Calibrating The SHARC-2 Images Produced by CRUSH

A. Kovács, Caltech

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1 Introduction

Accurately measured fluxes are the necessary prerequisite of good astronomical science. Converting map units of images produced by an instrument (e.g. SHARC-2) and a corresponding reduction software (e.g. CRUSH), to physically meaningful numbers is the essence of the calibration process. The calibration generally involves comparing the image response to known calibrations sources, and applying the thus deduced conversion factors to the science maps to obtain phyical fluxes from them. This is a straightforward approach, familiar to all astronomers, only as long as the comparison between calibration sources and science targets is trivial. What happens when the images of calibrators and science targets are **not** reduced the same way? In that case, one has to make an effort to understand, and quantify, the possible differences between various reduction approaches in order to make those different images truly comparable.

In this document, it will be examined, therefore, how different configurations of the CRUSH reduction pipeline affect the output images. Point sources will be of special interest henceforth.

In addition, it is recommended that you read the memo on the structure of the FITS output produced by CRUSH, and the ways they are meant to be used by the astronomer.

2 Apertures vs. Peak Flux

The first question the observer must decide on is whether to use peak fluxes or aperture fluxes. Both have their respective pros and cons.

2.1 Aperture Flux

Aperture fluxes measure the total integrated flux inside some aperture, one which hopefully includes all the relevant source structures. As such the natural unit of aperture flux is Jy (jansky), which is $WHz^{-1}m^{-2}$. The main advantage of aperture flux is that it is less dependent on assumptions about the beam quality or the source extent. As long as the aperture is chosen to be large enough to enclose all source structure – including the beam artefacts – it will provide a robust measure. For this reason, aperture fluxes are generally preferable. Naturally, it is up to the observer to decide what size aperture is necessary to enclose all the relevant emission. Unfortunately, the beam artefacts can become a problem. Beam measurements on Mars (Figure ?) reveal that ca. half of the total flux falls in the beam sidelobes which span an area with an approximate radius of 5'. As different size apertures will capture varying fractions of this widely distributed flux, the resulting calibration will be clearly affected. Somewhat luckily, the inner radius of these sidelobes is ca. 30", and thus the calibration will stay robust, and trouble free, as long as apertures are chosen smaller than this limiting size.

2.2 Peak Flux

The alternative is using peak fluxes. This, in practice means converting the measurement from a single map pixel into a flux that is normalized to an area. The normalizing area is usually a beam (meaning, the effective area of the beam, i.e. $\sqrt{2\pi}\sigma_{beam}$), but it can be any other area of preference (e.g. $arcsec^2$, deg^2 or sr). As such the typical unit of peak flux is $Jy/beam$ (or $Jy/arcsec^2$, Jy/deg^2, Jy/sr etc.). The trick is to make this into a meaningful number. In practice, peak fluxes are convenient for points sources, especially when the normalization area is chosen to be large enough to include all the source flux inside the main beam. The smallest such area is the beam itself. When maps are optimally filtered to beam resolution, peak flux will provide the highest signal-to-noise measure of the point source flux. Therefore, when S/N is an issue (e.g. extragalactic sources) peak fluxes provide the obvious answer. With some pitfalls, however. Peak fluxes, are only useful if the assumption on the beam size (and shape) are correct. If fluxes are normalized to the wrong beam area, the results will not provide a true measure of the total source flux. Similarly, sources that are extended, or even partially resolved (i.e. $d \ll FWHM$ not being the case) will present the same problem. Thus, special attention has to be given to either (i) measure the beam and normalize to the appropriate beam area, or (ii) measure the fraction of the total flux falling inside the chosen normalization area. For exdented sources, the normalizing beam should be increased to reflect the size of the source under the underlying beam, i.e. the normalizing beam is the telescope beam convolved with the source distribution. Of course, one can always chose to normalize point-like, or compact, sources to a larger beam, by trading off some S/N.

2.3 Once the Choice is Made...

In summary, it is recommended that one uses peak fluxes for low signal-to-noise point (or compact) sources, and use aperture fluxes for everything else. Naturally, calibration fluxes should be measured using the very same method that is chosen for the science targets. If one uses aperture fluxes for the science, the calibration should be performed using the same size apertured as well. Conversely, when the science uses peak fluxes, one should use the same normalizing area (beam size) to get peak fluxes from the calibrators.

