Introduction

This note attempts to outline the systems level criticality of the failure, or partial failure, of one or more of the SPIRE cold FPU sub-systems. There is no distinction made in this discussion of where the failure might occur: that is it could be mechanical failure of the cold system; a failure in the wiring harness or a failure in the control electronics or software. This note does not discuss the likelihood of any sub-system failing, only the scientific and operational consequences of the failure with a view to identifying the mission critical sub-systems and failure modes that must be addressed in the design of the sub-system and its drive electronics. For the purposes of this note, the SPIRE sub-systems are as shown in figure 1.

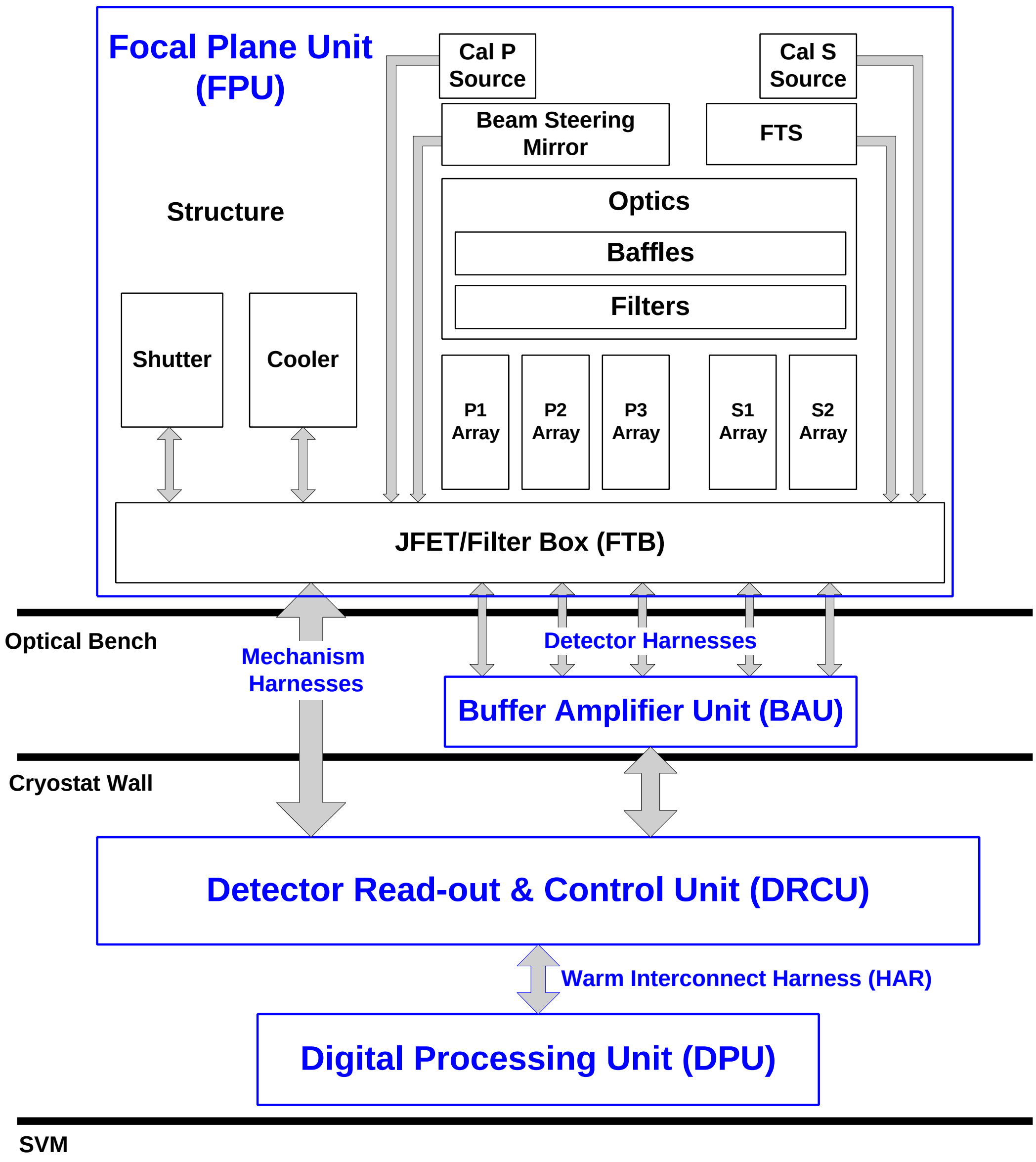

Figure 1: Schematic Representation of the SPIRE sub-systems

Sub-system Criticality

Sub-system	Failure mode	Consequence	Remedial Action	System Level Redundancy
1. Cooler	**a.** Loss of ^{3}He cooling	Total loss of instrument	None	None
	b. Partial loss of ^{3}He cooling (ineffective or inefficient recycling; abnormal thermal load at 300 mK etc etc)	Possible inability to operate all arrays simultaneously. Possible operational constraints if large impact on lifetime.	Operate instrument to minimise thermal load at 300 mK Operate only photometer or only spectrometer during one "recycle" Switch off arrays when not in use. Use only part of photometer arrays.	Fully flexible operations.
2. Photometer Arrays (all types)	**a.** Total loss of short wavelength array	Simultaneous three band photometry lost Mapping of large regions in three bands will be very much slower using spectrometer	Possible to use spectrometer with reduced sensitivity and reduced FOV (see note 1)	Spectrometer SW array
	b. Total loss of medium wavelength array	Ditto	Ditto	Spectrometer LW array
	c. Total loss of long wavelength array	Long wavelength photometry lost for whole of FIRST	None	None
3. Filled Photometer Arrays	**a.** Loss of one line of pixels of any array (see note 2)	More complex jiggle/chop mode required to achieve fully sampled FOV Small loss in scan mapping ability	Use BSM to "fill in" missing row or column in jiggle/chop mode Always scan "across" missing row or column in scan mode	Many rows and columns
	b. Loss of one block of pixels of any array	Depending on the size of the block (16x16 in CEA case?), will have to use up to full chop throw of BSM to recover fully sampled FOV. If block is greater than 2 arcmin then will need to use satellite Scan mode suffers a greater loss in	Use BSM to "fill in" missing block if less than 2 arcmin Use satellite and BSM together if greater than 2 arcmin	A few blocks per array (8 for SW how many for the others?) Block size <2

