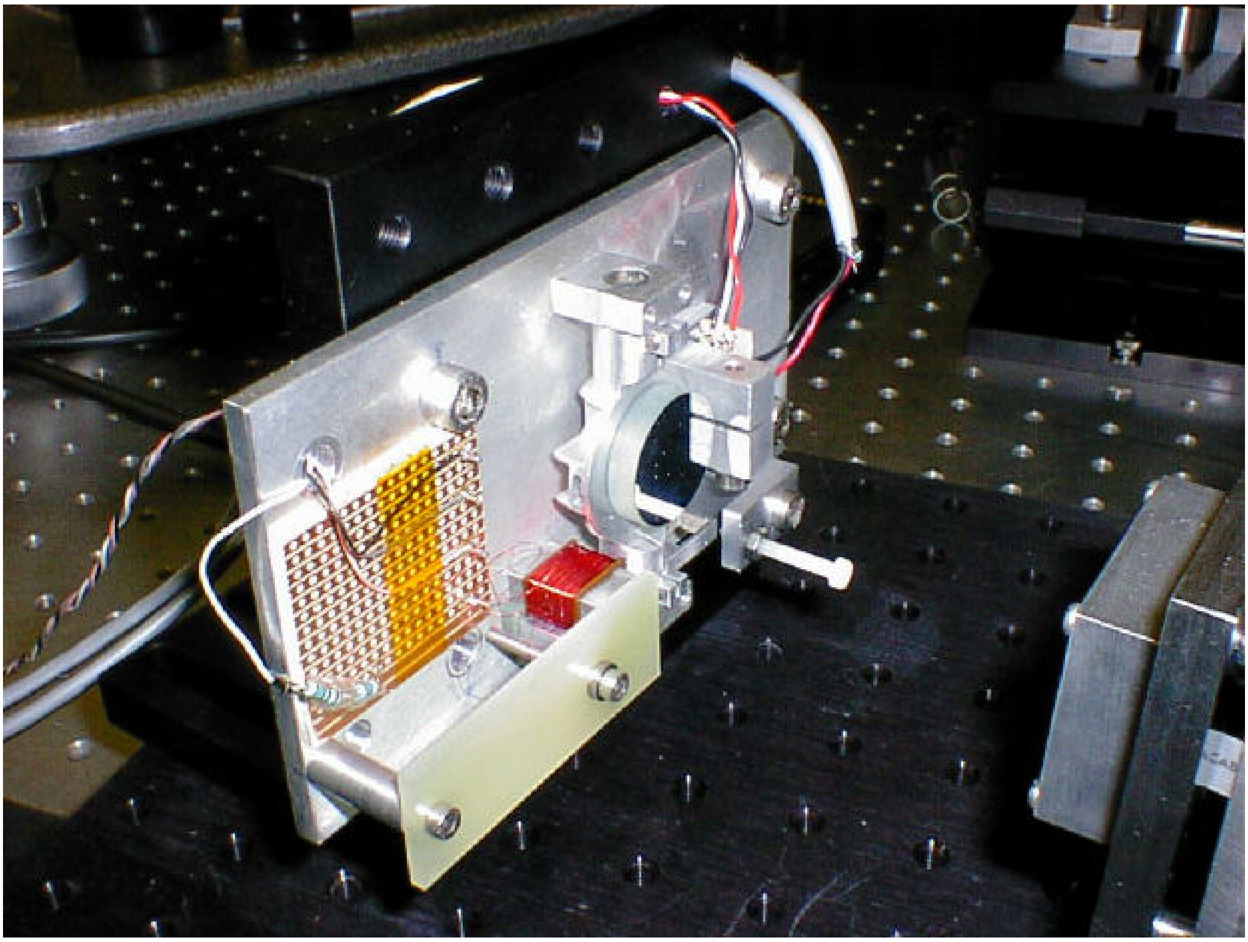
# Appendix 9: Prototype Test Report

As described in the development plan, single and two axis prototypes are being constructed and tested prior to the DM, in order to validate the design of the BSM and identify as early as possible any critical areas, or issues where further development work is needed. For example meeting the requirements for the positional stability and power consumption with the design presented here requires specific performance from the position sensors and the motor torque. The validity of many of these design assumptions can be tested to first order with warm tests of the simple single axis prototype, followed by cold tests and without the need for space rated components. The results of these tests and their conclusions are described in the following sections. The two-axis prototype, which is currently under construction, will be tested in a more rigorous fashion.

## 9 Single Axis Prototype Warm Tests

The single axis prototype BSM was machined to the design drawing so that it had approximately the correct mass. Since the prototype did not have a polished test spot on the surface, a glass mirror was mounted on it for the motor torque measurements. The motor was one of the PACs prototypes assembled in the BSM two coils/one-magnet configuration. A Dspace program constructed in the Simulink programming environment - which emulated the final controlling software (and hardware) - was used to control the motor and monitor the feedback. A PC based ADC provided the interface between the Dspace software and BSM hardware. A photograph of the single axis prototype is shown in figure 1.

Figure 1 - Single Axis Prototype



## 9.1 BSM Control System: Position Sensor Output Noise

### *9.1.1 INTRODUCTION*

The specification requires a maximum position error of 0.34%rms (including motor drift). Allowing 25% of this error to be electrical noise in the position sensor electronics means that the noise limit is 0.085 % of the output of the preamplifier when the mirror is at an end-stop, measured at approximately 11.2V magnitude (see page 13). This gives a maximum noise output of 9.5 mV. Since the BSM design is based on use of the ISOPHOT chopper position sensors, this ought to be the case - however the details of the performance of the position sensors were poorly documented and the SPIRE requirements differ in that they are far more demanding. We therefore carried out the following test of the position sensor output noise.

