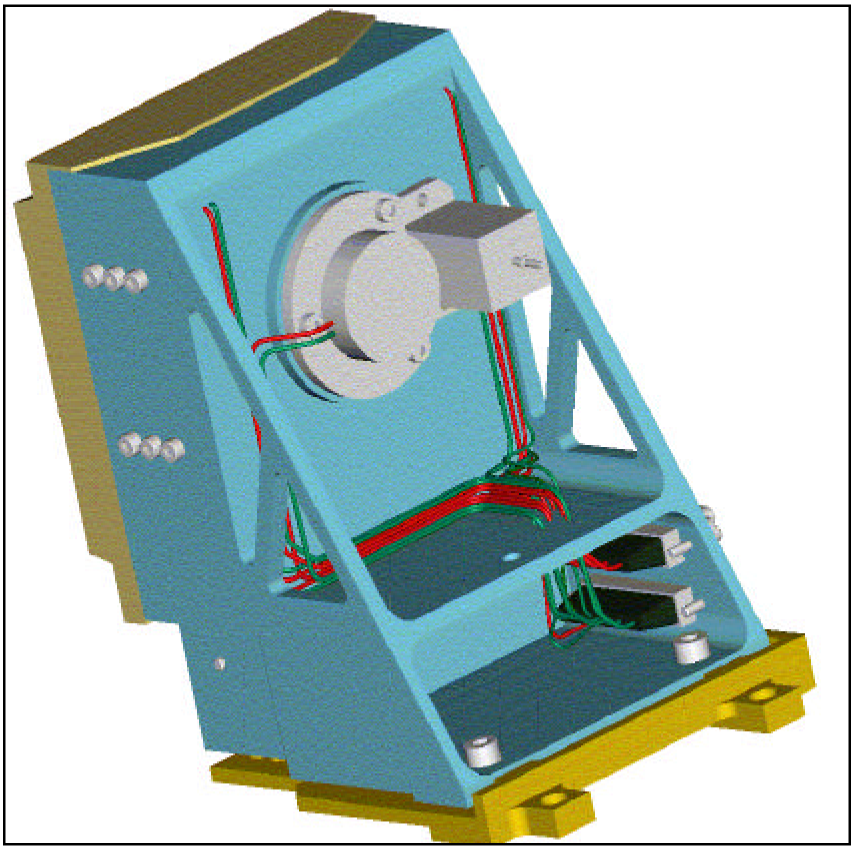


Figure 12: BSMm and BSMs. 3D view from Pro/E model looking from the rear. The PCAL unit is shown mounted at to the flat surface to the rear of the jiggle frame and motors.

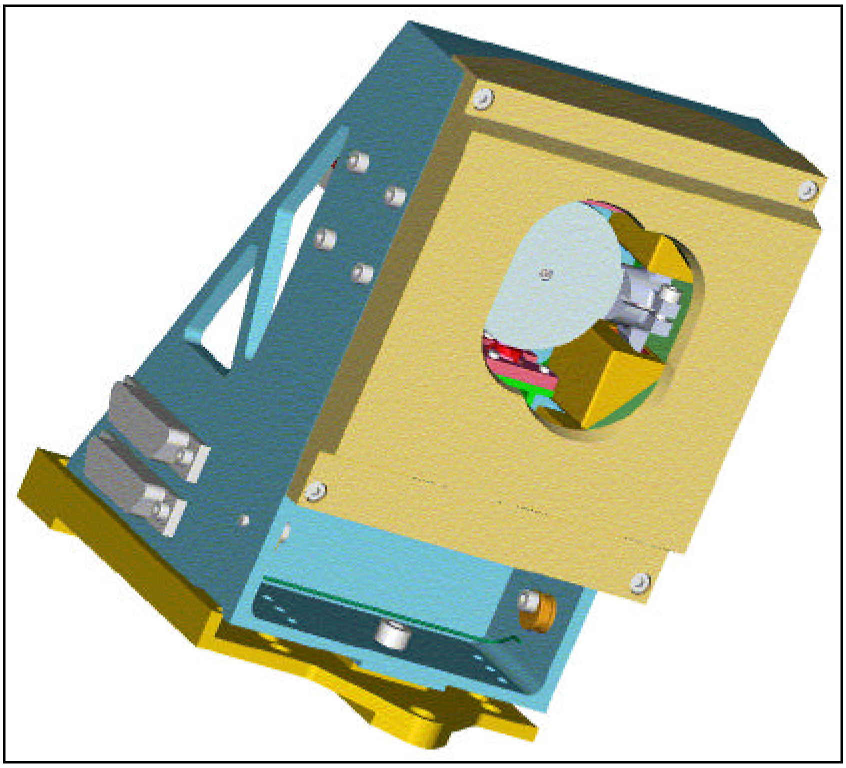


Figure 13 BSM showing the baseline baffle concept

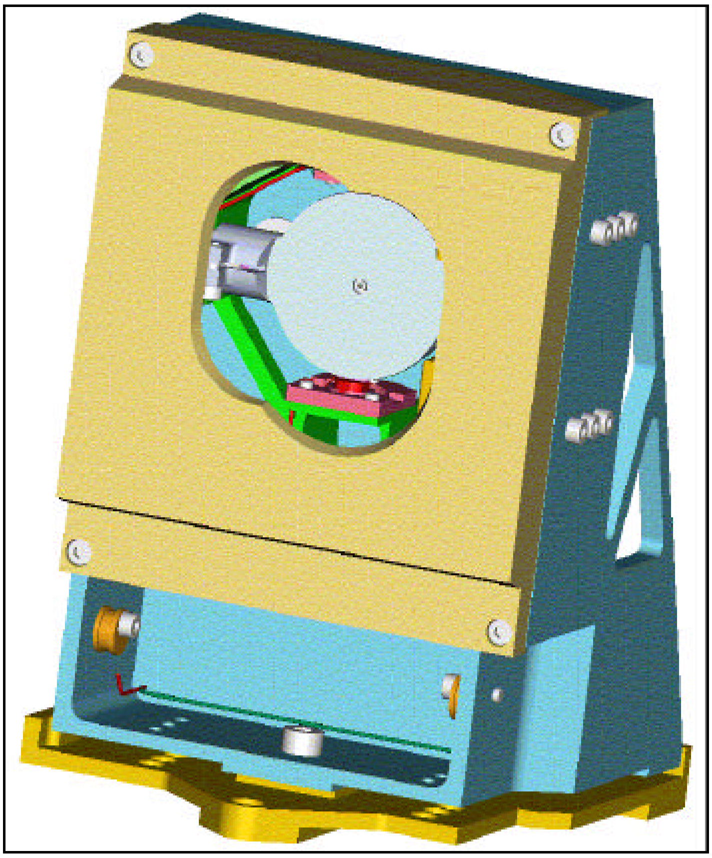


Figure 14 BSM showing the baseline baffle.This view fram a marginal ray point (apparent as the full circle of the mirror is projected on the baffle edge from the line of sight), shows that a small foul occurs between the motor and the optical beam. This issue is discussed fully in section 9 (optics)

7.3.2 BSMs FEA

An FEA of the structure has been performed to establish the likely induced stresses on launch, and the vibration modes. The results are detailed in Appendix 3B.

The model was analysed in Pro/Mechanica, based on the Pro/Engineer solid model with some small simplifications. Three runs were performed:

1. A three-axis static gravity load of 50G in each axis was applied to the structure. These were applied to give maximum tensile loads at the rear harness connection points.
2. A second run was performed as (1) but with point loads also applied at the relevant positions to simulate loads from the motors, jiggle and chop stage and attached components.
3. A basic vibration mode search for the first 12 resonant modes was performed.

Reported peak von-Mises and principle stresses were stresses peak at 36 MPa, situated around the connector mounting points. Using conservative values of permissible load (per BS8118), allowable stresses would be:

For fatigue

- 67 MPa friction grip bolted zones (not strictly applicable here as loads are not construction level friction grip)
- 96MPa for re-entrant features
- 76MPa small holes (dia < 3t)

For parent plate

- 240 MPa with suggested load factor of 2.5, i.e. a target of 96 MPa in this case

The permissible stresses for space rated components per rd 6 (ecss-e-30-part3a) are

- Margin of Safety = allowable stress limit / (actual stress x factor of safety)
- Where factor of safety = 1.25 on yield, 1.5 on ultimate, factor of 4 x (cycles) on fatigue.

7.3.3 Vibration Response

The principal resonant modes of the structure and the two suspended masses are presented below. The following discussion is repeated definitively in Annex B, as part of the BSM structural ICD.

The BSM structural interface forms a stiff body. The first twelve structural modes were determined by finite element analysis

FEA prediction for Response of structural interface		Approximate assembly response (see scale factor)
Mode	Frequency (Hz)	Frequency (Hz)
1	688	433
2	864	544
3	1781	1121
4	2715	1710
5	3058	1926
6	3284	2068
7	3345	2106
8	3614	2276
9	3957	2492
10	4097	2579
11	4677	2945
12	5185	3265
	mass of structure	291
	mass of assembly	734
	scaling for resonance	0.630

Table 3: Structural Interface Principal Modes

7.3.4 Scale factor

Pending a full resonant modes analysis, we may note that since the stiffness of the structural interface design remains unchanged, the assembly natural frequency scales as:

$$f_n = \frac{v\ (k/m)}{2\ ?}$$

hence, $f_{n(assy)} / f_{n(struct)} = v(\ m_{struct} / m_{assy})$

The mass of the structure used for the FEA modes search was calculated at 291gm, and the full assembly mass (excluding contingency, the baseplate and fasteners below the structure base) is predicted at 734 gm . This yields a scaling factor of ~ 0.63, used in Table 3.

7.3.5 Assumptions

As the structural response remains above 250 Hz it may be assumed to be stiff for subsequent analysis of the SPIRE structure. The actual combined system modes will differ from those presented, due to contributory effects from:

- the effect of bolted joints,
- the contribution of point masses mounted to the structure as distinct from the distributed structural mass
- the resonances of components mounted to it (particularly the baffle, launch lock and motor mounts)

7.3.6 Suspended Masses

The BSM suspended masses have first natural frequencies approximately as follow:

Axis	**Mode**	**Spring Stiffness (N-m/rad or N/m)**	**Inertia (kgm²)**	**Mass of suspended part (grammes)**	**1st Resonant frequency (Hz)**
Chop	**Torsional**	0.05875	1.70E-06		29.6
	Radial Orthogonal	1225887.6		16	1393.1
	Radial 45 degrees	875634		16	1177.4
	Axial	1751268		16	1665.1
Jiggle	**Torsional**	0.4625	4.65E-05		15.9
	Radial Orthogonal	2101521.6		88	777.8
	Radial 45 degrees	1576141.2		88	673.6
	Axial	3152282.4		88	952.6

Table 4 : Suspended Mass Principal Modes

The radial orthogonal rate is where the load is z-x plane or in the plane formed by the optical bench y axis and the BSM gut ray.

The 45 degree radial rate is where the load is applied in line with the plane of a flexure (oriented at 45 degrees to the orthogonal planes).

7.3.7 Outputs

The BSM will output a vibration to the Optical Bench during chopping and jiggling. The primary output will be at the chop and jiggle frequencies : 2 Hz and 0.5 Hz respectively, with harmonics TBD. Local TBD resonances of the BSM (eg of the baffle) may modify the harmonics.

Neglecting harmonics and any structural amplification (which should be small anyway, as the structure is stiff) the output forces take the form of a torque reaction in the structure in response to the acceleration of the mirror and jiggle frame in chop and jiggle.

An approximation to this torque reaction may be made by taking the inertia of the moving masses, and an average acceleration over the specified rise time.

BSM reaction loads summary table	Chop (*)	Jiggle (**)	Units
Torque reaction about chop axis (average)	7.12E-06	0	Nm
Torque reaction about jiggle axis (average)	0	9.74E-06	Nm
reaction force at hole at (242.57, 117.2, 526.863)	6.74E-05	1.43E-04	N
reaction force at hole at (351.861, 117.2, 521.426)	-3.37E-05	3.70E-05	N
reaction force at hole at (334.299,117.2, 467.198)	-3.37E-05	3.70E-05	N
** Chop reaction forces in optical bench y-axis* *** Jiggle reaction forces in optical bench z-x plane (normal to BSM jiggle axis)*			

Table 5: BSM Reaction Loads

Strictly, these reaction forces are in matched pairs with no net thrust effect. Thus an equivalent 'micro-g' output cannot be attributed to the BSM, i.e., a 'micro-g' input is only resolved at the interface between the optical bench and another supported system.

As a working figure, at a BSM mass of ~0.938 kg, the 'g' loading required to provide this type of force input combining the chop and jiggle loads gives a nominal acceleration at the front hole of 1.69E-04 m/s^2, i.e. an 'equivalent g loading' of 17.2 micro-g. In reality, the relevant mass is that of the whole structure, which is an order of magnitude more massive than the BSM, this accelerations attributable to the BSM will be below 2 micro-g.

7.4 Components & Declared Lists

7.4.1 Declared Components List (DCL)

The Mechanical declared parts list is maintained as a project configured document, SPIRE-ATC-PRJ-000709 and attached as Appendix 10

Additional electronic components are declared in section 2.

The combined DCL will be supplied as part of the Acceptance Data Pack for each of he BSM deliverable models.

7.4.2 Motor coils

The BSM motor coils are adapted from the PACS design, and will be supplied as space-rated items by Zeiss, via MPIA. Per RD13 the motor construction is:

The core material is Cryoperm 10 (Vakuumschmelze) with high permeability ($\mu_r > 10^5$) and high saturation fields ($B_S > 0.9T$), both at temperatures around 4K. This is laminated with ~112 sheets each at 0.1mm, glued and encapsulated with Stycast 1266 in layers of approximately 10µm thick. After vacuum degassing the laminates are milled to size and prepared for windings. The winding comprises 80-100µm 5N copper or 6N aluminium (970 or 1020 windings) . The winding material selection is TBD by MPIA/Zeiss.

7.4.3 Fasteners

All fasteners will be a cryogenic grade (i.e. austenitic) stainless steel. Fasteners will all be locked to withstand vibration. This is achieved by one of three methods:

- use of a locking insert in the tapped hole (preferred). The smallest locking inserts readily available are M2.5, and this is hence the generally preferred BSM fastener size. Torque control is important (TBC) in ensuring a locked connection, but the advantage of universal usage of these fasteners us that in general any obviously tight screw will be locked by default. Inspection of the tapped component at manufacture must verify that locking inserts have been assembled in to the component.
- The SPIRE optical bench thread sizes are UNC to match an elliptical closure insert favoured by the SPIRE structure supplier, MSSL.
- Where smaller thread sizes than M2.5 are required, a controlled amount of adhesive (Stycast – TBC) will be used under the fastener head. This provides a visual indication that the fastener is locked.

Fastener torque's are important and must be sufficient to ensure adequate lock up of joints, but not over-torqued where damage to the mounted components and the fastener or the thread may occur. Guidelines on fastener torque will be added to assembly drawings, and will be verified during prototype assembly.

Thread lock will not be used in the BSM, mainly as subsequent verification by inspection is difficult.

7.4.4 Materials

The declared materials list is maintained as a project configured document, SPIRE-ATC-PRJ-000710 and attached as Appendix 10

The DML will be supplied as part of the Acceptance Data Pack for each of he BSM deliverable models.

7.4.5 Declared Processes

The declared processes list is maintained as a project configured document, SPIRE-ATC-PRJ-000709 and attached as Appendix 10

The DPL will be supplied as part of the Acceptance Data Pack for each of he BSM deliverable models.

8. Thermal Control

8.1 Thermal Path

The BSM block diagram is shown in Figure 15 below.

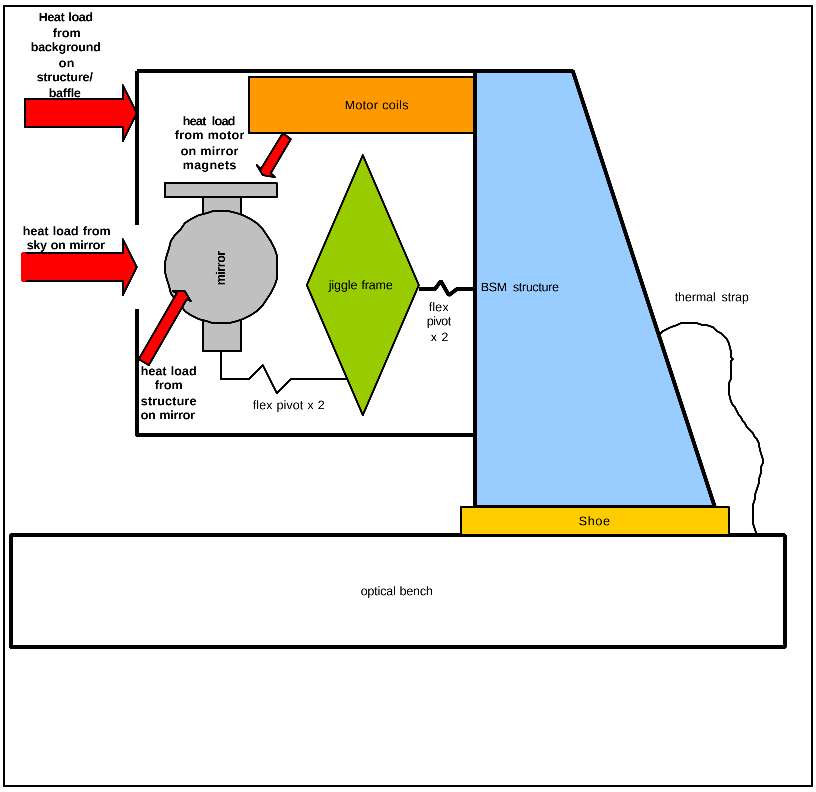


Figure 15 BSM thermal block diagram

8.1.1 Strap Connection

A provision has be made on the BSMs structure for a thermal strap tapping against the eventuality that thermal straps are required in addition to bolting to the SPIRE optical bench. These may be required in particular if the interface 'shoe' provides too high a thermal resistance, or if the optical bench sees heat loads from other mechanisms.