Sub-system	Failure mode	Consequence	Remedial Action	System Level Redundancy
		sensitivity		arcmin on sky
4. Feedhorn Photometer Arrays	**a.** One pixel fails	Slight increase in jiggle chop mode complexity to achieve fully sampled FOV Small loss in scan mode sensitivity If the pixel lost is one of the four “prime” pixels then another will have to be used for setting up the pointing of the observations (see note 3) If one of the prime pixels is lost then observations using satellite nodding are less efficiently carried out.	Use BSM to fill in for missing pixel if required by observation.	Four “prime” pixels in each array – redundant as two pairs? (see note 3)
	b. One row or column of pixels fails	Same as for filled array row/column	As for filled array row/column	Many columns; not so many rows (see note 3)
	c. One block fails	Same as for filled array block	As for filled array block	In principle as many “blocks” as rows? (see note 3)
5. Spectrometer Arrays (all types)	**a.** Loss of short wavelength array	Total loss of low/medium resolution spectroscopy on FIRST in 200-300 micron waveband	None	HIFI may cover this range at much higher spectral resolution
	b. Loss of long wavelength array	Total loss of low/medium resolution spectroscopy on FIRST in 300-400 micron waveband	None	HIFI will cover this range at much higher spectral resolution

Sub-system	Failure mode	Consequence	Remedial Action	System Level Redundancy
6. Filled Spectrometer Arrays	**a.** Loss of one line of pixels in any array	Loss of instantaneous full spatial sampling of FOV Loss in sensitivity in full spatial/spectral imaging mode	Use BSM to "fill in" missing row or column	Many (12?) rows and columns
	b. Loss of block of pixels in either array	If arranged as single block per 16x16 array then total loss of this channel	None	As per **5a.**
7. Feedhorn Spectrometer Arrays	**a.** Loss of any one pixel	If centre pixel then will have to nominate off axis pixel as "prime". Possible loss of sensitivity and spectral resolution using off-axis pixel Obtaining a fully sampled image will be more difficult.	Offset pointing of satellite from on-axis beam More complicated jiggle mode BSM operation to fill in for missing pixel.	Many pixels. Must have more than one co-aligned pixel in the two arrays (see note 4)
	b. Loss of any one line of pixels	If line passes through the centre then maybe impossible to have simultaneous spectrum of point source in both arrays (see note 4). Possible loss of sensitivity and spectral resolution using off-axis pixels. Obtaining fully sampled image will be more difficult	Offset pointing of satellite from on-axis beam More complicated jiggle mode BSM operation to fill in for missing line.	A few lines – especially in LW array Must have more than one co-aligned pixel for *any* line failing

