The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/122800

Please be advised that this information was generated on 2019-04-13 and may be subject to change.
SCUBA-2: on-sky calibration using submillimetre standard sources

J. T. Dempsey1⋆, P. Friberg1, T. Jenness1, R. P. J. Tilanus1, H. S. Thomas1, W. S. Holland2,3, D. Bintley1, D. S. Berry1, E. L. Chapin1,4†, A. Chrysostomou1, G.R. Davis1, A. G. Gibb4, H. Parsons1, E. I. Robson2

1Joint Astronomy Centre, 660 N. A’ohoku Place, University Park, Hilo, Hawaii 96720, USA
2UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ
3Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ
4Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver BC V6T 1Z1, Canada

ABSTRACT

SCUBA-2 is a 10000-bolometer submillimetre camera on the James Clerk Maxwell Telescope (JCMT). The instrument commissioning was completed in September 2011, and full science operations began in October 2011. To harness the full potential of this powerful new astronomical tool, the instrument calibration must be accurate and well understood. To this end, the algorithms for calculating the line-of-sight opacity have been improved, and the derived atmospheric extinction relationships at both wavebands of the SCUBA-2 instrument are presented. The results from over 500 primary and secondary calibrator observations have allowed accurate determination of the flux conversion factors (FCF) for the 850 and 450 µm arrays. Descriptions of the instrument beam-shape and photometry methods are presented. The calibration factors are well determined, with relative calibration accuracy better than 5 per cent at 850 µm and 10 per cent at 450 µm, reflecting the success of the derived opacity relations as well as the stability of the performance of the instrument over several months. The sample-size of the calibration observations and accurate FCFs have allowed the determination of the 850 and 450 µm fluxes of several well-known submillimetre sources, and these results are compared with previous measurements from SCUBA.

Key words: submillimetre – atmospheric effects.

1 INTRODUCTION

Ground-based submillimetre astronomy has progressed markedly in the last fifteen years. SCUBA-2 (Holland et al. 2013) is the successor to the highly successful SCUBA instrument (Holland et al. 1999) which was operational on the JCMT from 1998 to 2005. In both cases, a limitation of ground-based submillimetre observing lies in the attenuation and distortion of the incoming radiation by the atmosphere. The dominant source of this attenuation is absorption by water vapour which, even on high sites such as Mauna Kea, limits submillimetre observations to a few narrow wavebands between the strongest absorption lines.

The opacity in these bands can vary rapidly and markedly as a function of precipitable water vapour (PWV), particularly at shorter wavelengths. Rapid measurements of the line-of-sight PWV are required in order to compensate adequately for this attenuation in the observation. A model of the atmospheric transmission as a function of wavelength must be used to relate the PWV to the opacity in the filter bands of the camera. This relation must be determined accurately. Uncertainties affect the short-wavelength windows significantly as they are more opaque and are more highly attenuated as the weather becomes poorer. These atmospheric effects have been investigated previously for SCUBA (Archibald et al. 2002) and for Bolocam (Sayers et al. 2010).

The second parameter required to calibrate submillimetre continuum data is a measure of the optical throughput of both the telescope and instrument itself. This value is referred to as the flux conversion factor (PCF) which converts the measured power in picowatts (pW) into astronomical fluxes in janskys (Jy). To obtain this factor, a series of astronomical sources of known flux are observed, preferably in a range of atmospheric conditions and over an extended time. Variations in this factor are dominated by optical effects from thermal distortions of the dish (particularly in the early evenings). Poor focus or even submillimetre seeing in the atmosphere will also result in deviations in the peak flux of a compact source.

This paper describes the atmospheric transmission relations for both SCUBA-2 filter bands and how these are applied to

⋆ E-mail:j.dempsey@jach.hawaii.edu
† Present address: XMM SOC, ESAC, Apartado 79, 28691 Vil-aneuva de la Canada, Madrid, Spain

© 2012 RAS

The atmosphere limits ground based observations at submillimetre wavelengths, providing only a few semi-transparent windows even at a high, dry site such as the summit of Mauna Kea. SCUBA-2, like its predecessor SCUBA, has been designed to take advantage of the 850 and 450 $\mu$m atmospheric windows. The measured SCUBA-2 filter profile at both wavelengths are shown superimposed on the submillimetre atmospheric transmission windows in Figure 2. The filter profile at both wavelengths are shown superimposed on the submillimetre atmospheric transmission windows in Figure 2. The filter profiles were measured using a Fourier transform spectrometer on a single bolometer at a time. The filter profiles were measured on a number of bolometers moving away from the centre of the focal plane and no discernible difference was observed in the profile.

