PACS responsivity from standard stars observations

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1 Introduction

The responsivity of the bolometers is the quantity allowing for converting the electrical signal from the measurement chain into the physical unit of interest: the amount of incident power on the bolometers. This quantity is central in determining the performances of the instrument in a useful way for Joe Astronomer.

Responsivities were determined during the FM-ILT test campaign as a function of the infalling flux and the bolometer bias voltage by using a flux modulation of 0.5 pW/pixel between the two OGSE Black Body sources (see RD1, Req 1.1.1 bis). For the nominal bias (2.6 V in blue, 2.0 V in red), in
direct mode, the responsivities were measured to be respectively of $3.1 \times 10^{10}$ V/W and $3.2 \times 10^{10}$ V/W (see table in 1.1.2-F of RD1).

There are indications from early reports on flight data that the emission seen by the PACS bolometers has changed in the red channel with respect to the ILT measurements and the predictions for the telescope emission, while it is unchanged for the blue channel (see RD2). If confirmed, this would mean that we expect a reduced responsivity in the red band with respect to the ILT based predictions. In this report, I use standard stars measurements to independently determine the responsivity of the bolometers. I first review the expected result, the proceed with checking the expected flux from standards. I then proceed with the measures themselves.

2 Expected responsivities from the FM-ILT campaign

The responsivity of PACS bolometers depends on their biasing and on the amount of light they receive. During the FM-ILT, responsivity curves were determined using two calibrated black body sources. Figure 1 from RD1 shows the result of these measures for a matrix on the blue and the red array in direct mode.

![Figure 1: Responsivity as a function of the bias voltage and background of the blue (a) and red (b) arrays in direct mode from RD1](a) Blue array (Matrix 1) (b) Red array (Matrix 10)

In all our study, we will only consider data taken with the "Nominal" bias settings of 2.6 V in blue and 2.0 V in red, so we will in fact always look at cut along the y axis of figure 1. Moreover, we will determine responsivity from observations where the source can be on any array, not just arrays 1 or 10. In the processing, there is only one response by filter, and this un-uniformity is taken care of by the flatfield. Table 1 shows the average value of the non–masked pixels on a matrix basis and for the entire array. We see that matrices 1 and 10 are very representative of respectively the blue and red array. The result of the cut in figure 1 for the nominal settings is plotted in figure 2. From this
Table 1: Average value of the unmasked pixels per matrix and array in the flatfield (FM, version 2). Note that since the flatfield was normalized without taking into account masked pixels, the array value can be different from 1.0. Although the flatfields are slightly different between blue and green filters, the values averaged by matrices are identical at the percent level.

![Figure 2: Response as a function of the incident power on the bolometers for the blue and red arrays](image)

Now that PACS is in flight, the responsivity will depend on the incident power from the telescope on the bolometers. The background levels as a function of the mirror temperature are tabulated in RD3, table 2, where the excess light in the red band of 1.7 pW/pix is taken into account. At 85 K, we obtain a background of 1.78, 1.22 and 4.14 pW/pix in the blue, green and red band. This translates using figure 2, in expected responsivities of 3.19, 3.39 and $2.58 \times 10^{10}$ V/W. Comparing these values with the FM-ILT ones, we expect a reduced responsivity in the red.

[These values are different from the responsivities in RD3, table 2. What is wrong ???]

We will use standard stars observations to measure the responsivity directly.
3 PACS Standards power and flux densities

Responsivities appear in RD1 in units of V/W, and they correspond to the definition:

\[ R_{\text{ILT}} = \frac{V_{\text{bolo}}}{P_{\text{inc}}} \] (1)

Where \( V_{\text{bolo}} \) is the output voltage from the bolometer and \( P_{\text{inc}} \) is the incident power on the bolometer. The responsivities that are used in hipe are:

\[ R_{\text{hipe}} = \frac{V_{\text{bolo}}}{F_{\nu}} \] (2)

where \( F_{\nu} \) is the flux density of the source in the PACS photometric system. The unit of \( R_{\text{hipe}} \) are V/Jy. Going from one responsivity to the other is not completely straightforward.