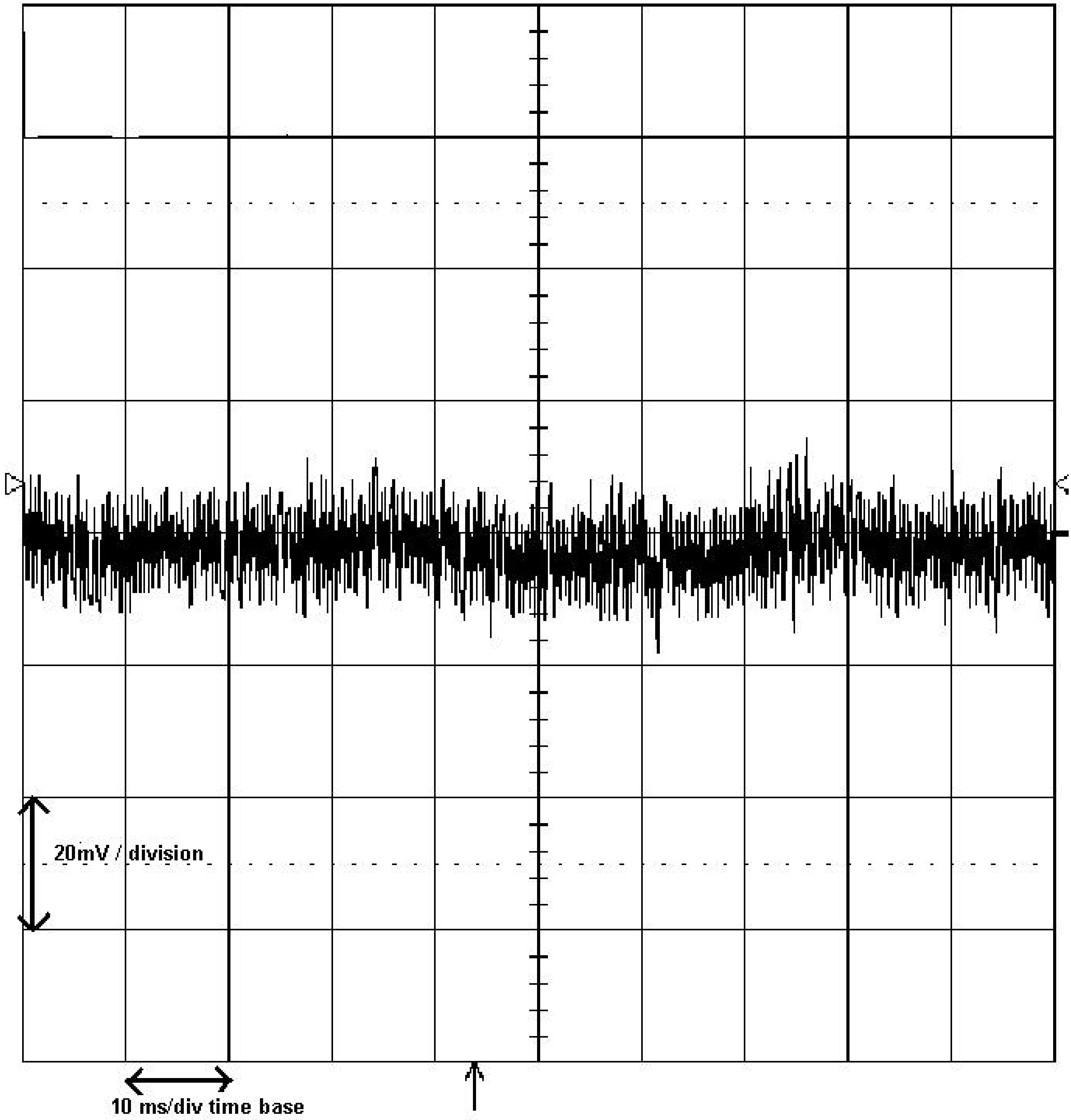
In order to investigate sightline noise in the single-axis BSM prototype, the output from the position sensor and its preamplifier was captured using a Tektronix TDS 224 digital oscilloscope, but without closing the BSM control loop. Therefore the noise measured was due to the sensor and its associated electronics (current source and preamplifier) only. The measured noise was then analysed in the frequency domain using the FFT function on a Hewlett Packard 3562A Dynamic Signal Analyser. If the noise had a flat spectrum, it would be sensible to anti-alias filter it to remove any high frequency element that would be folded down into the control loop bandwidth by the subsequent 10 kHz sampling process.

### *9.1.2 RESULTS*

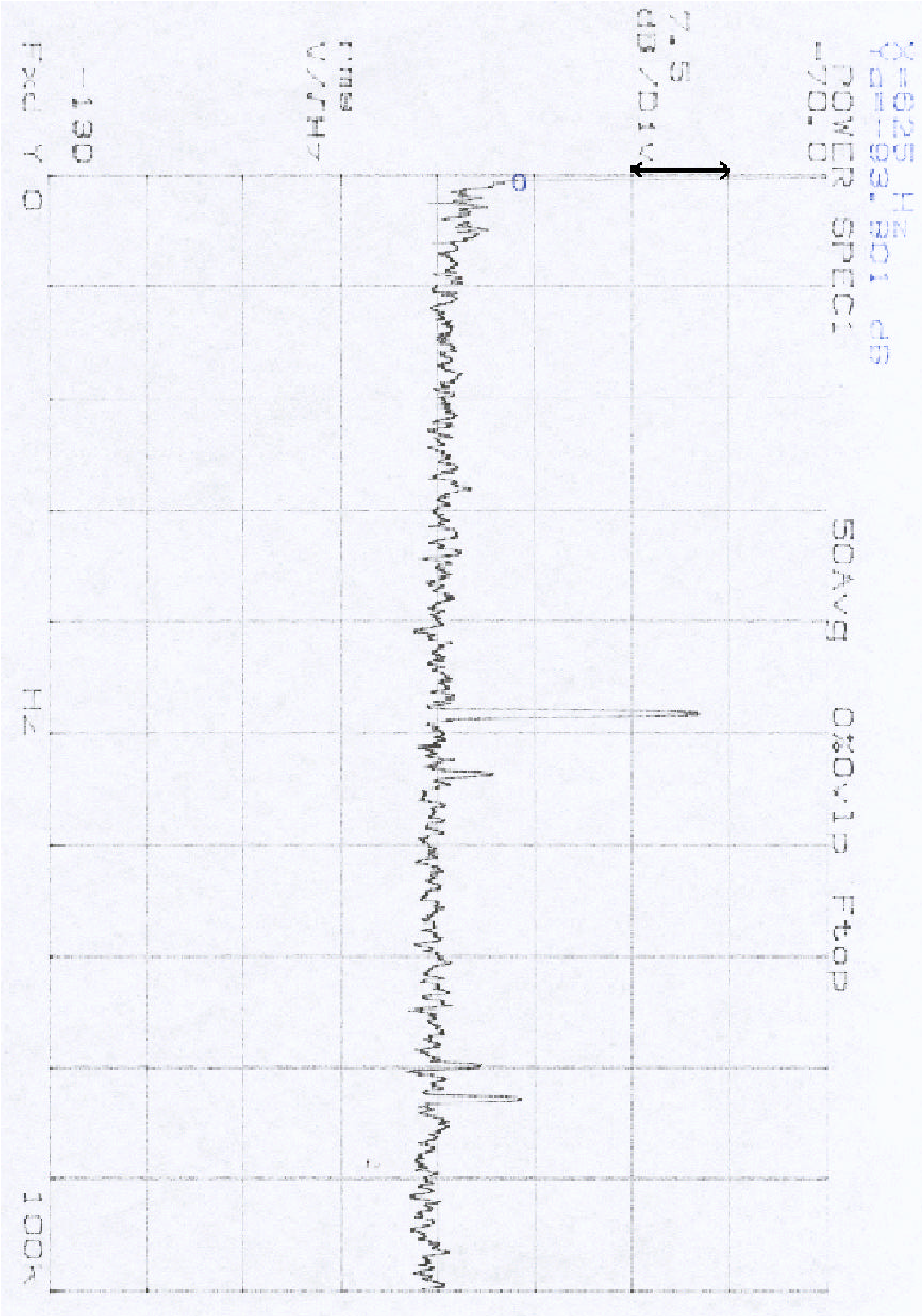
Figure 2 shows the output from the preamplifier, with the motor depowered. The amplitude of the noise is approximately 10mV.

