SPIRE Science Verification Review

RAL

January 26, 27 2006

Bolometer Array Performance Estimation from JPL EIDP Spreadsheets

Document Number: SPIRE-UCF-REP-002569

16 January 2006

Matt Griffin

Contents

1. Introduction and scope

This note summarises the JPL detector performance data for the PFM arrays, based on the EIDP set provided by JPL in January 2006:

pfm_plw_eidp_v7-1.xls
pfm_pmw_eidp_v11-1.xls
pfm_psw_eidp_v10-1.xls
pfm_slw_eidp_v16-1.xls
pfm_ssw_eidp_v11-1.xls

These spreadsheets are based on a combination of tests carried out on the arrays in the JPL BODAC facility, and modelling using well-established semiconductor bolometer theory.

The following performance measures are assessed in the spreadsheets and in this note:

- the Detective Quantum Efficiency (***DQE***) of the bolometer with respect to the absorbed power;
- the **optical efficiency** (h_{opt}) of the detector cavity-feedhorn combination;
- the **1/f knee frequency** (f_{knee}) of the detector noise spectrum;
- the **time constant** (t) characterising the detector speed of response;
- the **number of usable pixels** in each array

Comparisons are made with the **design values (DV)** and **minimum performance (MP)** values of the various parameters, as specified in the *Detector Subsystem Specification Document* (SSSD - SPIRE-PRJ-000456, Issue 3.2, Jan. 7 2003), as modified by RFW HR-SP-JPL-RFW-002, which reduced the requirements on DQE to take into account the thermometer resistance values that were achieved using the selected NTD material.

In addition, an overall figure of merit, proportional to mapping speed is calculated for each array. This is given by the mean value of the product of *DQE*, h_{opt}, and the fraction of usable pixels. The resulting figures are compared with those generated by using the design values.

As part of the analysis, revised versions of the above spreadsheets have been created, and are entitled pfm_plw_eidp_v7_MJG_additions.xls, etc. These contain various additional calculations, but none of the original contents of the spreadsheets have been edited in any way.

This document has been produced to assess the expected overall performance of the arrays in SPIRE, and its assumptions and conclusions will not necessarily be repeated in the formal verification documents for the SPIRE arrays.

2. List of requirements

According to the SSSD the detector performance requirements for the SPIRE PFM and FS detectors are stated as follows:

Specification ID	*Description*	*Requirement Reference*	*Minimum Performance*	*Design Value*
BDA-PER-01	*Maximum number of bad detectors in each BDA*	*IRD-DETP-R04 IRD-DETS-R04*	*11 (PLW) 22 (PMW) 35 (PSW) 5 (SLW) 9 (SSW)*	*4 (PLW) 9 (PMW) 14 (PSW) 2 (SLW) 4 (SSW)*
BDA-PER-02	*The ratio of photon NEP due to radiation absorbed by the detector and total NEP, given as (NEPphoton/NEPtot)^2* *NEP includes all sources of noise at 1 Hz, measured at 300 mK, assuming a total readout noise of 10 nV/ÖHz and the values in Table 3-1-2.*	*IRD-DETP-R01* *HR-SP-JPL-RFW-002*	*0.42 (PLW) 0.49 (PMW) 0.55 (PSW) 0.46 (SLW) 0.56 (SSW)*	*0.50 (PLW) 0.59 (PMW) 0.66 (PSW) 0.55 (SLW) 0.67 (SSW)*
BDA-PER-03	*The optical efficiency of the BDA horn and bolometer assembly for the photometer arrays over the optical passband. at the centre of the bandpass assuming ?^{2} throughput and a beam filling source*	*IRD-DETP-R01*	*0.65 (Phot) --- (FTS)*	*0.85 (Phot) 0.7 (FTS)*
BDA-PER-06	*The photometer detector time constant (based on a maximum modulation frequency of 2 Hz)*	*IRD-DETP-R02*	*32 ms (Phot) 14 ms (SLW) 8 ms (SSW)*	*18 ms (PLW) 13 ms (PMW) 11 ms (PSW) 4.2 ms (SLW) 4.2 ms (SSW)*
BDA-PER-10	*The 1/f knee frequency (frequency at which total noise is Ö2 larger than white level).*		*0.1 Hz*	*0.03 Hz*

