SPIRE

Using PCal Standard Flash Data to Detect LHe Adsorption onto the SPIRE Detectors

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1. Introduction

The SPIRE PFM 2 and 3 test campaigns at RAL were afflicted with periodic episodes of what appeared to be leaks of liquid helium onto the detectors. The response of the detectors to changing optical power levels was noticeably slower, particularly when performing the standard PCal flash sequences. In this note I shall describe the analysis of PFM3 PCal flash data with the aim of quantifying the level of contamination by liquid helium during the periods when the detectors were affected. Additionally, I shall demonstrate that analysis of PCal data during subsequent test campaigns could be used as an ‘early warning system’ for detecting periods of contamination and allowing suitable action to be taken before the situation worsens.

2. Data Analysis Method

For the purposes of this note I use two data sets from the PFM3 test campaign; one ‘normal’ test, when there was no sign of helium contamination (0x3000E2B7) and one ‘slow’ test towards the end of the campaign, during which the detectors demonstrated slower than normal response to the standard PCal flash sequence (0x3000E681). Additionally, I only show results for the central detector on the PWS array, E8. The analysis can be equally applied to all the other detectors in the same way but in general the results are consistent, if not between arrays then usually between all detectors on a single array.

For both PCal flash tests the instrument was viewing the Cold Black Body (CBB), switched off and at a temperature of ~6.4 K. The PCal flash sequences were both performed with a high level applied current of 3.8 mA, corresponding to a power level of ~2.9 mW. 15 PCal flashes were performed during each sequence, at a frequency of 0.25 Hz, i.e. 2 s on and 2 s off per flash. Slight adjustments are needed to the model described in this note if different operating conditions are used, however, the results do not suffer greatly if this is not done.

To increase the signal-to-noise ratio (SNR) of the data the response of the detectors to each of the 15 individual flashes was co-added into a single 4 s long time-line. The signal level was measured to be the difference between the last 1.5 s of each half flash, ensuring that the detector settling time between the on and off PCal levels is ignored in both test cases.

Because PCal cools down more quickly than it heats up the transition between on and off levels provides greater sensitivity to changes in the detector response. Therefore, only the switching off transition is analysed in this note. Note that the detector voltage responds in a negative sense to optical power, so the response plots presented in this note go from low to high as PCal goes from on to off.

3. The Model

There are three things that combine to give the final detector time-line during a PCal flash sequence. Firstly, PCal itself takes a certain amount of time to heat up or cool down in response to a change in applied power. Secondly, the detectors respond to the change in illumination power provided by PCal. Finally, the detector voltage is filtered and sampled by the on-board electronics – by a low-pass filter that effectively suppresses frequencies in the time-line that are higher than 5 Hz (0.2 s). With this model I aim to reduce the number of free parameters to just one: the time constant of the detector under investigation.