Figure 3 shows the frequency spectrum of the sensor and preamplifier over a 100KHz bandwidth. Implementing a high frequency filter into the electronics can easily eliminate the large peaks at and after 50kHz. Figures 4 and 5 show the spectra for low frequency bandwidth. Figure 5 demonstrates that by even crudely shielding the preamplifier - in this case a very thin metal shield was used - will reduce extraneous noise significantly.

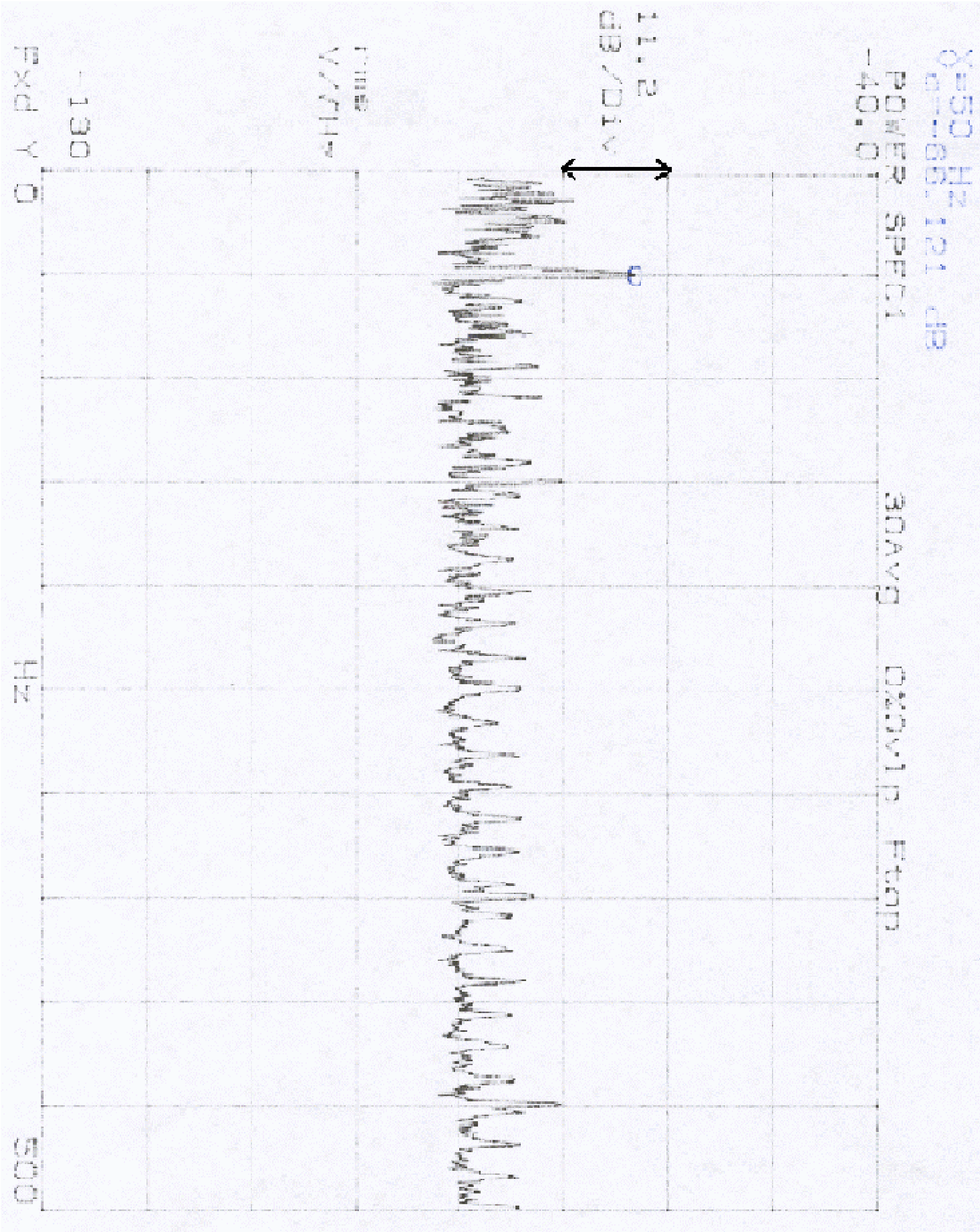
**Figure 2 - Noise in the Sensor and Preamplifier electronics**