Atmospheric attenuation at a given waveband in the submillimetre can be described as follows, assuming a plane-parallel atmosphere:

$$\text{Atmospheric attenuation} = \text{Transmission} \times \text{Observing time} \times \text{Flux density}$$
3.1 The Water Vapour Monitor

The extinction coefficient, $\tau$, must be explicitly determined for each observing waveband. The Caltech Submillimetre Observatory (CSO) has a fixed-azimuth 225 GHz tipping radiometer that has been in operation throughout the lifetime of both SCUBA and SCUBA-2 (Radford 2011). This completes a skydip every fifteen minutes and calculates a zenith opacity using a plane-parallel atmospheric model. The wavelength dependent extinction relations for SCUBA were calculated as a function of the CSO tipper 225 GHz opacity (Archibald et al. 2002). The JCMT has a 183 GHz water vapour monitor (WVM) installed in the receiver cabin that measures the precipitable water vapour (PWV) along the line-of-sight at 1.2-second intervals (Wiedner et al. 2001). The WVM has the advantage of better time resolution, which is important given that SCUBA-2 collects data at a rate of 200 Hz.

In general, skydips taken with the 345 GHz HARP instrument (Buckle et al. 2009) on the JCMT, as well as previous comparisons between SCUBA skydips and the CSO tipper show that the atmosphere deviates from a plane-parallel approximation about 30 per cent of the time, particularly in the early evening when the atmosphere is unstable.

We can then directly compare the opacity derived in this way by the WVM to the independently produced CSO 225 GHz opacity. The WVM and CSO values show excellent correlation for the stable part of the night between 9 pm and 3 am, with deviations occurring in the early evening and at sunrise when conditions become more variable. The PWV at zenith ($\text{PWV}_{\text{zen}}$) is related to the opacity at 225 GHz, $\tau_{225}$, by:

$$\tau_{225} = 0.04 \times \text{PWV}_{\text{zen}} + 0.017,$$

where $\text{PWV}_{\text{zen}}$ is in units of millimetres. The comparison between the CSO 225 GHz opacity at zenith and the PWV at zenith from the WVM for a full year of observing in 2011 is shown in Figure 3.

3.2 Tau relations

The extinction coefficients at each SCUBA-2 wavelength will be described in terms of the PWV determined by the water vapour monitor. The relation was derived by collating the calibration observations of sources of known flux taken over the six month period from 2011 May until 2011 October, and then in additional science time until 2012 May. These observations were reduced without applying any assumed extinction correction and then fitted using a least-squares algorithm to the following formula, where the precipitable water vapour (PWV) is measured in millimetres:

$$\tau_\lambda = a \times (\text{PWV} - b).$$

The resulting extinction coefficients at each wavelength are:

$$\tau_{\lambda_{500}} = 0.179 \times (\text{PWV} + 0.337)$$

and

$$\tau_{\lambda_{450}} = 1.014 \times (\text{PWV} + 0.142).$$

The data from which these extinction coefficients were determined is presented and discussed in Section 5.3 below. The quality of these fits is thus determined by the scatter and systematics in the calibrator data, and is accounted for in the resulting error quoted for the flux conversion factor in Section 5.4. The SCUBA-2 extinction correction coefficients in terms of the opacity at 225 GHz are:
4 SCUBA-2 BEAM SHAPE

The JCMT beam as seen with SCUBA-2 has been determined from good quality maps of Uranus obtained between 2011 May and 2012 June. The maps were reduced using the method described later in Section 2. The maps co-add the measured signal from all working bolometers. Individual bolometer scans of Uranus show that the beam profile varies from the centre to the edge of the focal-plane by less than 5 per cent. The individual maps were then co-added after adjustment for pointing differences. The size of Uranus was $\sim 3.5$ arcsec during this period. This reduction filters map structures on scales approximately larger than 5 arcmin (Chapin et al. 2013). Thus any beam contribution larger than this will not be seen in SCUBA-2 maps.

The beam is described here in terms of two Gaussian components - a main-beam Gaussian, $G_{\text{MB}}$, and an additional error-beam component, $G_e$ describing the response due to large scale surface distortion and diffraction (Airy pattern). While the main beam is well described by a Gaussian this does not apply to the second component. However, using a Gaussian is a simple way to capture the volume of this error-beam. A more complete description of the second component would be asymmetric and stationary in azimuth and elevation as a result of the mounting of the telescope. It is also well known that the point source efficiency is affected by thermal surface distortions early in the evening and mid-morning. The associated aberrations would increase and possibly extend the second component. Drops of aperture efficiency as large as 50 per cent have been reported in the 450 $\mu$m heterodyne systems, and

$\tau_{\text{GB}} = 4.6 (\tau_{\text{M12}} - 0.0043)$ and $\tau_{\text{e0}} = 26.0 (\tau_{\text{M12}} - 0.012)$, to allow easy comparison with the previous extinction terms for SCUBA.