The flux density in the PACS photometric system is by definition the flux density that a source with a so-called "flat spectrum" body, i.e. a spectrum such that \( \nu F_{\nu} = \text{cte} \) would have at the PACS reference wavelength and that would generate the same signal as the astronomical body of interest. This definition translate in the following equation:

\[
\int S_{\nu} T_{\nu} A_{\text{eff}} t_{\text{mir}} d\nu = P_{\text{abs}} = \int F_{\nu} \frac{\nu}{\nu_{\nu}} T_{\nu} A_{\text{eff}} t_{\text{mir}} d\nu
\] (3)

Where \( S_{\nu} \) is the star spectrum in Jy, \( A_{\text{eff}} \) is the telescope effective aperture, \( t_{\text{mir}} \) is the mirror transmission and \( T_{\nu} \) is the product of the filter transmission and bolometer absorption. Simplifying eq 3 we obtain the PACS flux density as:

\[
F_{\nu} = \frac{\int S_{\nu} T_{\nu}^{\prime} d\nu}{\int \frac{\nu}{\nu_{\nu}} T_{\nu} d\nu}
\] (4)

The left-hand term of equation 3 correspond to the power absorbed by the bolometer \( P_{\text{abs}} \). This is not the incident power on the bolometer \( P_{\text{inc}} \) that appear the definition of \( R_{\text{ILT}} \) in eq 1. The incident power \( P_{\text{inc}} \) is given by:

\[
P_{\text{inc}} = \int S_{\nu} T_{\nu} A_{\text{eff}} t_{\text{mir}} d\nu
\] (5)

where \( T_{\nu} \) is the filter transmission. We have

\[
T_{\nu}^{\prime} = T_{\nu} A_{\nu}
\] (6)

where \( A_{\nu} \) is the bolometer absorption.

The PV plan (v 1.5) gives fluxes for the 8 PACS primary standards. Unfortunately, these fluxes are the monochromatic fluxes of the star spectrum at the reference wavelength of the filter (i.e. \( S_{\nu}(\lambda_{\nu}) \)) not the flux density in the PACS photometric system \( F_{\nu} \) in the notation of eqs. 3 and 4. While the reference wavelength for the PACS system were chosen so that the difference between the two are small, since these eight stars are our primary standards, we believe the correct values \( F_{\nu} \) should be used.

We have recomputed for each star the incident power using eq. 5, the absorbed power using eq. 3 and the corresponding PACS flux density using eq. 4. For the input spectra \( S_{\nu} \), we use the L. Decin

\footnote{This appellation of "flat spectrum" is extremely misleading for astronomer coming from the optical realm where a flat spectrum is a spectrum with \( F_{\nu} = \text{cte} \). Think AB magnitude system...}
spectra model spectra from 2009A available on the wiki. These spectra are only computed up to 200 µm and were extrapolated by a power low up to 500 µm to allow the computation in the red band. Figure 3 present the spectrum, the PACS bands and the extrapolation for one of the standards. For the filter transmission $T_\nu$, we use the file `PCalPhotometer_FilterTransmission_FM_v2.fits`. For the bolometer absorption $A_\nu$, we use `PCalPhotometer_Absorption_FM_v2.fits`.

Table 2 gives for all standards the monochromatic flux of the star at the filter reference wavelength as given in RD4 ($S_\nu(\lambda_r)$), the in band incident power ($P_{inc}$), the in band absorbed power ($P_{abs}$) and the flux density of the star in PACS photometric system ($F_\nu$).

Figure 3: Spectrum of α Boo from the L Decin (2009A) model (plum), together with the blue, green, red passbands. The Spectra has been extrapolated to 500 µm (dark line) using a power law.

