Atacama Pathfinder EXperiment

LABOCA/SABOCA Photometric observing modes

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Photometric observing modes for Laboca and Saboca

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Table of contents

1 Purpose

This document provides a summary of the photometric observing mode for LABOCA and SABOCA.

2 Scope

This document applies to the LABOCA and SABOCA facility instruments.

3 Documents

3.1 Applicable documents

AD-01	APEX LABOCA Instrument Specifications	APEX-MPI-SPE-0008
AD-02	APEX Standard Hardware Interfaces	APEX-MPI-ICD-0003
AD-03	APECS Bolometer Observing Software	APEX-MPI-DSD-0019
AD-04	Multi-beam FITS Raw Data Format	APEX-MPI-ICD-0002
AD-05	LABOCA commissioning report	APEX-MPI-TRE-0025
AD-06	SABOCA commissioning report	APEX-MPI-TRE-0030

3.2 Reference documents

RD-01	LABOCA Optics Design Description	APEX-MPI-DSD-0018
RD-02	LABOCA Design Description	APEX-MPI-DSD-0016
RD-03	BoA Design Description	APEX-MPI-DSD-0017
RD-04	LABOCA Handling Document	APEX-MPI-MAN-0016
RD-05	LABOCA Commissioning Plan	APEX-MPI-PLA-0013

4 Definitions

Within this document we will use the following definitions, or the understanding shall be:

APEX	Atacama Pathfinder EXperiment
MPIfR	Max-Planck-Institut für Radioastronomie
LABOCA	Large APEX Bolometer Camera
APECS	APEX Control Software
FOV	Field Of View
wobbler	Chopping secondary mirror
BoA	Bolometer Data Analysis software package

5 Photometric observing modes

Because LABOCA and SABOCA are sparsely sampled arrays, any mapping mode with the arrays implies that a given position on the sky is only seen by a detector for ~1/16 of the observing time for a nyquist sampled map. For observations aiming to determine the flux of an object at a given position on sky (e.g. observations of high-z galaxies with know positions), it is therefore highly desirable to use observing modes with a larger integration time efficiency.

5.1 APEX wobbler modes

The APECS control system offers two modes for operating the wobbler: the asymmetric and the symmetric mode. The telescope movement for both modes and the resulting data on sky as a function of time is shown in Fig. 1. To keep a symmetric optical configuration while using the wobbler, the telescope is pointed always half way (in azimuth, the chopping direction) between the on and the off position. In the asymmetric mode the pointing center is always on one side so that the source signal is always located at the +dAz wobbler position. In the symmetric mode the telescope is moved to the other side of the source in each 2nd sub-scan (nodding). This means the former off position now becomes the on position. This way optical imbalances between the two nod-phases are efficiently removed.

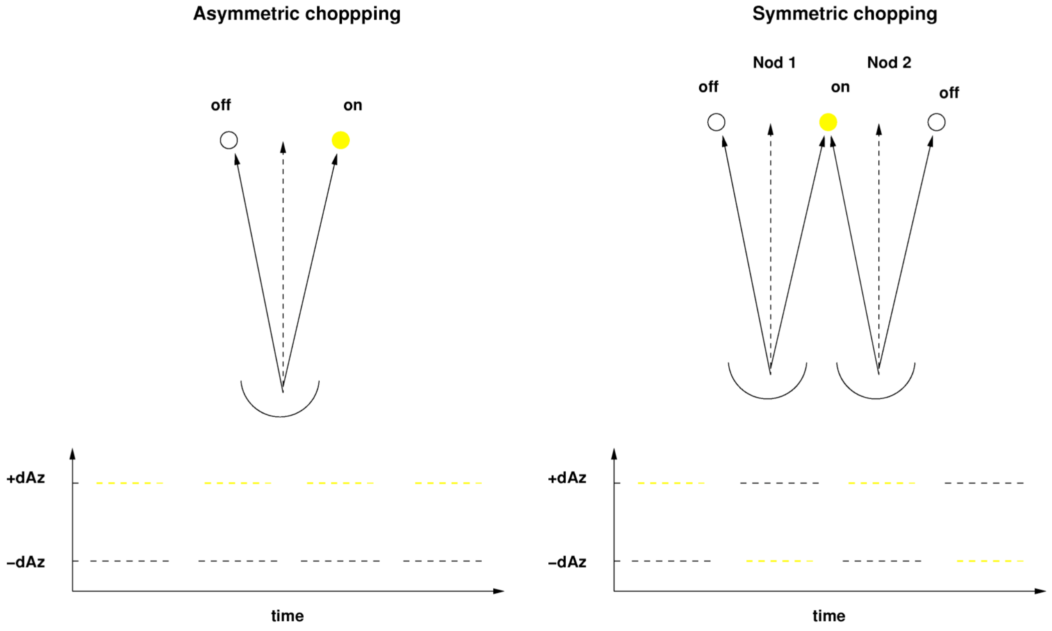

Figure 1: Top: Telescope (beam) movement for the asymmetric (left) and the symmetric (right) chopping. In the symmetric mode the telescope is moved by the wobbler throw in azimuth for odd sub-scans so that the former on

position becomes the off-position. This efficiently cancels out imbalances in the central part of the array (see Fig.1) Bottom: On and OFF signal as a function of time for the asymmetric and the symmetric chopping mode