Sub-system	Failure mode	Consequence	Remedial Action	System Level Redundancy
7. Feedhorn spectrometer arrays (ctd)	**c.** Loss of any block of pixels	If whole array is a single block then total loss of this channel. If arranged as small (say 7-element) blocks then impossible to avoid loss of centre pixel. Very difficult/slow to obtain fully sampled image.	Offset pointing of satellite from on-axis beam Nod satellite to fill in missing block for mapping.	A few blocks in SW array – only one for LW array. Must have more than one co-aligned pixel for *any* block failing in SW array
8. Beam Steering Mechanism	**a.** Total loss	All jiggle/chop modes lost No modulation of signal in pointed modes – must use bias modulation If feedhorn arrays implemented then: Full sampling of FOV in photometer only possible in scan mode Full sampling of FOV is not possible in spectrometer Partial recovery of spatial sampling possible using satellite fine raster - slow Optimum sampling algorithms cannot be used leading to potential loss in signal/noise – any super resolution modes are lost. Photometry of extended sources will be difficult without chop – use satellite instead with loss in efficiency due to overheads	Use scan mode for full sampling of FOV Satellite nodding must be used to remove any telescope temperature drift and to replace chopping for extended sources Satellite fine raster mapping could be used to partially recover sampling for feedhorn arrays	Two axes in BSM – total failure less likely Bias modulation must be implemented for all detector options. Satellite operations

Sub-system	**Failure mode**	**Consequence**	**Remedial Action**	**System Level Redundancy**
8. Beam Steering Mechanism (ctd)	**b.** Loss of chop axis	Pixel chopping still possible – large chopping lost If feedhorn arrays implemented then: Full sampling of FOV in photometer only possible for special arrangement of pixels (? see note 5) Full sampling of FOV is not possible in spectrometer (? see note 5) Photometry of extended sources will be difficult without chop – use satellite instead with loss in efficiency due to overheads	Satellite nodding must be used to remove any telescope temperature drift and to replace chopping for extended sources	Satellite operations
	c. Loss of jiggle axis	If feedhorn arrays implemented then: Full sampling of FOV in photometer only possible for special arrangement of pixels (? see note 5) Full sampling of FOV is not possible in spectrometer (? see note 5)	None needed for filled arrays Use satellite fine raster to partially compensate for loss of jiggle axis for feedhorn arrays	Satellite operations
	d. Partial failure: High dissipation; sticking; restricted range of movement etc	Reduction in use of chopper Slower chop rate Increased systematic noise Increase in straylight from higher temperature motor	Change method and/or frequency of operation; chop down or, in extremis, go to only scan mode to modulate signal	Flexible operations – well defined backup modes
9. FTS Mirror Mechanism	**a.** Total loss	Loss of all low /medium resolution spectroscopy on FIRST	None	HIFI covers part of wavelength range at much higher spectral resolution

Sub-system	Failure mode	Consequence	Remedial Action	System Level Redundancy
	b. Partial failure: High dissipation; sticking; restricted range of movement etc	Reduction in use of spectrometer Loss of higher spectral resolution Increased systematic noise Increase in straylight from higher temperature motor	Change method and/or frequency of operation; slow mirrors down or, in extremis, go to step and integrate using BSM to modulate signal	Flexible operations – well defined backup modes
10. FTS mirror position sensor	**a.** Total loss	Inability to accurately know where the mirrors are or correct velocity Increase in systematic noise	Use motor current to reconstruct mirror position for rapid scanning Use motor current commanding to go to fixed positions and go to step and integrate using BSM to modulate signal	Ditto
	b. Partial loss – loss in signal or loss of one or more detectors	More noise on mirror position - may prevent accurate velocity correction Increase in systematic noise	Slow mirrors down	Ditto
11. Photometer calibrator	**a.** Total loss	Inability to monitor drift in detector responsivity Calibration will be slower leading to loss in instrument efficiency	Set up network of secondary astronomical calibration sources over as much of sky as possible.	Secondary calibrators identified before launch (ground based program?)
	b. Partial failure – loss in output or frequency response; higher than expected dissipation etc	Possible loss in accuracy of detector responsivity drift Make take longer to calibrate thus reducing instrument efficiency	Reduce number of calibration operations Reduce operating frequency – in extremis use as DC source with detector bias modulation. Reduce temperature of operation	Flexible operations – well defined backup modes
12. Spectrometer	**a.** Total loss	No compensation for telescope background	Gain switching in amplification	Flexible operations