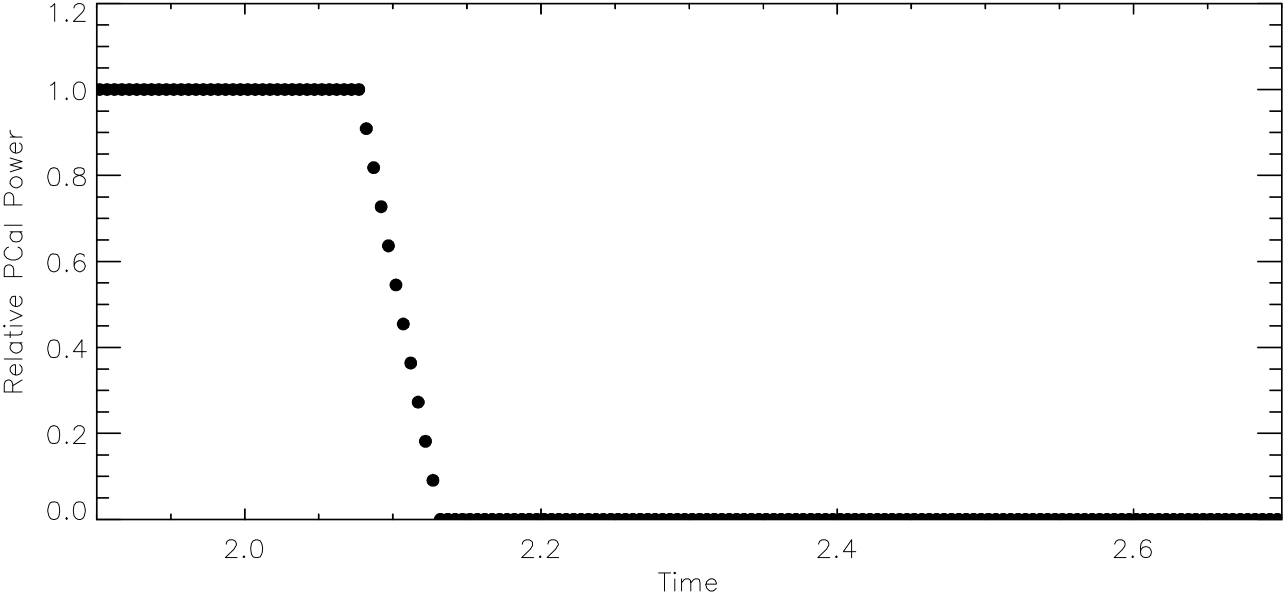
3.1 PCal Response

The current applied to PCal is reported in the SCU data and gives some indication as to when PCal is switched off. However, I found it necessary to add an offset of ~77 ms between the time that the SCU PCal current drops to zero and when PCal actually begins to cool. Without this offset it is impossible to fit any reasonable model to the PCal detector data. I am assuming that this value is intrinsic to all the PCal flash data and so it is kept constant for all the tests. This is not something I am entirely happy with, as it is an extra parameter that can be tweaked with no real justification, however, for the ‘normal’ test it is the only unknown parameter and so it can be fixed with reasonable certainly.

At unit level both the rise time and the fall time of PCal was measured for a range of applied powers. I assume for this analysis that the fall time of PCal during PFM3 is the same as it was at unit level. For an applied power of 2.9 mW, as in the standard PCal flash investigated here, the 90% fall time was ~50 ms.

The cooling curve is approximately linear with time so for the purposes of this model I assume that the illumination power of PCal falls from maximum to zero in 55 ms in a linear fashion, as shown in Figure 1.

Figure 1. Relative PCal illumination power during the period that it cools down after being switched off.



3.2 Detector Response

The SPIRE detectors are single time-constant devices, in that they respond to a step change in illumination power in the same way that an RC circuit does. For a small decrease of PCal illumination power this response can be summarised by the following equation: $V(t) \propto 1 - \exp(-t/\tau)$, where $\tau = C/G$. Here C and G are the heat capacity and the dynamic thermal conductance, respectively, of the detector at a given temperature. It is assumed that these values do not change appreciably over the PCal flash sequence, so that a single time constant, τ, can be used throughout. This is justified since the illumination power of PCal amounts to ~0.2 pW at the detector arrays, when using a high power level of 2.9 mW, which is equivalent to ~3 mK change in the temperature of the detectors. Such a small change in temperature results in a negligible change in τ as PCal is switched on and off.

For PSW-E8 the time response based on the JPL EIDPs is τ=4.2 ms. From the loadcurve analysis it varies between 6.7 and 5.0 ms over the full range of applied bias, with τ~6 ms for the typical bias applied during PCal standard flashes. For the purposes of this analysis a difference of 2 ms in τ makes a negligible difference to the model fits under 'normal' operating conditions so I shall assume a nominal value of τ=5 ms for this detector. In practice it is extremely hard to determine the time response of the detectors under 'normal' conditions, using PCal data, because the response of PCal and the 5 Hz analogue electronics filter dominate the overall shape of the data time-line.

To obtain a model detector time-line I start with a baseline representing the detector during the PCal on period. The relative response of the detector is calculated for each small change in PCal power, as it is varied over the switch off period of 55ms, in steps of 5 ms (Figure 1). Using smaller time steps makes almost no difference to the final model fit so convergence is achieved.