A clearance hole for M4 is nominally provided on the rear BSMs 'shelf' to take a nut and bolt clamping a thermal wick end-tab. The position, thermal strap end details and hole size are all TBC.

8.1.2 Heat Path to Mirror

One area of concern is thermal path through to the mirror, which includes two sets of flex pivots, five bolted joints and two adhesive or clamp-fit (TBC) joints.

Calculations (appendix 6) indicate that the chop axis flex pivots restrict the thermal path (i.e. are significantly less than all bolted joints and/or of material sections downstream).

As the specified instrument cooling rate is to be no more than 20K/hour the thermal shock and differential expansion issues are minimised. However, a remaining issue - more so for ground based tests at ATC than for the integrated instrument, is that thermal load on the mirror from cryostat background radiation is significant compared to the ability to dissipate the load via the pivots.

Results of calculations (appendix 6) are shown in the chart below, and indicate that with cryostat background temperatures of >30K the thermal specification that the mirror 'not exceed the BSMs temperature by >1K' would not be met.

For tests, this may require that a thermal IR filter be fitted to the test cryostat radiation shield, or that the temperature validation tests are performed with the radiation shield aperture closed.

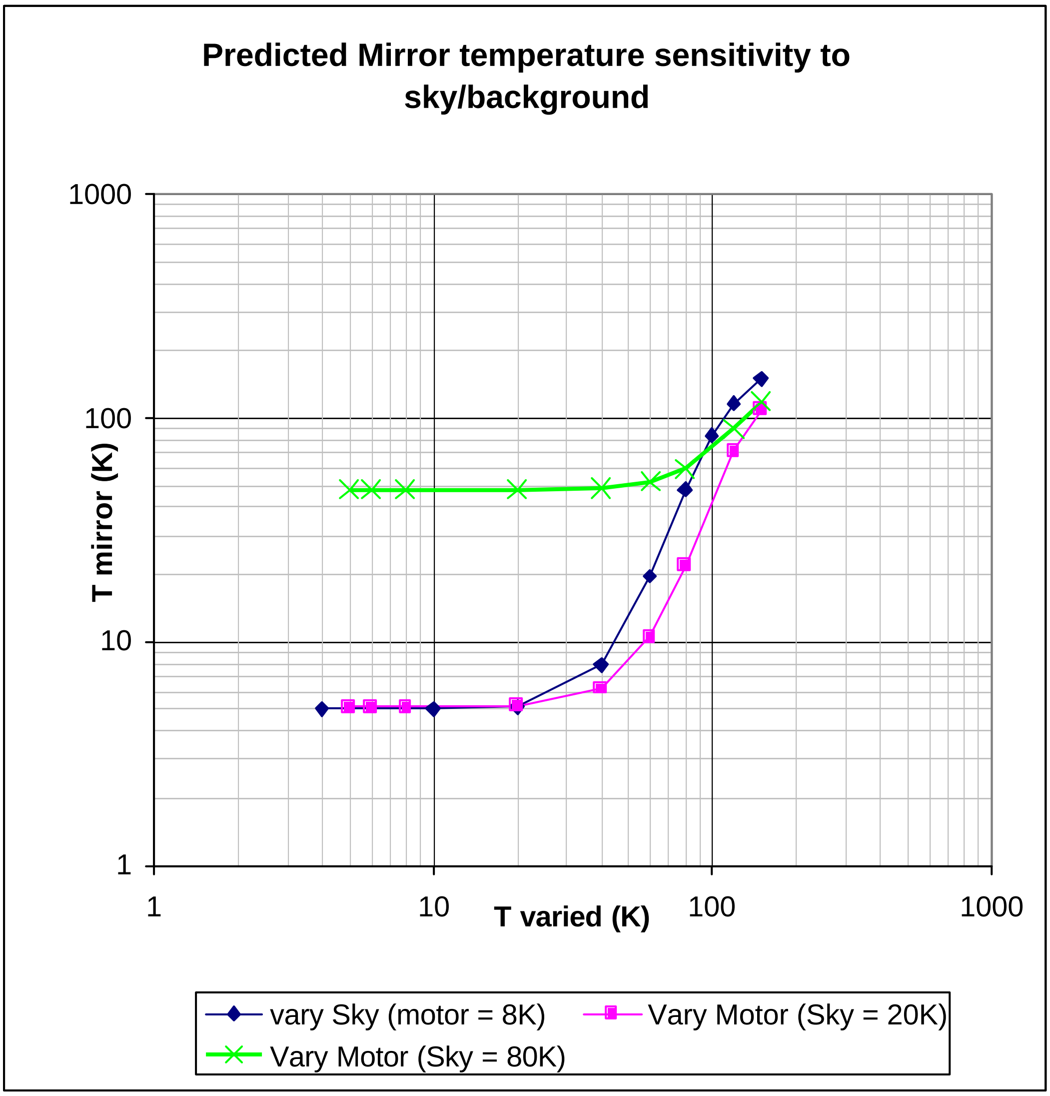


Figure 16: predicted mirror temperature at varying background radiation loads. The Sky or Motor coil temperature is varied (x-axis) and the predicted mirror temperature shown (y-axis). The local radiation from motor copils is shown to be a small effect

The jiggle stage sensor cables will provide some thermal path, though they will not be locally heat sunk..

An option exists to improve cooling path - during cooldown the chop and jiggle stages will be driven to the end of travel, or against the deployable end stop where the end-of travel end stop will be designed to provide some thermal contact for cooling. Thus, in the baseline design (TBC) a thermal end-stop will be adopted as with the PACS chopper [rd 13] provide an additional cooling path.

8.1.3 Heat Path to Motors

A second concern is that the motor coils may overheat, causing either life reduction or a thermal hot spot visible to the detectors. To minimise eddy current losses the motors would ideally be housed in a machined non-metallic (e.g. G10 or Vespel) block. However, this would effectively isolate them from the heat sinking of the structure. An aluminium block on the lower half of the motor clamping, with a Vespel SP-1 top cap, provides a compromise permitting good thermal contact but preventing complete eddy current loops from forming.

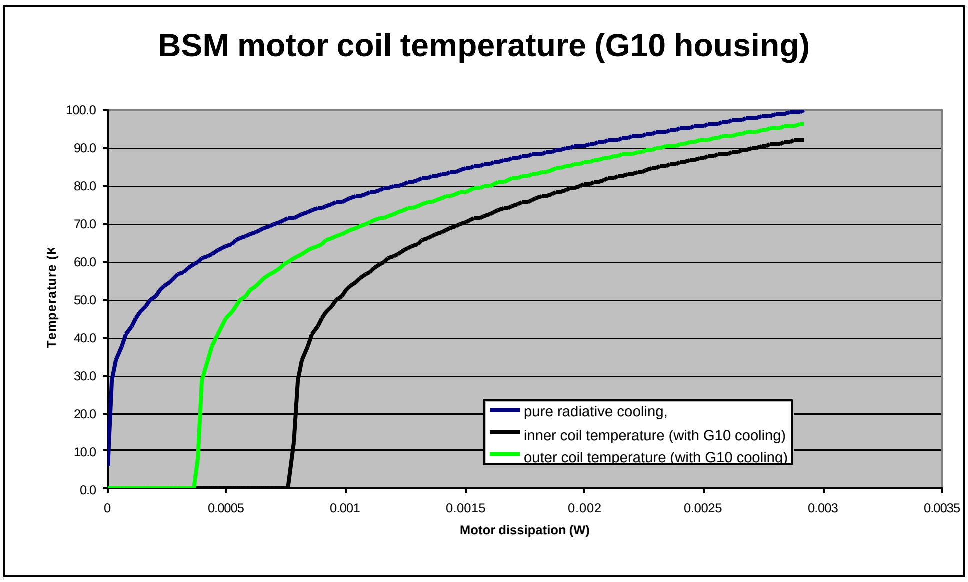


Figure 17 : Cooling with G10. At dissipations of 1mW the motor coils would radiate at 50-70K

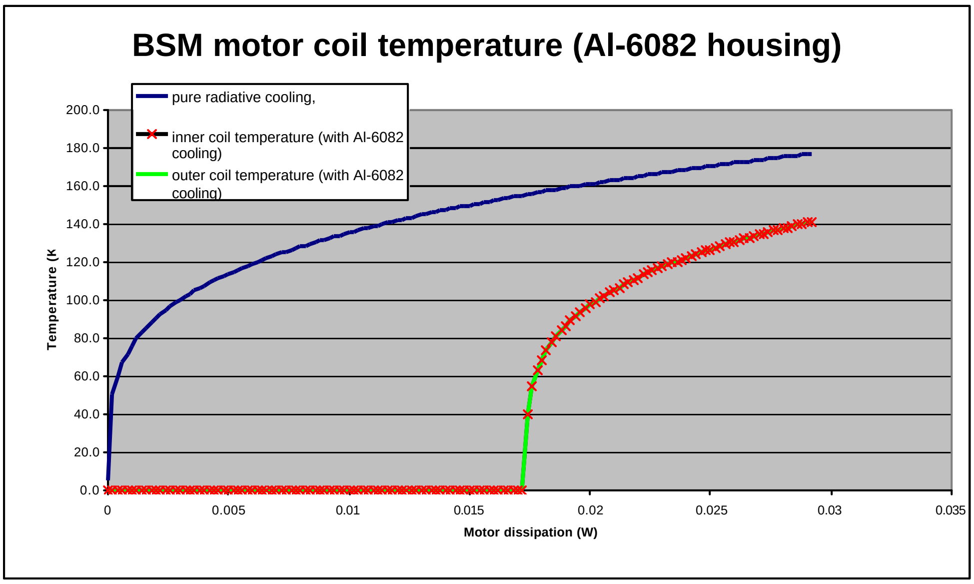


Figure 18: Cooling with aluminium: at dissipations below 18mW the background temperature would remain in specification (<1K)

The possibility of local hot spots may remain, and is dealt with by a combination of a local baffle around the motors, combined with heat sinking of this local shield.

8.1.4 Magnetic shielding

Strong stray magnetic fields around the motor coils would be undesirable if they interfered with the BSM magneto-resistive sensors or the instrument detectors. No EMC requirement has yet been set by the SPIRE systems team, and it is assumed that the local BSM requirement dominates.

The ideal magnetic shield enclosure would be similar to those discussed for local heat shields above. However, magnetic shielding is generally achieved by thin sheets of a magnetically soft material (e.g. mu-metal) built up in layers. This would be difficult to achieve around the BSM motor assemblies within the compact space envelope currently envisaged. In contrast a heat shield may be of monolithic construction, making fabrication and fastening easier.

Basic lab tests (appendix 9) indicate no problems with the magneto-resistive sensors even when deliberately placed close to the operating BSM motors, which has lead the BSM design to de-emphasise full magnetic shields.

The ATC needs to collaborate further with MPIA to establish what the effects of material selection and BSM housing design are.

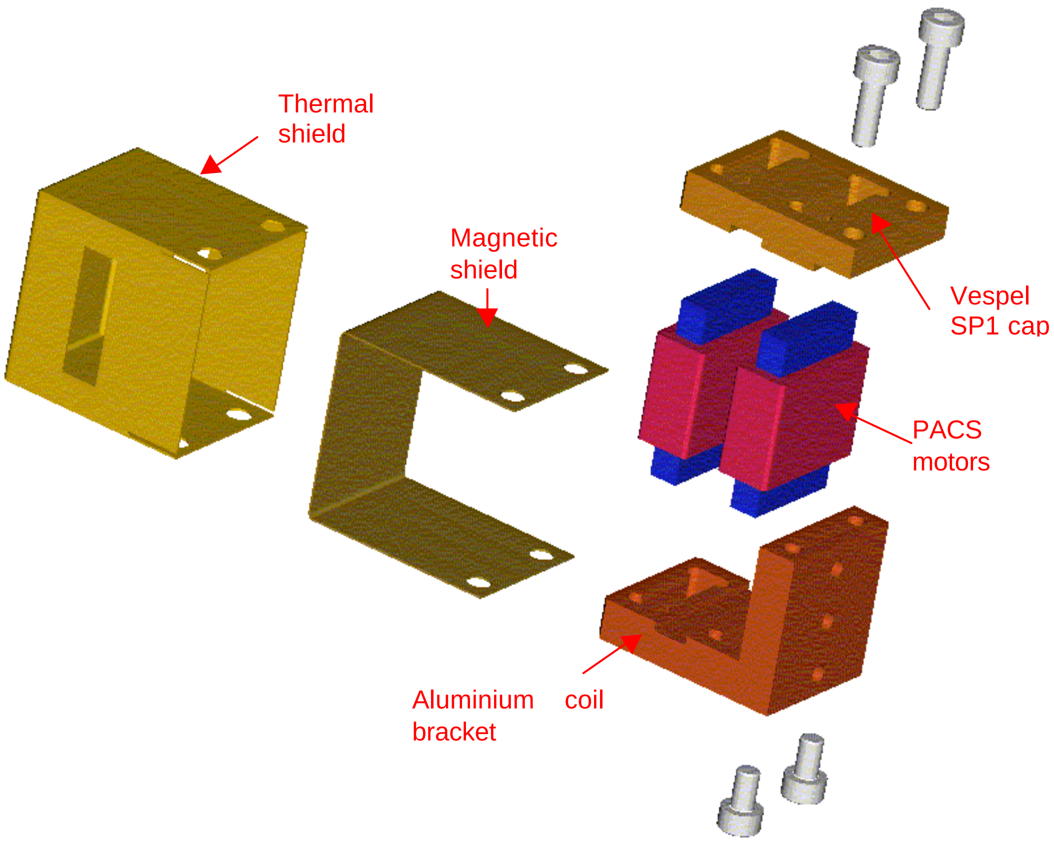


Figure 19 Assembly of a shielded motor assembly (SPIRE-BSM-020-005) with both magnetic and heat shielding

Drawing SPIRE-BSM-020-005 , illustrated in Figure 19 above shows the motor block assembly. The option exists to use the outer thermal shield (-005) to encapsulate conventional magnetic shielding (-004) or to incorporate magnetic shielding directly by plating the inside of the thermal shield with Niobium (super conducting and hence magnetic shielding below 9K). The baseline however is to fit no magnetic shielding (TBC).

8.2 Thermometers

The operating temperature of the BSMm will be 4-6K and the mirror or structure is to rise by no more than 1K from the nominal operating temperature.

The temperature of the BSMm will be monitored using a Lakeshore Cernox 1030 sensor, illustrated in Figure 20 below. This component is in fact more precise, and operates at lower temperatures (to 1.4 mK) than required by the BSM. However, to simplify spacecraft electronics and software architecture a common thermistor – driven by the requirements of the SPIRE cooler – is adopted.

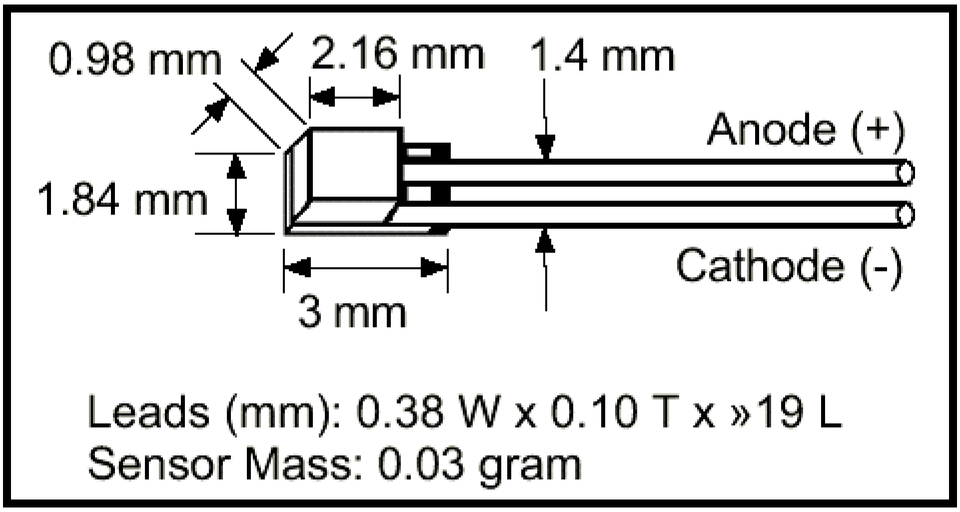


Figure 20 Cernox 1030 sensor (SD package)

CX-1030-CU copper canister , Figure 21 below, incorporates the above sensor, and provides for greater ease of mounting.