Sub-system	**Failure mode**	**Consequence**	**Remedial Action**	**System Level Redundancy**
calibrator		Increased systematic noise on low resolution spectra Dynamic range limit hit on amplifiers/digitisation Loss of automatic absolute calibration – calibration will be slower leading to loss in instrument efficiency	chain to avoid problems with digitisation noise Methods to reduce data rate will be required as will now need 16 bits to encode detector signals around ZPD Slow down mirrors Take only data from centre detectors More "lossless" data compression In extremis go to step and integrate using BSM. Use of secondary astronomical calibration sources	– well defined backup modes Secondary calibrators identified before launch (ground based program?) or use sources identified by HIFI?
12. Spectrometer calibrator (ctd)	**b.** Partial failure – loss in output; higher than expected dissipation etc	Not possible to compensate properly across whole wavelength range Increased systematic noise on low resolution spectra	Run source at a lower temperature; use the spectrometer less often.	Flexible operations - well defined backup modes.
13. Thermometers and thermal control system	**a.** Loss of one or more structure; mechanism or warm electronics thermometers	No real impact in flight – behaviour of cold instrument well known from ground test One exception is that loss of some thermometers may cause problems with diagnosis of any problems	Use nearest neighbour	Many thermometers more important ones will have full redundancy
	b. Loss of 300 mK thermometers (on evaporator or detectors)	Makes detector calibration more difficult	Use thermometers at other locations on 300 mK stage.	At least six thermometers on 300 mK stage

Sub-system	**Failure mode**	**Consequence**	**Remedial Action**	**System Level Redundancy**
	No thermal control case			Well defined and tested backup modes
13. Thermometers (ctd)	**c.** Loss of 300 mK thermometer on control node in thermal control circuit	Possible increase in systematic noise for all detectors	If possible use thermometers at other locations on 300 mK stage	Multiple redundancy of control node thermometers. Back up mode of using thermometers at other locations fully defined and tested on the ground.
	d. Loss of heater(s) on control node in thermal control circuit	Possible increase in systematic noise for all detectors	Run cooler open loop	Multiple redundancy of control node heaters. Back up mode of using cooler open loop fully defined and tested on the ground

Table 1: Criticality analysis for the SPIRE cold FPU sub-systems.

Notes:

1. Use of Spectrometer to cover for Photometer

The spectrometer will have about half the throughput of the photometer over the 200-300 μm band and the 300-400 μm band. Its performance above 400 μm is not guaranteed and we should not rely on it for redundancy purposes. The field of view of the spectrometer will be ~2x2 arcmin for filled arrays and 2.6 arcmin diameter for the feedhorns. The area is thus approximately 5 arcmin^2. The area of the FOV for the photometer is 4x8 = 32 arcmin^2.

The speed of mapping will to first order be ~ (0.5)*(5/32) = 0.078 or 13 times slower.

2. Failures in filled arrays

The loss of a line of pixels of pixels is indicated in figure 2.

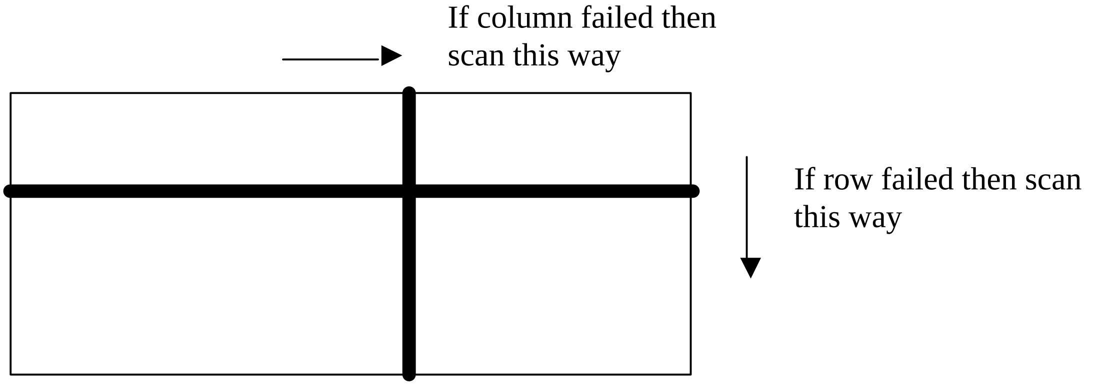

Figure 2: Loss of a row or column. To avoid complicated scan modes, the direction of scan should be “across” the line as shown.