3.3 5 Hz Filter

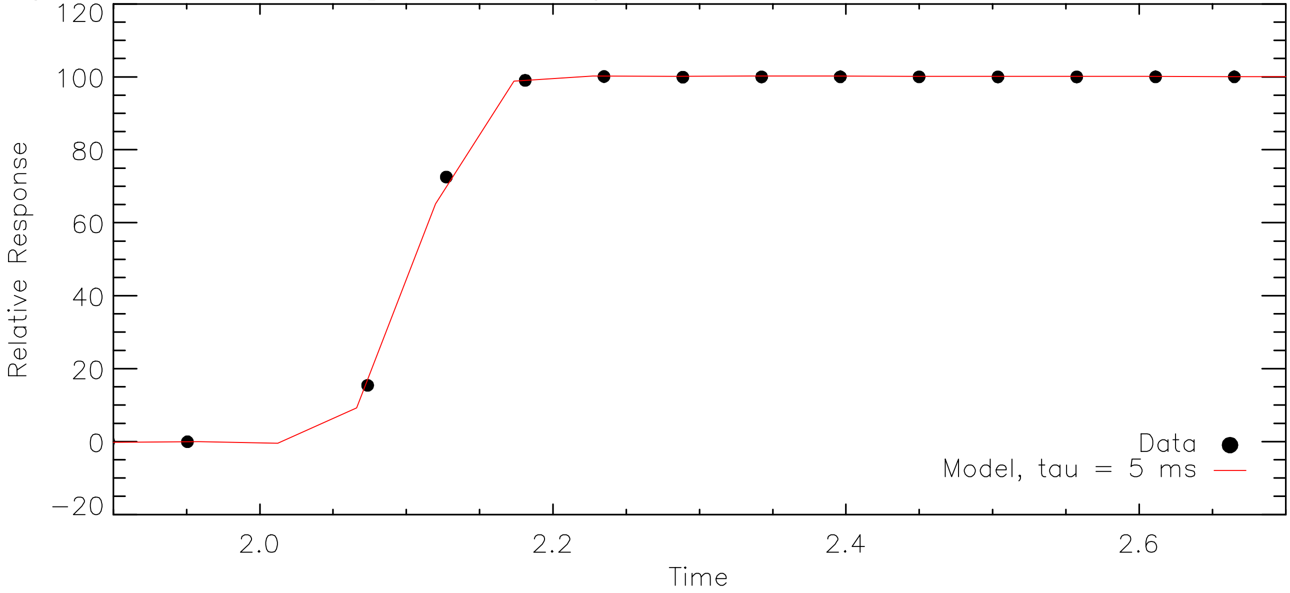
Before the model can be compared to the data it must be low-pass filtered in the same way that the real data is. This is achieved by applying the 5 Hz quadrapole Bessel filter present in the readout electronics. The model time-line is Fourier transformed and multiplied by the filter frequency response. The inverse Fourier transform should then be equivalent to the real data. Although it makes no difference to the final shape, the model data is also sampled at the same frequency as the real data before the comparison.

4. Results

Because the response of PCal should not change from one flash sequence to the next (assuming the same power level is used) and the 5 Hz filter is also constant, the only thing that could change between PCal tests is the response of the detectors. Therefore, the model is adjusted simply by varying the value of τ. The next two figures show the model applied to the ‘normal’ (Figure 2) and ‘slow’ (Figure 3) tests.

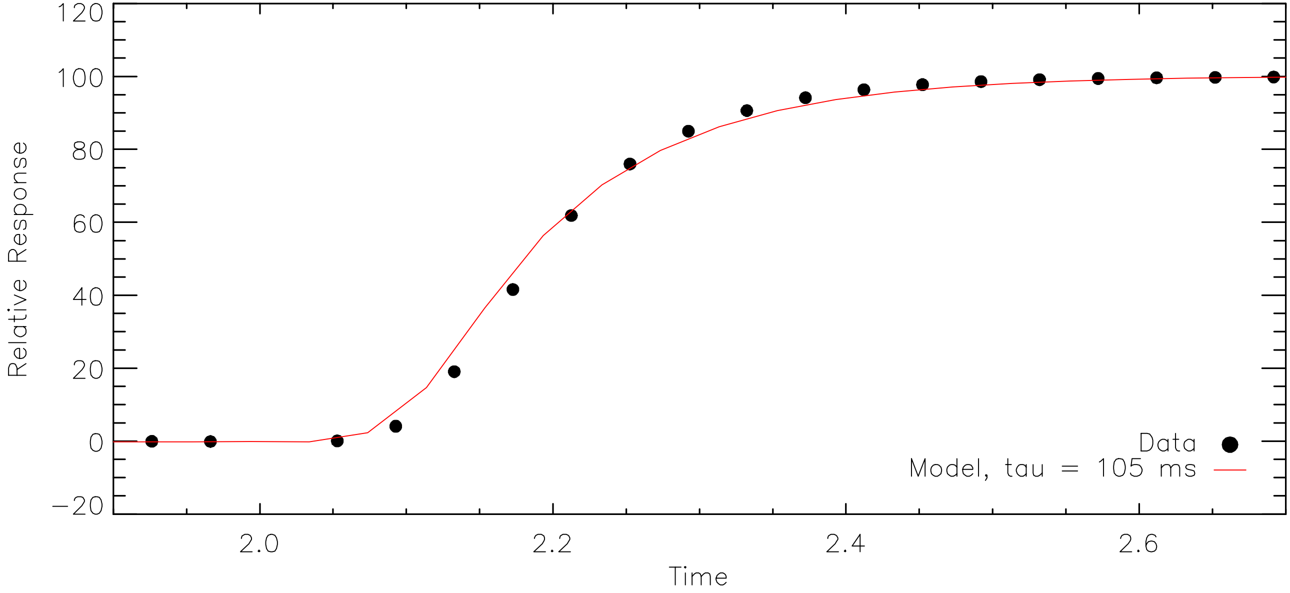
For the ‘normal’ test the nominal value of τ=5 ms provides an excellent fit to the data (see Figure 2), although anything from 0-8 ms gives acceptable fits.