Specification ID	*Description*	*Requirement Reference*	*Minimum Performance*	*Design Value*
JFET-PER-01	*Median noise of JFET module over 100 – 300 Hz (nV/ÖHz)*	*IRD-FTB-R01*	*15*	*7.0*
JFET-PER-02	*Maximum number of bad JFET pairs corresponding to each BDA*	*IRD-DETP-R04 IRD-DETS-R04*	*11 (PLW) 22 (PMW) 35 (PSW) 5 (SLW) 9 (SSW)*	*4 (PLW) 9 (PMW) 14 (PSW) 2 (SLW) 4 (SSW)*

Notes:

BDA-PER-01: A "bad detector" is here defined as one that does not achieve, at the BDA output, performance compatible with the minimum performance values for BDA-PER-2 to 10.

JFET-PER-02: A "bad JFET pair" is here defined as one that does not achieve, at the JFET output, a noise level of less than the minimum performance level.

BDA-PER-01 and JFET-PER-02: The minimum performance requirement on yield are quoted individually above for both the BDAs and JFETs. This is designed to ensure an overall yield of at least 0.75 for the system at the JFET outputs. As long as this is achieved, the JFET and BDA yield do not both need to be at or above their minimum performance yields.

Notes:

The bolometer performance estimation assumes the following nominal photon NEPs (W/ÖHz) referred to power absorbed at the detector:

PLW: 4.6×10^{-17}
PMW: 6.3×10^{-17}
PSW: 8.2×10^{-17}
SLW: 10.5×10^{-17}
SSW: 13.6×10^{-17}

The optical loading and photon NEP assume the following nominal optical efficiencies of the bolometer and feedhorn combinations:

PLW 0.65
PMW 0.65
PSW 0.65
SLW 0.65
SSW 0.70

Additional notes:

1. BDA-PER-10 (on 1/*f* knee frequency) is actually not critical for the FTS detectors as the FTS signal frequencies are in the 3-10 Hz range.

2. BDA-PER-02:
   (i) The *DQE* values in the SSSD assume a heat-sink temperature of T_o = 0.3 K at the BDA interface.
   (ii) Note that the values quoted in the JPL EIDPs have not been updated with respect to RFW HR-SP-JPL-RFW-002. The following table summarises the differences:

Array	**Min. Perf.**		**Design**	
	EIDP value	**Correct value**	**EIDP value**	**Correct value**
PLW	0.46	0.42	0.55	0.50
PMW	0.53	0.49	0.63	0.59
PSW	0.53	0.55	0.63	0.66
SLW	0.50	0.46	0.60	0.55
SSW	0.59	0.56	0.71	0.67

3. Tests results and analysis

3.1 Tests carried out

BODAC tests included the following:

- load curves;
- optical efficiency by comparison of absorbed power with power from a known black body;
- time constant using an external chopped source;
- dark (zero radiant loading) noise spectrum at appropriate bias.

3.2 BODAC data analysis methods and assumptions

Based on the load curves and other known data, the parameters of the bolometer model are found, and these are used to predict the bolometer noise voltage, responsivity, and detector *NEP* (NEP_{det}) under two different circumstances:

(i) dark;
(ii) the nominal operating radiant loading.

In each case the heat-sink temperature is taken as 0.3 K, and the bias point is set at the optimum value for the radiant loading.

The *DQE* requirement has not been verified directly. Measurements have been made on the arrays under radiant submillimetre loading, but at absorbed power levels greater than the levels corresponding to the photon noise NEPs specified above. In addition, data have been taken at bath temperatures higher than the 300-mK value to which these specifications apply.