5.2 Wobber observing modes

5.2.1 Chopping with a single pixel

Wobbler on-off observation on a single pixel is the simplest chopping mode. This mode allows us to use the symmetric wobbler setup, which nodes the telescope each sub-scan. The advantage of this mode is, that a bolometer close to the optical axis can be used which together with the telescope nodding most efficiently removes the optical imbalances of the system (see Sect. 5.3). In this mode, however, only a single bolometer observes the source (for up to 50% of the time), which implies that a single pixel chop mode does not have the highest possible on-source efficiency.

5.2.2 Chopping on bolometer pairs and triples

A potentially more time efficient way for on-off observations with the wobbler is to chop between 2 (or 3) bolometers. For such an observing mode the wobbler throw is no longer a free parameter but is determined by the separation of the bolometer pair (triple) used for the observations. As the wobbler only allows to chop in azimuth, the geometry of LABOCA limits the observing mode to four possible pairs with separations of ~70”, 100”, 170” and 250” (see Fig. 2 left). For chopping on these pairs only the asymmetric wobbler setup can be used, without nodding of the telescope between sub-scans. For chopping between three bolometers the same geometrical limitations apply as for chopping on pairs. Within the LABOCA array there are only 2 triples that can be used for this chop mode with separations of 160” and 200” (see Fig. 2 right). Both triples are located towards the edges of the array. The chopping between three bolometers uses the symmetric wobbler mode, with nodding between sub-scans. This implies that the central bolometer is on-source for each nod-cycle, while each of the outer bolometers only sees the source every second nod-cycle.

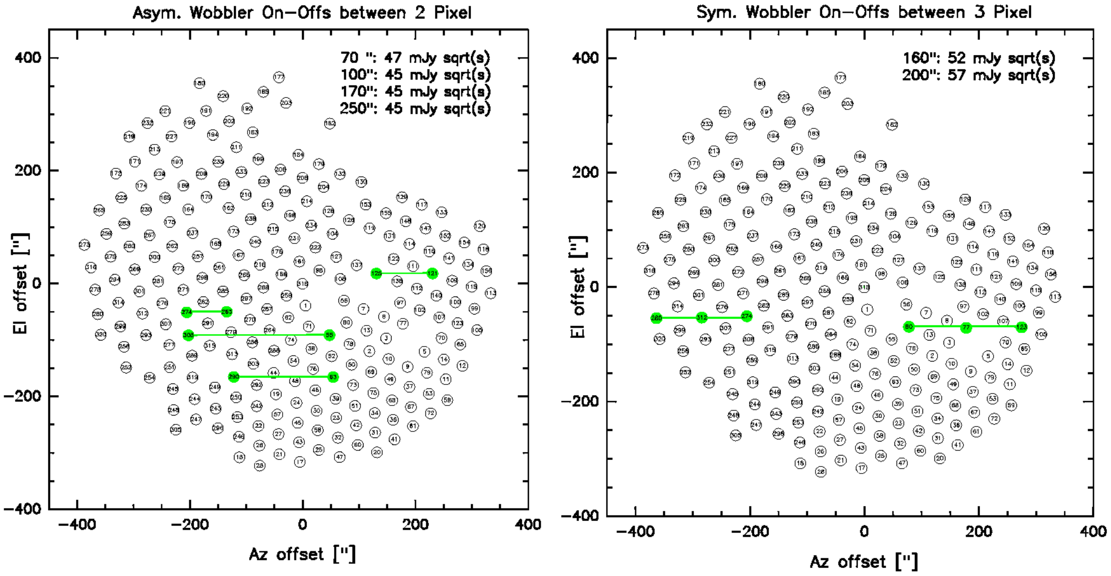

Figure 2 Location of bolometer pairs (left) and bolometer triples (right) of LABOCA, which allow to chop on multiple pixels in the array. The associated wobbler throws and the mean sensitivity of each pair is given in the figure.

5.3 Spill over - optical imbalances

Due to the asymmetric illumination of the chopping secondary there is a strong imbalance between the signal for the on and the off phase while using the wobbler. For LABOCA this spill over imbalance is of order 20 Jy across the array even for small wobbler throws. For the symmetric wobbler mode the average between both nod cycles reduces this imbalance to ~1Jy over the full array (Fig. 3). Fig. 3 also shows, that for the symmetric chopping the nodding efficiently removes the imbalance within the central ~100'' of the array.