Figure 4 shows the co-added Uranus maps at both wavelengths. The upper plots show the inner detail of the beam pattern, while the lower plots show the low-level emission at larger scales. Normalised radial slices through the beam in the azimuth (blue) and elevation (cyan) directions are shown in Figure 5. More distinct asymmetry is noted in the 850 $\mu$m cuts than at 450 $\mu$m. The beam shape was then fitted as the normalised sum of the two Gaussian components as given by:

$$G_{\text{total}} = \alpha G_{\text{MB}} + \beta G_s,$$

where the Gaussian profile, $G$, is described as $\exp[-4 \ln 2(r/\theta)^2]$ where $\tau$ is the radial distance from the centre in arcseconds and $\theta$ is the full-width half maximum (FWHM) in arcsec. The result of the Gaussian fitting is given in Table 1. The integral of the profile provides the volume,

$$V = \frac{\pi}{4 \ln(2)} (\alpha(\theta_{\text{MB}})^2 + \beta(\theta_s)^2),$$

in arcsec$^2$. The widening effect resulting from the finite size of Uranus has been removed from the widths given in the table. The main beam widths are close to theoretical values estimated with a 3 dB taper - these are 7.4 and 12.75 arcsec, respectively. This includes widening caused by the finite pixel size $F/2\lambda$ at 850 $\mu$m and $F/\lambda$ at 450 $\mu$m.

Figure 5 shows the co-added Uranus maps at both wavelengths. The upper plots show the inner detail of the beam pattern, while the lower plots show the low-level emission at larger scales. Normalised radial slices through the beam in the azimuth (blue) and elevation (cyan) directions are shown in Figure 5. More distinct asymmetry is noted in the 850 $\mu$m cuts than at 450 $\mu$m. The beam shape was then fitted as the normalised sum of the two Gaussian components as given by:

$G_{\text{MB}} = 26.0 (\tau_{\text{M12}} - 0.012)$, to allow easy comparison with the previous extinction terms for SCUBA.
satisfactorily described by this model. Subtracting the modeled main-beam Gaussian from the co-added Uranus map in Figure 4 and integrating over the remaining volume allows empirical comparison of the error-beam with that described by the model. The measured error-beam is 24 and 39 per cent of the total integrated flux at 850 and 450 \( \mu \)m, respectively, compared to 25 and 40 per cent predicted by the model. The size of the second Gaussian is rather close to the first maximum in the Airy pattern from a uniform aperture. The maxima are roughly at diameters 40 and 20 arcseconds for 850 and 450 \( \mu \)m, respectively.

Strong point sources observations clearly show a low-level emission ring at large scales (see Figure 5). The feature results from a slight mis-match between the telescope focal length and the focal length of the individual panels. The ring is 350 and 183\( \prime\prime \) in diameter at 850 and 450 \( \mu \)m, respectively. Though visible, the contribution to the beam integral is less than 1 per cent (850 \( \mu \)m) at large scales (see Figure 4). The feature results from a slight mis-match between the telescope focal length and the focal length of the individual panels. The ring is 350 and 183\( \prime\prime \) in diameter at 850 and 450 \( \mu \)m, respectively. Though visible, the contribution to the beam integral is less than 1 per cent (850 \( \mu \)m) at large scales (see Figure 4).

5 FLUX CALIBRATION

Nightly flux calibration is achieved by observation of astronomical sources with known flux properties. To convert the measured signal of a source from picowatts to janskys a flux conversion factor must be applied. The primary factors affecting the FCF are the optical path to the detectors, including the shape of the dish, and the filter profiles at each wavelength. If the optical quality is stable, and flat-fielding of the instrument and extinction correction are properly applied, the FCF should be a constant factor.

5.1 Calibration sources

Mars and Uranus were the primary calibrators. The brightness temperatures of these planets were obtained using the JCMT FLUXES software \cite{Privett2005} based on models from Wright \cite{Wright1976} and Moreno \cite{Moreno2010} respectively. It should be noted that the newer Uranus brightness temperatures differ from those used for SCUBA (a decrease of approximately 5 per cent and 2.5 per cent at 850 \( \mu \)m and 450 \( \mu \)m respectively). Wright \cite{Wright1976} estimates an uncertainty in the Mars model flux of \( \pm 5 \) per cent. The Uranus model is quoted as having an absolute uncertainty of 5 per cent. Secondary calibrators were observed on a nightly basis were CRL 618 and CRL 2688. A set of additional potential secondary calibrators were also observed and are listed with their SCUBA fluxes in Table 1.

Figure 6. Aperture photometry curve of growth normalised for a 60 arcsec aperture, at both wavelengths.