For advice on how to calculate aperture or peak fluxes on SHARC-2 maps, please read (reference to memo).

3 CRUSH Specific Corrections

CRUSH, the reduction utility for SHARC-2 maps, uses an iterative approach to separate source from other interferring signals, such as sky-noise or instrumental drifts. However, some signal structures can never be successfully seperated in this way (or any other way, really!), and can simultaneously belong to both source and to one or many of the other signal sources. Nonetheless, these degenerate signals, must be assigned one way or another. If one choses to interpret all degenerate signals as source, then one will get the truest possible measure of the source map, albeit a crude one at that, as the map noise will likely be dominated by the residuals from those degenerate signals. One gets cleaner, nicer looking maps, if the degeneracies are removed from the source, and assigned to the other models instead. However, some of the true source signals will be inherently degenerate too, and therefore some fraction of the true source structure will be removed (reassigned) from the source model inherently. When all degeneracies are thus reassigned, the map noise will be dominated by photon noise and approach the fundamental limit of the instrument sensitivity. At the same the the resulting source model, while impeccably clean looking, will be missing some structure. This undesired 'filtering' effect is not unique to the CRUSH, it is not a shortcoming of CRUSH, rather it is an intrinsic property of the data (a combination of instrument specifics and the observing mode) itself. In many ways, this is similar to the 'filtering' produced by chopping, or the infamous 'chopping artefacts' that affect chopped (position swithed) data.

Fortunately, the filtering effect of CRUSH is systematic and therefore it can be characterized. As a result, the maps produced can be appropriately corrected to provide true flux measures for the desired science tatgets. Most of the 'missing' source structure is filtered away when the source is assumed to be point-like or compact (`-compact` flag or `EXTENDED_PRESERVE_TURNS` key with a value larger than 0) and if one, or more, of a handful of critical signal models precedes the source model in the reduction pipeline. (You can follow the CRUSH console output to see what models are solved from before the source is first approximated in the pipeline.) The default CRUSH reduction assumes that sources are extended, and is thus immune to these effects. The critical models, and their filtering effects are discussed further below.

There are a few other CRUSH settings, which are not related to such degeneracies, but will also affect the source filtering, and therefore the calibration. These are image smoothing, the extent of sky rotation in the set of scans, and explicit filtering of the maps. Discussions of these too will follow below.

3.1 The Correction in General

Each of these systematic effects will reduce (filter) of the source flux by some fraction κ, relative to the flux prior, modifying the measured flux by a factor of $(1-\kappa)$. Thus, the total measured flux, will be,

$$F_{measured} = (1-\kappa_1)\ (1-\kappa_2)\ ...\ (1-\kappa_N)\ F_{true}$$

relative to the true flux i.e., the total modifying factor is the product of the individual modifying factors. Conversely, the true flux can therefore be estimated as,

$$F_{true} \approx \frac{F_{measured}}{\prod_i (1-\kappa_i)}$$

Once the appropriate correction factor is calculated for some set of scans, it can be applied to those scans via the `-scale` option to `crush`. Similarly, entire images can be scaled via the same option to `imagetool`.

3.2 Row Polynomials precede Source Map

The detector array of SHARC-2 is composed of monolithic rows of detectors. Similarly, the corresponding electronics, such as JFET heating, biasing, readout etc., are also organized in matching rows of 32 pixels. Thus, it is not entirely unexpected that entire detector rows should have individual characters. For reasons that are not entirely clear to us yet, some or all of these rows produce signals with an unmistakable 1/f signiture. These signals are typically equivalent to about $1Jy$ in one second, and therefore, if untreated, they are capable of significantly reducing the instrument sensitivity, producing striping like map artefacts. If a polynomial of order n is fitted to each row containing N_r active pixels, sources (with Gaussian profiles) will produce a virtual row offset,

$$F_{row} \approx (n+1) \times \frac{\sqrt{2\pi}\ \sigma_{source}}{4.77'' \times N_r} \times F_{peak}$$

Which flux will be assigned to the row drifts, whenever the row polynomials are estimated before the first source model estimate is made. Since there are 12 rows altogether, the average number of pixels per (active) row can be estimated in terms of the total number of active pixels N_a (which is reported by crush and is easily available from the FITS output), as $\langle N_r \rangle \approx N_a/12$. In that case, the source flux will be reduced by the fraction:

$$\kappa_{row} \approx 2.68\ (n+1)\ \frac{FWHM/''}{N_a}$$

For point-like sources ($d \ll FWHM_{beam}$), and 'intact' rows, the reduction is 1/16 under the default row-polynomial model settings, except when the `-deep` option is specified, ignoring 4 pixels on both sides of the row and consequently producing a flux reduction by roughly 1/12. This reduction will occur for both aperture and point source fluxes.

