Calibration Cryostat Filter Model

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Change Record

Date	Index	Affected Pages	Remarks
11-November-2000	Draft 0.1	All	First draft to Peter Ade and Anna Orlowska
05-October-2001	Issue 1.0	All	Formal issue with introduction, reference documents etc. Corrections to IDL source code.

Applicable Documents

	Title	Author	Reference	Date
AD 1	Outline Specification of the SPIRE instrument calibration facility	B. Swinyard	SPIRE/RAL/N/0058	03-March-2000
AD 2	Telescope Simulator Optical Design	M. Ferlet	SPIRE-RAL-NOT-000622	22-May-2001

Host system	Windows 2000
Word Processor	Microsoft Word 2000
File	Filter model.doc

1 Introduction

The main requirement for the cryostat filters is to reduce the signal power at the SPIRE detectors from external sources (e.g. 3000K blackbody on 300K background) to the same magnitude as seen in flight. The Mathcad model of the instrument produced by Matt Griffin put these powers at [AD1]

Band1 (210-290μW) = 7.44pW
Band2 (300-400μW) = 5.26pW
Band3 (417-583μW) = 4.77pW

The second requirement for the filters is to limit the heat loads on the 10K and 4K environment so that the hold time on the cryogen tanks is optimised. The baseline design for the cryostat gives a hold time of 100hours with the SPIRE instrument off. Obviously this hold time would be compromised if there was a significant heat load from the 300K environment.

The purpose of this technical note is to define a simple model that will represent the filtering scheme of the calibration cryostat, and estimate the thermal heat loads on the filters at each temperature stage. The reasons for developing this model are twofold; First, thermal modelling packages such as ESATAN generally use broad band values for emissivity, reflectance and transmission. It is not trivial to incorporate the type of spectral properties that we wish to model. Secondly the filter models developed by Bruce/Matt were based on an earlier version of the cryostat and have not been updated to reflect the current design [AD1].

2 Radiometric Model

I've basically taken Bruce's Mathcad model of the cryostat and instrument filter model and recoded it in IDL so that I can feed in different filter characteristics to control the power at the instrument detectors.

The power contribution at the detector is given by

$$P(A\Omega,\lambda,T,\tau_d,\varepsilon)=\int_{\lambda\,\mathrm{min}}^{\lambda\,\mathrm{max}} A\Omega\tau\varepsilon L(\lambda,T)\,d\lambda\times10^{12}\ \text{pW} \qquad 1)$$

Where λ is the wavelength in μm, T is the temperature in K, τ_d is the transmission/reflectance through intervening filters/mirrors to the detectors, and ε is the emissivity. The throughput AΩ is diffraction limited, i.e.

$$A\Omega=\left(\lambda\times10^{-6}\right)^2 \qquad 2)$$

The radiance, L(λ,T) is calculated using the Planck function

$$L(T,\lambda)=\varepsilon\frac{2hc^2}{\lambda^5\exp\left(hc/kT\lambda\right)-1}\ \text{Wcm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1} \qquad 3)$$

The bandwidth of the SPIRE channel covers the range λmin to λmax. I have used the values from Bruce's calculations as given in table 1 below.

Table 1. SPIRE channel bandwidths and resolving power used in calculations.

λ	λmin	λmax	dλ	R=dλ/λ
250	210	290	80	0.32
350	300	400	100	0.33
500	417	583	166	0.332

The transmission from element *i* to detector, τ_d is

$$\tau_d=\prod_{j=i+1}^{N}\tau_j \qquad 4)$$

Using the filter properties given in Bruce's original calculations, the IDL model gives:

Band 1 (210-290µm) = 8.170pW (8.167pW)
Band 2 (300-400µm) = 5.668pW (5.666pW)
Band 3 (417-583µm) = 5.257pW (5.254pW)

These are in good agreement with results from the Mathcad model (shown in brackets).

The filter model has not been modified since March 2000 when it was used for the outline specification of the calibration facility. Since then the cryostat design has developed and the model needs to incorporate the following changes [see AD2]

- Removal of flip mirror at 77K
- Change of 4.3K window to 10K
- Thermal cut-offs in 77K window, 10K window and 4.3K ND Filter 1.

The properties of the filters are shown in table 2 below.