5.2 Observation method and data reduction

All calibrators were observed using a daisy scan-pattern \cite{Holland2013}, designed specifically for observation of point and compact sources, with observations lasting approximately four minutes each. The data were reduced using the SMURF routine \textsc{makemap} \cite{Chapin2013, Jenness2011}, using a parameter file designed specifically for bright point sources. The reduction of compact calibrators uses a combination of common-mode rejection and high-pass filtering of the bolometer data (which effectively suppresses information on scales larger than 3.3 arcmin) to remove low-frequency noise. The ringing one might expect from such filtering is then controlled by constraining the map to a value of zero beyond 60 arcsec from the source (well beyond the bulk of the power in the central lobe) for all but the final iteration. For point-like sources, the gain (independent of the brightness of the source) is effectively one. These parameters are discussed in detail in Section 4.1 of \cite{Chapin2013}. The calibrations were taken between 2011 May and 2012 May, and over 500 observations (at each wavelength) were included in this analysis. Maps were regridded to a 1-arcsec pixel scale, to optimise the quality of the fits to the peak of the beam.

5.3 Aperture photometry

The total integrated flux for each calibrator map was calculated in a 60 arcsec diameter aperture, with the background level calculated within an annulus of inner diameter 90 arcsec and outer diameter 120 arcsec (1.5 and 2.0 times the source aperture). As discussed in Section 4, the SCUBA-2 beam has a broad error-beam, and a 60 arcsec aperture does not fully encompass the beam, particularly at 850 \( \mu \)m. However, increasing the aperture, and thus by necessity, the annulus, beyond this size showed a significant increase in noise, and produced larger scatter in the results.

The 60 arcsec aperture was chosen as a compromise between minimising the scatter in the results whilst optimising the total flux measurement. The curve of growth in Figure 6 shows the ratio of Aperture flux to Total Flux for a co-add of several Uranus observations, normalised to an aperture of 60 arcsec. At 450 \( \mu \)m,

\begin{table}
\centering
\caption{Results of two component Gaussian fits}
\begin{tabular}{lll}
\hline
 & 450 \( \mu \)m & 850 \( \mu \)m \\
\hline
FWHM Main beam (\( \theta_{\text{MD}} \)) & 7.9\( \prime\prime \) & 13.0\( \prime\prime \) \\
FWHM Secondary Comp. (\( \theta_{\text{S}} \)) & 25\( \prime\prime \) & 48\( \prime\prime \) \\
Rel. Amp. Main Beam (\( \alpha \)) & 0.94 & 0.98 \\
Rel. Amp. Secondary Comp (\( \beta \)) & 0.06 & 0.02 \\
Rel. Vol. Main & 0.6 & 0.75 \\
Rel. Vol. Secondary Comp & 0.4 & 0.25 \\
\hline
\end{tabular}
\end{table}

\cite{Moreno2010} “Neptune and Uranus planetary brightness temperature tabulation” ESA Herschel Science Centre. http://ftp.scipps.edu/pub/hsc-calibration

© 2012 RAS, MNRAS 000 [1][2]
The FCF is simply described as the ratio between the known flux \( S \), in Jy, and the measured signal in pW, \( I_0 \), summed over the source. To apply the FCF when calculating a flux integrated over a source, the size of the pixels in the output map must also be taken into account. This factor is called the FCF_{\text{arcsec}}, and is given by:

\[
\text{FCF}_{\text{arcsec}} = \frac{S}{I_0 A},
\]

where \( A \) is the pixel area in arcsec\(^2\), giving the units of Jy pW\(^{-1}\) arcsec\(^{-2}\).

It is sometimes preferable to measure the peak flux of a source, rather than the integrated value. To fit the peak of each calibration map, a Gaussian-like 2D fit was applied to each calibrator using the KAPPA application BEAMFIT (Currie et al. 2008), with the power index allowed to be a variable in the fit. Unlike the total flux calculated in a large aperture, the source peak is highly susceptible to errors in telescope focus, as well as temperature-dependent distortions in the dish shape, most noticeable early in evening observations. The peak FCF, \( \text{FCF}_{\text{peak}} \), is simply the ratio of the known peak flux in Jy to the measured peak flux in pW.

### Table 3. When integrating over an aperture of diameter, \( d \), in arcseconds, the FCF given in Section 5.4 must be divided by the following factor, given in columns denoted 450\( \mu \) and 850\( \mu \). The factors are derived from the measurements plotted in Figure 6. These factors are only valid for unresolved sources.

<table>
<thead>
<tr>
<th>( d ) (arcsec)</th>
<th>450( \mu )</th>
<th>850( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.72</td>
<td>0.69</td>
</tr>
<tr>
<td>25</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>30</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>35</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>40</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>45</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>50</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>55</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>65</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>70</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>75</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>80</td>
<td>1.02</td>
<td>1.04</td>
</tr>
<tr>
<td>85</td>
<td>1.03</td>
<td>1.05</td>
</tr>
<tr>
<td>90</td>
<td>1.03</td>
<td>1.05</td>
</tr>
<tr>
<td>95</td>
<td>1.03</td>
<td>1.06</td>
</tr>
<tr>
<td>100</td>
<td>1.03</td>
<td>1.07</td>
</tr>
<tr>
<td>105−120</td>
<td>1.03</td>
<td>1.08</td>
</tr>
<tr>
<td>&gt;120</td>
<td>—</td>
<td>1.09</td>
</tr>
</tbody>
</table>

This aperture underestimates the total flux by approximately 4 per cent while at 850\( \mu \) this value is approximately 8 per cent. In the results presented here, the Uranus calibration maps and the secondary sources are both reduced using a 60 arcsec aperture, therefore no correction is required in the FCF values quoted below. However, if a different aperture size is chosen for a science source, the result needs to be divided by the appropriate factor derived from Table 3 and listed for reference in the lookup Table. These factors are only applicable to photometry of unresolved sources.