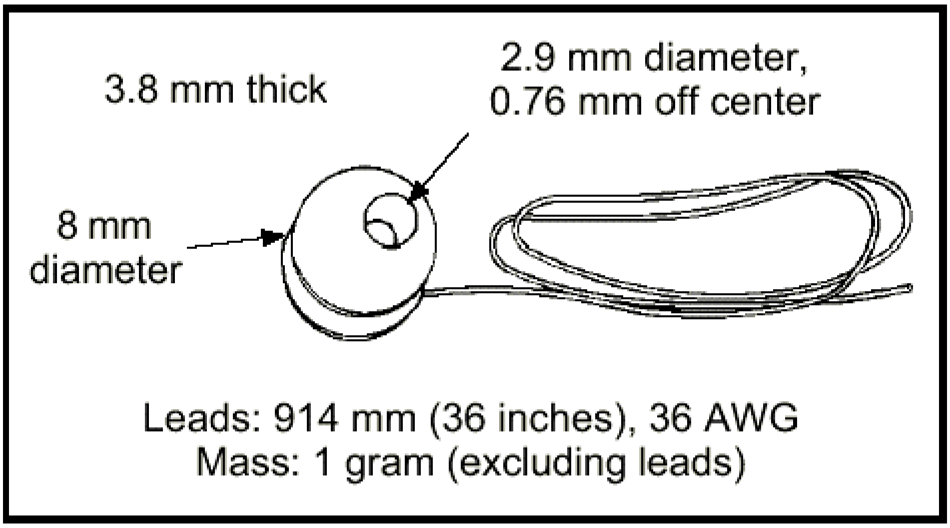


Figure 21 Cernox 1030-CU package

This device is sensitive over the 1.4K to 325K region. For cost reasons, flight rated but uncalibrated sensors will be procured centrally (e.g. by RAL) and calibrated against a calibrated sensor.

The maximum temperature rating is 325K, as shown in the data sheet Appendix 6, but as the specified soldering temperature exceeds this, no particular concerns are identified for bake-out at 353K.

The thermometers will be mounted to the BSMs – and a convenient location is identified as being in the front 'pocket' underneath the mechanism. This location allows space for mounting and for running the thermometer wires, and is will provide a representative temperature of the motor and flex pivot-mounting environment, but could not be used to isolate heating or friction in a particular component.

During ATC testing a wider range of local positions will be explored (e.g. on mirror surface, on baffle). The ATC preferred thermistor is the lakeshore DT-470, which has compatible mounting interfaces (indeed care will need to be taken to tag non-flight thermistors to prevent confusion) .

8.3 Coatings

No coating requirements have been specified by SPIRE.

ATC assumes the BSM will be :

- widely gold-coated to control emmisivity, and enhance thermal contacts at bolted joints, or
- Anodised where no emissions control requirements exist but where corrosion control is required

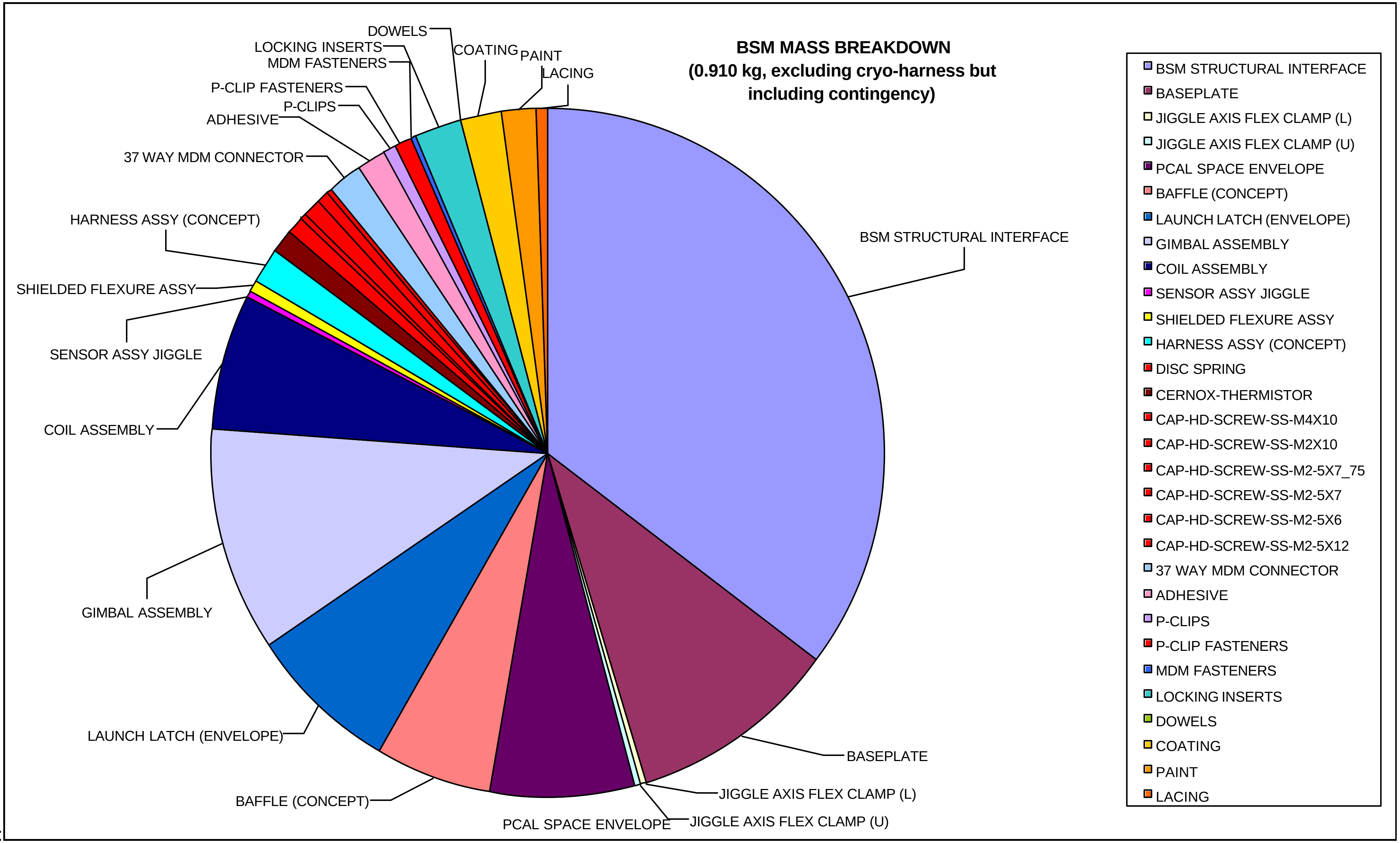
Given the extended storage and cleanliness requirements, gold plating will be used as a corrosion control technique where required. Gold plating of aluminium components will typically require a post-machining polishing process (mechanical or chemical), a copper flash, a nickel plating layer and a final gold plating. In some cases the intermediate Nickel coat may be omitted. Plating details and process parameters for each component drawing are TBC

8.4 Surface Finish

Surface finish will be specified on component drawings as required.

8.5 Mass budget

The overall BSM mass budget, including the prime and redundant cryogenic harness is specified as less than 1100 gm, including harness. A full mass budget breakdown is given in Annex B, and illustrated below. The structural interface is the bulk of the mass, and could be addressed further to find additional light-weighting, though at additional cost.


BSM MASS BREAKDOWN
(0.910 kg, excluding cryo-harness but
including contingency)
DOWELS
LOCKING INSERTS
MDM FASTENERS
COATING
PAINT
LACING
P-CLIP FASTENERS
P-CLIPS
ADHESIVE
37 WAY MDM CONNECTOR
HARNESS ASSY (CONCEPT)
SHIELDED FLEXURE ASSY
SENSOR ASSY JIGGLE
COIL ASSEMBLY
GIMBAL ASSEMBLY
LAUNCH LATCH (ENVELOPE)
BAFFLE (CONCEPT)
PCAL SPACE ENVELOPE
JIGGLE AXIS FLEX CLAMP (U)
JIGGLE AXIS FLEX CLAMP (L)
BASEPLATE
BSM STRUCTURAL INTERFACE
BSM STRUCTURAL INTERFACE
BASEPLATE
JIGGLE AXIS FLEX CLAMP (L)
JIGGLE AXIS FLEX CLAMP (U)
PCAL SPACE ENVELOPE
BAFFLE (CONCEPT)
LAUNCH LATCH (ENVELOPE)
GIMBAL ASSEMBLY
COIL ASSEMBLY
SENSOR ASSY JIGGLE
SHIELDED FLEXURE ASSY
HARNESS ASSY (CONCEPT)
DISC SPRING
CERNOX-THERMISTOR
CAP-HD-SCREW-SS-M4X10
CAP-HD-SCREW-SS-M2X10
CAP-HD-SCREW-SS-M2-5X7_75
CAP-HD-SCREW-SS-M2-5X7
CAP-HD-SCREW-SS-M2-5X6
CAP-HD-SCREW-SS-M2-5X12
37 WAY MDM CONNECTOR
ADHESIVE
P-CLIPS
P-CLIP FASTENERS
MDM FASTENERS
LOCKING INSERTS
DOWELS
COATING
PAINT
LACING

:

9. Optics

9.1 General

The BSM is a critical part of the overall SPIRE optical design (AD4). The BSM, designated CM4 in the optical scheme, allows for chop and jiggle motion to ensure full sampling of the instrument arrays without the overhead of moving the entire spacecraft. Fine pointing corrections may also be provided.

Requirements of the optical design (LAM) and stray light and baffling control (RAL) drive the BSM mirror design. Optical beam space envelopes, based on 20% oversize photometer and spectrometer beams are presented to ATC by RAL in the form of IGES surfaces and the BSM space envelope based around this.

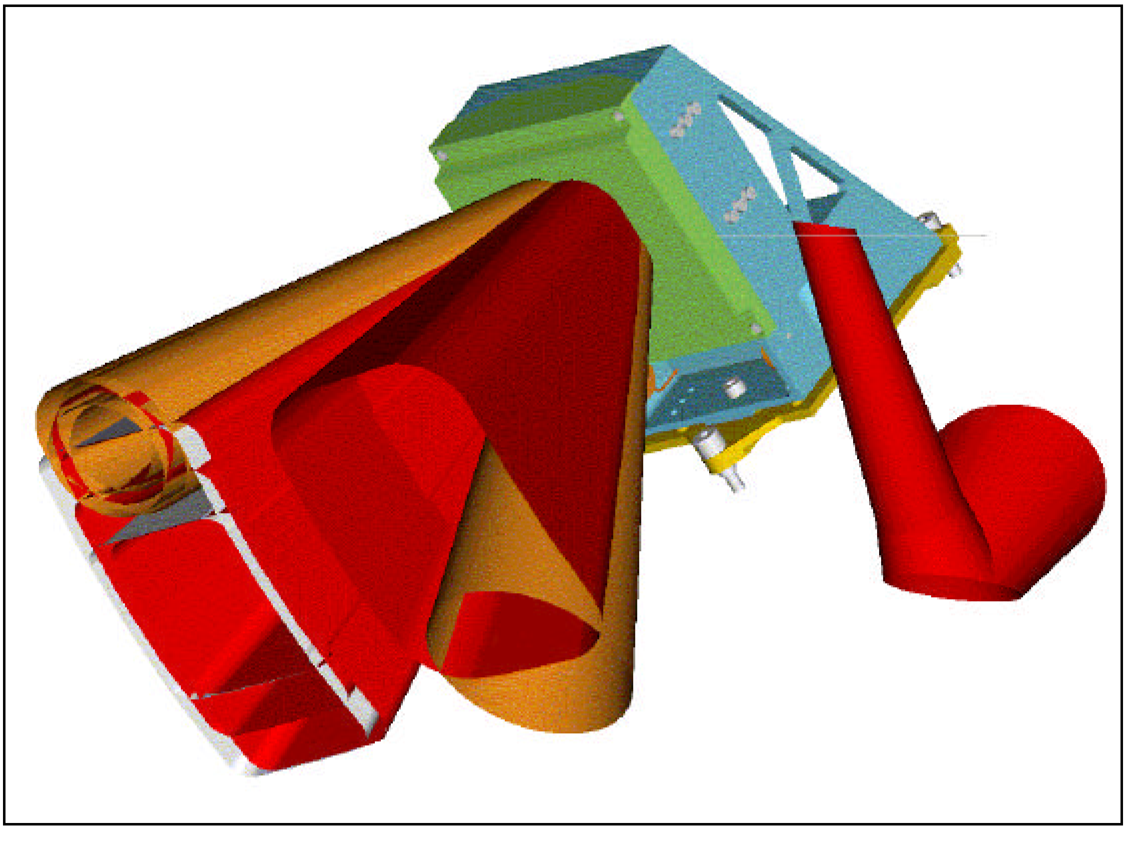


Figure 22: BSM with space envelopes provided by RAL

The requirements of the optical design are encapsulated in the BSM specification document and it is to these purely mechanical parameters that the BSM is designed.

9.2 Mirror

The required (AD1) minimum mirror diameter is 32 mm. These requirements are derived from RD1 – Spire optics diffraction description.

The BSM design incorporates a 32.5mm diameter mirror. The monolithic mirror is incorporated into the chop axis and light-weighted from behind. The mirror is produced in aluminium 6061 alloy, thermally stabilised, as per ATC stabilisation procedure (RD8) , and diamond machined (MCD turned) to an optical finish.

The mirror surface of the BSM is required to

- Be flat to <100nm P-V to allow for optical testing. This is a tighter specification than the 1µm rms. (2µm WFErms.) is required for functioning of the instrument.
- Have a surface roughness of <10nm (rms).
- The reflectivity of the mirror surface >99% in the wavelength range 200 - 670 µm. This will not be measured; it is assumed that this will be satisfied by aluminium to BS 6061. (The emissivity of the mirror surface <1% in the wavelength range 200 - 670µm.)

For the purposes of interferometric testing at 633nm this surfaces specification will be adequate for testing of the surface form. At this wavelength the reflectivity will be approximately 80% which is more than sufficient.

These surface requirements are readily met by standard diamond machining techniques.

No requirement is placed on the BSM for any post-machining mirror surface coating. The mirror will be stored in a dry environment to prevent deterioration.

The BSM is required to have a central aperture, nominally of 2.8mm minimum diameter, to accommodate the PCAL source 'light pipe'. Various options for the size of the central aperture have been proposed to allow for masking of the telescope secondary mirror, and for stray light control (RD9,10). These range from hole sizes of ~4 to 6 mm diameter, with some possibilities for offsets in x or y by up to 0.5mm or slightly elliptical profiles. As the optimum option has not been determined, the baseline BSM aperture remains 2.8mm diameter. A larger diameter of up to 8mm may be accommodated before significantly impacting the mirror rib structure. It may be necessary to put a black coating on the mirror in an annulus around the 2.8mm hole rather than increasing its diameter. It is RAL's responsibility to specify the size of the hole or black annulus. Final sizing of the hole will be determined by RAL once the telescope secondary design has been fixed.

9.3 Baffle

The baseline design has no baffle, just a pierced plate over the structure with the aperture sized to pass the oversized beams.

For this to be acceptable the no part of the BSM structure must be hotter than 1K above the ambient temperature, and there must be no part of the structure clipping the 20% oversized the beams. To meet the latter requirement it will be necessary to make minor alterations to the current BSM structure. Thermal modelling of the motors will be required to be confident that they, as the only heat sources within the BSM (except for PCAL) will be sufficiently well heat sunk and shielded not to be seen as hotter than one degree above ambient.

The alternative is a complex machined partial baffle intruding into the mechanism, described in what follows. It should be noted that no baffling scheme that can be implemented on the current design and allowing for a 20% oversized beam would completely hide the structure of the BSM from being seen by the detectors.

The baffle or plate mounts to the BSMs front surface via 4 off M2.5 self-locking screws. The flanges at the top and bottom serve primarily to block the jiggle-frame flex pivot apertures, preventing contamination ingress and reducing light leakage paths

Precision location of the baffle has not been included at this conceptual level. Given the comfortable 20% optical oversizing, the requirement on location would be driven by the need to avoid mechanical fouls. Dowel pins on the flanges could serve for location if required.

Figure 23: BSM baffle concept: general plate thickness 1mm The baseline design would be the same as this but have no 'cone'.

9.4 Light Tight Enclosure

There is no firm requirement on light tightness placed upon the BSM. This matter should be considered part of the baffling.