It is therefore necessary to carry out an analysis to extrapolate from the measured data to the nominal operating conditions in order to assess whether or not the specified performance will be achieved under those conditions. Such extrapolation is inevitably model-dependent because some assumptions have to be made concerning the bolometer noise, and how the noise measured under dark conditions will scale when adjusted to the nominal conditions.

The theoretical *DQE* is calculated in the JPL spreadsheet based on Mather bolometer theory with no excess noise:

$$DQE = \frac{NEP_{ph}^2}{NEP_{ph}^2 + NEP_{det}^2}, \tag{1}$$

where NEP_{ph} is the calculated photon noise referred to the nominal absorbed radiant power and NEP_{det} is the detector *NEP* at the loaded operating point, evaluated according to Mather theory for Johnson (J), phonon (P) and load resistor (L) noise, and including an amplifier (A) noise contribution of 10 nV Hz$^{-1/2}$:

$$NEP_{det}^2 = \left(NEP_J^2 + NEP_P^2 + NEP_L^2 + NEP_A^2\right)^{1/2}. \tag{2}$$

The measurements of the bolometer noise made under dark conditions can be compared with the theoretical values expected from an ideal bolometer with the relevant parameters. The measured noise should be greater than or equal to the theoretical prediction. Let the factor by which the measured dark noise exceeds the theoretical value be *f*. We can identify three simple schemes for extrapolating the results to nominal operating conditions, as described below.

Best case: Here we assume that, unlike in the dark condition, there will be no excess noise over and above the theoretical level - the *DQE* will be given by the theoretical value. This is what is currently assumed in the JPL spreadsheets, which use equation (1) to calculate the detector *NEP*, and consequently the theoretical *DQE*.

Worst case: We could make the pessimistic assumption that, under nominal operating conditions, the overall noise level will be degraded by the same factor as for the measured dark noise:

$$DQE(\mathrm{Worst}) = \frac{NEP_{\mathrm{ph}}{}^2}{\left(NEP_{\mathrm{ph}}{}^2 + NEP_{\mathrm{det}}{}^2\right)f^2}, \tag{3}$$

Intermediate case: It is likely that the actual performance lies somewhere between these two extremes, although it is difficult to predict how the excess noise measured dark will scale with background. As a simple intermediate case, we assume that only the detector noise level is degraded by the same factor as for the measured dark noise:

$$DQE(\mathrm{Intermediate})) = \frac{NEP_{\mathrm{ph}}{}^2}{\left(NEP_{\mathrm{ph}}{}^2 + (f.NEP_{\mathrm{det}})^2\right)}. \tag{4}$$

This intermediate approach has been adopted in this analysis.

For the purpose of formal acceptance of the FM and FS bolometer arrays, it has been agreed that a TBD value of the factor f will be used to determine compliance.

Important assumptions:

1. ***DQE* specifications:** Here we adopt the (less stringent) *DQE* specifications as listed in RFW HR-SP-JPL-RFW-002.
2. **Bolometer responsivity:** In calculating the *DQE*, the JPL spreadsheets assume that the bolometer responsivity (with respect to the absorbed power) is given by the theoretical value. This is normally a fairly well justified assumption for NTD bolometers operating at ^{3}He temperatures.
3. **BODAC gain:** The spreadsheets include two versions of the noise levels (in the *Mather_Dark* worksheets). One set is based on a total gain for the BODAC electronics chain of 80,000, and the other is for a gain of 57,300. The results are significantly different in the two cases - the lower value for the gain results in correspondingly higher values for the detector noise. We assume in this analysis is that the higher value of 80,000 applies.
4. **Excess noise factor:** In cases where the measured value of f is less than unity (i.e., measured dark noise is *less* than the theoretical prediction), a value of $f = 1$ has been adopted on the ground that it is not physically realistic for the noise to be less than the theoretical value.
5. **Extrapolation to 2-Hz chopping frequency:** The SSSD specifications on *DQE* are for a chopping frequency of 2 Hz. Here for simplicity we use the 1-Hz noise (slightly pessimistic) and the DC responsivity (slightly optimistic). Given the generally low values of both the 1/f knee frequencies and the time constants, this simplification is justified.
6. **FTS optical efficiencies:** For the FTS arrays, the values of optical efficiency quoted in the JPL spreadsheets are taken as valid for the purpose of BDA performance verification. (However, it should be noted that the estimation of the optical efficiency and signal coupling as a function of wavelength for these over-moded feedhorns are still under analysis, and the impact on instrument sensitivity will need to be carefully assessed.)
7. **JFET yield:** In this analysis, the yield of the SPIRE JFETs is taken to be 100% - i.e., all JFETs are assumed to be functioning and performing to specification.