Table 2: Filter temperatures transmission, emissivity, passbands for SPIRE calibration cryostat

Interface	T (K)	ε	τ	λ_{min} (µm)	λ_{max} (µm)
Telescope Simulator	300.0	1	0	0	1000
Cryostat Window	300.0	0.1	0.9	100	1000
77K Window	77.0	0.1	0.9	100	1000
10K Window	15.0	0.1	0.9	125	1000
4K ND Filter 1	4.3	0.9	0.1	150	1000
4K ND Filter 2	4.3	0.925	0.075	150	1000
Instrument Filter	12.0	0.1	0.9	200	700
M3	12.0	0.005	0.995	20	1000
4K Filter	4.3	0.1	0.9	200	700
Chopper	4.3	0.005	0.995	20	1000
M5	4.3	0.005	0.995	20	1000
2-K Filter	2	0.1	0.9	200	700
M6	2	0.005	0.995	50	1000
Aperture Filter	2	0.1	0.9	200	700
M7	2	0.005	0.995	50	1000
M8	2	0.005	0.995	50	1000
Band Pass Filter	0.3	0.1	0.7	210	290
Telescope Simulator	300	1	0	0	1000

Using the values for the current cryostat design in Table 2, we obtain.

Band 1 (210-290µm) = 8.428 pW
Band 2 (300-400µm) = 5.839 pW
Band 3 (417-583µm) = 5.403 pW

3 Thermal Model

We now need to consider the heat loading on the different stages of the cryostat. For this we need to extend the filter model described above to include geometry of the cryostat filters. The model I have presented here assumes that the apertures are circular and concentric to give an order of magnitude figure for the fluxes at each surface.

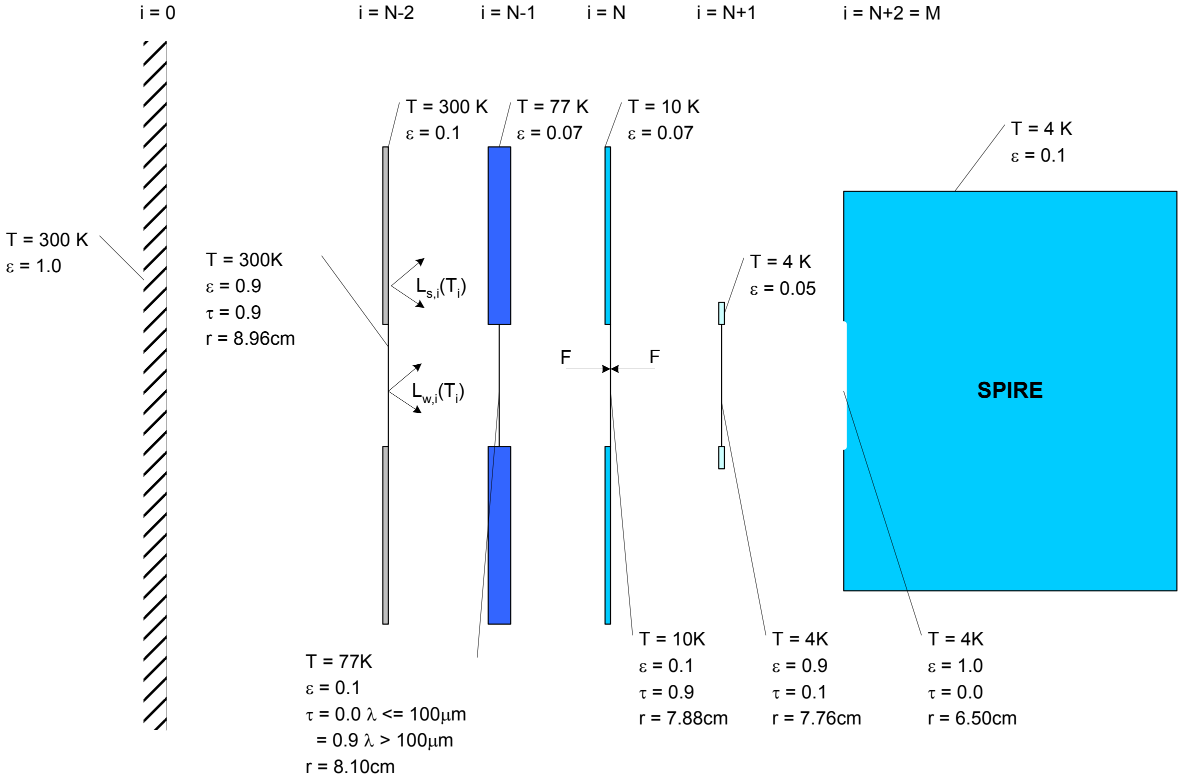

Figure 1: Thermal model for SPIRE Cryostat filters.