9.5 Harness Feed-Through

The BSM wiring harness to the motors require the mechanism enclosure to be pierced in 4 (TBC) places for motor wiring feed through. These openings are at the rear of the BSM, which faces away from all optical elements of the SPIRE design. If required, a gland type (TBD) feed through would be used to prevent stray light leakage.

9.6 Alignment

Alignment tolerances for the optical train are given in RD11, Spire optical alignment verification plan. These require that the BSM be positioned to ±0.1mm in x, y and z, with a total angular precision that would allow for the maximum total angular alignment error of the mirror, in the event of failure, to be ±0.36º.

Although the BSM provides for steering corrections and offsets, it remains desirable to provide precise location on the desired optical path such that a failure of the drive motors would leave the BSM in the failsafe position within 0.36 degrees of the nominal (0,0) position.

Rough calculations[2] show that direct mounting of the BSM to the optical bench would require that holes were placed with approximately +/- 0.17mm precision, and that the BSM rest position toleranced to +/- 0.2 degrees. The hole position tolerance is achievable, but the BSM rest angle may prove more problematic (as it will be attitude dependent) and an overly tight tolerance will increase assembly costs exponentially.

To allow additional latitude in the BSM assembly precision shoulder bolts will be used to locate on the optical bench a mounting 'shoe' with three machined pads, as commonly used in ATC cryogenic mechanisms. The BSMs proper will mount to this shoe, with the precise location (and the provision for one-off corrective machining) provided by mounting against the pads.

For alignment, the shoe would be placed upon the SPIRE optical bench and actual positions measured via CMM. The as assembled BSM rest position and BSMs dimensions will have been characterised at ATC and the relevant offsets required would then be calculated. The shoe would be removed from the bench and machined to provide pitch roll and yaw adjustment, then re-positioned.

The shoe, (drawing SPIRE-BSM-020-001-002) has been drawn to nominal size, but would be produced with +1mm oversized thick pads to allow for machining.

This scheme also allows removal of the BSM from the optical bench for trouble-shooting during AIV without loss of alignment.

9.7 OGSE

For alignment of the SPIRE optical train, a fixed mirror replaces the BSM whilst other systems are aligned (e.g. using a laser). The fixed mirror would be 'Optical Ground Support Equipment' – OGSE and would be supplied by ATC. The fixed mirror is required because the BSM is susceptible to vibrations when not damped or served to the (0,0) position powered. The resulting vibrations would make alignment work difficult, and the BSMe would not be connected/powered up during initial alignment.

The BSM OGSE has not yet been designed. It will probably comprise a mounting structure similar to the BSMs with a fixed, standard commercial optical quality, flat mirror mounted to it.

There is an option to make the fixed mirror compliant with the 'standard' SPIRE mirror mounting scheme – this would also allow use of the standard CMM spherical mounting tool which will be used for other SPIRE mirrors (see **SPIRE Alignment Tools Specification** and RD11– Spire optical alignment plan) . This might incur extra cost, so is not the baseline.

The BSM OGSE would be mounted to the spire mount shoe as described for the BSM alignment. The OGSE would need to replicate any offset of the BSM rest position, which could be achieved by shimming of the fixed mirror or machining of the structure.

[2] Maximum mount hole pitch approx. 110mm. Allow BSM assembly to have errors of 0.2 degree, leaving 0.16 degrees for mount holes. Tan(0.16)x110 = 0.3mm, but allocate across 3 holes = sqrt(0.3^2/3) = 0.17mm

10. BSM Electronics & Controls

10.1 Control System Design

The control system for the BSM is based on a nested velocity and position loop scheme. In the case of the Chop axis, an additional loop is used to limit the mechanism acceleration to prevent instability due to limited current loop slew rate.

The required velocity and acceleration signals are obtained from the system position and torque demand signals using a second-order observer for the mechanism. The observer is essentially a model of the mechanism, and includes flex joint spring rate and inertia. Though the model can never be exact, internal error correction feedback ensures an accurate estimation of the required parameters.
All control functions are implemented in software, allowing considerable flexibility – for example, in the event of some faults, such as a broken flex joint or loss of position signal, some degree of control can still be obtained, though of course performance is not to full specification.

Section 10.5 describes the simulation of the mechanism, electronics and software in Matlab-Simulink.

The electronics required to implement the control scheme is fairly simple, and limited to
a) Pre-amplification of the position signal from the magneto-restive sensor
b) Power amplification of the motor drive signal
c) A-D and D-A conversion to and from the software controller

10.2 Parameters

Normally, the control parameters are fixed and require no adjustment. However, all parameters used in the control algorithms can be changed if required, for example in the event of a fault. Each axis has 28 parameters for servo control.

In addition, there is a lookup table for step response profiling, to enable a minimum-power step movement to be realised. The Chop axis table has 15 entries, and the Jiggle table has 25 entries.

By use of flags and switches in the software, the structure of the controller can also be changed (in particular to suit fault conditions) by setting appropriate parameters as required.

10.3 Dynamic Analysis

See section 7.2.2.3 (Mechanism mechanical analysis)

10.4 Simulink Model

The Matlab-simulink model used to predict performance and establish control parameters includes all the significant linear and non-linear effects. With regard to the following figure, the main model elements are described.

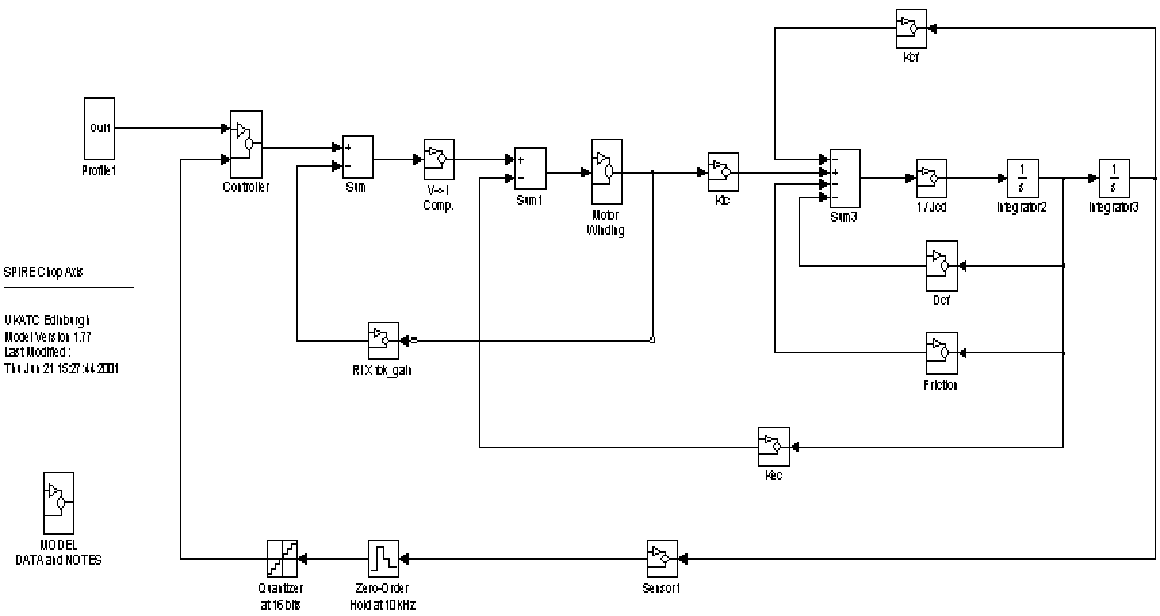


Figure 24 Similink model

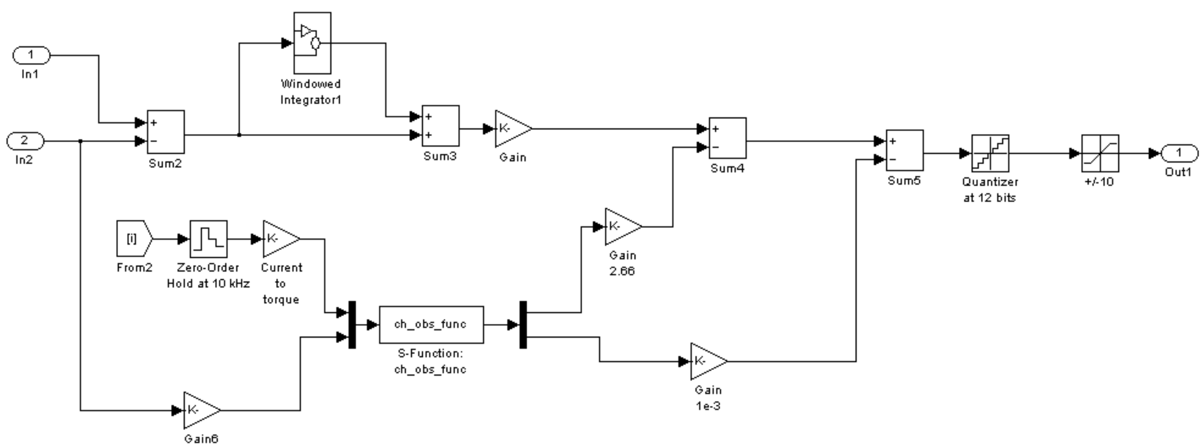


Figure 25 Controller

The controller includes a ‘windowed’ integrator, to ensure zero position error, the state observer, implemented as a matlab ‘S-function’, and the A-D converter.

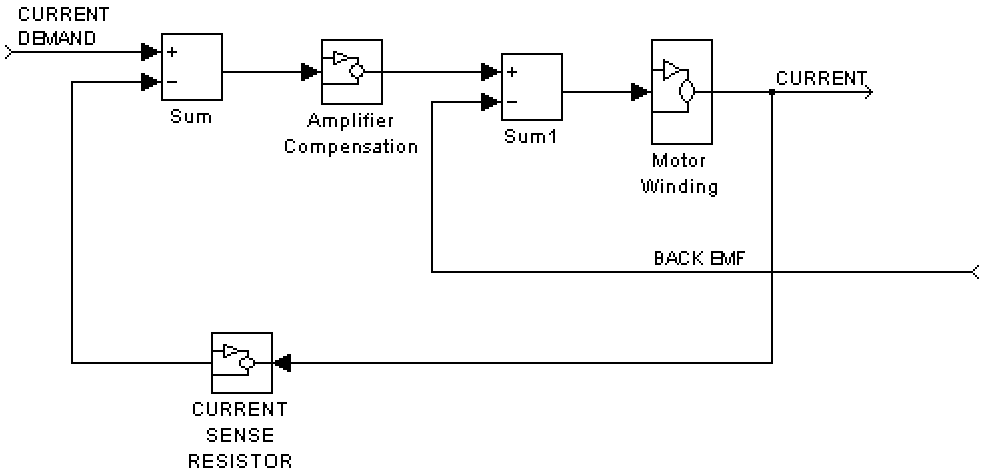


Figure 26 Power Amplifier

The power amplifier model includes voltage limiting in the elctronics and limited bandwidth.

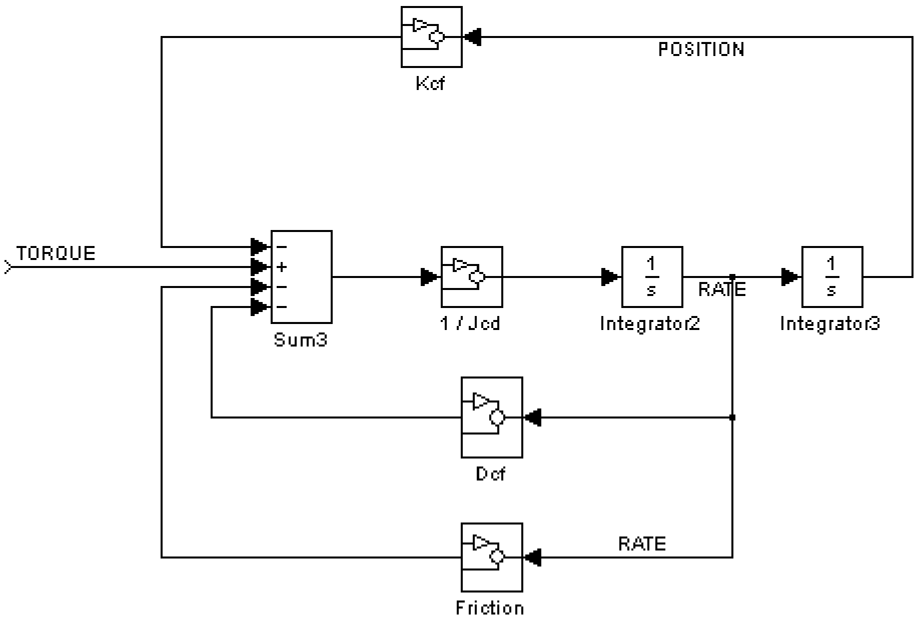


Figure 27 Mechanism

The mechanism model includes the flex joint spring force, the flex joint mechanical damping, and friction block which used only when modelling the fault condition with a broken joint.

10.5 Predicted Performance

10.5.1 Power Dissipation

System power calculations have been produced as follows.

The calculations are made using the mathematical modelling package 'Mathcad 7.0'.

The BSM comprises two motors and two position sensors. The motors are composed of stators wound from either aluminium or copper wire, and rare earth permanent magnets. The position sensors are regarded as fixed resistors for the purposes of this analysis, though in use this resistance changes slightly, say +/- 10%.
The BSM mirror is constrained by low friction torsional springs, which require a constant force for a constant angle – this relationship is linear.

In operation, the mirror quickly slews between two fixed points, and stops for a relatively long time period, here called 'stare'. Power is calculated for the slew and stare movement phases, though due to the much longer period spent at the fixed locations, this phase dominates the average power calculations.
The stare power is caused by the constant force required to hold the angle against the support springs.

The power dissipation is calculated using the relationship
P = I*I*R
where
P = power (watts)
I = current (Amps)
R = Resistance (Ohms)

The step movement is in fact a controlled sinusoidal edge, so the step time specification is converted into an equivalent frequency to calculate power.
That is, if the mirror were moved sinusoidally back and forth between two fixed angles A and B, from A to B to A would take one cycle, so half of one sine period (e.g. from A to B) would take the specification step time.
This allows calculation of the maximum acceleration, and using the known spring constants, the total torque required from the motor.

The power dissipation calculations assume that the peak acceleration torque is required for the whole step time, which is very pessimistic.
However, as the total power over time is dominated by the required spring force in the stare mode, this is not important.

Angle Step Time, Chop $tsc := 0.015$

Angle Step Time, Jiggle $tsj := 0.05$ (Goal)

$\omega c := \frac{2\cdot\pi}{2\cdot tsc}$ $\omega c = 209.44\cdot s^{\,} \cdot \frac{rad}{s}$ $\omega j := \frac{2\cdot\pi}{2\cdot tsj}$ $\omega j = 62.832\cdot s^{\,} \cdot \frac{rad}{s}$

Inertias $Ich := 1.7\cdot 10^{-6}\cdot kg\cdot m^2$ (2 May 2001)

$Iji := 45\cdot 10^{-6}\cdot kg\cdot m^2$

Step angles (2.4 deg chop, 0.6 deg jiggle)

$\theta ch := 0.042\cdot rad$

$\theta ji := 0.0105\cdot rad$

Spring torques

$Ksch := \frac{0.047\cdot N\cdot m}{rad}$ $Ksji := 0.37\cdot\frac{N\cdot m}{rad}$

$Tsch := \theta ch\cdot Ksch$ $Tsch = 1.974\cdot 10^{-3}\cdot N\cdot m$

$Tsji := \theta ji\cdot Ksji$ $Tsji = 3.885\cdot 10^{-3}\cdot N\cdot m$

Peak acceleration $\alpha ch := \omega c^2\cdot\theta ch\cdot\frac{rad}{s^2}$ $\alpha ch = 1.842\cdot 10^3\cdot s^{-2}$

$\alpha ji := \omega j^2\cdot\theta ji\cdot\frac{rad}{s^2}$ $\alpha ji = 41.452\cdot s^{-2}$

Therefore acc. torque $Tach := Ich\cdot\alpha ch$ $Tach = 3.132\cdot 10^{-3}\cdot N\cdot m$

$Taji := Iji\cdot\alpha ji$ $Taji = 1.865\cdot 10^{-3}\cdot N\cdot m$

Peak torque required is (acceleration + spring/4) for 0 to max angle step,
for (-max angle) to (+max angle) it is (acceleration - spring/2)

0 deg to Max : $Tch := Tach + \frac{Tsch}{4}$ $Tch = 3.625\cdot 10^{-3}\cdot N\cdot m$

$Tji := Taji + \frac{Tsji}{4}$ $Tji = 2.837\cdot 10^{-3}\cdot N\cdot m$

-Max to +Max :

$$\mathrm{Tach} - \frac{\mathrm{Tsch}}{2} = 2.145 \cdot 10^{-3} \cdot \mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-2}$$

$$\mathrm{Taji} - \frac{\mathrm{Tsji}}{2} = -7.714 \cdot 10^{-5} \cdot \mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-2}$$