The loss of a block of pixels is indicated in figure 3

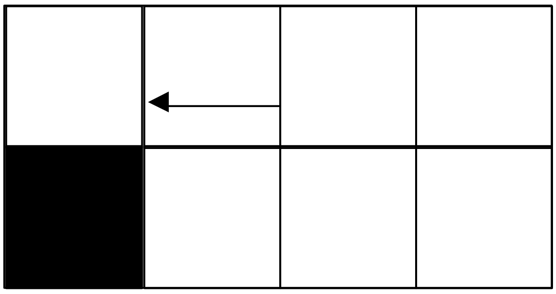

Figure 3: Loss of a block of a filled arrays for the case of 16x16 pixel arrays making up the 32x64 short-wavelength array. The arrow indicates the distance required for the BSM to move - 2 arcmin – to cover failure of any block in pointed mode

3. Failures in photometer feedhorn arrays

As shown in the Operating Modes Document, if the three arrays have central wavelengths of 250, 333 and 500 μm then there will be four co-aligned pixels along the central long axis of the arrays. Any one of these four positions can be used as the prime detector for placing a point source on the array for simultaneous observations in all four bands. It makes the chopped observations easier if the source can be swapped from one prime position to another so these should be counted as two pairs for redundancy purposes.

When the satellite is nodded one pixel of the alternate pair is used – see figure 4. If either of the central two prime detector locations suffers a failure then nodded observations will be much less efficient as several non/chop positions will be need to make up for the loss of the co-aligned pixels across the three arrays.

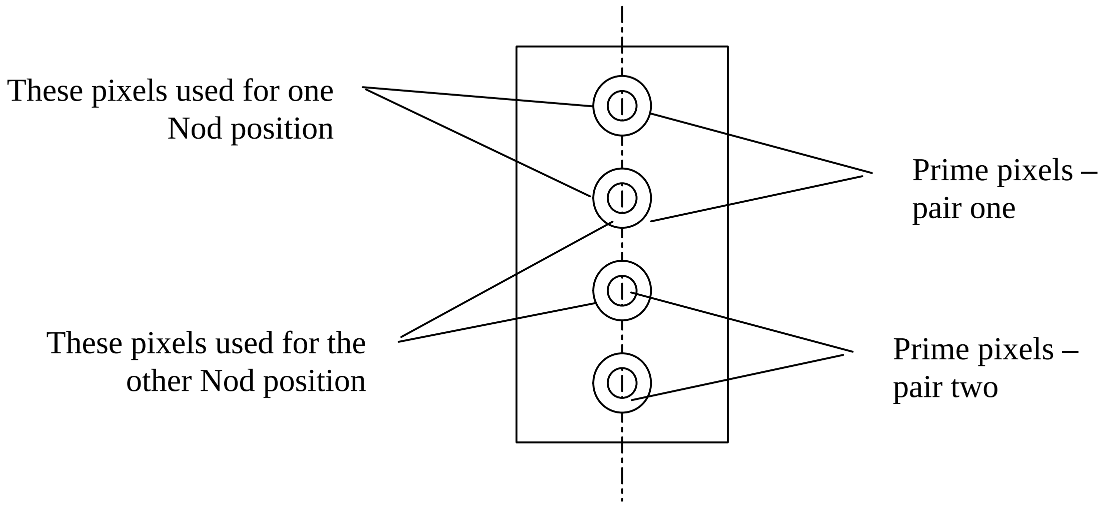

Figure 4: Sketch showing arrangement of co-aligned "prime" pixels on feedhorn arrays. The source is chopped from one of the pixels in a pair to the other. When the satellite is nodded one pixel of the other pair is used.