8. **Pixels not yet verified:** For most of the arrays, there are some pixels whose performance has not been completely evaluated due to problems with BODAC. These "problem pixels" are flagged in the spreadsheets and we eliminate them from the analysis under the assumption that they actually perform to specification. This can only be verified by tests at instrument level.
9. **Performance in SPIRE:** the subsystem-level performance of the arrays addressed in this note will be achieved in SPIRE provided that the appropriate operating temperature, radiant background power levels obtain, and there are no additional sources of noise in the system.

4. Summary of array performance

The tables below summarise the performance of the flight arrays.

Dead pixels are detectors which do not function at BDA level, and will be non-operational in SPIRE.

Otherwise excluded pixels are detectors which work, but have not been completely verified in the course of the JPL tests, mainly due to problems with the BODAC test facility. They are not included in the analysis. These detectors will be operational in SPIRE, but their performance and compliance with requirements will need to be verified by instrument-level tests.

4.1 PLW array

Total no. of pixels	43
No. of dead pixels	0
No. of otherwise excluded pixels	4 A1: BODAC dead for one run. E6: Low S/N due to BODAC setup. Optical efficiency not measured. D4: BODAC moderately noisy C4: BODAC slightly noisy
f_{knee}	All compliant; highest = 84 mHz; median = 56 mHz
h_{opt}	All compliant; median = 0.77; rms variation = 4%
DQE	DV = 0.50; MP = 0.42 All compliant Median = 0.52; rms variation = 5.4%
t	DV = 32 ms; MP = 18 ms All compliant; median = 5.9 ms
Number of bad pixels (assuming all excluded pixels are compliant and 100% JFET yield)	0 (MP = < 11)
Fraction of usable pixels (assuming all excluded pixels are compliant)	1 (= 43/43) The pixels that are formally non compliant will still be usable.
Overall figure of merit: Mean of $DQE*\eta_{opt}$*Fraction of usable pixels	Design value: (0.50)(0.85)(39/43) = 0.39 Min perf value: (0.42)(0.65)(32/43) = 0.20 Achieved: 0.39 with 7% rms variation Comment: design value of 0.85 for η_{opt} is no longer considered feasible. A more realistic value is 0.75, giving $DQE*h_{opt}$ = 0.34. The achieved performance is thus better than the realistic design value.

4.2 PMW array

Total no. of pixels	88
No. of dead pixels	0
No. of otherwise excluded pixels	15 E11: BODAC dead A5, C5, F7, E10, E11, B11, C9, G2: BODAC noisy C3, G11, G13, B12, E1, E5: BODAC slightly noisy
Pixels flagged as problem pixels but included as data are compliant	C13, B5, A6, A13
f_{knee}	All compliant; highest = 61 mHz; median = 44 mHz
h_{opt}	All compliant; median = 0.70; rms variation = 5.5%
DQE	Design value = 0.59; Min perf = 0.49 Median = 0.56; rms variation = 8.8% 67 of 73 compliant 6 non compliant pixels: A6 (0.48); C7 (0.45); B5 (0.45); B3 (0.43); G8 (0.40); E4 (0.46)
t	Design value = 32 ms; Min perf = 18 ms All compliant; median = 5.7 ms
Number of bad pixels (assuming all excluded pixels are compliant and 100% JFET yield)	6 (MP = < 22)
Fraction of usable pixels (assuming all excluded pixels are compliant)	1 (= 88/88) The pixels that are formally non compliant will still be usable.
Overall figure of merit: Mean of *DQE**η_{opt}*Fraction of usable pixels	Design value: (0.59)(0.85)(79/88) = 0.45 Min perf value: (0.53)(0.65)(66/88) = 0.24 Achieved: 0.40 with 11% rms variation Comment: design value of 0.85 for h_{opt} is no longer considered feasible. A more realistic value is 0.75, giving *DQE**h_{opt}*Fraction usable = 0.40. The achieved performance is thus comparable to the realistic design value.