The flux incident on filter N of a series of windows is a sum of contributions from the other filters and shields, such that.

$$P_N = \sum_{i=0}^{N-1} P_i + \sum_{i=N+1}^{M} P_i \qquad 5)$$

where the spectral flux at wavelength λ from interface *i* at temperature *T* in K is

$$\begin{aligned} P_i(\lambda) = {} & A_N \Omega_{w,i-N} \tau_{i-N}(\lambda) \varepsilon_f(\lambda) L_{w,i}(T_i,\lambda) + \\ & A_N (\Omega_{s,i-N} - \Omega_{w,i-N}) \tau_{i-N}(\lambda) \varepsilon_s(\lambda) L_{s,i}(T_i,\lambda) \end{aligned} \qquad 6)$$

and

A is the aperture area
$\Omega_{w,i-N}$ is the solid angle between aperture *i* and *N*
$\Omega_{s,i-N}$ is the solid angle between shroud *i* and *N*
τ_{i-n} is the transmission between apertures *i* and *N*
ε_f is the filter emissivity
ε_s is the shroud emissivity

The solid angle for aperture *i* at a distance x from interface *N* is.

$$\Omega_w = 2\pi(1-\cos\theta) = 2\pi\left(1 - \frac{x_{i-N}}{\sqrt{r_N^2 + x_{i-N}^2}}\right) \text{ sr} \qquad 7)$$

For the shrouds I assume a solid angle of 2π.

However, an aperture situated between two interfaces, *j*, will limit the field of view from filter *N* to interface *i*, so that the intervening aperture defines the AΩ. I.e:

$$\Omega_{w,i-N} = \begin{array}{c|l} \Omega_{w,i-N} & \Omega_{w,i-N} \le \Omega_{w,j-N} \\ \Omega_{w,j-N} & \Omega_{w,i-N} > \Omega_{w,j-N} \end{array} \quad \text{for the filters} \qquad 8)$$

and

$$\Omega_{s,i-N} = \begin{array}{c|l} 2\pi & |N-i| = 1 \\ \Omega_{s,j-N} & |N-i| > 1 \end{array} \quad \text{for the shields} \qquad 9)$$

The transmission between interfaces is

$$\tau_{i-N} = \begin{array}{c|l} \tau_{i+1}\tau_{i+2}..\tau_{N-1} & i < N \\ \tau_{N+1}\tau_{N+2}..\tau_{M-1} & i > N \end{array} \qquad 10)$$

For this work I have taken the filter dimensions from the telescope simulator optical model [AD2].

Table 3: Dimensions of cryostat filters

Window	**Radius (cm)**	**Distance from SPIRE FP (cm)**
300K Window	8.984	72.9
77K Filter	8.219	57.8
12K Filter	7.843	50.3
4.3K ND1	7.735	47.8
4.3K ND2	7.735	47.3
SPIRE Aperture	6.42	21.7
SPIRE Focal Surface	5.334	0.0

The materials and emissivities for the shrouds/ filter mounts are given in Table 4.

Table 4: Emissivities of cryostat vessels.

Interface	**Material**	**Emissivity**
Vacuum Vessel – 300K	Stainless Steel	0.1
77K Radiation Shield	Stainless Steel	0.1
12K Filter	Copper	0.05
4.3K ND1	Copper	0.05
4.3K ND2	Copper	0.05
SPIRE	Aluminium	0.1

Substituting the values for tables 2, 3 and 4 into the model gives the heat fluxes shown in Table 5 below.

Table 5: Heat loads at cryostat filters

Window	**Flux W**
300K Window	2.56
77K Filter	1.96
12K Filter	6.69x10^{-3}
4.3K ND1	3.63x10^{-4}
4.3K ND2	3.02x10^{-5}
SPIRE Filter	3.97x10^{-6}

4 Conclusion

As I have already stated, the model only gives an approximate value of the heat fluxes at the different interfaces. The result could be improved by including the following:

- Use thermal modelling or stray light analysis programs to compute view factors based on the actual dimensions of the filters and surroundings. This would obviously take time and effort, but could be done if required.

- Use real optical properties for the filters. In this version of the model I have assumed that the transmissions/emissivities are spectrally flat. This is obviously not true, especially for the vacuum window. It would be interesting to see how variations in these properties affect the heat loads on the various stages and more importantly, the power at the SPIRE detectors.