Therefore make required motor torque = 0.01 N-m for chop and jiggle

POWER DISSIPATION

Assuming the MPIA 'small' motors were used, with a 20 deg.C resistance of 260 ohms, and an effective torque constant of 0.11 N-m/A, and R(hot)/R(cold) = 500:1 (800:1 in PACS) using pure aliminium conductors

Motor resistance

$$\mathrm{Ra20} := 260$$

$$\mathrm{Ra4k} := \frac{\mathrm{Ra20}}{500} \qquad \mathrm{Ra4k} = 0.52$$

Motor Torque Constant

$\mathrm{Ktc} := 0.11 \cdot \mathrm{N} \cdot \mathrm{m}$ (per Amp)

$\mathrm{Ktj} := 0.17 \cdot \mathrm{N} \cdot \mathrm{m}$ (per Amp)

Duty Cycle

$$D := 0.05$$

Power at 20 deg.C :

$$\mathrm{Pchop\_20} := \left(\frac{\mathrm{Tsch} + D \cdot \mathrm{Tach}}{\mathrm{Ktc}}\right)^2 \cdot \mathrm{Ra20} \qquad \mathrm{Pchop\_20} = 0.098 \quad \mathrm{W}$$

Power at 4 deg.K :

$$\mathrm{Pchop\_4k} := \left(\frac{\mathrm{Tsch} + D \cdot \mathrm{Tach}}{\mathrm{Ktc}}\right)^2 \cdot \mathrm{Ra4k} \qquad \mathrm{Pchop\_4k} = 1.951 \cdot 10^{-4} \quad \mathrm{W}$$

Power at 20 deg.C :

$$Pjig\_20 := \left(\frac{Tsji + D \cdot Taji}{Ktj}\right)^2 \cdot Ra20 \qquad Pjig\_20 = 0.142 \quad W$$

Power at 4 deg.K :

$$Pjig\_4k := \left(\frac{Tsji + D \cdot Taji}{Ktj}\right)^2 \cdot Ra4k \qquad Pjig\_4k = 2.848 \cdot 10^{-4} \quad W$$

Total BSM Power is calculated by adding powers for sensors and motors

Total sensor power is 2 * [1mA * 1 mA * 400 ohm (max)] = 0.8 mW

$$Sensors := 0.8 \cdot 10^{-3}$$

$$Pt\_20 := Sensors + Pchop\_20 + Pjig\_20$$

Total power at 20 deg.C : $Pt\_20 = 0.241$ W

$$Pt\_4k := Sensors + Pchop\_4k + Pjig\_4k$$

Total power at 4 deg.K : $Pt\_4k = 1.28 \cdot 10^{-3}$ W

If copper wire instead of aluminium wire is used for the motors, then Ra(4k) = Ra(20C) / 100, instead of / 500

$$Ra4k := \frac{Ra20}{100} \qquad Ra4k = 2.6$$

$$Pchop\_20 := \left(\frac{Tsch + D \cdot Tach}{Ktc}\right)^2 \cdot Ra20 \qquad Pchop\_4k := \left(\frac{Tsch + D \cdot Tach}{Ktc}\right)^2 \cdot Ra4k$$

$$Pjig\_20 := \left(\frac{Tsji + D \cdot Taji}{Ktj}\right)^2 \cdot Ra20 \qquad Pjig\_4k := \left(\frac{Tsji + D \cdot Taji}{Ktj}\right)^2 \cdot Ra4k$$

$$Pt\_20 := Sensors + Pchop\_20 + Pjig\_20$$

Total power at 20 deg.C : $Pt\_20 = 0.241$

$$Pt\_4k := Sensors + Pchop\_4k + Pjig\_4k$$

Total power at 4 deg.K : $Pt\_4k = 3.199 \cdot 10^{-3}$

Therefore using copper wires in the motors should still meet the BSM power specification, but with considerably reduced design margin (0.8 mW instead of 2.7 mW).

The Simulink model has also been used to estimate the BSM dynamic power performance.

The power dissipation of the BSM is dominated by the torque required to keep the axes at fixed non-zero positions against the spring force. Acceleration forces are of comparatively short duration.
The total power is computed to about 2 mW at 4 deg.K.

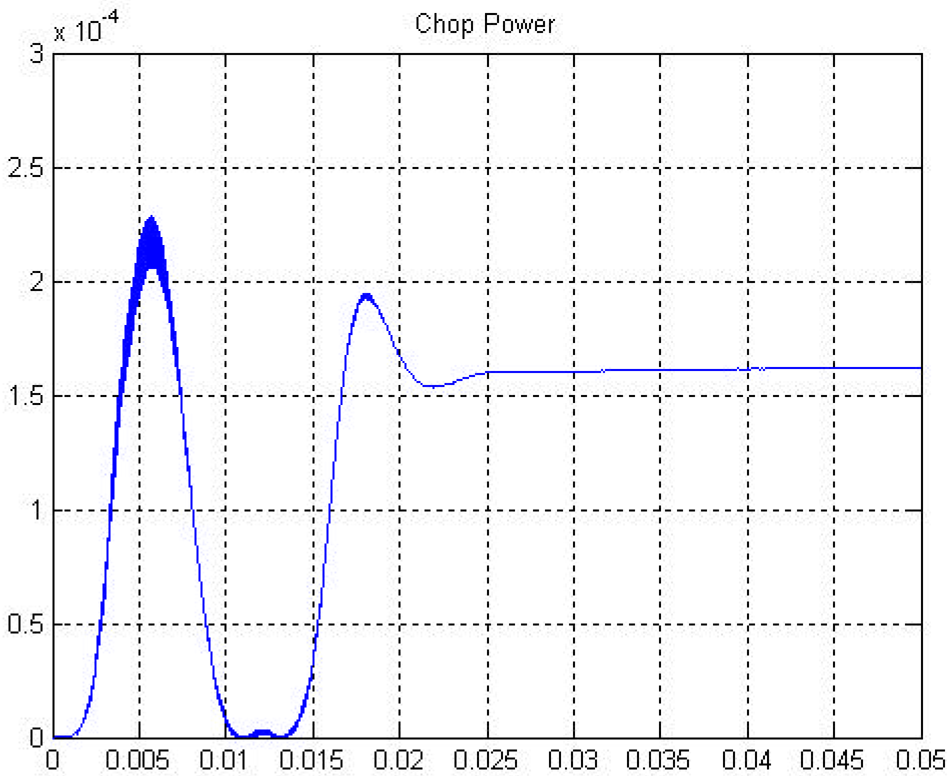


Figure 28 Predicted power (chop stage)

10.5.2 Rise Time

The position rise times are within specifications for both axes (Simulated 15 mS Chop, 40 mS Jiggle, for specification 20 and 50 mS respectively)

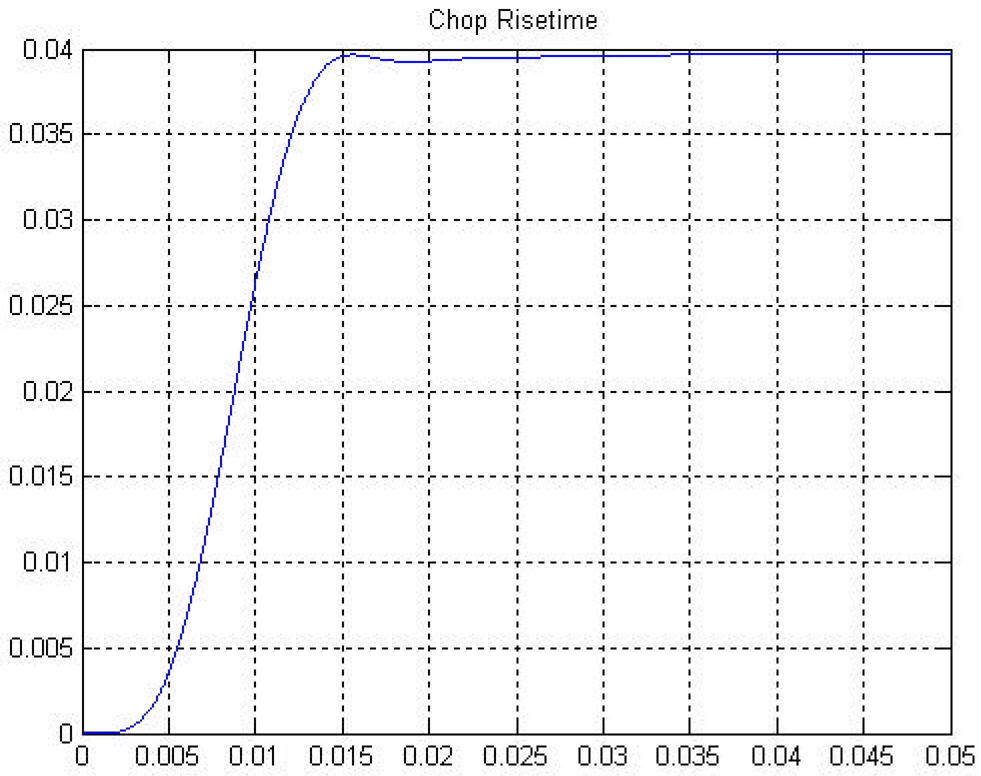


Figure 29 : Predicted chop stage risetime

10.5.3 Positional Stability

Tests on a single-axis prototype show that stability should be near specification at about 6 arcsec in 5 hours, but require improved angle measurement apparatus to verify this.
Currently the angle measurement system drifts by approximately the same amount as the required specification figure.

10.5.4 Gain and Phase Margins

System gain and phase margins are described in the document ‘BSM Control Systems Analysis’, which indicates robust stability margins for the BSM control loops, allowing reasonable parameter variations without significantly affecting BSM performance.

10.6 BSMe Electronics

The Electronics specified by UKATC designed by LAM takes the following form.

10.6.1 Block Diagram

In simplified form, this illustrates the interconnects between the BSM and its electronics.
The BSM mechanism motors and launch latch are powered from the Warm Electronics. The BSM position sensors are preamplified by the Warm Electronics.
The A-D and D-A functions, and the controlling code, operate within the LAM MAC board.
Finally, data and commands are exchanged via the MAC board to the SPIRE system.

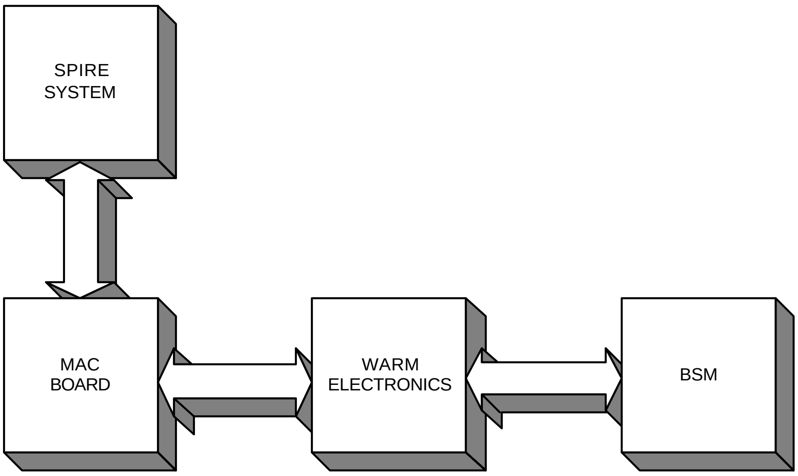


Figure 30 : Warm electronics overview

10.6.2 Position Sensors (Current Source)

The current sources use precision voltage sources (AD584) and voltage-to-current amplifiers.

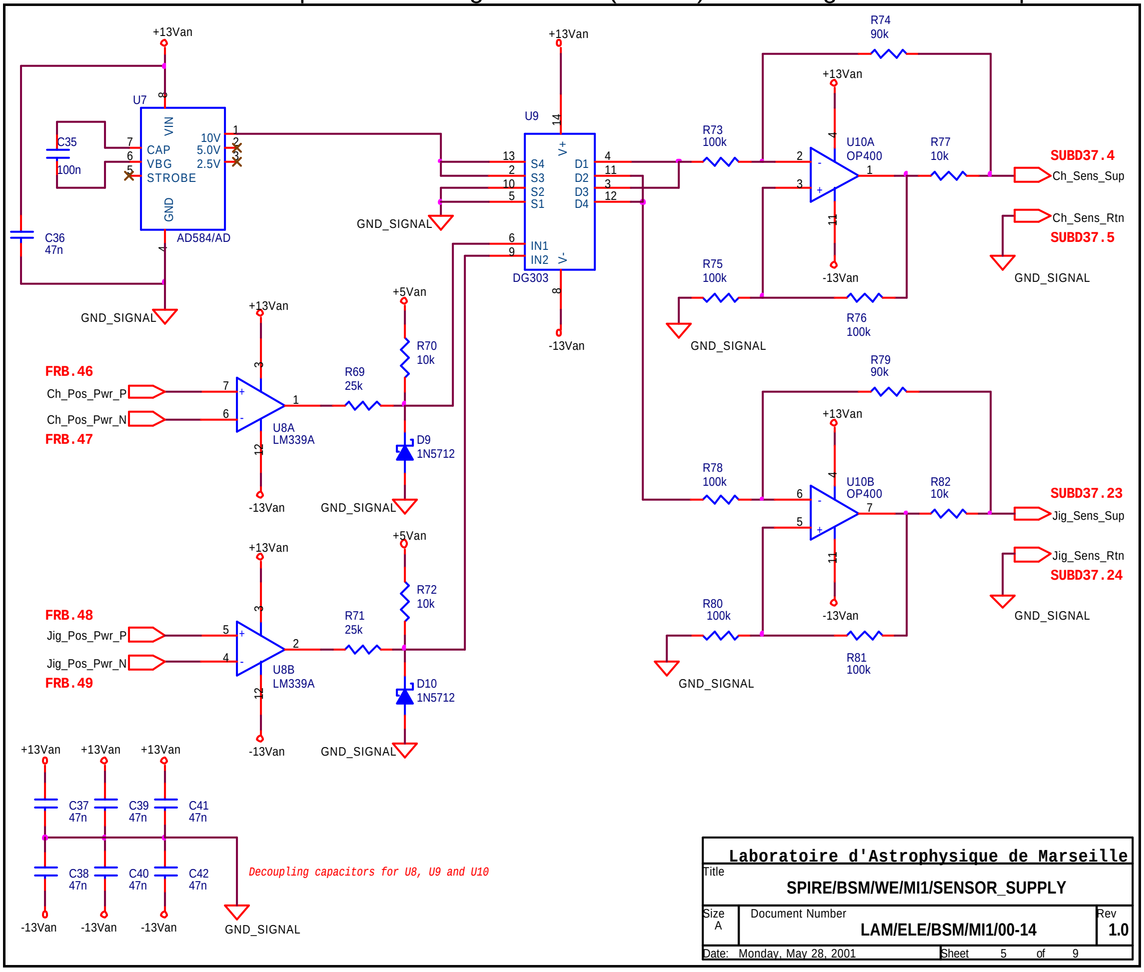


Figure 31 sensor supply

10.6.3 Position Sensor Read-Out Circuit

The position sensor outputs are differentially amplified to reduce noise pickup using monolithic instrumentation amplifiers.

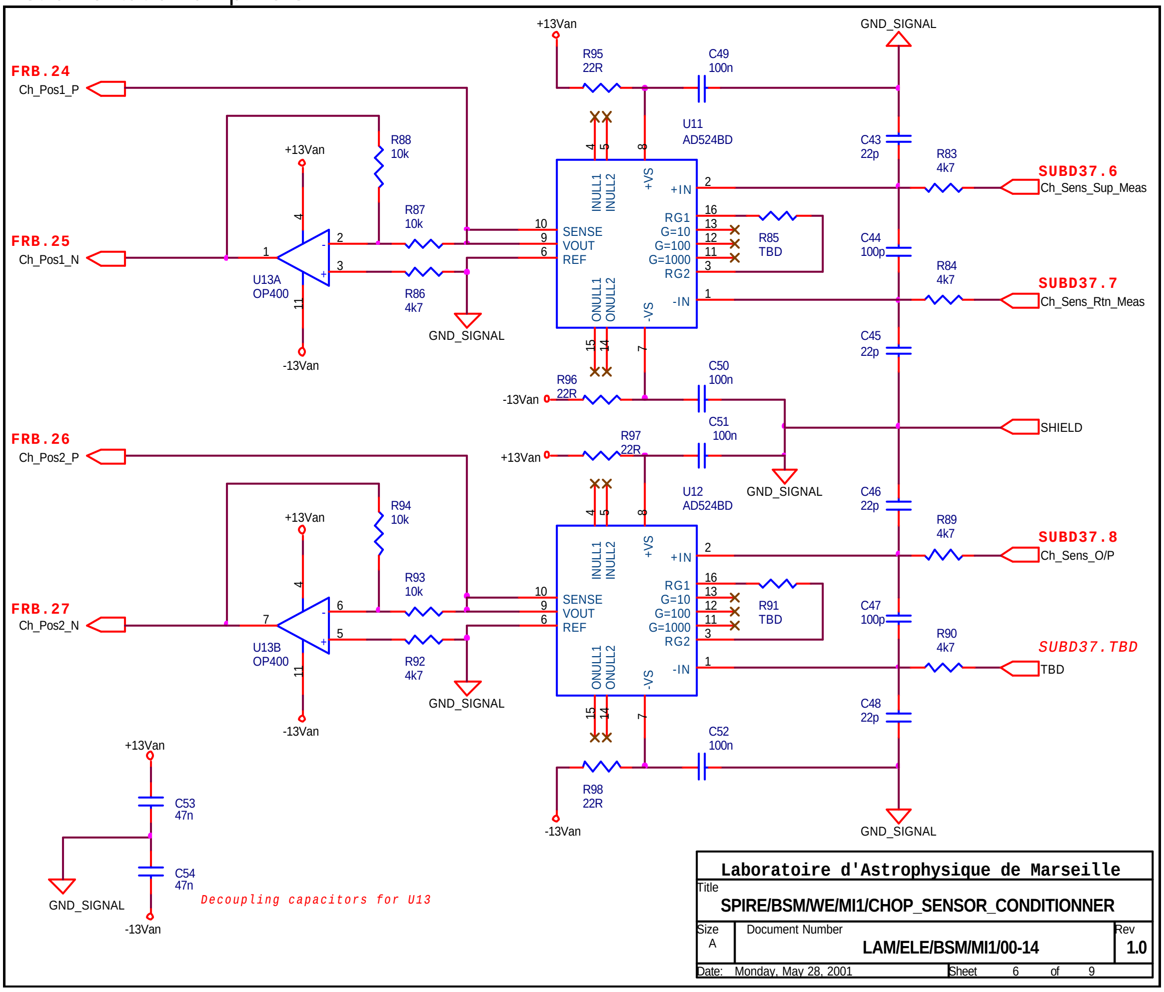


Figure 32 Chop sensor conditioner

10.6.4 Motor Power Amplifiers

The motors are driven by voltage-to-current amplifiers, which as well as reducing the effects of motor electrical time constant on the control loop, ensure stable operation with the large changes in motor resistance between cryogenic and ground test temperatures.