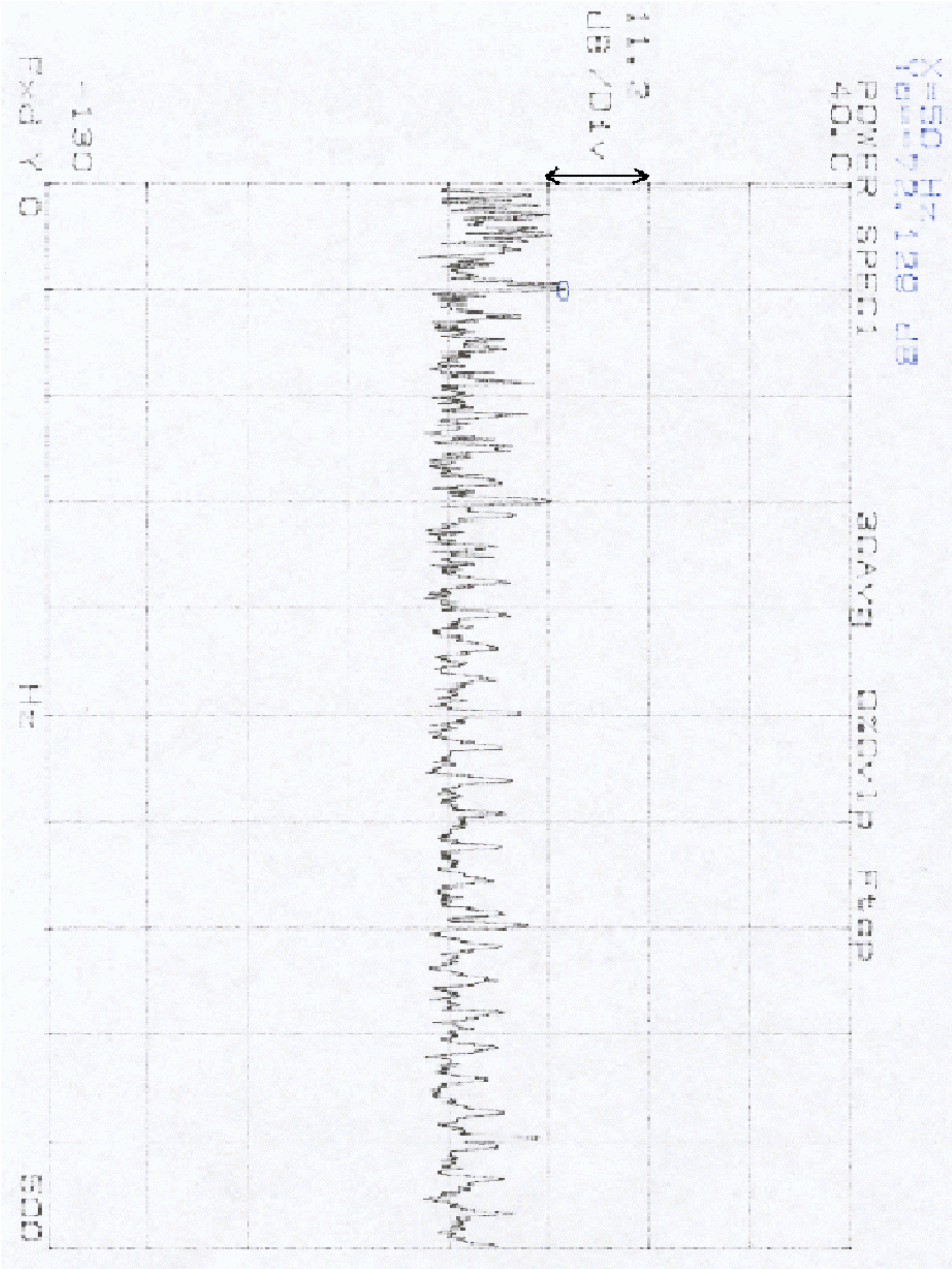
## Figure 3 - 100kHz spectrum bandwidth



## Figure 4 - Ungrounded low frequency spectrum (500Hz bandwidth)



## Figure 5 - Grounded low frequency spectrum (500Hz bandwidth)



#### 9.1.3 CONCLUSION

These tests demonstrate that the noise output of the sensor and preamplifier can be easily brought within the required parameters by implementing a high frequency filter into the sensor electronics and by ensuring that they are properly electromagnetically shielded from external interference.

## 9.2 BSM Electronics: Motor Torque Constant

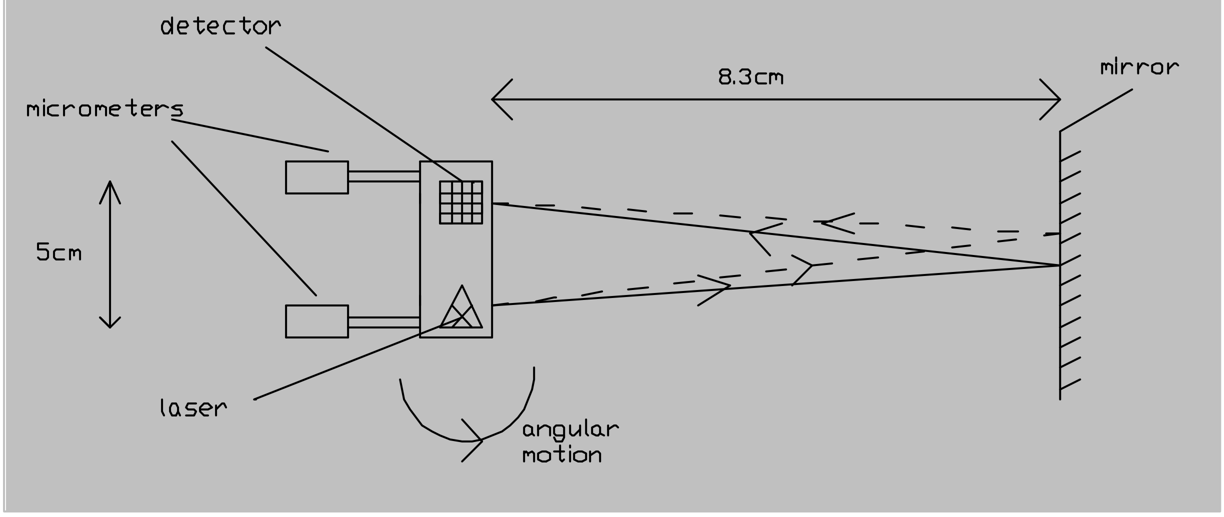
### 9.2.1 INTRODUCTION

The motors used for the BSM are constructed from parts used in the MPIA-designed PACS system. Though the MPIA motors were designed in a thorough manner, UKATC has neither the expertise nor necessary magnetic modelling software to follow a similar process to produce a space-qualified motor. It was in any case desirable to build on the extensive MPIA experience in this area and have some commonality of design between PACS and SPIRE.