### 5.4 Results

Figures 7 and 8 show the results of the FCF calculations for the standard calibrators, Uranus, Mars, CRL618 and CRL2688. Figure 7 shows FCF_{\text{arcsec}} as a function of time (top), and versus atmospheric transmission (bottom). At both wavelengths the results show no systematic deviation, indicating the instrument and optical performance were consistent during this year-long period.

Figure 8 shows the same comparisons, but for the FCF_{\text{peak}}. These results show larger deviation from the mean, particularly at 450\( \mu \). This is to be expected given this measure is more susceptible to focus and temperature variations in the optics, however, again, no systematic deviation is observed. Figure 9 shows the histogram distribution of FCF_{\text{arcsec}} and FCF_{\text{peak}} for the combined set of calibrations at 850\( \mu \) (top left panel) and 450\( \mu \) (top right panel). The resulting mean FCFs at each wavelength are thus:

\[
\text{FCF}_{\text{850}} = 2.34 \pm 0.08 \text{ Jy pW}^{-1} \text{ arcsec}^{-2}
\]

and

\[
\text{FCF}_{\text{450}} = 4.71 \pm 0.5 \text{ Jy pW}^{-1} \text{ arcsec}^{-2}.
\]

The corresponding peak FCF results are:

\[
\text{FCF}_{\text{850,peak}} = 537 \pm 26 \text{ Jy pW}^{-1}
\]

and

\[
\text{FCF}_{\text{450,peak}} = 120 \pm 1.09 \text{ Jy pW}^{-1}
\]
The error is the 1-σ deviation from the mean. The relative flux calibration is thus better than 5 per cent at 850 µm and ∼ 10 per cent at 450 µm. In comparison, the relative flux calibration of SCUBA from Jenness et al. (2002) was 10 per cent at 850 µm and 20 per cent at 450 µm. Current instruments with comparable wavebands include LABOCA, on the APEX telescope (Siringo et al. 2009), which measures a calibration accuracy of 10 per cent at 870 µm and BOLOCAM, at the Caltech Submillimeter Observatory, with an 8 per cent uncertainty at 1.1 millimetres (Aguirre et al. 2011). SHARC-II, the 350 µm bolometer camera at Caltech Submillimeter Observatory, reports a calibration uncertainty of 15 per cent (Kovács et al. 2006), and as it shares the same site as SCUBA-2 it provides a point of comparison for the SCUBA-2 450 µm accuracy, as the 350 µm and 450 µm atmospheric windows are similarly affected by small variations in PWV. This improvement by a factor of two in the calibration accuracy at both wavelengths, in comparison to SCUBA, can be attributed to the increased time-resolution measurements of the atmospheric conditions by the WVM, and the stability of the instrument performance.

The absolute calibration accuracy must also take into account the uncertainty in the modeled fluxes of our primary calibrators, Mars and Uranus, which as noted in Section 5.1, are both ± 5 per cent. Less than a percent difference is observed in the mean FCF derived for the calibrators using only one or other of these sources implying that the estimate of the uncertainty on these models is an upper limit and we have a better calibration than the addition of this error estimate would suggest. Taking the case that we have an overall model error of 5 per cent, the quadrature addition of the model error and relative FCF error would give an upper limit on the absolute calibration uncertainty of 8 per cent at 850 µm and 12

\[
\text{FCF}_{[450]}^\text{peak} = 491 \pm 67 \text{ Jy pW}^{-1}. \tag{12}
\]
per cent at 450 \(\mu\)m.

The lower panels in Figure 9 compare the FCF\(_{\text{peak}}\) versus FCF\(_{\text{arcsec}}\) at each wavelength. This allows an empirical estimation of the beam area, \(A_E\), by fitting the linear relation between the peak and integrated values. The beam areas derived in this way therefore determine the effective FWHM at each wavelength. Assuming a gaussian beam, the effective FWHM, \(\theta_E\), at each wavelength can be determined as \(\sqrt{A_E/(1.2)}\), resulting in \(\theta_E\) of 14.1 and 9.6 arcsec at 850 and 450 \(\mu\)m respectively. Note that this is wider than the fit to the main beam component at each wavelength as shown in Table 4 as it accounts for the extended emission in the shoulders of the beam. The effective FWHM should relate to the derived, two-component beam as \(\theta_E = \sqrt{\alpha(\theta_{MB})^2 + \beta(\theta_E)^2}\). The \(\theta_E\) predicted from the two-component model gives 14.6 and 9.8 arcsec at 850 and 450 \(\mu\)m respectively, which compares reasonably with the estimate derived from the calibrations.