Figure 2. 'Normal' detector response to PCal being switched off.



For the ‘slow’ test the best fit to the data was found using a value of τ=105 ± 5 ms (see Figure 3). Although the fit is still very good there is some indication that the model does not completely describe the data, with the data points falling below the model in the early part of the transition and falling above the model later on. This will be discussed more in section 7.

Figure 3. 'Slow' detector response to the same PCal flash sequence as in Figure 2.



5. Implications for Liquid Helium Adsorption

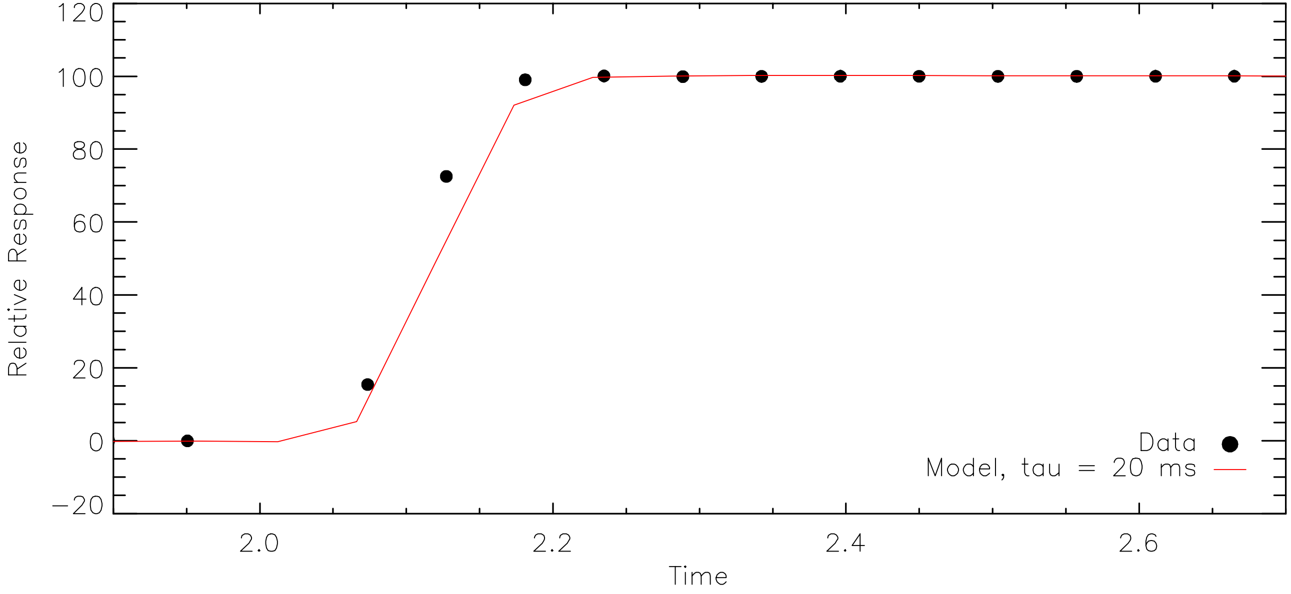
Assuming that the increase in the time-response of the detector is due to a film of LHe adsorbed onto the crystal, it is a fairly easy matter to calculate the mass of He involved.