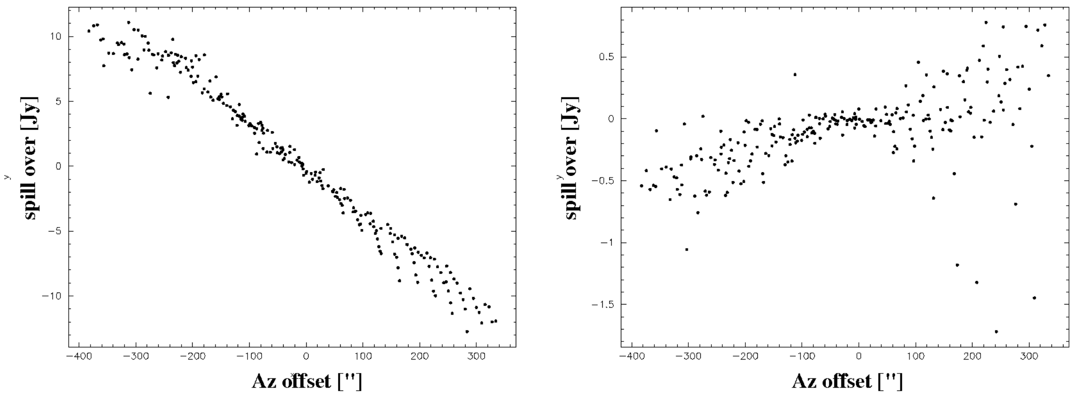

Figure 3: Spill over imbalances for each bolometer of LABOCA as a function of azimuth position on the array for asymmetric wobbler observations (left) and for symmetric wobbler observations including nodding between sub-scans (right).

This plot demonstrates that in order to minimize systematic imbalances (which introduce spurious source signals) it is required to use symmetric chopping (see Fig. 1) on a bolometer near the optical axis (azimuth offset close to the center of the array).

6 On sky observations

Tests for the photometric observing mode for LABOCA were done during MPIfR science time in 2008/9 focusing on chopping between 2 and 3 bolometers. Some additional tests for chopping on a single bolometer with LABOCA were done during ESO time in 2009. Technical time for testing and implementing the single pixel chop mode for LABOCA and SABOCA was allocated in March 2010. The marginal weather conditions in that run permitted observations with SABOCA for only two nights. This good weather time was partly used to update the pointing model of SABOCA, a requirement for reliable photometric observations.

6.1 Chopping on pairs and triples with LABOCA

All scans for chopping on 2 or 3 bolometers are heavily affected by the imbalances. Copping on pairs using the asymmetric wobbler mode is hopeless because the spill over completely dominates the signals on individual bolometers. Combining the signals of the two on-bolometers does not remove the spill over completely because none of the bolometer pairs for LABOCA is located symmetric with respect to the optical axis.

Symmetric chopping on 3 bolometers removes the spill over more efficiently for the central bolometers. This is shown in Fig. 4 where we show the signals from a scan taken on channels 180, 312 and 274 (160” wobbler throw). For the outer bolometers 180 and 274 the spill over imbalance makes the determination of the gains unreliable leading to wrong fluxes for these channels. This implies that only the central channel can be used to determine the source flux. This reduces the chopping on 3 bolometers to a single pixel chop, which can be done more efficiently with smaller imbalance near the optical axis of the array. We conclude from these tests that wobbler observation with LABOCA can only be done reliable with the single pixel on-off mode. For SABOCA we do not expect that the situation for chopping on pairs is different and no triples aligned in Azimuth exist.

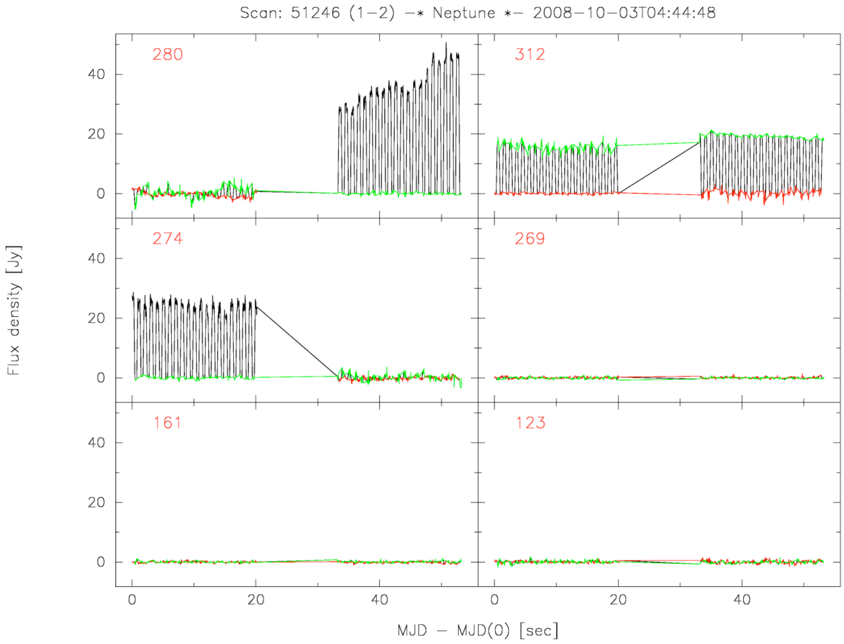

Figure 4: On-off signal shown for a symmetric wobbler scan on pixels 280, 312 and 274. Green line is the on-phase, red line the off-phase for the central bolometer (312).