6 CALIBRATION SOURCE FLUXES

Several well-studied submillimetre point sources were also regularly observed as potential new calibrators. Using the new extinction corrections and FCFs derived above, these sources were calibrated and compared with previous determinations of their flux. Table 4 shows the calibrator fluxes for all potential calibrators that were observed. In all cases, a co-added map of a large set (or in some cases, all) of the observations was produced and the integrated fluxes were calculated in a 60 arcsec aperture as described in Section 5.2. The table reports the integrated fluxes and also the peak fluxes as derived from a single Gaussian fit to the source profile.

6.1 CRL 618

CRL 618 is also extremely well-observed in the submillimetre (Sandell 2003; Jenness et al. 2010; 2002; Siringo et al. 2009) and is compact, with a measured FWHM of 13.7 and 8.0 arcsec at 850 and 450 \(\mu\)m, respectively. Figure 10 shows CRL 618 at both wavelengths. The calculated integrated flux at 850 \(\mu\)m is slightly higher at 5.0 Jy in comparison to results presented by Jenness et al. (2002), though the result does fall within their 0.5 per cent error range. The possibility that this source varies over time has been suggested (Knapp et al. 1993). No source variability was seen in the SCUBA-2 results between 2011 July and 2012 May, which agrees with the results from SCUBA between 1997 and 2005 as presented by Jenness et al. (2010). At 870 \(\mu\)m, LABOCA measure a peak flux of 4.9 \pm 0.2 Jy beam\(^{-1}\) (Siringo et al. 2009) which agrees well with our result of 4.89 \pm 0.24 Jy beam\(^{-1}\). At 450 \(\mu\)m, the integrated and peak fluxes agree extremely well with the published SCUBA counterparts.

6.2 CRL 2688

CRL 2688 is a well-known compact submillimetre source that has been used as a calibrator for SCUBA (Sandell 2003), and other submillimetre instruments including BLAST (Truch et al. 2008). Over 170 observations of the source were taken with SCUBA-2 during 2011 and early 2012, and the co-added map of 55 of the best weather observations is shown in Figure 11. At 850 \(\mu\)m, the source is compact, though possibly slightly resolved, and the measured FWHM is 14.2 arcsec. At 450 \(\mu\)m, we measure a FWHM of 9.4 arcsec indicating the source is extended. This is in agreement with previous measurements and this extended emission is entirely contained within the 60 arcsec aperture used to calculate the photometry. Fluxes are in good agreement with the measurement of the peak flux by Sandell (2003); Siringo et al. (2009) and the integrated flux by Jenness et al. (2002).

6.3 Arp 220

Arp 220 is an ultra-luminous nearby galaxy and is well-studied in the submillimetre. Several publications have investigated the continuum flux at 850 \(\mu\)m (Dunne et al. 2000; Eisenfeld et al. 2000; Seiffert et al. 2007) and 450 \(\mu\)m (Dunne et al. 2000). At 850 \(\mu\)m, we calculate an integrated flux of 0.81 \pm 0.07 Jy, compared with previous determinations ranging from 0.78 Jy (Sakamoto et al. 2008) to 0.83 Jy (Dunne et al. 2000). At 450 \(\mu\)m, the integrated flux of 5.4 Jy agrees reasonably with the SED fit from Truch et al. (2008). There are no published continuum fluxes for this source at 450 \(\mu\)m (Truch et al. 2008) fit an SED to Arp 220 using a combination of published submillimetre and far-infrared flux densities, to calculate interpolated flux densities in their 250, 350, and 500 \(\mu\)m BLAST bands (the last of which overlaps significantly with the...
Table 4. Measured fluxes of SCUBA-2 secondary calibrators