3.3 MUX Offsets precede Source Map

SHARC-2 boasts 384 detector pixels in total. However, the A/D system can handle 256 channels only. To make the detector signals fit, the two halves of every row are multiplexed against one another. Despite our best efforts to provide the best possible multiplexing scheme and hardware, some or all rows occasionally produce signals that appear to be a multiplexing offsets. These also show a 1/f behaviour on similar time and flux scales as the row drifts. As a single offset is fit to every row, the flux reduction effect is the same as for the row-polynomial model with the constant order only. Therefore,

$$\kappa_{MUX} \approx 2.68\ \frac{FWHM/''}{N_a}$$

I.e., for point sources and 'intact' rows, the reduction again is 1/16 unless the `-deep` option is specified, in which case it is 1/12. The reduction is expected for both aperture and peak fluxes.

3.4 Regional Correlations precede Source Map

It has been known since the days of chopped observations, that 'chopping noise' will grow as the separation of on and off beams increases. In other words, the larger spacial scales have more sky noise power. Deep SHARC-2 maps exhibit exacltly that sort of behaviour with low spacial frequency noise (baselines) dominating the image, depite the best cleaning efforts with other parameters. One way to deal with this is to filter away the low spacial frequency components of maps, leaving only the high frequency structures of interest. CRUSH performs this filtering through its Regional Correlations Model, which measures the correlated sky signal locally inside a tapered region around each and every detector pixel (hence the name), at short time intervals. This locally correlated signal is then removed from the data. It should not be surprising then, that some of the source structure will appear similar to such local correlations, and will be consequently removed. The filtering effect for regions of size R (as set by `-regionSize=R` flag or `REGIONAL_CORRELATION_SIZE=R` key) is well defined, and can be calculated for a Gaussian source profile (with $FWHM$) as,

$$\kappa_{region} \approx = \left(\frac{FWHM/''}{R} \right)^2$$

For point sources with 9" FWHM, this simply becomes,

$$\kappa_{region} \approx \left(\frac{9}{R} \right)^2$$

Note, that the Regional Correlation Model is disabled by default, and is only activated when the `-deep` option is specified, or if it is explicitly enabled via the `-Iregion` flag or `REGIONAL_CORRELATION_TURN` key, and the model precedes the first source approximation. Since the effect is true spacial filtering the flux reduction will occur for both aperture and peak fluxes.

3.5 Extended Sources

The default CRUSH reduction initially assumes the presence of extended sources (same as `-extended`), and therefore none of the above discussed filtering effects will apply. However, the maps produced thus may have excessive levels of noise artefacts, and therefore more agressive reduction parameters may be desired. If extended sources are reduced with ther `-compact` or `-deep` flags the fluxes will be reduced similarly to what was already discussed above. The exact filtering effect for some generic extended source distribution is difficult to calculate. However, if the source structure of interest can be approximated with a Gaussian profile, the above discussion holds, with FWHM being the appropriate width of the specific source structure.

3.6 Sky Rotation

Having substantial sky rotation among the set of scans simultaneously reduced by CRUSH helps disentangle some of the degenerate signals. This is usually the case for science targets that are typically observed for one or several hours. However, calibration scans are typically short scans, of only a few minutes in length, with insignificant amount of sky rotation. Therefore, single calibration scans are not necessarily representative the full flux reducing effect on science targets. In general, single scans will suffer more flux reduction than sets with sky rotation. It is difficult to put an exact quantification to this effect, but it is measured (by Dowell) to be on the order of $3 - 5\%$ i.e.,

$$\kappa_{(single\ scan)} \approx 0.03 - 0.05$$

One way around is to use the combined calibration scans before and after the science set if the same object was observed at both times. While this effect is in general small enough to be ignored altogether, the pedantic astronomer may care to either avoid it, or otherwise measure it.