6.2 Single pixel on-offs

An example for a symmetric on off with LABOCA on pixel 71 (near the optical symmetry axis) is shown in Fig. 5. The scan shows the large imbalance between the two nodding phases, which demonstrates that only the combination of both nodding phase can be used to reliably determine the flux of the source. This is shown in Fig. 6 (bottom) where we show the resulting flux when both nodding phases are combined (average of subscan 1&2, 3&4, 5&6 and 7&8). These numbers agree within 2% for the four combined nodding phases. Fig. 6 (top) shows the cumulative flux combining the individual measurements, which yields a flux density consistent with the flux determined from a map just before this scan (within 1% in this example).

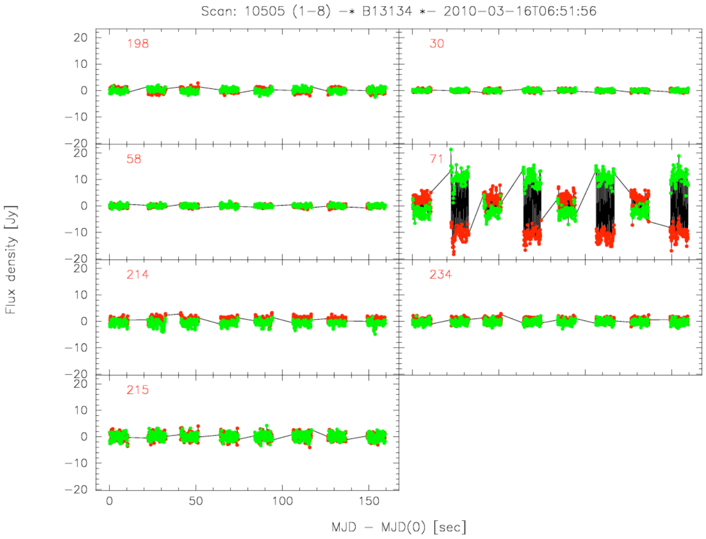

Figure 5: On-off signal shown for a symmetric wobbler scan on pixel 71 (middle right). Green line is the on-phase, red line the off-phase. Six surrounding bolometers are shown for comparison.

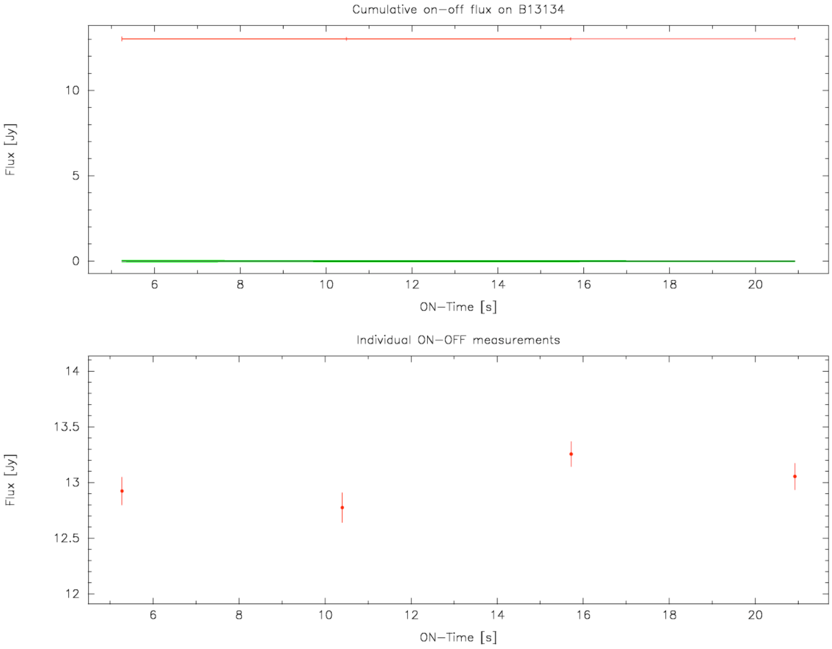

Figure 6: Top: Cumulative on-off flux (red) for scan 10505 on B13134, a secondary LABOCA calibrator. The (barely visible) black line at zero shows the average flux of the off bolometers, the green lines the scatter between the off bolometers. Bottom: flux of the individual subscans combining the signals of both nodding phases (see Fig. 5). The resulting flux determined from this scan is 13.025 +/- 0.060 Jy, average flux of the off bolometers is -11.0 +/- 26.3 mJy.