Based on simple calculations, it was concluded that two coils and one magnet (from the PACS three-coil two-magnet design) would give the required torques for our lower inertia BSM system. Therefore the motor ‘design’ task is limited to simply verifying this conclusion, by testing.

In order to establish the motor torque constant, the single-axis prototype was tested with various applied voltages, and the subsequent angular movement measured using the ‘C.D.L.’ Tilt Measurement Apparatus (TMA). Figure 6 demonstrates the set-up and configuration of the TMA.

Figure 6 - Tilt Measurement Apparatus Configuration



As the axis was restrained by the flex pivot mountings, which have a known spring constant, the angular movement could be converted to an equivalent force and the motor torque constant derived.

### *9.2.2 RESULTS*

Firstly, the TMA was calibrated using a simple laser reflection against a fixed scale, as shown in figure 6.

The following results were obtained:

Mirror distance to TMA = 8.30E-02 m

| Beam Movement | TMA o/p | angle | Scale Factor rad/pixel |
|---|---|---|---|
| 1.00E-04 | 262 | 2.00E-03 | 7.63E-06 |
| 2.00E-04 | 525 | 4.00E-03 | 7.62E-06 |
| 3.00E-04 | 787 | 6.00E-03 | 7.62E-06 |
| 4.00E-04 | 1045 | 8.00E-03 | 7.66E-06 |
| 5.00E-04 | 1316 | 1.00E-02 | 7.60E-06 |

Average Scale factor = 7.63E-06 Rad/pixel

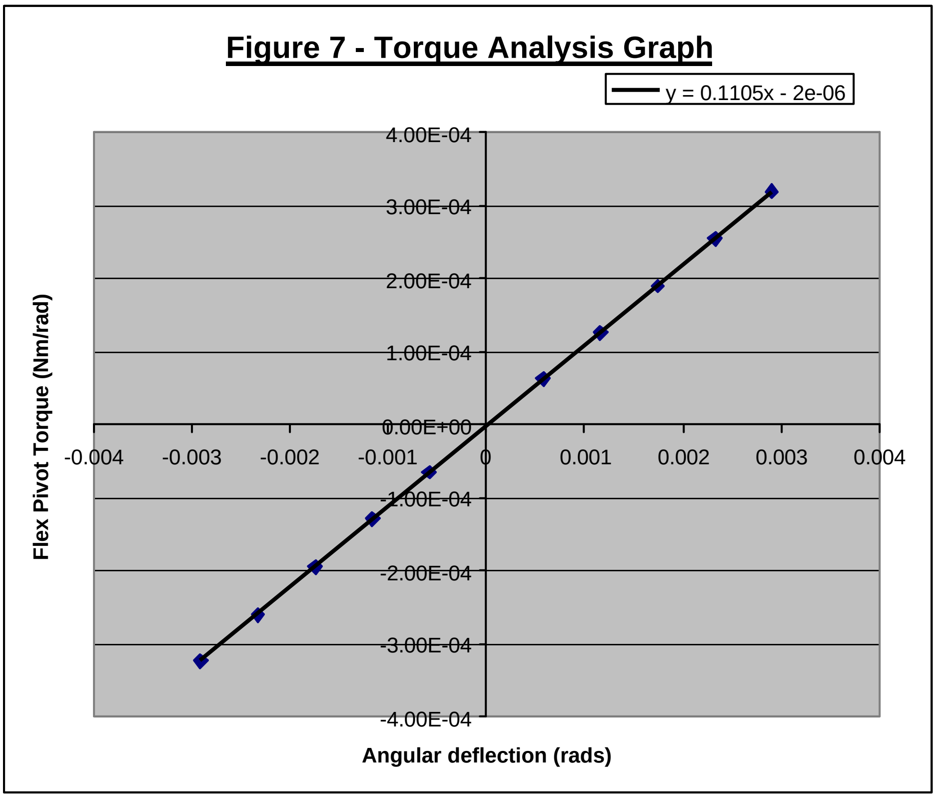
The following test data was obtained by applying a range of voltages to the motor, and using the following measurements and catalogue data:

| | | | |
|---|---|---|---|
| Resistance of coils + series resistor | = | 1720 | ohm |
| Flex pivot scale factor (2 off) | = | 6.40E-02 | N-m/Rad |
| Mirror distance to TMA | = | 8.30E-02 | m |
| Micrometer-to-pivot distance | = | 5.00E-02 | m |
| Magnet distance from centre of rotation | = | 1.70E-02 | m |

| Volts | Current | TMA o/p | angle | Torque | Kt Nm/A | Kf N/A |
|---|---|---|---|---|---|---|
| 5 | 0.002906977 | 655 | 5.00E-03 | 3.20E-04 | 0.109972917 | 6.47E+00 |
| 4 | 0.002325581 | 522 | 3.98E-03 | 2.55E-04 | 0.109553173 | 6.44E+00 |
| 3 | 0.001744186 | 390 | 2.97E-03 | 1.90E-04 | 0.109133429 | 6.42E+00 |
| 2 | 0.001162791 | 259 | 1.98E-03 | 1.26E-04 | 0.108713685 | 6.39E+00 |
| 1 | 0.000581395 | 130 | 9.91E-04 | 6.34E-05 | 0.109133429 | 6.42E+00 |
| -1 | -0.000581395 | -132 | -1.01E-03 | -6.44E-05 | 0.110812405 | 6.52E+00 |
| -2 | -0.001162791 | -265 | -2.02E-03 | -1.29E-04 | 0.111232149 | 6.54E+00 |
| -3 | -0.001744186 | -398 | -3.04E-03 | -1.94E-04 | 0.111372064 | 6.55E+00 |
| -4 | -0.002325581 | -532 | -4.06E-03 | -2.60E-04 | 0.111651893 | 6.57E+00 |
| -5 | -0.002906977 | -662 | -5.05E-03 | -3.23E-04 | 0.1111482 | 6.54E+00 |

| | | Kt Nm/A | | Kf N/A | |
|---|---|---|---|---|---|
| AVERAGE VALUES | = | 0.110272334 | +/- 0.011 | 6.486607909 | +/- 0.649 |

(Error originates from 10% error in flex-pivot scale factor, which is the dominating error in test data. The above data is below presented as a graph.)