For the two PCal tests reported here the temperature of the detectors was ~350 mK, giving a heat capacity for PSW-E8 of C=0.48 pJK^{-1}. An increase of τ from 5 to 105 ms means that the heat capacity of the crystal has increased by a factor of 21 ($^{+5}_{-4}$). Therefore the increase in heat capacity during the 'slow' test, associated with the LHe film, was C_{LHe} = 9.6 ($^{+2.4}_{-1.9}$) pJK^{-1}. The heat capacity of LHe is roughly exponential with temperature over this temperature range, with C_{LHe}(350 mK) ≈ 7e8 pJK^{-1}g^{-1} = 4.65e-15 pJK^{-1}atom^{-1}. To achieve the increase in the heat capacity of the crystal therefore requires some 2 ($^{+0.6}_{-0.3}$) e15 atoms of He.

6. Detecting He Leaks Using PCal Standard Flash Data

Although measuring the time-response of the SPIRE detectors using this method is difficult – since PCal and the 5 Hz filter dominate the appearance of the data under 'normal' conditions – it is possible in principle to detect relatively small changes in τ and so spot the early stages of a potential helium leak. Figure 4 shows the 'normal' test data again but with a slightly slowed detector response model overlaid. Once the detector time-response has slowed to around 20 ms the difference to 'normal' behaviour becomes clear, even to the untrained eye.

Figure 4. The same data as shown in Figure 2 but with an overlaid model showing a slightly slower detector response, τ=20 ms.



Comparing PCal standard flash data to a 'normal' model trace in this way could provide a powerful early warning of impending trouble caused by helium leaking into the detector arrays. This analysis could be done moments after each flash sequence, in the case of ground test campaigns, or as the data is telemetered to the ground each day during flight. A simple test metric could take the form of a sum of all residuals between the data and the 'normal' model for all detectors on each array, for example. When the metric exceeds a given threshold the data should be inspected more closely and appropriate action could be taken to remove the contamination if deemed appropriate.

6.1 Minimum Detectable Helium Mass

Assuming that the minimum detectable change in τ is a factor of 4 (a conservative estimate, assuming the nominal τ=5 ms), that corresponds to an increase in heat capacity for the average detector of C_{LHe} = 1.5 pJK^{-1} (assuming a nominal detector heat capacity of 0.5 pJW^{-1}.) Therefore, the quantity of helium adsorbed by each detector would be 3.2e14 atoms = 2.1e-12 g.

7. Discussion

This note reports on only a single detector on one array but the analysis can easily be extended to all the detectors on all three arrays. In general all the detectors on a given array seem to be affected in a similar way by a helium leak, although in some cases the different arrays are affected to different degrees, for some reason. During the PFM2 test campaign, for example, the PSW array was more badly affected than the others, whereas in PFM3 the three photometer arrays were more similarly affected.

It was mentioned in section 4 that the model does not perfectly fit the data when τ becomes large. This indicates that the model is incomplete to some degree. There are two factors that could account for a small part of the discrepancy but cannot account for all of it. The heat capacity of both the detectors and of LHe increases with increasing temperature, which means that τ will be slightly larger when the detectors are warmer, i.e. when PCal is on. As the detectors cool down, after PCal is switched off, τ will decrease slightly causing the detectors to respond marginally quicker. This agrees qualitatively with the model over-predicting the cooling rate initially while under-predicting it later on. However, the variation in detector temperature of ~3 mK between PCal being on and off is not nearly enough to account for the discrepancy seen between the data and the model.

Model incompleteness does not prevent the current incarnation from being used as an early warning system, however, as detecting a slow down in the detector time-response does not require accurate modelling of the 'slow' test, only requiring a good fit to 'normal' data.

Finally, this analysis was performed using data taken while the arrays were viewing the CBB, but the situation is somewhat different under different operating conditions. For example, when viewing the room, or a very hot CBB (say 28 K), the operating temperatures of the detectors is more like 510 mK rather than 350 mK. In this situation the effect that adsorbed liquid helium has is more pronounced because the heat capacity of LHe is higher by a factor of ~3.7 at this higher temperature (C_{LHe}(510 mK) $\approx$ 2.6e9 pJK^{-1}g^{-1}). This means that theoretically the technique presented here is more sensitive to detecting leaked helium when the SPIRE arrays are under a high optical loading. In this case the minimum detectable mass of helium would be more like 5-6e-13 g per detector (c.f. section 6.1). In fact, during PFM2 in particular, the slowness of the PSW array was far more pronounced when the arrays were viewing the room than when viewing the CBB. This behaviour supports the theory that it is indeed a film of LHe on the detector crystals that is responsible for the degraded time-response.