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CRL618</td>
<td>04:42:53.67</td>
<td>+36:06:53.17</td>
<td>113</td>
<td>5.0 ± 0.2</td>
<td>12.10 ± 1.05</td>
<td>4.80 ± 0.24</td>
<td>11.50 ± 1.4</td>
<td>y</td>
</tr>
<tr>
<td>CRL2688</td>
<td>21:02:18.27</td>
<td>+36:41:37.00</td>
<td>173</td>
<td>6.13 ± 0.211</td>
<td>29.10 ± 2.5</td>
<td>5.64 ± 0.27</td>
<td>24.9 ± 2.9</td>
<td>y(a)</td>
</tr>
<tr>
<td>Arp220</td>
<td>15:34:57.27</td>
<td>+23:30:10.48</td>
<td>20</td>
<td>0.81 ± 0.07</td>
<td>5.4 ± 0.7</td>
<td>0.79 ± 0.9</td>
<td>5.2 ± 0.8</td>
<td>y</td>
</tr>
<tr>
<td>PV Cep</td>
<td>20:45:54.39</td>
<td>+67:57:38.8</td>
<td>21</td>
<td>1.35 ± 0.05</td>
<td>10.6 ± 0.86</td>
<td>0.82 ± 0.04</td>
<td>5.7 ± 0.65</td>
<td>n</td>
</tr>
<tr>
<td>MWC 349</td>
<td>20:32:45.53</td>
<td>+40:39:36.6</td>
<td>14</td>
<td>2.19 ± 0.08</td>
<td>3.2 ± 0.25</td>
<td>2.21 ± 0.11</td>
<td>3.4 ± 0.26</td>
<td>n</td>
</tr>
<tr>
<td>HD169142</td>
<td>18:24:29.78</td>
<td>-29:46:49.37</td>
<td>12</td>
<td>0.58 ± 0.02</td>
<td>3.41 ± 0.24</td>
<td>0.52 ± 0.03</td>
<td>2.21 ± 0.25</td>
<td>y(a,b)</td>
</tr>
<tr>
<td>V838 Ori</td>
<td>05:38:19</td>
<td>-17:02:2</td>
<td>3</td>
<td>2.00 ± 0.07</td>
<td>10.4 ± 1.0</td>
<td>1.55 ± 0.09</td>
<td>7.8 ± 1.00</td>
<td>y</td>
</tr>
<tr>
<td>HL Tau</td>
<td>04:31:38.44</td>
<td>+18:13:57.65</td>
<td>9</td>
<td>2.42 ± 0.08</td>
<td>10.3 ± 0.86</td>
<td>2.32 ± 0.1</td>
<td>8.3 ± 1.03</td>
<td>y</td>
</tr>
<tr>
<td>BVP 1</td>
<td>17:43:10.37</td>
<td>-29:51:44.00</td>
<td>4</td>
<td>1.55 ± 0.05</td>
<td>16.9 ± 0.8</td>
<td>1.37 ± 0.07</td>
<td>11.5 ± 1.5</td>
<td>y</td>
</tr>
</tbody>
</table>

[I] indicates integrated flux measurements. [P] indicates peak flux measurements. Error is quadrature addition of uncertainty in the FCF measurement and the rms noise in the co-added map for each calibrator. Notes: y/n indicates if the source will continue to be observed as a SCUBA-2 calibrator. (a) Extended emission at 450 μm. Col. 4 gives the number of observations taken per source between 2011 July and 2012 May. (b) Low S/N measurement, particularly at 450 μm. Accuracy of these flux densities is uncertain, and further observations are required.

SCUBA-2 450 μm bandpass). The resulting fluxes derived from 20 observations of the source in 2011 June and July show good agreement with previous results. From a selection of observations in the best conditions, this unresolved source shows a measured FWHM of 13.1 arcsec at 850 μm and 7.95 arc sec at 450 μm. This agrees with the main-beam Gaussian fit in Table 1. Though faint, Arp 220 will continue to be observed as a calibrator for SCUBA-2 in good weather.

6.4 PV Cep

PV Cep is an irregular variable star, with strong extended emission at both SCUBA-2 wavelengths. This is reflected in the increased integrated flux in comparison with its peak value. It is, for these reasons, unlikely to be used as a standard calibrator. The peak fluxes at both wavelengths are significantly lower than the background-corrected flux densities reported by Sandell et al. (2011) and this is quite likely a result of the variability of the source. Sandell et al. (2011) also postulate that their background fitting at 450 μm might produce elevated 450 μm results. Figure 13 shows the well-resolved image of the circumstellar disk, and surrounding extended emission. PV Cep will not be a regularly observed calibrator as CRL 2688 offers a better alternative in this part of the sky.

6.5 MWC 349

MWC 349, while quite close to CRL 2688, has the advantage of being a point source object. Rejected as being too faint for calibration with SCUBA, it is satisfactorily detected at both wave lengths with SCUBA-2 as shown in Figure 14 and unresolved, with measured FWHM of 13.2 and 7.9 arc sec at 850/450 μm respectively, agreeing well with the main-beam Gaussian fit in Table 1. At 850 μm, we measure a flux of 2.19 ± 0.08 Jy, lower...
Figure 15. 850 µm (left) and 450 µm (right) image of HD 169142. The
colour scale is linear as shown in the colour bar on the right hand side. In
each map, the five contours scale linearly from the peak signal as shown in
Table 4 down to the 3-σ detection level (0.03/0.17 Jy at 850/450 µm respec-
tively).

by a statistically significant amount to the 2.6 ± 0.07 Jy seen
by Sandell et al. (2011). It is an emission-line star with strong
free-free emission. We also detect a lower 450 µm flux of 3.2 ±
0.25 Jy, in comparison to the 5.0 ± 1.1 Jy SCUBA observation
reported by Sandell et al. (2011). Sandell et al. (2011) suggest that
the background-subtraction method adopted with the SCUBA data
produced questionably high 450 µm fluxes in some cases, though
this does not explain the flux discrepancy at 850 µm. As these
data were taken in a short period and with a long interval since
the SCUBA measurements, source variability cannot be ruled out.
CRL 2688 remains a preferred calibrator to this source, which will
not be regularly observed.