### *9.2.3 CONCLUSION*

The tests indicate that an average motor torque constant of 0.11 Nm/A can be obtained for the BSM Chop axis motor. As can be seen from figure 7, the flex-pivot torque varies linearly with the angular deflection of the mirror.

By extrapolation, Figure 7 predicts that at the maximum required angular deflection (+/- 0.042 rad) the motor torque will produce an acceleration sufficient to meet the Angle Step Time requirements. The motor torque will also be enough to meet the required settling times.

## 9.3 SPIRE: Current Source Test

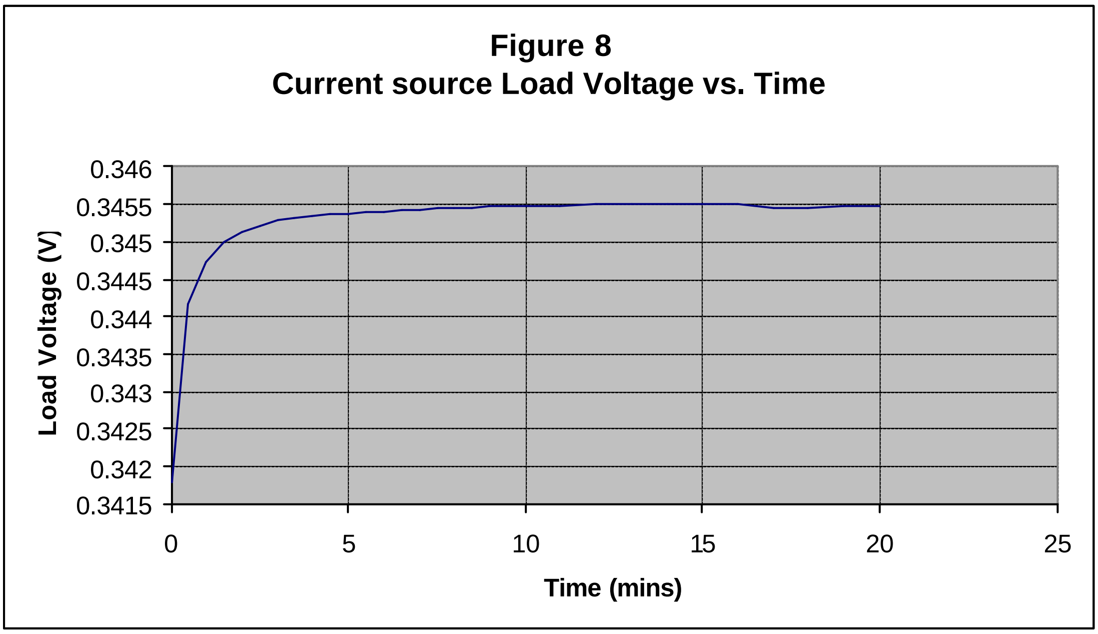
### *9.3.1 INTRODUCTION*

Current source stability directly impacts the long-term stability of the BSM mirror. In order to verify the current source stability with time the ISOPHOT current source design (which is used on the SPIRE BSM) was built with 1% resistors and a 0.1% 333 ohm load and was tested by measuring the load voltage over time using an H-P 3478A multimeter.
Voltage supplies were maintained at +/- 15.1V.

### *9.3.2. RESULTS*

| Time – min. | Load Voltage | % variation from start |
|---|---|---|
| 0 | 0.34180 | 0 |
| 0.5 | 0.34418 | 0.696314 |
| 1 | 0.34472 | 0.854301 |
| 1.5 | 0.34499 | 0.933294 |
| 2 | 0.34513 | 0.974254 |
| 2.5 | 0.34522 | 1.000585 |
| 3 | 0.34528 | 1.018139 |
| 3.5 | 0.34532 | 1.029842 |
| 4 | 0.34535 | 1.038619 |
| 4.5 | 0.34537 | 1.04447 |
| 5 | 0.34538 | 1.047396 |
| 5.5 | 0.34539 | 1.050322 |
| 6 | 0.34541 | 1.056173 |
| 6.5 | 0.34542 | 1.059099 |
| 7 | 0.34543 | 1.062025 |
| 7.5 | 0.34544 | 1.06495 |
| 8 | 0.34544 | 1.06495 |
| 8.5 | 0.34546 | 1.070802 |
| 9 | 0.34547 | 1.073727 |
| 10 | 0.34548 | 1.076653 |
| 11 | 0.34549 | 1.079579 |
| 12 | 0.34550 | 1.082504 |
| 13 | 0.34550 | 1.082504 |
| 14 | 0.34550 | 1.082504 |
| 15 | 0.34550 | 1.082504 |
| 16 | 0.34550 | 1.082504 |
| 17 | 0.34546 | 1.070802 |
| 18 | 0.34545 | 1.067876 |
| 19 | 0.34548 | 1.076653 |
| 20 | 0.34549 | 1.079579 |
| | | |

The results are also plotted in the following graph:




*9.3.3 CONCLUSION*

It is clear (assuming that there is negligible variation in the 0.1% precision resistor) that the source current - after an initial warm-up period - settles to a value that is constant to about 30 PPM. The current source stability will therefore be a negligible component of the position stability requirement, which corresponds to about 0.16% over 4 hours.

## 9.4 Preliminary Cross-talk test

*9.4.1 INTRODUCTION*

An instruction to move the BSM to a given position will consist of two independent orthogonal steps. Given the proximity of motor coils and position sensors it is important that there is no significant cross talk between the motor coils of one axis and the position sensor of the other. If the sensor from one axis was able to detect magnetic field fluctuations caused by motion in the other axis the controlling hardware/software would try to compensate for what it would see as a position error thus reducing position accuracy.

In order to verify that cross talk would be unlikely in the two-axis prototype the sensor output with the motor on was compared to that with the motor off. If there was no distinct change in the results then it would seem unlikely that cross talk would occur.