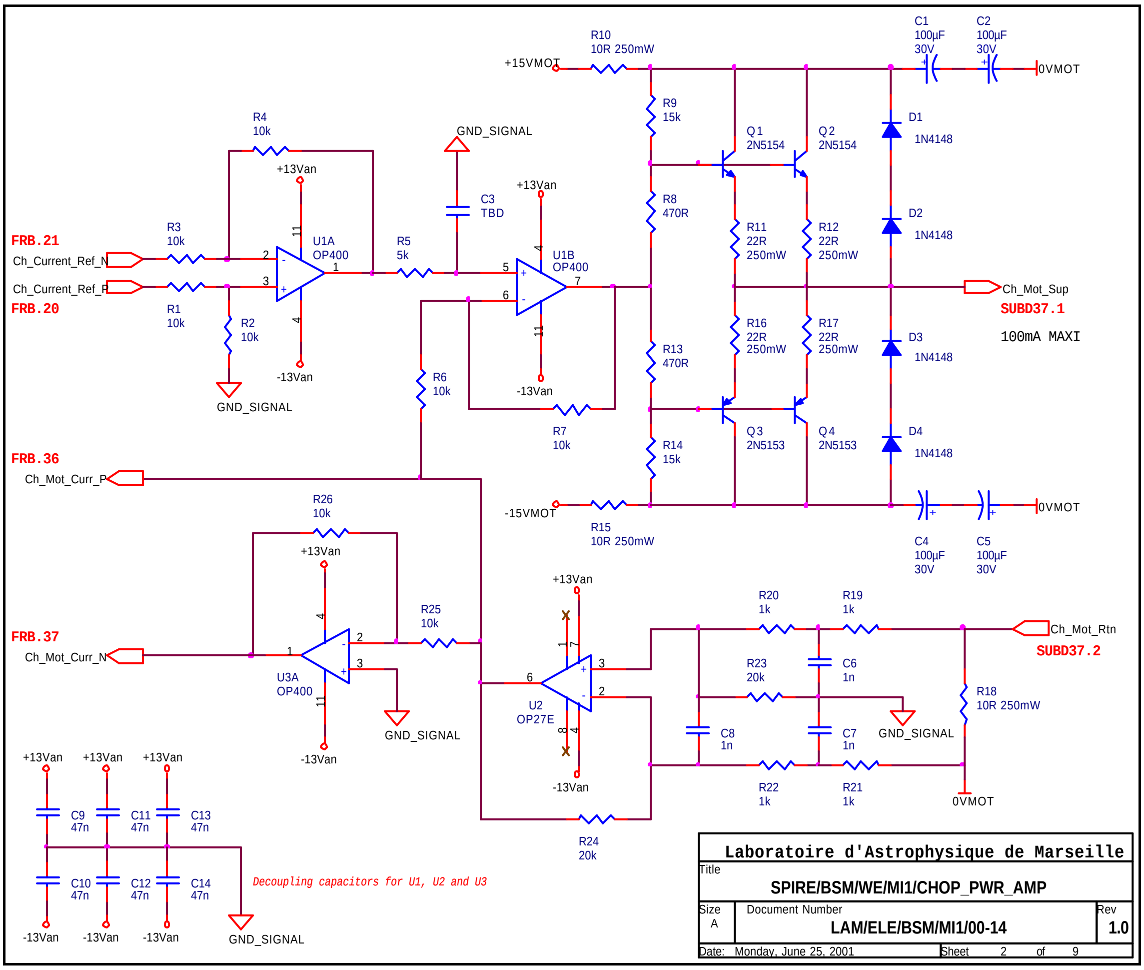


Figure 33 Chop Power Amp

10.6.5 Thermometry

Standard Cernox 1030 thermometers are used to sense local temperature on the BSM.

10.6.6 Power Supply

Power Supplies are standard +/- 15V and +5V supplies suitable for analogue electronics and digital electronics respectively.

10.6.7 Grounding Scheme

The grounding scheme ensures no electrical contact with the BSM structure, with the exception of overall screens on harness wire bundles from connectors, that should connect to chassis. Inner screened wires will terminate at the required component without any connection – however, the end at the warm electronics will be terminated to the local electrical ground for EMC screening.
Overall electronics screening and grounding policy is agreed between UKATC, LAM and SPIRE systems.

10.6.8 Harness/Cables

Electronic/Electrical

The BSM wiring harness is designed to minimise EMC and cross-talk by suitable screening, and is described in detail in the UKATC BSM Electronic Interface document, Annex G.

Mechanical

The BSM prime and redundant harness are separate. Each harness includes the motor, sensor, thermometry and PCAL cables and interfaces via a fully populated 37-way MDM connector, as specified in AD5. The harness is run to the BSM as described in AD6, with a total length of 415 (TBC) mm.

It is TBD whether PCAL has a redundant element. If it does not, then the 4 wires and common screen from PCAL will run only to the prime BSM harness' 37 way MDM connector. The BSM redundant connector will in effect have 5 spare pins.

The approximate harness runs are shown below (note that cut-outs and mounting arrangements are TBD)

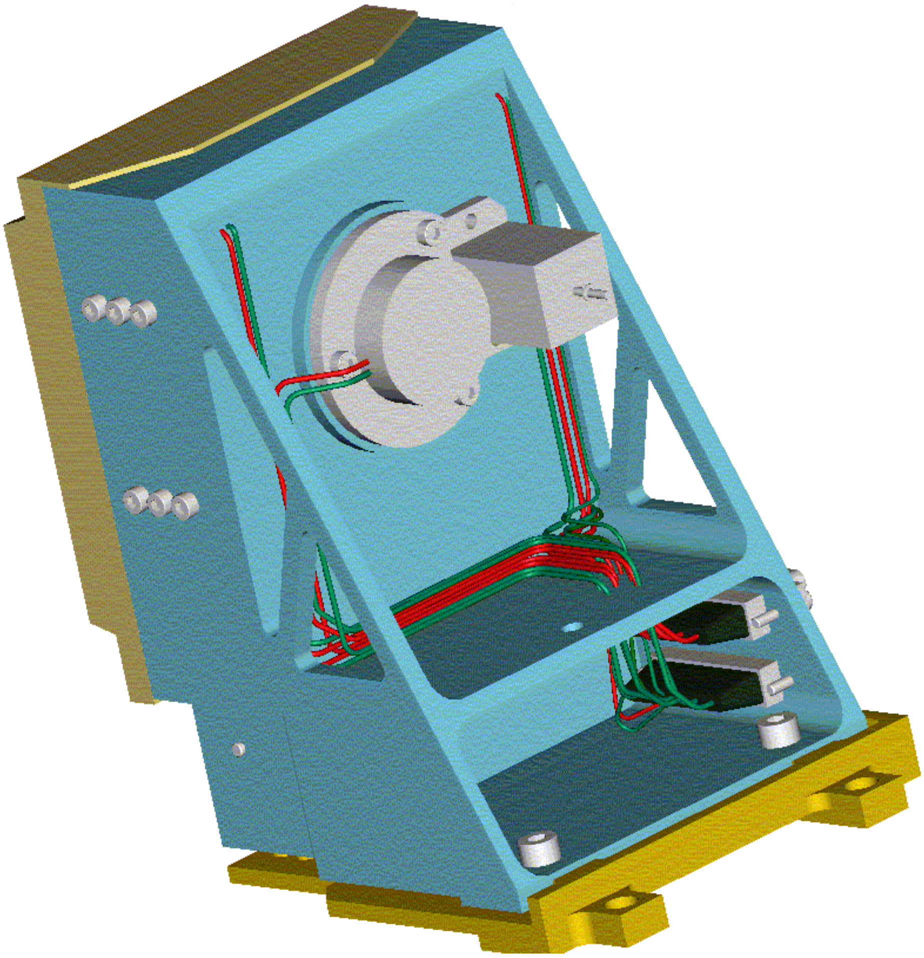


Figure 34 BSM on-board harness run (concept) showing prime and redundant harness runs

Figure 34 above shows a conceptual local harness routing on the rear of the BSM. The prime harness (red) and redundant harness (green) follow a similar path , though the above concept has not been optimised to allow the removal of a single harness without having to disturb the other.

Key issues to be incorporated in developing this harness concept are to:

1) provide apertures for the wiring to pierce the structural members.
2) Avoid light leaks, if required (TBD)
3) Provide for stake out of the harness, via P-clips, lacing and adhesive. (note that p-clips will require locking fasteners)

10.6.9 Interface to Digital Controller

The A-D and D-A interfaces, which are within the LAM MAC board, using SEi 78705 ALPRP 16-bit and Sei 7846 RP 16 bit converters respectively, ensure in particular an accurate position signal conversion, which is essential for BSM angle stability and accuracy.

10.7 Components & Declared Lists

10.7.1 Component List

The detailed component list will be issued when the detailed design is finalised.

Generally, pre-space models will use MIL-STD parts, and space-rated models will use ESA/SCC parts obtained through the SPIRE common parts procurement system, for all electronics associated with the BSM, that is the BSM mechanism, Warm Electronics and MAC board.

Parts for the Warm Electronics and the MAC board are being ordered by LAM.

10.7.2 Processes Soldering

UKATC wiring and assembly personnel are being trained at approved agencies in sufficient time for BSM assembly of space-rated parts. Therefore the soldering process used will conform to the required ESA standards

10.7.3 Processes Crimping

UKATC wiring and assembly personnel are being trained at approved agencies in sufficient time for BSM assembly of space-rated parts. Therefore the crimping process used (if any) will conform to the required ESA standards

10.8 Electronics Systems Interfaces

10.8.1 MCU

The BSM does not interface directly with the MCU, however the DSP controller (MAC board) that runs the BSM control code also communicates with the MCU, so there is an indirect interface that is jointly defined by UKATC and LAM.

10.8.2 Command Modes

The BSM has the following main operating modes.

1. LAUNCH
The BSM is un-powered, but the launch latch can be activated and the motor coils are shorted.

2. OFF
The BSM is un-powered, the launch latch is de-activated

3. ON - POINTING
The BSM is powered, and the position loop is active

4. ON - DIAGNOSTIC
As mode 3, but data is stored for subsequent transfer to the MCU for downloading via telemetry.

5. UPDATE
The MAC board accepts new control parameters from the MCU.

10.8.3 Command List

1. LAUNCH

SIGNAL	FUNCTION	STATE
Launch Latch Activate	Close Launch Latch, Short coils	HI = Activate
Launch latch Deactivate	Open Launch Latch	HI = Deactivate

2. OFF

None

3. ON - POINTING

SIGNAL	FUNCTION	STATE
Chop position demand	Chop position loop input	
Jiggle position demand	Jiggle position loop input	

4. ON - DIAGNOSTIC

SIGNAL	FUNCTION	STATE
TBD		

5. UPDATE

SIGNAL	FUNCTION	STATE
TBD		

10.8.4 EGSE

The BSM mechanism is tested using the dSPACE system.
The control software can be modelled in real-time, or the BSM mechanism and associated electronics can be emulated for testing the software.
The dSPACE system emulates the following Simulink model of the BSM mechanism (one axis shown).

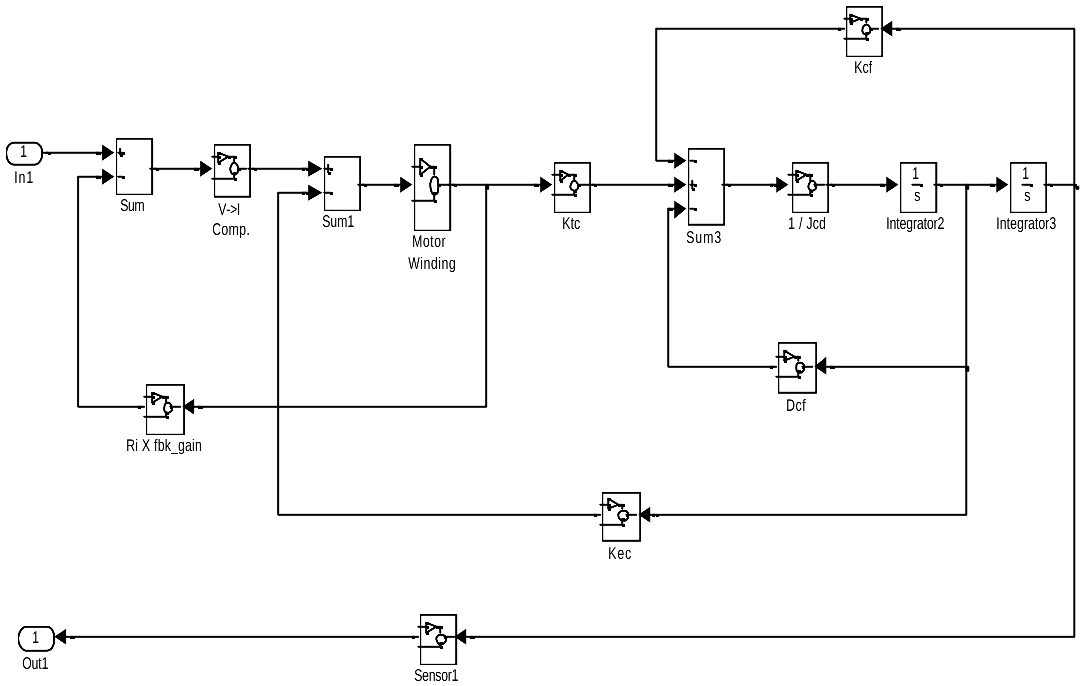


Figure 35: The model includes the mechanism with its inertia, flex joint spring and damping, and the motors, power amplifiers and position sensors.

11. Reliability & Redundancy

In the BSM design redundancy principles have been implemented so as to avoid single point failures, and the propagation of failures to other subsystems, by means of dedicated redundancy and specific protection devices. Where redundancy can not be realised the architecture is designed to limit the effects of a failure.

The BSMe consists of two complete separate circuits (situated on the same double Eurocard, but supplied by separate connectors). This provides complete parallel redundancy, with main and redundant position sensors and motors, driven by separate main and redundant analogue boards, which are in turn supported by separate main and redundant MACs and DPUs as shown in Figure 36 below.. The harnesses, both warm and cryogenic, are also maintained as separate systems.