4. Failures in spectrometer feedhorn arrays

The feedhorn arrays for the spectrometer will be hexagonally close packed with 37 detectors for the shortwavelength (central wavelength 250 μm) array and 19 detectors for the longwavelength (central wavelength 350 μm) array. The outer edges of each array will likely suffer from reduced performance due to vignetting – the outer ring of pixels in each array is therefore not to be considered for redundancy purposes. We therefore would have truly redundant arrays of 19 and seven pixels respectively.

If the pixels are arranged to be operated, i.e. sharing electronics or wiring, in rows as shown in figure 5; then the loss of the central line in either array will mean that there would be no co-aligned pixels. This means the loss of the simultaneous wavelength coverage for a single pointing of the satellite.

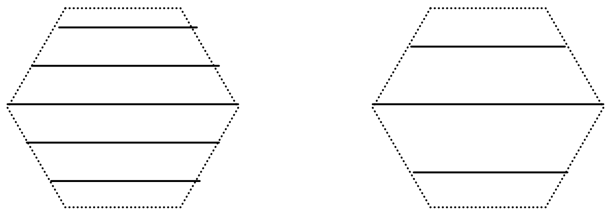

Figure 5: Sketch showing the possible arrangement of rows of pixels within the 250 and 350 µm arrays in the spectrometer. The rows are of 3,4,5,4,3 and 2,3,2 pixels respectively.

The alternative might be to allow the pixels to share systems (electronics or wiring) in hexagonal blocks of, say, seven pixels. This is as problematic because a) hexagons don’t tessellate and b) one again cannot avoid the centre pixel in the longwavelength array.

5. Arrangement of feedhorns for fully sampling with one chop/jiggle axis?

For at least the spectrometer arrays, it would be possible to make fully sample images with only one BSM axis operating if the feedhorn arrays were orientated at 14.5^{o} with respect to the chop axis direction as shown in figure 6. This is the same as the proposed direction of satellite scanning for the photometer arrays to make fully sampled scanned images. The photometer arrays could also be orientated like this to give fully sampled images with only one BSM axis, however doing this both reduces redundancy within the array and makes chopped/nodded observations more complicated to carry out.

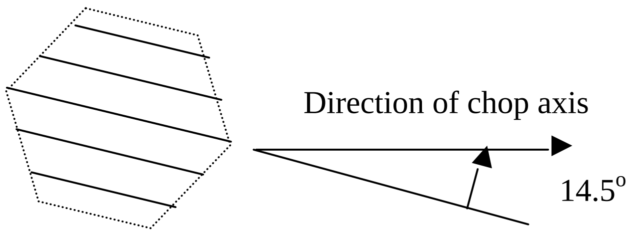

Figure 6: Sketch showing the possible rotation of the 250 and 350 µm arrays in the spectrometer to allow the images to be fully sampled using only one axis of the BSM.

Conclusions

The mission critical failures are those in the table where there are no straightforward system level redundancies – i.e. where "None" appears in the **Remedial Action** and/or **System Level Redundancy** columns. To summarise these are:

- Total loss of the cooler
- Total loss of the photometer long wavelength array
- Total loss of either spectrometer array
- Total loss of the FTS mirror mechanism

All other failures will lead to a greater or lesser degree of loss of performance and difficulty of operation, but they do not lead to a total failure of either the photometer or spectrometer scientific goals. The redundancy and reliability of these sub-systems must be addressed as a first priority.

The following recommendations can also be made from the analysis of the array failure criticality discussed here.

1. Filled arrays should be operated in rows or columns in preference to blocks. This is especially true for the spectrometer, where the loss of one block of pixels means the loss of a whole channel. If this is impossible due to the architecture of the arrays, then extra care must be taken in the systems design to ensure that any failure modes that lead to the potential loss of the entire block are eradicated.

2. The photometer feedhorn arrays should be arranged, i.e. sharing of control lines; amplifiers; ADC's etc, in rows or columns; preferably rows as this gives maximum redundancy. Especial care must be taken over the reliability of the inner two prime pixels in each array as the loss of any one of these across the three arrays would cause a loss in operational efficiency.

3. The loss of the central pixel of the spectrometer feedhorn arrays will cause a lot of difficulty in the operation of the spectrometer. Consideration should be given to the arrangement of the spectrometer feedhorn pixels to try to provide some redundancy.

4. Consideration should be given to rotating the spectrometer feedhorn arrays so that the loss of one axis of the beam steering mirror does not prevent the taking of fully sampled spectral images. This could also lead to more efficient operation of the spectrometer when taking fully sampled spectral images.