6.2.1 Single Pixel On-Off sensitivity and efficiency

For the single pixel chopping for LABOCA we selected the most sensitive and stable bolometer near the optical axis as default bolometer (pixel 71). This pixel has a sensitivity of ~40 mJy $\sqrt{s}$. Since the reduction uses the phase difference to determine the signal, the effective noise equivalent flux density (NEFD) is a factor $\sqrt{2}$ higher which results in NEFD=55mJy $\sqrt{s}$ for the LABOCA on-off mode. For SABOCA the on-offs are done on the central channel (pixel 1) which has a sensitivity of ~105mJy $\sqrt{s}$ (effective NEFD ~150mJy $\sqrt{s}$). This means that for a typical on-source efficiency of 30% (see below) the photometric observations of point sources are a factor of 4.8 (LABOCA) and 6.2 (SABOCA) faster than the FoV mapping mode.

For both arrays the observations have three free parameters: the wobbler frequency, the wobbler throw and the nodding time. We investigated the dependency of the data quality and the observing on-source efficiency as a function of these parameters. We define the on-source efficiency as the fraction of observing time spent on-source after removing all dumps that are flagged in the reduction (e.g. dumps when the wobbler moves from the on to the off position). The on-source efficiencies for different wobbler frequencies and nodding times are given in Table 1 & 2.

Wobbler throw: The source signals do not show a significant dependency on the wobbler throw and its effect of the on-source efficiency is negligible. So this parameter can safely be adjusted to the astronomical needs within the wobbler specifications. We recommend a wobbler throw of ~3x the beam size for point sources (e.g. 50” for LABOCA and 25” for SABOCA). Note that we define the wobbler throw here as the true angular distance on-sky between the on and the off position (while the apecs wobbler command takes half of this distance (the amplitude) as input parameter).

Wobbler frequency: We investigated wobbler frequencies between 0.5 and 2.0Hz in steps of 0.5Hz. The on-source efficiency changes by a factor of 2 between these frequencies with the highest efficiency for the slowest wobbler frequency (see Table 1 for values). We do not find significant differences for the on-off signals as a function of the wobbler frequency. E.g. for the high redshift QSO BR1202-0725 we get 30.7 +/- 2.6 mJy and 28.0 +/- 3.1mJy for the 0.5Hz and 2.0 Hz chopped data, respectively. The small dependence of the data quality on the wobbler frequency largely results from the correlated noise removal steps in the data reduction. These remove the atmospheric fluctuations efficiently from the on bolometer (using the off pixels) so that a large fraction of the high frequency fluctuations from the atmosphere do not need to be chopped away.

Nodding time: The nodding time has a significant influence on the on-source efficiency since each nod takes in the current version of the control system about 6 seconds. We have tested nodding times between 10 and 120 seconds (see Table 2 for values). Since the nodding is required to remove the optical imbalances, the time scales of the variations of the imbalances in principle determine the maximum nodding time. This time, however, is poorly constrained and also depends on the atmospheric stability. From our test we do not find a significant decrease of the data quality even for the longest nodding times in stable conditions. From our long integrations on faint sources (which have typically been done with a nodding time of 60 seconds) we do, however, find subsequent sub-scans where the imbalances do change significantly, leading to wrong fluxes for the corresponding nodding pair. This is shown in Fig. 7 (bottom) where we show the flux for individual nodding pairs for our integration on BR1202-0725. The poor data quality at the end of this integration is easily visible due to its much higher scatter. For long integrations these outliers are therefore easy to recognize and the BoA reduction provides an rms based clipping method to remove them.