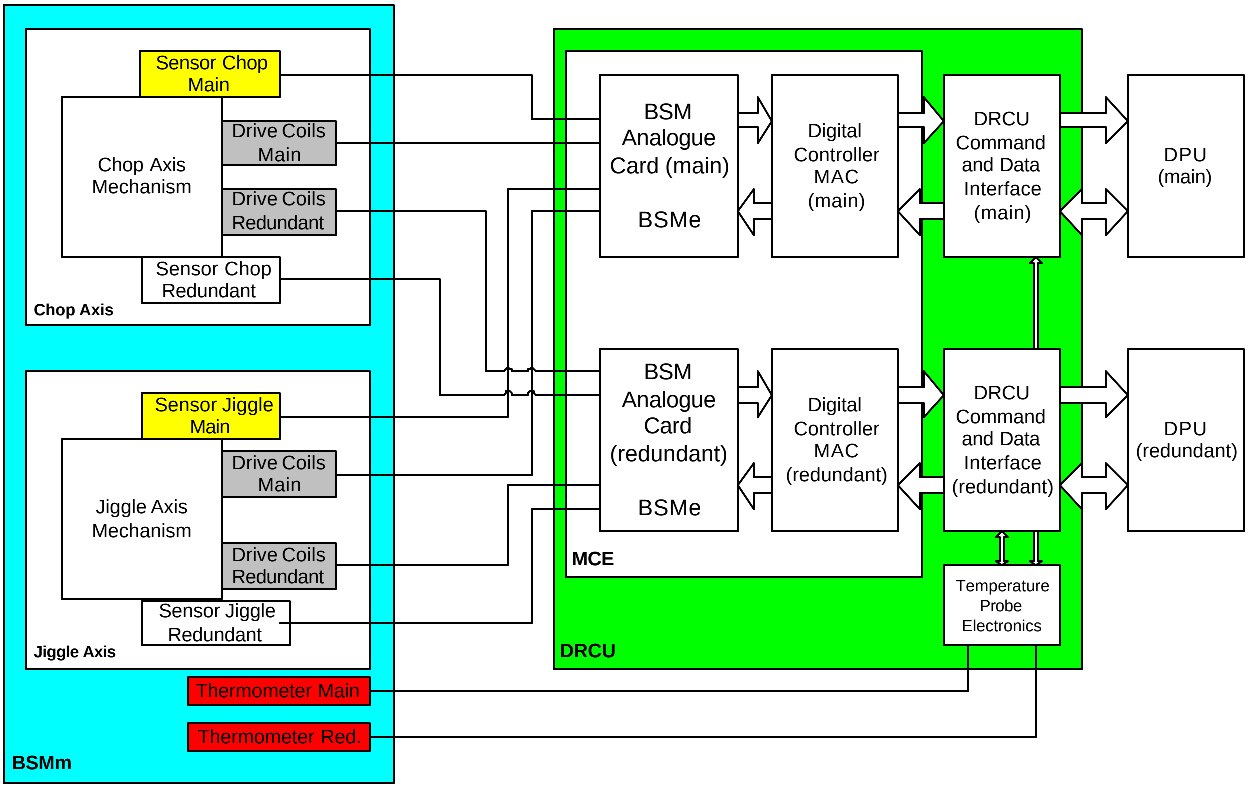


Figure 36 : BSM electronics architecture showing parrallel redundancy

The BSMe redundancy scheme will not be able to operate independently of the SMEC mechanism. A failure in the primary system of either mechanism results in both switching to the redundant schemes. Equally, the PCAL and thermometry units carried aboard the BSMs would be required to switch at the same time.

The BSMs and BSMm mechanical design incorporates little redundancy. The structural parts are in general over-designed from a strength viewpoint in order to give adequate stiffness. The structures are maintained at very low stress levels during launch and even lower stresses during orbit. The primary sources of stress will be those induced on assembly and thermal cooldown. The components are manufactured from space-proven materials with good fatigue and stress corrosion cracking properties. The design includes the ability to limit the motion of the BSM during launch, to protect the flexures, and physical limits to the motion in the event of a component failure.

The design of the BSMs and BSMm should be such that the BSM will meet the reliability requirements for SPIRE as set out in the IRD (AD-1). In summary this is that a failure of the BSM should not lead to a total loss of the instruments ability to do science, albeit with loss of efficiency due to the need to use a backup observing mode. If for some reason the BSM were unable to move in either axis at all, then science could be obtained using the scan mapping mode - although there would be a serious loss of efficiency/sensitivity. The jiggle axis would provide some limited ability to modulate signal in event of a catastrophic failure in the chop axis and much worse than expected 1/f noise. In order to ensure that SPIRE can obtain data in the event of a BSMm failure, the mechanism must fail such the field of view of the FTS is still available, and that large or unpredictable offsets of the photometer field are not required.

This is achieved by ensuring *by design* that in the event that there is no drive signal reaching the BSM the mirror will be within +/- 0.18 degrees of the nominal bore-sight, and that in the event of a complete mechanical failure the mirror will be within +/- 1 degree of its nominal position.

11.1 Reliability Block Diagram

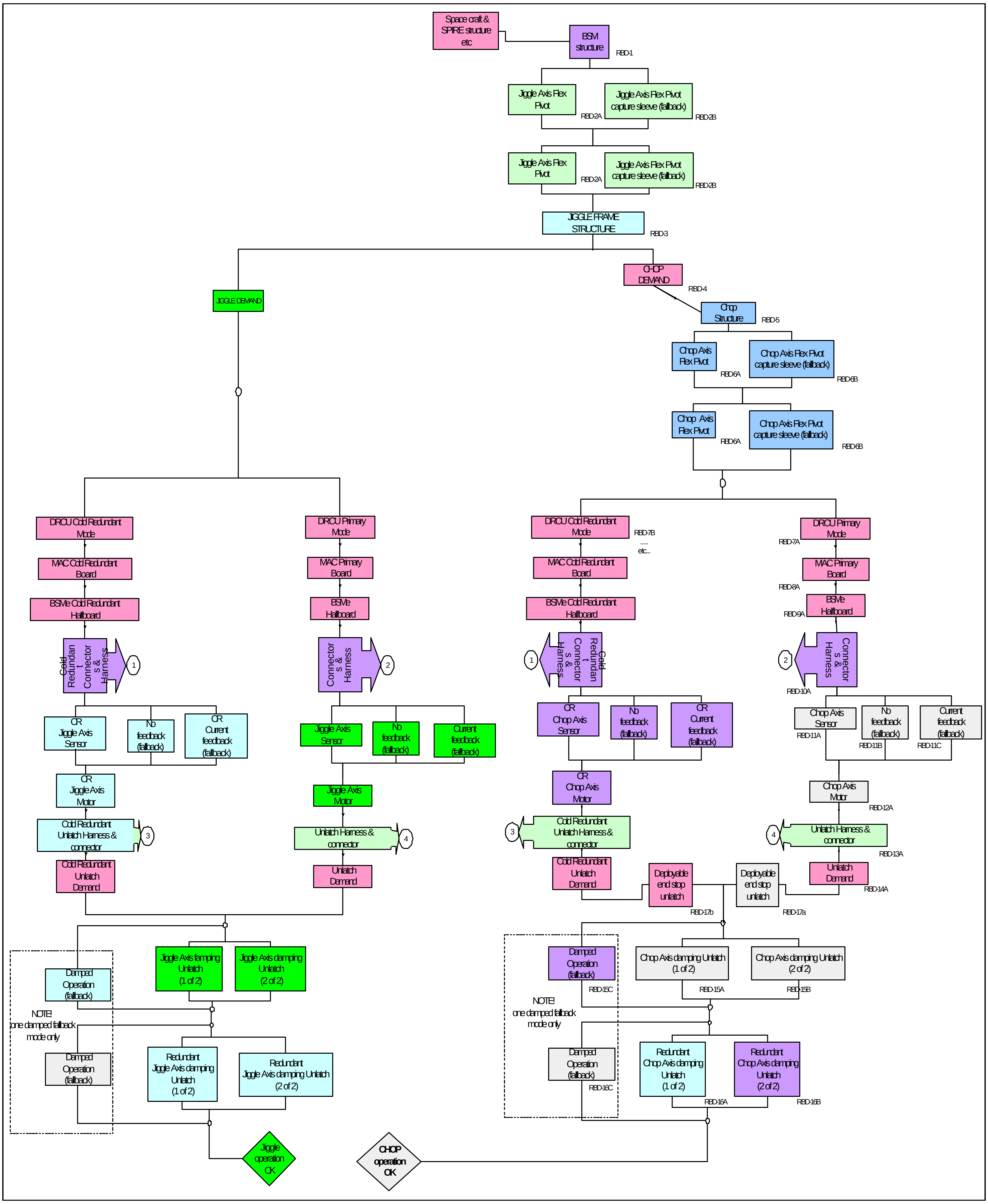


Figure 37 Reliability Blcok Diagram, BSM

11.2 Single Point Failures

A Reliability Block Diagram is considered above. At this level it is apparent that

1. Wiring harness is a potential Single point failure, unless both the BSMe 'half' boards have an individual cable harness with it's own connectors.
2. The BSM structure and jiggle frame are SPF's. No surprise, but it reinforces the requirement for analysis of these structures for survival, and possible additional tests (e.g. to verify the FEA).
3. Assuming we have a launch damper (shorted motor coils), In the primary operations mode the launch damper 'unlatch' command must unlatch the primary mode motor coil, BUT MUST ALSO unlatch the cold redundant motor coils latching circuit. Vice versa for the redundant mode. This is discussed in the BSME schematic Subsystem Specification Document (Beam Steering Mechanism, Figure 4).
4. The same comment as (1) applies for the cables which send the unlatch command - they should remain separate and parallel.

11.3 FMECA

A failure modes, effects and criticality analysis (FMECA) has been performed, in accordance with the product assurance plan. The full detail is presented in the FMECA work-sheets included as appendix 4.

The FMECA ‘viewpoint’ is that of normal operation, with the observing mode being assumed to require combined chop and jiggle motion of the BSM.

A FMECA for the other states – off, standby, thermal cooldown, launch, have not been performed. For the first two the main implications are understood to be electronic. Cooldown and Launch failures have been folded into the main FMECA, as this is more pragmatic than creating a duplicate analysis.

For each element of the reliability block diagram, a number of failure modes and their implications are considered. The analysis is limited to considering a single component failure at any one time, except for cold redundant components where the operation is exposed only after a prime mode has failed.

The principal recommendations resulting from the FMECA are :

11.3.1 Control Software :

- We need to guard against a software command to unlatch when we don't want to.
- Observation Definition Software needs to be robust handling chop/jiggle requests (i.e. not forgetting them or sending wrong one, or out of range value ......)
- The bistable deployable end stop relay may have an indeterminate state, in which case the MCU must be robust against it.
- MCU needs voltage limiter on analogue outputs, and software needs similar check to prevent the system from being driven out of range.
- need to set invalid sensor range flags in WE (MCU) software

11.3.2 Electronics :

- for latch solenoid, must be able to turn off power to launch latch solenoid with good redundancy. leaving a solenoid switched on would boil of all the cryogens fast.

11.3.3 Mechanical :

- Mirror surface should be tested for print through of light weighting
- Good process control on magnet adhesive is required
- The flex pivot mounting is critical.
- End stops must be well characterised.

11.4 Critical Components Identification

We assume that items which require declaration here are those which "fail to meet the project requirements" for *failure tolerance*, or undetectable loss of redundancy.

As discussed above for SPIRE the failure tolerance is total loss of science - i.e. a failure of the BSM which would result in (a) large pointing offset for the photometer or/and (b) inability to take data with the FTS due to loss of its field of view. i.e. critical components would be those whose failure would result in the BSM failing to meet the required fail safe positions defined in SPIRE-ATC-PRJ-000460, 4.2.13 and 4.2.14.

No such components were identified, but the design must ensure that the fail-safe positions are met should one or more flex pivots or motors fail.

12. Interface Control Documents

12.1 ICD Philosophy

The BSM interfaces with other subsystems in the SPIRE instrument. The interface to each sub-system is specified in the relevant Interface Control Document. For each ICD there will be:

- An ICD document.
- Where required, an ICD drawings (or equivalent electronic design information) with distinct drawing numbers. A copy of the drawings will be included within the document, probably in postscript or pdf format.

All these ICD's will be collected internally as an annex to this document (the **BSM Design Description**.) Each ICD annex will be self-contained, with a version number and date.

12.2 BSM ICD Master Reference Table

This section presents a table showing:

- which institute UK ATC interfaces to,
- the relevant documents the interfacing institute is supplying to the rest of SPIRE,
- which UK ATC documents their ICD information is fed from.

Whenever UK ATC update and release interface information with any party we will update the relevant annex and the master table, as well as the design description document.

Although this may leads to multiple updates of the design description, this is felt essential in order to ensure the design and interfaces are kept in lock-step.

Table 6: BSM interface master reference table

ID	Sub-System	Organisation responsible [3]	External ICD document	Internal ATC ICD document	Internal ATC ICD drawing/ file
1	BSM-SPIRE	RAL	Instrument Requirements Document (IRD). SPIRE-RAL-PRJ-000034 v0.30 May.00	SPIRE-ATC-PRJ-000587 Annex A	SPIRE-BSM-021-001-001
2.1	Structure – BSM	MMSL	ICD Structure - Mechanical I/F SPIRE-MSS-PRJ-000xxx v1.0 April 2001	SPIRE-ATC-PRJ-000587 Annex B	SPIRE-BSM-021-002-001
2.2	Structure – BSM	MMSL			SPIRE-BSM-021-002-002 (IGES file)
2.3	Thermometry	RAL	TBD		SPIRE-BSM-021-002-003
3	Photometer Calibration Source - BSM	UoW, Cardiff	TBD	SPIRE-ATC-PRJ-000587 Annex C	SPIRE-BSM-021-003-001
4	Launch Latch – BSM	LAM (TBC)	Spectrometer mirror mechanism design description LAM.SPI.PJT.NOT.200008 Ind 3	SPIRE-ATC-PRJ-000587 Annex D	SPIRE-BSM-021-004-001
5.1	Optics – external finish	LAM	Optical System Design Description SPIRE-LAM-PRJ-000447 Draft 1 18.Dec.00	SPIRE-ATC-PRJ-000587 Annex E	SPIRE-BSM-021-005-001
5.2	Optics – BSM	RAL	TBD		SPIRE-BSM-021-005-002
5.3	Baffles – BSM	RAL	TBD		SPIRE-BSM-021-005-003
6	Cryo-Harness	RAL / MSSL	SPIRE Harness Definition. SPIRE-RAL-PRJ-000608 Issue: 0.3 30.May.01 Harness routing : TBD (MSSL)	SPIRE-ATC-PRJ-000587 Annex F	SPIRE-BSM-021-006-001

[3] .i.e. responsible for feeding ICD info upwards to SPIRE system design

ID	Sub-System	Organisation responsible [3]	External ICD document	Internal ATC ICD document	Internal ATC ICD drawing/ file
7.1	MCU-BSM	LAM	Agreement by both parties on ATC design description and Annex G	SPIRE-ATC-PRJ-000587 Annex G	SPIRE-BSM-021-007-001
7.2	On Board Software - BSM	LAM	TBD		SPIRE-BSM-021-007-002
8	Photometer Bolometer Arrays - BSM	MSSL	ICD Structure - Mechanical I/F SPIRE-MSS-PRJ-000xxx v1.0 April 2001	Sub-System Specification EMC/ exported vibration ???	
9	Spectrometer Bolometer Arrays - BSM	MSSL	ICD Structure - Mechanical I/F SPIRE-MSS-PRJ-000xxx v1.0 April 2001	Sub-System Specification EMC/ exported vibration ???	
10	FPU Simulator - BSM	TBD	TBD	TBD	
11	Instrument Simulator - BSM	TBD	TBD	TBD	

12.3 Description of ICD contents

12.3.1 Top level system

This is the ATC's top-level assembly including optical bench, optical beams, cryo-harness, thermal strap, thermometry and any other system level interfaces. A multi-sheet drawing (SPIRE-BSM-021-001-001), is used to show all relevant interfaces clearly, though many of these items will be themselves references to other institutions files (e.g. RAL IGES optical beams).

This document is mainly used for internal consistency checks of external data supplied from a variety of sources, and may not necessarily be formally communicated to any one external party. It may however, tie in well with the IRD or IID-B.

12.3.2 Structural interface

- The main structural interface drawing (SPIRE-BSM-021-002-001), includes a layout of the BSM assembly (SPIRE-BSM-020-001) showing the principal dimension, to the mirror surface from the interface, as well as the shoe dimensions, mounting details and the full space envelope. 3d information views would also be shown. A mass estimate, CoG, MoI, principle resonant modes are also included.
- Additionally, a full IGES or STEP interface file is allocated a distinct ICD number (SPIRE-BSM-021-002-002) and will be treated as the master 3D interface with MSSL.
- Thermometry.

12.3.3 PCAL interface

PCAL interface drawing - a toleranced space envelope sketch of PCAL, also indicating distance from an optical reference point (possibly cross-referenced to one of the other ICD's). Also shows Mass, nominal CoG,, details connector position.

12.3.4 Launch latch interface

This comprises a toleranced space envelope sketch. Also shows Mass, nominal CoG and electrical information. Depending on procurement process selected (TBD) this could alternately be treated as a straight procurement-to-drawing and the ICD deleted.

12.3.5 Optical interface

12.3.5.1 Finish

Specifies the external optical finish of BSM assembly.

12.3.5.2 Mirror Interfaces

This shows mirror position (toleranced dimensions tying into the BSM subsystem spec), size, range of travel, surface finish (or calls mirror part drawing for this - we don't want it to appear twice!).

12.3.5.3 Baffle Interface

This shows baffle shape and position (toleranced dimensions tying into the BSM subsystem spec), surface finish (or calls mirror part drawing for this - we don't want it to appear twice!). We may call 'back' on the top level SPIRE-BSM-021-001 for any issues to do with optical beams supplied as IGES files by RAL.