### 4 Scan–Map Responsivity

In order to compute the responsivity, we have used all the primary standard observations of OD 108 and 118. The data reduction was as follow:

1. We used the build `hcss-2.0.474`
2. The `WPR` status is used to identify the filter used instead of the `BAND` status.
3. `photFlagBadPixels` using the ”sneak preview” mask.
4. `photFlagSaturation` looking for both ADC and read-electronics saturations.
5. `photConvDigit2Volts`
6. `photMMTDeglitching` was done using the options implementing the Starck et al. (1999) algorithm. Pixels within 10” of the standard star were not deglitched.
4.1 Red Responsivity

The results for the red filter/array is presented in table 3. Figure 4 present the histogram of the $R_{ILT}$ responsivities.

A few results can be noted:

- The star $\beta$ UMi appears systematically in excess.

- The median value of the responsivity in the ILT sense, excluding $\beta$ UMi is $2.7 \times 10^{10} V/W$, very close from the predicted value of $2.6 \times 10^{10} V/W$ we obtained in section 2.

- The median value of the responsivity in the hipe sense is 0.00080 V/Jy, a factor 1.38 lower than the responsivity currently in hipe (calfile FM_v1).
4.2 Blue Responsivity

The results for the blue filter/array is presented in table ???. Figure 5 present the histogram of the $R_{\text{ILT}}$ responsivities.
A few results can be noted:

- The star $\beta$ UMi appears systematically in excess.
- The median value of the responsivity in the ILT sense, excluding $\beta$ UMi is $2.0 \times 10^{10} \text{V/W}$, far from the predicted value of $3.1 \times 10^{10} \text{V/W}$ we obtained in section 2.
- The median value of the responsivity in the hipe sense is $0.00096 \text{V/Jy}$, a factor 1.74 lower than the responsivity currently in hipe (calfile FM_v1).

4.3 Green Responsivity

TBC

A Scan map reduction script

```python
1 def standardReduction(obsid, side, rastar, decstar):
2     """
3     Reduce a scan map observation of a standard star into a map.
4     The map is returned, but also saved to disk as file map_zzz_yyyyy.fits
5     where zzz is the filter and yyyyy the obsid.
6     Inputs are:
```
obsid - long : the obsid
side - string : the channel to be reduced, 'red' or 'blu'
rastar - float : the R.A. of the star
decstar - float : the declination of the star

sto = getLocalStore('CPV')
obs = getObsContext(obsid, sto)
calTree = getCalTree("FM", "BASE")
if side == 'red':
    frames = obs.refs['level0'].product.refs['HPPAVGR'].product.refs[0].product
    NbCols = 32
    NbRows = 16
    filterWidth = 32
    distFilter = 15
    distMask = 10
    filter = 'red'
    ff = calTree.photometer.flatField.red['FlatField'].data
    outputPixelsize = 2.0
elif side == 'blu':
    frames = obs.refs['level0'].product.refs['HPPAVGB'].product.refs[0].product
    NbCols = 64
    NbRows = 32
    filterWidth = 20
    distFilter = 15
    distMask = 10
    outputPixelsize = 1.0
    # fix the status
    wpr=frames.getStatus("WPR")
    band=frames.getStatus("BAND")
    idGreen = wpr.where(wpr == 0)
    idBlue = wpr.where(wpr == 1)
    if idGreen.length() > 0:
        if band[idGreen][0]=='BS':
            print 'WARNING for Green filter: WPR=0 was erroneously assigned BS, now reset to BL'
            band[idGreen] = String('BL')
    if idBlue.length() > 0:
        if band[idBlue][0]=='BL':
            print 'WARNING for Blue filter: WPR=1 was erroneously assigned BS, now reset to BS'
            band[idBlue] = String('BS')
    frames.setStatus("BAND",band)
if idGreen.length() > idBlue.length():
    filter = 'Green'
    ff = calTree.photometer.flatField.green['FlatField'].data
    print "This is a GREEN observation"
else:
    filter = 'Blue'
    ff = calTree.photometer.flatField.blue['FlatField'].data
    print "This is a BLUE observation"
else:
    print "Unknown side: %20s" %side
    return 0