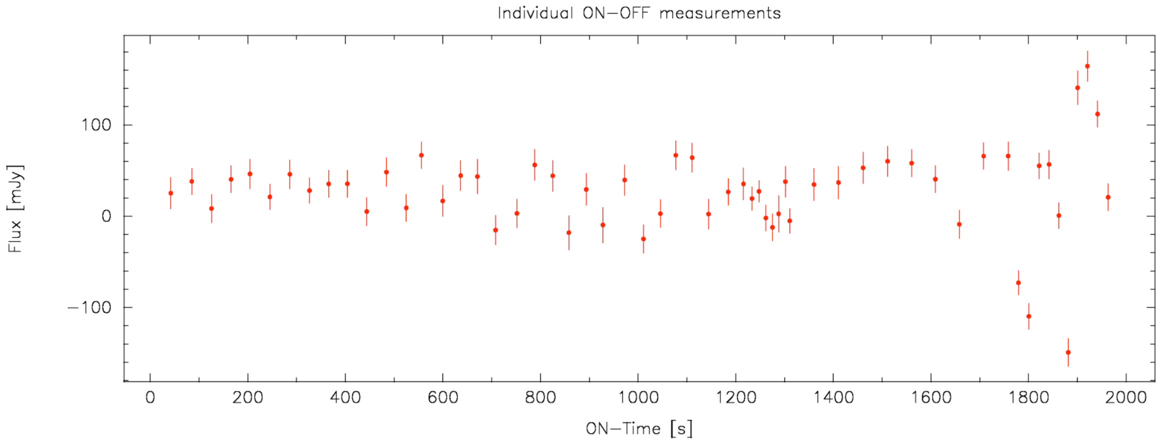

Figure 7: Individual fluxes for each nodding pair observed in our long integration on the high-z QSO BR1202-0725. The much higher scatter during the end of the integration is due to instable atmospheric conditions for which the imbalances change significantly between the nodding. These unreliable data points can be automatically flagged in the BoA reduction.

Given that the on-source efficiencies do only slowly increase for nodding times above 30 seconds (see Table 2) we recommend to use a nodding time of 30s as default and to only use longer nodding times for very stable conditions.

For short on-off integrations outliers due to imbalances are much more difficult to detect (due to the lower number of nodding pairs collected for these observations). We therefore recommend that all observations should have at least 6 sub-scans (3 nodding pairs). E.g. a short integration of 60s should be carried out using `woo(t=10,r=3)` rather than `woo(t=30,r=1)` although the overheads for the latter command are smaller (see Sect. 6.3 for a description of the observing abbreviations).

Wobbler throw: 50”, Nodding time: 60 s			
0.5 Hz	1.0 Hz	1.5 Hz	2.0 Hz
35%	30%	22%	16%

Table 1: On source efficiency as a function of the wobbler frequency for a fixed wobbler throw of 50’’ and a nodding time of 60 seconds.

Wobbler throw 50”, Wobbler frequency 1.0 Hz			
10s	30s	60s	120s
18%	27%	30 %	33%

Table 2: On source efficiency as a function of the nodding time for a fixed wobbler frequency of 1.0 Hz and a wobbler throw of 50’’.

6.2.2 Single Pixel On-Off verification for LABOCA

For the on sky verification of the single pixel on-off mode for LABOCA we observed strong (a few Jy), medium bright (~100 to few hundred mJy) and faint high-z sources with known flux. For the bright source a short map was done before the on-off for comparison. For the fainter sources we used targets that have been mapped by LABOCA in previous projects or where the 870 μm flux is known from the literature (e.g. high-z sources that were observed by SCUBA in the past). Observations on strong sources typically give the best agreement with very low scatter (typically about 5% or better). For fainter sources the agreement is somewhat worse with a scatter of typically 10%. This is expected because these maps have been taken in different observing runs (and partly with different instruments) so that the absolute calibration error enters into the comparison. To ensure that the observing modes (and the data reduction) do not suffer from small systematic errors we also integrated the blank sky. These tests verify that the photometric observing mode with a single pixel average to zero within the uncertainties.

A list of source fluxes observed with the single pixel on-off mode is given in Table 3. Our deep integration on the z=4.7 QSO BR1202-0725 is shown in Fig. 8.