6.6 HD 169142
HD 169142 is a well-studied Herbig AeBe Star, and was selected
as a study source for SCUBA-2 calibration to probe the sensitivity
limits of the instrument, particularly at 450 µm. Sandell et al.
(2011) find that the disk may be resolved, and report a flux density
of 0.57 Jy at 850 µm and 3.34 Jy at 450 µm. We measure an
asymmetric disk with a fitted FWHM of 15.5×13.4 arcsec at
850 µm which agrees with this finding. This is the faintest source
observed with SCUBA-2 in this study and the 850 µm flux of
0.58 Jy and 3.41 Jy agree with the values measured by Sandell
et al. (2011) within the uncertainty. The co-added maps of the
source are shown in Figure 15.

6.7 V883 Ori
V883 Ori is FU Orionis star, which has a similar right ascension to
a preferred calibrator, CRL 618 but has the advantage of being in
the south. Sandell & Weintraub (2001) observed this with SCUBA
and found it to be unresolved, with little evident extended emission
(though they suggest a possible emission region to the eastern
edge of the 850 µm map). They measured a background-corrected
flux density of 1.41 ± 0.02 Jy at 850 µm and 9.45 ± 0.17 Jy
at 450 µm. Additional observations with SCUBA measured an
average peak flux at 450 µm flux of 7.28 ± 0.07 Jy (Barnard
2005). We measure an 850 µm integrated flux of 2.0 ± 0.07 Jy
and a 450 µm integrated flux of 10.4 ± 1 Jy. Siringo et al. (2009)
reports an integrated flux from LABOCA at 870 µm of 1.93 Jy,
which agrees within our error range. The SCUBA-2 and LABOCA
measurements both disagree with the lower 850 µm integrated flux
measured by Sandell (2003) by a statistically significant margin.

6.8 HL Tau
HL Tau is a young T Tauri star, and was used as a secondary
calibrator for SCUBA (Sandell 2003; Jenness et al. 2002). It is
well studied in the submillimetre, particularly as imaging suggests
a low-mass companion object in the parent disc material (Greaves
et al. 2008). The SCUBA-2 maps here do not detect a significant
amount of this disc with a measured FWHM at 850 µm of 13.8 arc
sec and 8.3 arc sec at 450 µm. The integrated fluxes agree well at
both wavelengths with the measurements of Jenness et al. (2002).
Only a small sample of data was taken of this source in the period
available. Further observations will be conducted to explore the
properties of the extended emission with better S/N.

6.9 BVP 1
Figure 18 shows the SCUBA-2 images of BVP 1, a bright, compact
submillimetre source located near the galactic centre. SCUBA
observations of the source are to date the only published results
at these wavelengths, and Barnard et al. (2004) measured a peak
flux at 1.069/11.318 Jy at 850/450 µm respectively. It is a good
potential secondary calibrator for SCUBA-2 as there is a paucity
of good calibration candidates in this region of the sky. With only
to thank Doug Johnstone for his comments and input to this paper.

REFERENCES

Figure 18. 850 μm (left) and 450 μm (right) image of galactic source BVP 1. The colour scale is linear as shown in the colour bar on the right hand side. In each map, the five contours scale logarithmically from the peak signal as shown in Table 3 down to the 3-σ detection level (0.144/0.46 Jy at 850/450 μm respectively). The correlated background structures are likely a result of the proximity of the source to the galactic centre.

7 CONCLUSIONS
SCUBA-2 is fully commissioned and currently running very successful science operations on the JCMT. Atmospheric calibration at both wavelengths has been optimised using new line-of-sight opacity algorithms and the derived atmospheric extinction relations are shown here. Using a large sample of primary and secondary calibrator observations, the flux conversion factors (FCF) for the 850 μm and 450 μm arrays are deduced and an investigation of the instrument beam-shape and photometry methods is given. The relative flux calibration is better than 10 per cent at both wavelengths. The sample-size of the calibration observations and accurate FCFs have allowed the determination of the 850 μm and 450 μm fluxes of several well-known submillimetre sources and these results are presented.

ACKNOWLEDGMENTS
The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada. Additional funds for the construction of SCUBA-2 were provided by the Canada Foundation for Innovation. The authors would like...