4.3 PSW array

Total no. of pixels	139
No. of dead pixels	4 C12: Non functional bolometer G2: Noisy bolometer J7: Non functional bolometer A13: Unusable due to extremely slow speed of response (*t* = 360 ms)
No. of otherwise excluded pixels	12 H16, E9, G9: Dead BODAC JFETs F1, F14: Dead BODAC LIA G6, F7, G7, F8, B5, A2, H7: BODAC noisy
Pixels flagged as problem pixels but included as data are compliant	F12, F16, H8, G8: Data seem OK A11: Unusually high *t* (15.8 ms) – but actually < max allowed (32 ms) A10, D11: OK except for high *t* (41, 45 ms)
f_{knee}	All compliant except three which are slightly out of spec. (100 mHz): F14 (110 mHz), D14 (117 mHz), A11 (102 mHz). Median = 46 mHz
h_{opt}	106 of 123 compliant with MP value of 0.65 Of 17 non-compliant, 14 are above 0.6 and lowest = 0.57. Overall median = 0.70.
DQE	All compliant with MP value of 0.55. Two non-compliant are B1 and C15 (both 0.57). Overall median = 0.69 (close to DV of 0.7)
t	121 of 123 compliant. Median = 5.2 ms Two non-compliant detectors A10, D11 (41, 45 ms) are usable.
Number of bad pixels (assuming all excluded pixels are compliant and 100% JFET yield)	23 (MP = < 35; DV = < 14) 4 dead 17 non compliant on optical efficiency 2 non compliant on time constant
Fraction of usable pixels (assuming all excluded pixels are compliant)	0.971 (= 135/139) The pixels that are formally non compliant will still be usable.
Overall figure of merit: Mean of *DQE**η_{opt}*Fraction of usable pixels	Design value: (0.66)(0.85)(125/139) = 0.50 Min perf value: (0.55)(0.65)(104) = 0.27 Achieved: 0.48 with 9% rms variation Comment: design value of 0.85 for η_{opt} is no longer considered feasible. A more realistic value is 0.75, giving *DQE**h_{opt} *Fraction usable = 0.45. The achieved performance is thus slightly better than the realistic design value.

4.4 SLW array

Total no. of pixels	19
No. of dead pixels	0
No. of otherwise excluded pixels	0
Pixels flagged as problem pixels but included as data are compliant	0
f_{knee}	Quoted as < 30 mHz for all pixels. All pixels have f_{knee} < 100 mHz based on 1 Hz and 0.1 Hz noise measurements.
h_{opt}	Design value = 0.7; No Min. perf. value Median = 0.75; Min = 0.72; Max = 0.80; 3% rms variation
DQE	Design value = 0.55; Min perf = 0.46 17 of 19 compliant; median = 0.59 Two non compliant: C5 (0.178) and E3 (0.317) C5 has strong excess dark noise. E3 has excessive noise at 1 Hz (where *DQE* is calculated), but is actually OK at 0.1 Hz – possible problem with measurement rather than with the detector?
t	Design value = 4.2 ms; Min. perf. = 14 ms All of 19 compliant. Median = 5.4 ms
Number of bad pixels (assuming all excluded pixels are compliant and 100% JFET yield)	2 (DV = < 2; MP = < 5)
Fraction of usable pixels (assuming all excluded pixels are compliant)	0.947 (= 18/19) C5 is taken as not usable, but E3 as usable.
Overall figure of merit: Mean of *DQE**η_{opt}*Fraction of usable pixels	Design value: (0.55)(0.7)(17/19) = 0.34 Min perf value: (0.46)(0.7)(14/19) = 0.24 Achieved: 0.40 with 22% rms variation Comment: Achieved exceeds design value. However, estimation of optical efficiency for FTS arrays is known to be problematical and remains under investigation.