pointing = obs.auxiliary.pointing
hk = obs.refs['level0'].product.refs['HPPHK'].product.refs[0].product['HPPHKs']
# Fudge the caltree
fa = FitsArchive()
arrayInst = fa.load("PCalPhotometer_ArrayInstrument_sneak.fits")
calTree.photometer.arrayInstrument = arrayInst
badPixels = fa.load("PCalPhotometer_BadPixelMask_sneak.fits")
calTree.photometer.badPixelMask = badPixels
frames = detectCalibrationBlock(frames)
frames = findBlocks(frames, calTree=calTree)
bbid = frames.getStatus('BBID')
idx = bbid.where(bbid == 215131301)
first = idx.toInt1d()[0]
nbnow = nbini - first
frames = frames.select(Int1d.range(nbnow)+first)
frames = photFlagBadPixels(frames, calTree=calTree)
frames = photFlagSaturation(frames, calTree=calTree, hkdata=hk, check="full")
frames = convertChopper2Angle(frames, calTree=calTree)
frames = photAddInstantPointing(frames, pointing, calTree=calTree)
frames = photAssignRaDec(frames, calTree=calTree)
org = frames.copy()
frames = photMMTDeglitching(frames, scales=3, nsigma=5, mmt_mode='multiply', incr_fact=2)

# compute distance to standard star
deg2rad = Math.PI / 180.
rarad = frames['Ra'].data * deg2rad
decrad = frames['Dec'].data * deg2rad
rastarrad = rastar*deg2rad
decstarrad = decstar*deg2rad
inside = COS(rarad - rastarrad) * COS(decrad) * COS(decstarrad) + SIN(decrad)*SIN
(dist

dist = ARCCOS(inside) / deg2rad * 3600
sel = dist.where(dist < distMask)
for c in range(sel.length()):
    frames.setSignal(i[c], j[c], k[c], org.getSignal(i[c], j[c], k[c]))
    frames.setMask("MMT_Glitchmask", i[c], j[c], k[c], False)
Master = frames.getMasterMask()
print "Master", Master[i[0], j[0], k[0]]

# high pass filtering
newmask = Bool3d(NbRows, NbCols, frames.getNrFrames())
sel = dist.where(dist < distFilter)
r = sel.toInt1d() / frames.getNrFrames()
map = photProject(frames, outputPixeilsize=outputPixeilsize, calibration=True, calTree=calTree)
map.meta.set('filter', StringParameter(filter))
fa = FitsArchive()
fa.save('map_' + filter + '_%i' % obsid + '.fits', map)
return map
### Table 2: Flux densities of PACS primary standards.

For each star and each band are given the monochromatic flux of the star at the filter reference wavelength as given in RD4 ($S_\nu(\lambda_r)$), the in band absorbed power ($P_{\text{abs}}$) and the flux density of the star in PACS photometric system ($F_{\nu_r}$).

<table>
<thead>
<tr>
<th>Star</th>
<th>Blue: $\lambda_r = 70\mu$m</th>
<th>Green: $\lambda_r = 100\mu$m</th>
<th>Red: $\lambda_r = 160\mu$m</th>
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<td></td>
<td>$S_\nu(\lambda_r)$ (Jy)</td>
<td>$P_{\text{inc}}$ (pW)</td>
<td>$P_{\text{abs}}$ (pW)</td>
</tr>
<tr>
<td>$\alpha$ Boo</td>
<td>15.336</td>
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<tr>
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<tr>
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<td>0.6372</td>
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<td>0.2523</td>
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<tr>
<td>$\alpha$ CMa</td>
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<td>Star</td>
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Table 3: Responsivity mesurements for the red array
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<th>OBSID</th>
<th>OD</th>
<th>Star</th>
<th>Speed (&quot;/s)</th>
<th>Measure (mV)</th>
<th>Resp (×10(^{10}) V/W)</th>
<th>Resp (mV/Jy)</th>
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Table 4: Responsivity measurements for the blue array