The experiment was as follows;

1) Position sensor was held in its correct position and it was verified that there was an output when the motor was powered.

2) Removed the sensor and held it in the position of the Jiggle axis sensor. Here no signal was picked up at the output of the sensor amplifier, whilst the chop motor was running. The output from the sensor was the same as when power is removed from the motor, i.e. noise in the sensor circuit only (see figure 2).

3) Moved the sensor close to the motor and still no output was obtained hence there should be no cross talk between the position sensors of the two axes.

4) Replaced the position sensor and found that the sensor had to be very close to the mirror before an output was obtained

### *9.4.2 CONCLUSION*

The results of this experiment strongly suggest that there should be no cross talk between the two axes, therefor positional accuracy will not be jeopardised. This will be confirmed with more precise tests on the two-axis prototype.

## 9.5 Single Axis proto-type Cold tests

### *9.5.1 INTRODUCTION*

In order to test the performance of the BSM at the operating temperature of 4K the single axis prototype described above was fixed inside the cryostat and was cooled in two stages, firstly to 77K using liquid Nitrogen and then to 4K using liquid Helium. As the mirror cooled significantly slower then the base-plate it was concluded that the flex pivots are poor heat conductors - in order for the mirror to cool at a reasonable rate an aluminium shield had to be place over it.

The primary motives for cooling the single axis prototype were;

a) to check whether the power dissipation in the motor coils were within the required parameters (approximately 2mW)
b) measure the resistance of the motor coils at operating temperature
c) to look for changes in the BSM's performance when cooled for potential faults

**Power Dissipation Tests**

Using a Phillips PM5135 Function Generator, an AC voltage wave - sinusoidal, frequency 2Hz - of varying amplitude was used as the input to the motor. An ammeter was placed in series with the input signal so that the rms current could be measured, and thus the total power dissipated in the drive circuit could be calculated. The output from the sensor was viewed on a Tektronix TDS 224 oscilloscope.

To find the resistance of the coils at 5K and at room temperature the coils were probed with a FLUKE multimeter. It was found that the resistance dropped from 330$\Omega$ at room temperature to 60$\Omega$ at 5.2K.

*9.5.2 POWER DISSIPATION RESULTS*

Test results at 5.2K

| Voltage (V) | Current (A) | Total Power (W) | Sensor offset (V) | sensor fdbk (pk-pk) (V) |
|---|---|---|---|---|
| 0.5 | 2.75E-03 | 9.72E-04 | -4.6 | 6.4 |
| 1 | 5.80E-03 | 4.10E-03 | -3.6 | 12.6 |
| 1.5 | 8.90E-03 | 9.44E-03 | 0 | 16.4 |
| 2 | 1.14E-02 | 1.61E-02 | 0 | 18.8 |
| 2.5 | 1.41E-02 | 2.49E-02 | 0 | 22.4 |
| 3 | 1.73E-02 | 3.67E-02 | 0 | 22.4 |
| 3.5 | 1.97E-02 | 4.88E-02 | 0 | 23.2 |
| 4 | 2.14E-02 | 6.05E-02 | 0 | 23.2 |
| 4.5 | 2.46E-02 | 7.83E-02 | 0 | 23.2 |
| 5 | 2.75E-02 | 9.72E-02 | 0 | 23.2 |

Test results at 295K

| Voltage (V) | Current (A) | Total Power (W) | Sensor offset (V) | sensor fdbk (pk-pk) (V) |
|---|---|---|---|---|
| 0.5 | 5.70E-04 | 2.02E-04 | -7.60E-01 | 7.60E-01 |
| 1 | 1.55E-03 | 1.10E-03 | -7.60E-01 | 1.4 |
| 1.5 | 2.00E-03 | 2.12E-03 | -7.60E-01 | 2.9 |
| 2 | 2.63E-03 | 3.72E-03 | -7.60E-01 | 3.8 |
| 2.5 | 3.35E-03 | 5.92E-03 | -7.60E-01 | 5 |
| 3 | 3.92E-03 | 8.32E-03 | -7.60E-01 | 6 |
| 3.5 | 4.70E-03 | 1.16E-02 | -7.60E-01 | 7.2 |
| 4 | 5.21E-03 | 1.47E-02 | -7.60E-01 | 8.2 |
| 4.5 | 5.80E-03 | 1.85E-02 | -7.60E-01 | 9 |
| 5 | 6.60E-03 | 2.33E-02 | -7.60E-01 | 9.8 |

These results were then plotted on a graph:

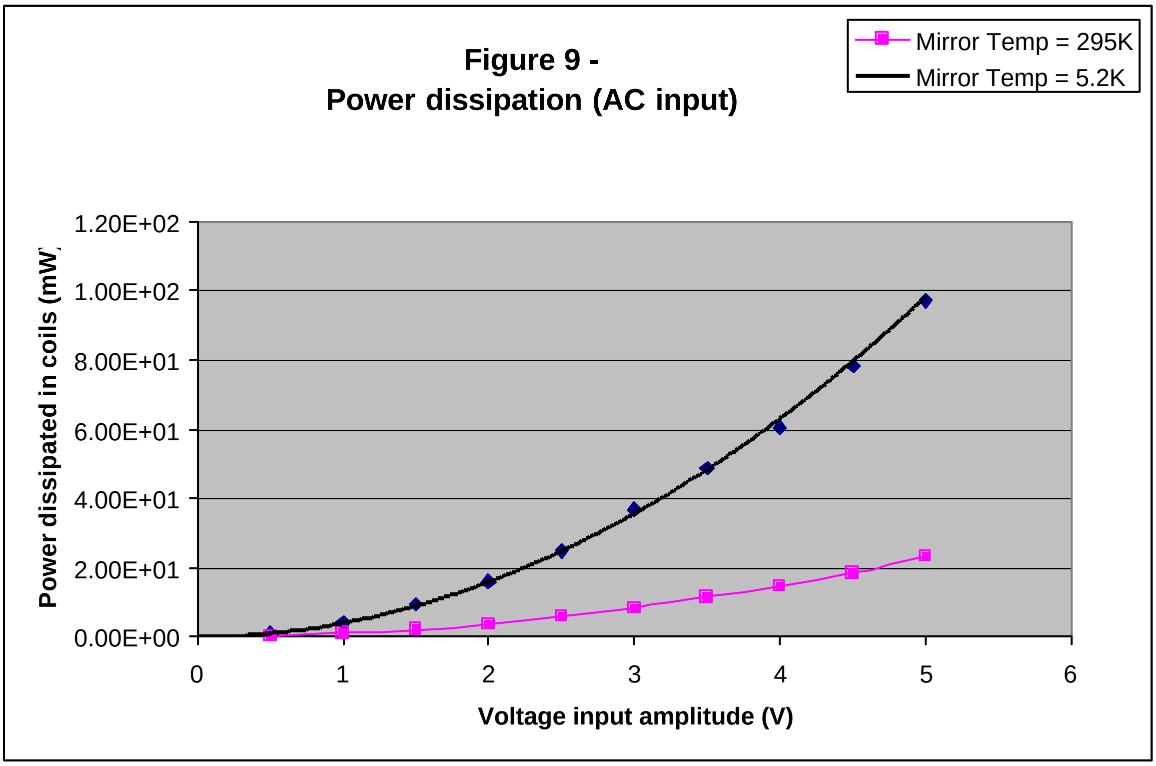


Figure 9 -
Power dissipation (AC input)
Mirror Temp = 295K
Mirror Temp = 5.2K
Power dissipated in coils (mW)
1.20E+02
1.00E+02
8.00E+01
6.00E+01
4.00E+01
2.00E+01
0.00E+00
0
1
2
3
4
5
6
Voltage input amplitude (V)

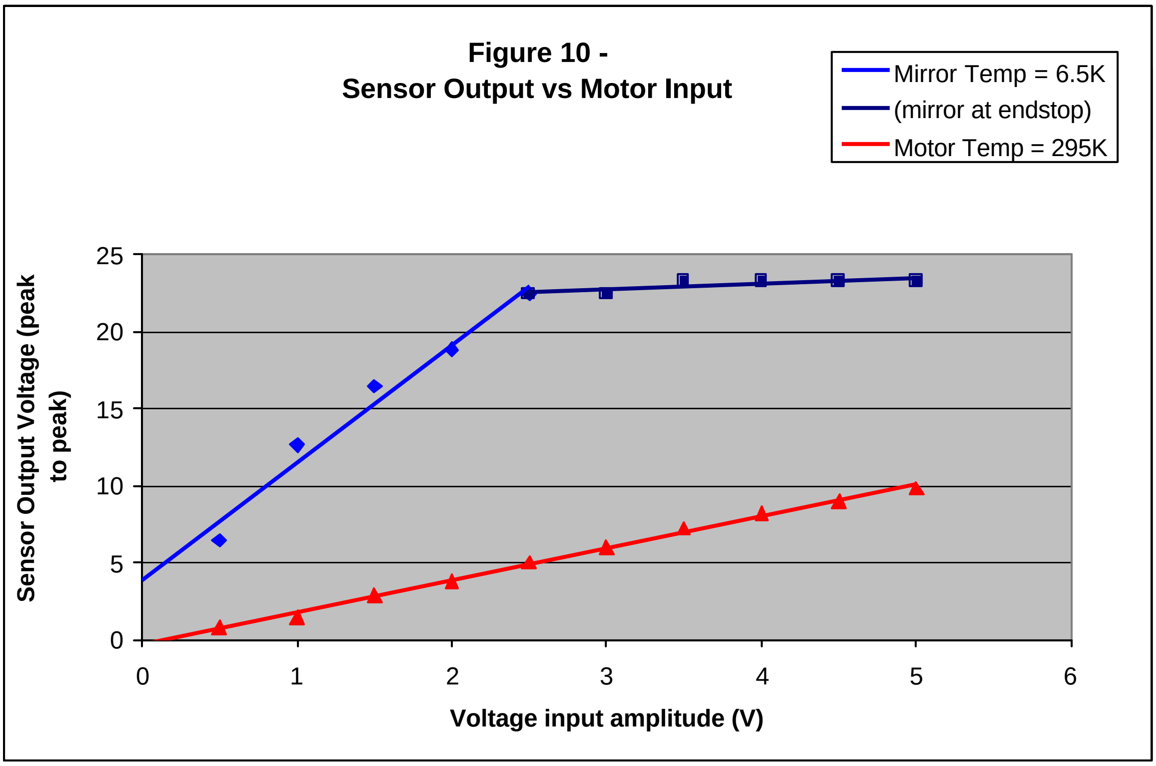


Figure 10 -
Sensor Output vs Motor Input
Mirror Temp = 6.5K
(mirror at endstop)
Motor Temp = 295K
Sensor Output Voltage (peak to peak)
25
20
15
10
5
0
0
1
2
3
4
5
6
Voltage input amplitude (V)

*9.5.2 POWER DISSIPATION CONCLUSION*

Far more power is dissipated when the motor is cold. This is because as the temperature decreases the resistance of the coils will decrease, so if the input voltage is kept constant as the temperature drops the current (and therefore the power dissipated) through the coils will increase. Figure 10 shows the sensor output levels at about 2.5V suggesting the motor has reached its endstop. It also indicates that a current of around 22mA will be sufficient to drive the motor to an end-stop.
There are two reasons why the measured power dissipation in these tests was far greater then the 2.5mW requirement. The first is that the single-axis prototype motor coils were constructed out of copper, which is not superconductive at 5K. It is hoped that aluminium, which has a far lower resistance when cold, will be used in future test (and the flight) models. A coil resistance of 5 $\Omega$ (combined with a reduced input voltage) would be sufficient to bring the dissipation down to the specification requirement. An input voltage of 0.11V would generate the 25mA current required to move the motor to an endstop. A second reason is that in these tests a 2Hz continuous sine wave was used as the motor input signal whereas a DC input would have been a better representation (in practice the mirror would not be continuously moving). It is possible that this may have also significantly effected the results.
More cold tests are required (and are planned) to verify these conclusions.

## 9.6 Two- Axis proto-type

The two-axis prototype is, at the time of writing, nearing completion. More varied and rigorous tests are planned for the two-axis model, including a repeat of all the tests described here on the Jiggle axis. Figure 11 shows the Two-Axis Prototype at its current status.

Figure 11 - Two-Axis Prototype