4.5 SSW array

Total no. of pixels	37
No. of dead pixels	2 D5: Bolometer non-functional F4: Noisy bolometer – effectively unusable
No. of otherwise excluded pixels	1 D6: Dead BODAC channel
Pixels flagged as problem pixels but included as data are compliant	0
f_{knee}	Quoted as < 30 mHz for all pixels. All pixels have f_{knee} < 100 mHz based on 1 Hz and 0.1 Hz noise measurements.
h_{opt}	Design value = 0.7; No Min. perf. value Median = 0.72; Min = 0.64; Max = 0.87; 10% rms variation
DQE	Design value = 0.67; Min perf = 0.56 All of 34 compliant. Median = 0.72
t	Design value = 4.2 ms; Min. perf. = 14 ms All of 34 compliant. Median = 4.4 ms
Number of bad pixels (assuming all excluded pixels are compliant and 100% JFET yield)	2 (DV = < 4; MP = < 9)
Fraction of usable pixels (assuming all excluded pixels are compliant)	0.946 (=35/37)
Overall figure of merit: Mean of *DQE**η_{opt}*Fraction of usable pixels	Design value: (0.67)(0.7)(33/37) = 0.42 Min perf value: (0.56)(0.7)(28/37) = 0.30 Achieved: 0.49 with 7% rms variation Achieved exceeds design value. However, estimation of optical efficiency for FTS arrays is known to be problematical and remains under investigation.

5. Conclusions and comments

Yield: This is better than specification in all cases.

***DQE*:** A significant number detectors are below spec. with the *DQE* as calculated here. But it is important to note that:

(i) the *DQE* estimation is model dependent, and the method used here is not necessarily completely reliable;
(ii) most detectors that are below spec. are still usable, and the non-compliance of *DQE* is offset by the high yield.

Time constant: The detector speed of response is considerably better than spec. except for a very few pixels.

1/*f* knee frequency: This is better than specification except for a very few pixels.

Optical efficiency: The optical efficiency of the photometer detectors is generally in spec. with respect to the MP values. It should be noted that the design value of 0.85 which was originally specified is now regarded as unrealistic. A more realistic value of 0.75 should be adopted.

For the FTS arrays, the as-measured efficiency is generally better than spec. The uncertainties and difficulties in estimating the efficiency for the over-moded FTS feedhorns should be noted.

Overall figure of merit: The most useful single measure for quantifying the array performance is the figure of merit defined above: $DQE*h_{opt}$*(Fraction of usable pixels). This parameter is directly proportional to observing speed. The table below summarises the performance of the arrays based on this parameter:

	Array observing speed figure of merit		
Array	**Current design value**	**Realistic original design value**	**Achieved value**
PLW	0.34	0.37	0.39
PMW	0.40	0.42	0.40
PSW	0.45	0.47	0.48
SLW	0.34	0.38	0.40
SSW	0.42	0.44	0.49

Notes:

- Current array design value: This is the value derived from the formal requirements.
- Realistic original design value: This is the value originally specified, but corrected to incorporate a physically realistic feedhorn efficiency.
- Achieved value: This is the value derived from the unit-level measurements, as described above.

In all cases, if we adopt a realistic value for the optical efficiency, the achieved figure of merit is comparable to or better than the design value. Values for the FTS arrays must remain tentative until the mode coupling of the FTS feedhorns is better understood.