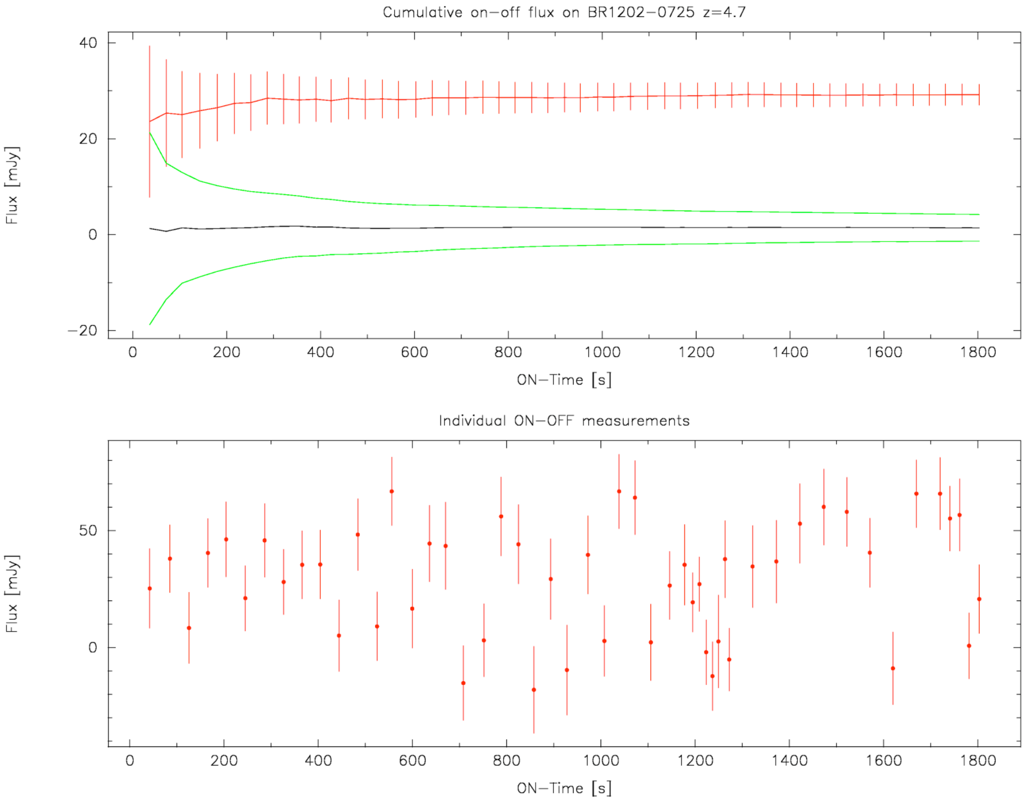

Figure 8: Top: Cumulative on-off flux on the high-z QSO BR1202-0725 (red) using LABOCA. The black line shows the average flux of the off bolometers, the green lines the 1σ uncertainties of the off bolometers. Bottom: Individual on off measurements computed from each nodding pair.

Source	Map/Lit. flux	LABOCA on-off	ratio
B13134 (calibrator)	12.9 +/- 0.9 Jy	13.3 +/- 0.1 Jy	1.03
Carina	38.3 +/- 0.9 Jy	37.5 +/- 0.5 Jy	1.02
PKS0745	780 +/- 50mJy	735 +/- 8 mJy	0.94
IRAS10456	100 +/- 13 mJy	113 +/-5.5 mJy	1.13
Angelina (asteroid)	24.8 +/- 5.0 mJy (model flux)	30.0 +/- 3.6 mJy	1.21

BR1202 (z=4.7)	32.0 +/- 4.0 mJy (@900μm SMA flux)	28.7 +/- 2.0 mJy	0.89
SMMJ14009 (z=2.9)	15.6 +/- 1.9mJy (SCUBA flux)	14.7 +/- 2.2 mJy	0.94
blank sky	0.0	-1.64 +/- 1.72 mJy	ok within 1 σ

Table 3: Comparison of source fluxes for different intensity ranges obtained with the single pixel photometry mode with LABOCA to the source flux from map or the literature. For the asteroid Angelina the source flux is based on a model (Lundgren priv. comm.)

6.2.3 Single Pixel On-Off verification for SABOCA:

Due to the small amount of observing time with suitable weather conditions for SABOCA in March 2010 only a limited number of test observations have been carried out. These include observations of bright source such as the asteroid Pallas, the nuclei of Arp220 and Centaurus A, the faint high redshift QSO BR1202-0725 and the blank sky. All observations confirm that the single pixel on-off mode with SABOCA yields reliable results within the calibration uncertainties. All sources, except BR1202-0725 were also observed in mapping mode for flux comparison. For BR1202-0725 we compare our results to those from the literature. The blank sky observations were done for 2 hours (telescope time, ~2000 seconds on-source) and integrate to zero intensity within the errors (see Fig. 9). These measurements are summarized in Table 4.