12.3.6 Harness

Harness interface and grounding scheme. We probably also absorb an electrical drawing into the Pro/E or pro-intralink scheme here

12.3.7 BSM warm electronics (BSMe)

- Warm electronics drawings and model.
- Software interfaces to drive BSMe with MCU

12.4 Note on ICD drawing numbers

These are contained within the same drawing management system as the main models, but are identified distinctly by drawing description/title and also be an allocated number set.

For a given build the design data is : SPIRE-BSM-bb**0**-aaa-ccc

Where bb = build (e.g. Development model = 02), 0 identifies design data, aaa = assembly, ccc = component

However for an ICD the scheme is: SPIRE-BSM-bb**1**-iii-fff

Where bb = build (e.g. Development model = 02), 1 identifies interface data, iii = interface ID, fff = ICD file

13. Assembly, Integration & Verification

13.1 General

AIV requirements are primarily programmatic, and met through the product assurance plan (AD3), the test plan and development plan (RD5). These programmatic issues are not discussed in the design description

However, there are several design implications and features of relevance, which are discussed below.

13.2 Assembly

The BSM design is compatible with assembly in a class 1000 clean room. Volatile materials are avoided, and all components are capable of immersion/cleaning with isopropyl alcohol or in an ultrasonic bath.

The development and product assurance plan requires that parts are fully traceable for build configuration control on deliverable models, and where test data forms part of the qualification process. For all components of adequate size the design drawing identifies a location to permanently mark the component drawing number, revision and serial number. Components of small size will either be marked with the serial number alone (which shall be unique for all components and cross-referenced to drawing number, revision and manufacturing lot). Below a certain size of component (e.g. small fasteners, P-clips) the components will be 'bagged and tagged', with the packaging identifying the part numbers.

The method of marking each component is TBD, and will usually be based on engraving or etching. Where components are subject to high stress levels the design drawing will ensure that marking will not act as a stress raiser.

The BSM design is inevitably comprised of small components within a tightly packed assembly. Consideration has been given to access for fasteners and wiring harness, and additional lessons learnt from prototyping will be incorporated into the design via the change-control process. The BSM comprises several sub-assemblies and the tight alignment tolerance leaves the design vulnerable to tolerance stack up if not correctly approached. The following design features and assembly aids are incorporated into the design:

13.2.1 Flex pivot protection sleeves:

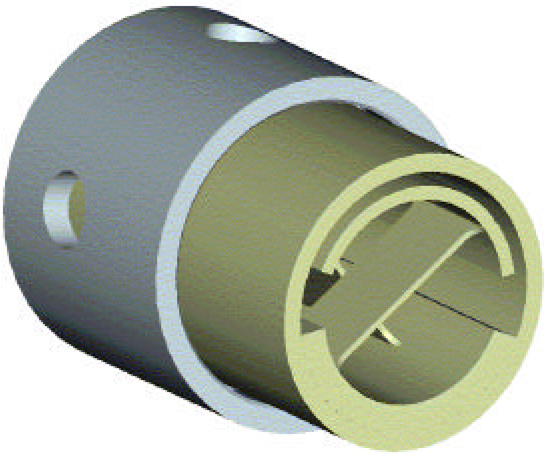


Figure 38 flex pivot mounted in protection sleeve (note holes for adhesive- this allows glue to be added after assembly and reduces risk of adhesive being placed on moving parts)

The flex pivots are sized as a light push fit, avoiding buckling loads on the flexures during installation. To ensure survival of warm vibration and maintain position during build, the pivots are fixed with a cryogenic space rated adhesive - Eccobond or Stycast (TBD). The pivots are not marked for identification, but the flex pivot sleeves may be identified externally as they are required in handed pairs. A discussion drawing (SPIRE-022-001) is produced to demonstrate correct alignment technique on subsequent integration.

13.2.2 Mirror handling

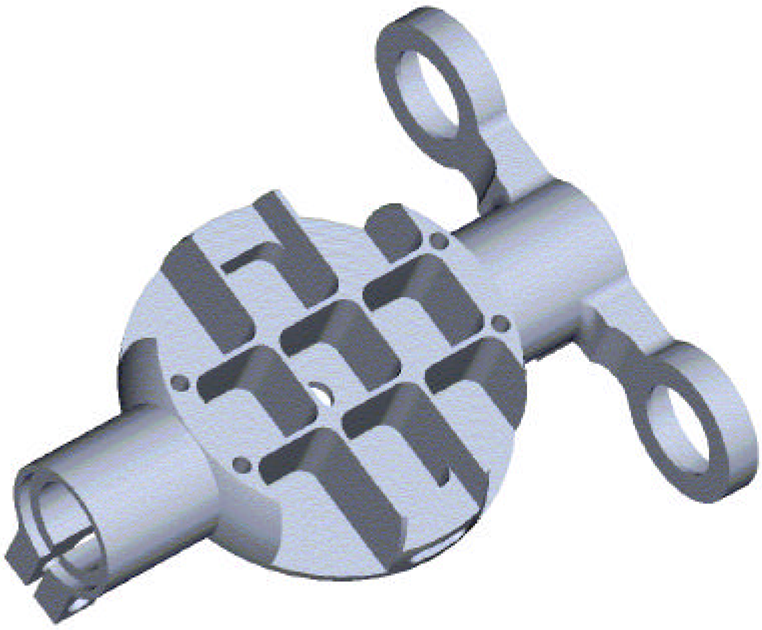


Figure 39 underside of mirror showing light-weighting and 4-off tapped holes for priocess mounting

The chop stage and mirror have four tapped holes on the mirror backing structure. These provide a clamping facility for optical machining, and are useful in subsequent processes. Inserts are not placed in the threads to avoid print through at cryogenic temperatures.

13.2.3 Chop Stage (drawing SPIRE-BSM-020-004)

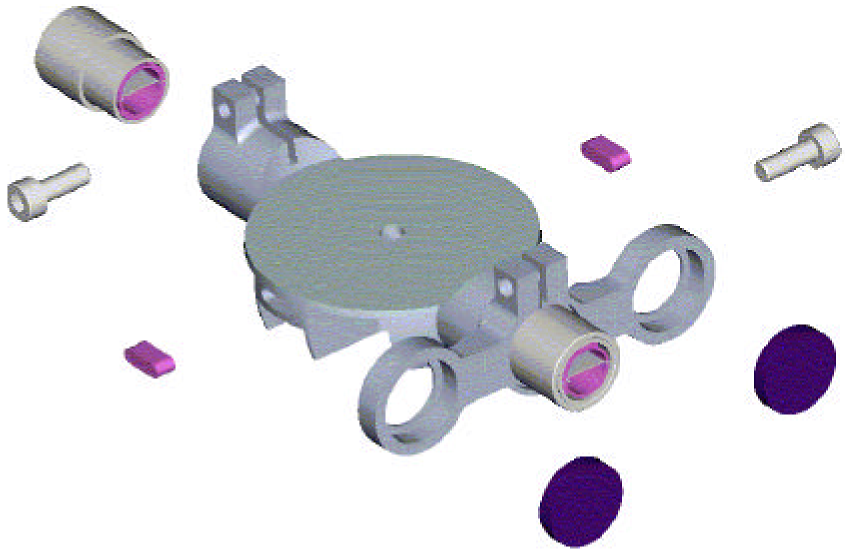


Figure 40 Chop stage assembly showing sensor cores (pink), magnets (purple) and flex-pivots

The insertion of flex pivots into the chop stage is facilitated by an open fit, clamped up by a screw after assembly and alignment.

The sensor cores are pushed into the bottom of their pockets, facilitating positioning, and glued in place.

The magnets are currently a slight push fit, again seating in the bottom of a pocket and retained by a fillet of adhesive. The magnets are relatively brittle components and the fit may need to be opened out if problems are found in prototype and development model builds (TBC).

13.2.4 Motor Assemblies (drawing SPIRE-BSM-020-005)

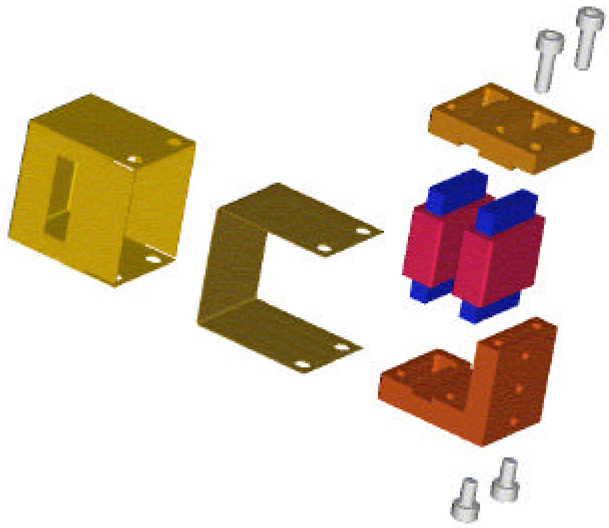


Figure 41 Motor assembly

Alignment of the motor air gaps is a critical design parameter - both to optimize torque performance and to avoid the possibility of fouls.

A design aim is to avoid shimming or adjustment of the assemblies, as with 4 off motor assemblies per BSM model there will be strong advantages to interchangeability.

The prototype coils supplied by MPIA do not have sufficient dimensional consistency to allow a direct fit without adjustment.

Therefore, it is proposed that the motor assemblies be bolted together with the coil cores as a loose fit in their pockets. An assembly jig (drawing/design TBD) will locate the motor coils with high precision with respect to the coil bracket mounting face and hold them in place whilst the adhesive cures. This will produce an assembly with high precision (25-50 microns) repeatability on mounting.

Once the Zeiss motor design is frozen, it may be possible to assemble based on supplied interface dimensions, but this is TBC.

13.2.5 Jiggle assembly (drawing SPIRE-BSM-020-003)

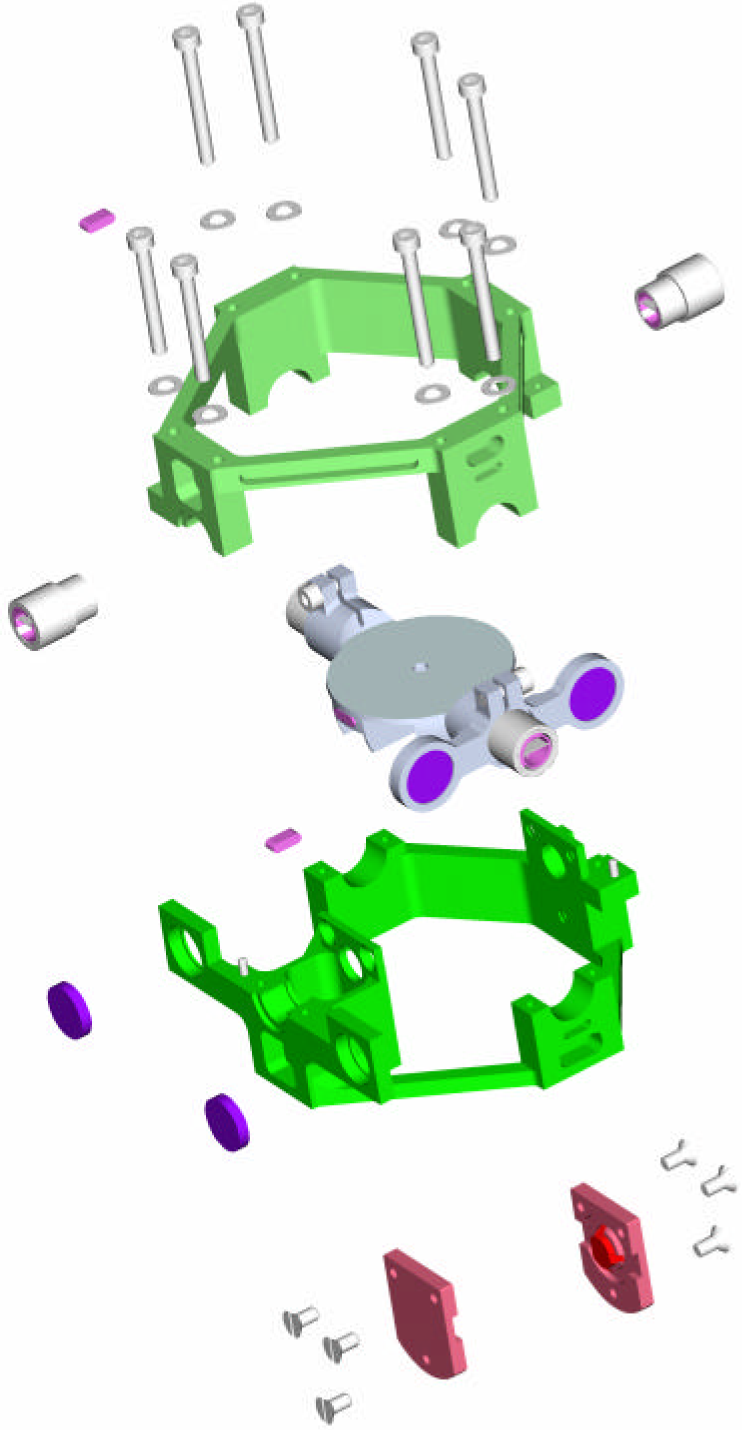


Figure 42 Jiggle stage assembly showing jiggle frame (green), sensor cores (pink), Infineon sensors (red)

Alignment of the mirror at the correct geometric location is important,

- to minimise optical alignment of the BSM on integration to SPIRE
- to ensure that the distance between the chop axis magnet lever-arms and the jiggle axis bores is correct, to prevent fouls between the magnet lever-arms and the drive motor assemblies.

- the mirror must be located flat within the jiggle frame so that it's rest position will be within the fail-safe tolerance.

This task is complicated because

- the flex pivots will easily take a small pre-load during the assembly process, and thus spring back to an undesired position when done.
- The presence of strong magnets attracted to local objects creates offsets or lack of control,
- The need to fit the 'lower' chop axis motor housing during the build of this assembly adds a dead weight to one lever arm.

Consequently an assembly jig is envisaged. This would

- hold the chop stage assembly flat and facing upwards
- Hold the lower jiggle frame flat and facing upwards (avoiding shear loads on the flex pivots by a light spring mounting)
- Provide a set of mounting holes to position the motor assembly in place
- Provide a spigot to locate the mirror centroid and a reference face to align the jiggle frame to.

Having positioned the components, and performed a feeler gauge check that the flex pivot gaps and motor air gap are nominal, the upper jiggle frame would be lowered into place and bolted up.

The assembly would be freed from the jig, and the rest position of the mirror checked. Pending prototype and development model experimentation it remains possible that a small preload will occur and the process might need to be repeated until the tolerance were met. (It is anticipated that some process parameters such as the torque-up pattern of the eight jiggle frame screws will need to be worked out).

13.2.6 Jiggle frame to structure assembly

The complete 2 axis gimbal mount and remaining three motor assemblies are installed at this stage. The use of assembly jigs for the gimbal and motor assemblies, and CNC machining of the structure, the tolerance stack up is limited (as compared to the 10+ components which would contribute to stack up if jigging were not used). Therefore the motor air-gaps are achievable to tolerance without adjustment on assembly.

To meet the jiggle axis rest position tolerance a further jig is envisaged to hold the BSM structure flat and assist in setting the jiggle frame angle. Ideally, the jig would reference from the actual mirror surface (or the mirror rear surface accessible via the central PCAL mounting holes)

13.2.7 Harness routing

The motors and sensors will have flying leads soldered to them at the sub-assembly stage. These flying leads will then be routed through apertures in the BSMs bulkheads and staked down as appropriate. The attachment of the flying leads into the on-BSM connectors will require soldering/crimping operations on an assembly which will be 'clean' at that point.

The BSM and PCAL may be protected by covering/enclosure (with only the flying lead exposed) and the soldering operation could then be performed outside the ATC clean room (or indeed inside, if local extract facilities can be made available without contaminating the clean room).

13.3 Integration

All components are capable of withstanding bake out to 80 deg C (note however that this is close to the magnet material specified limit and close control of the bake out process will be required).

The PCAL interface provides for a toleranced hole and mounting face, and no mechanical problems are envisaged.

The alignment issues of integration to the SPIRE optical bench are discussed elsewhere in this document (section 7 Mechanical and section 9,Optical)

13.4 Verification

Verification / test plans for the design is outlined in RD 5

13.5 Transport & Storage

The BSM will be transported in a sealed container, purged with dry nitrogen. As postal service vibration loads are well known to be more rigorous than launch loads, the device will be hand carried where at all possible.

A transport lock may be provided (TBD), and if so will be 'red flagged' for removal before use and identified as such in the ADP.

The transport container will provide for storage facilities also. Components and sub-assemblies will be stored in dry Nitrogen environments where required. For corrosion control and protection during handling, components will in general be gold plated, anodised or sealed/potted as applicable.

13.6 Handling

No special handling requirements are envisaged, beyond normal care and attention.

13.7 Test Programme & Test Matrix

The Verification / test plans for the design are outlined in RD 5

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