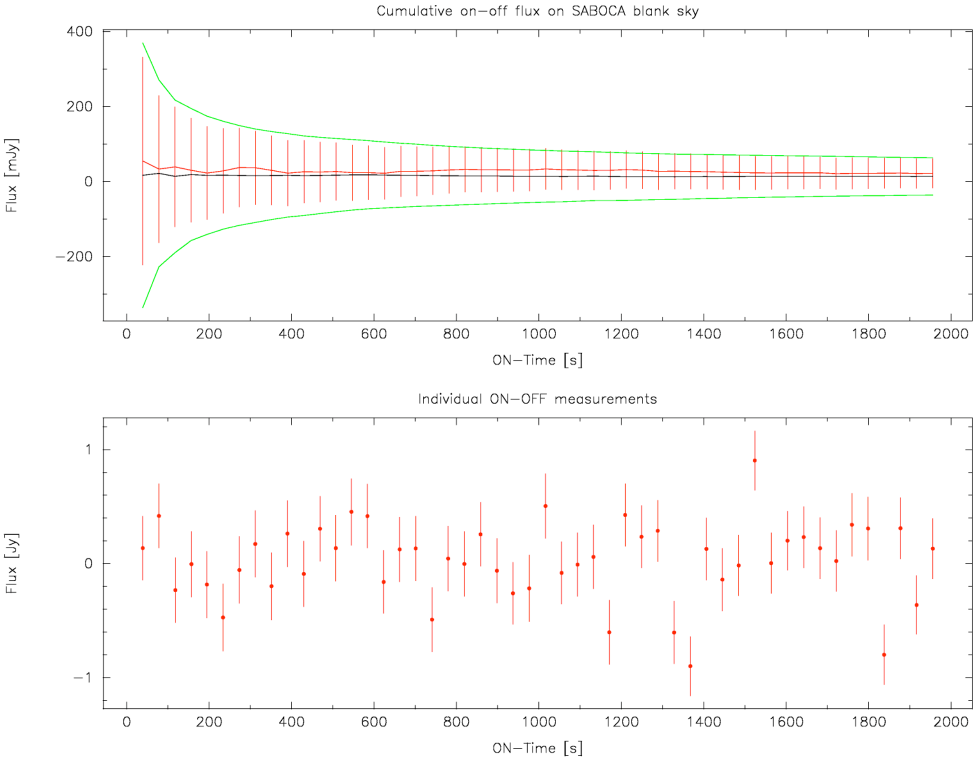

Figure 9 Top: Cumulative on off flux on the blank sky using SABOCA (red). The black line shows the average flux of the off bolometers, the green lines the 1σ uncertainties of the off bolometers. Bottom: Individual on off measurments determined from each nodding pair.

No systematic tests have been carried out to investigate the most suitable wobbler frequencies and nodding times. But since the atmospheric stability 350μm is typically much higher than at 870μm (high opacity, so less atmospheric variations with time) we expect that our optimization can also be applied to SABOCA.

Source	Map/Lit. flux	SABOCA on off	ratio
Pallas	9.4 +/- 0.5 Jy	8.6 +/- 0.1 Jy	0.91
Centaurus A	7.0 +/- 0.3 Jy	7.07 +.- 0.05 Jy	1.01
Arp220	11.3 +/- 0.5 Jy	11.6 +/- 0.1 Jy	1.03
BR1202-0725	106 +/- 0.7 mJy	116 +/- 23 mJy	1.09
blank sky	0.0	22.0 +/- 39.0mJy	ok within 1 σ

Table 4: Comparison of source fluxes for different intensity ranges obtained with the single pixel photometry mode with SABOCA to the source flux from maps or the literature (in case of BR1202-0725)

6.3 Implementation into the Apex control system

We have predefined observing abbreviations for the LABOCA and SABOCA single pixel on-off mode that are automatically loaded with the configuration files for both bolometers at APEX. The commands are summarized in the table below.

Command	Description
LABOCA On Off Appriviations:	
`woo(t,r,f,throw)`	Symmetric LABOCA wobbler on-off scan on pixel 71 (default). Takes the integration time, the number of repetitions, the wobbler frequency and the wobbler throw as parameters. The integration time also defines the nodding time and is by default set to 30 sec. The total integration time is controlled by number of repetitions (in multiples of 30 sec). Default t=30sec, r=3, f=1Hz, throw = 50''.
`woo71(t,r,f,throw)`	Same as woo
`woo30(t,r,f,throw)`	Same as woo but using pixel 30 (similar sensitivity as 71, close to the optical axis). Can be used in case pixel 71 is unstable or has other problems
`woo58(t,r,f,throw)`	Same as woo but using pixel 58 (similar sensitivity as 71, close to the optical axis). Can be used in case pixel 71 is unstable or has other problems
SABOCA On Off Appriviations:	
`swoo(t,r,f,throw)`	Symmetric SABOCA wobbler on-off scan on pixel 1 (default). Takes the integration time, the number of repetitions, the wobbler frequency and the wobbler throw as parameters. The integration time also defines the nodding time and is by default set to 30 sec. The total integration time is controlled by number of repetitions (in multiples of 30 sec). Default t=30sec, r=3, f=1Hz, throw = 25''.

7 On Off reduction using BoA:

The reduction functions to reduce the On-Off data from LABOCA and SABOCA have been included in the latest BoA version that is available at MPIfR and also via the ESO web page. We refer to the Boa manual and the help of the reduction functions for details. In brief, the LABOCA and SABOCA on off scans can be reduced using in single command:

```
doOO([scan1,scan2],tau=0.3,weak=1,filename='out.dat',update=1,clip=2.0)
```

The doOO command takes a list of scans (this can contain only a single scan) and the appropriate opacity (determined from a skydip or the APEX radiometer) as an input. The weak option refers to the expected source flux and should be set to 0 for sources with flux densities larger than ~500mJy for LABOCA and ~3 Jy for SABOCA. The weak = 1 allows the best reduction for faint sources which are well within the noise of the time stream. The reduction determines the flux for each nodding phase of the scans and keeps them in an array. The cumulative source flux is computed error weighted from these individual numbers at the end of the reduction. The function plots at the end of the reduction a figure similar to Figs. 6, 8 and 9 with the individual values from the nodding pair at the bottom and the cumulative source flux at the top. The individual results from the nodding pairs can be stored in a file (option filename). New scans (or scans with different zenith opacities) can be added with the update option. The clip option allows use to remove measurements of a single nodding pair that fall outside the specified clip range (sigma clipping, see Sect. 6.2.1).