3.7 Image Smoothing

Smoothing images will improve their appearance and the signal-to-noise ratios, for which reason some smoothing is almost always desirable. Smoothing will not affect aperture fluxes, as long as the aperture was chosen to be large enough such that the widended source remains enclosed. Smoothing, however will reduce peak fluxes as it effectively changes the beam normalization area. In effect the image beam will be widened by the smoothing. Unless this renormalization is already accounted for (e.g. maps are cast into $Jy/beam$ units), the effective peak reduction will be,

$$\kappa_{smooth} = \frac{S^2}{FWHM^2 + S^2}$$

For a peak flux normalization by $FWHM$ and smoothing by a Gaussian weighting function with $FWHM = S$. The special case of 9" FWHM beam normalization (e.g. $Jy/9''beam$ units), this is

$$\kappa_{smooth} = \frac{S^2}{9^2 + S^2}$$

Effectively reflecting the 9" FWHM normalizing beam growing to $\sqrt{9^2 + S^2}$ arcsec FWHM.

4 Additional Notes.

4.1 Image Units

CRUSH offers to write maps in various different units via the `-unit=` option or `MAP_UNIT` key. Alternatively, maps can later be recast into new units with the same option of `imagetool`. The units can either be voltage units, reflecting the detector voltage that the unattenuated source would produced in the absence of an atmospheric backgorund. The voltage units recognised by the CRUSH software are `V`, `mV`, `uV`, `nV`, and `pV` are available. Alternatively, CRUSH maps may be written in pseudo peak flux units of `Jy/beam`, `Jy/arcsec**2` or `Jy/sr`. Note, that these latter units will show only approximate peak flux values, calculated with the built-in calibration factor, and should not be used unless scaled with the appropriately deduced calibration corrections (see above). For this reason, the CRUSH default is to keep maps in the more inconvenient voltage units of `uV`, thus forcing the astronomer to perform the calibration and the consequent conversion to flux units rigorously.

The pseudo peak flux unit of $Jy/beam$ is somewhat peculiar, as the beam normalization area is automatically recalculated for map smoothing. I.e, the initial normalizing beam size of 9" FWHM is automatically increased to the smoothed beam size. If $Jy/beam$ units are used there is no need to correct peak fluxes for any smoothing that was applied. For all other units, the described smoothing corrections are necessary.

The default beam, used for the nornalization of $Jy/beam$ units, is $8.5''$ FWHM and can be changed via the `-beam` option or `SHARC2_BEAM_FWHM` configuration key to `crush` to any other preferred value.

4.2 Calibration at the Time of Observing

Observers should not be reminded that frequent calibration scans are pivotal to deriving a robust calibration factors for the science scans. It is recommended that SHARC-2 users calibrate at least every hour, with at least one suitable calibration source as near to the science target (especially in elevation) as possible. Using more (and better) calibrators and performing calibrations more frequently will almost certainly improve the accuracy of your science results.

The best calibration sources are some of the planets, their satellites and many of the asteroids. Additionally there is a range of galactic and a few extragalactic sources that are also suitable calibrators. Please refer to the SHARC-2 calibration web-site at:

`http://www.submm.caltech.edu/~sharc/analysis/calibration.html`

for a list of frequently used calibration sources and their updated fluxes.

When using peak fluxes for the calibrator and science targets, the deduced calibration factor will be dependent on the beam shape and quality. Therefore, special attention should be given to making sure that the telescope focus is maintained thuogh the entire night and at all elevations. Focus drifts are common, and trends versus elevation or ambient temperature can often be observed. Ultimately, it is the beam quality and its variations that will limit the calibration accuracy, once all other factors are appropriately accounted for.

The use of peak fluxes also presumes that good pointing is maintained during the observations, or otherwise reconstructed later. This is because, the random apparent movement of the observed source resulting from poor pointing will tend to 'smudge' the source, effectively producing a widened beam, whose effects are analogous to the effect of poor beam quality (focus). While the CSO pointing model requires constant adjustments, the observer can identify and characterize residual pointing scans, if the necessary pointing data is available. It is believed that the 3" pointing accuracy of CSO specification can be achieved this way.

5 Conclusion

The different reduction options, and pipeline configurations, that CRUSH uses to provide the highest quality images for the various objects of different brightness and varied spacial extend, will respond to source structures in slightly different ways. These differences, nonetheless, are systematic and can be well characterised. A number of correction factors have been derived and presented, with the purpose of making differently reduced images ultimately comparable, thus facilitating the calibration process. While the focus on point source response was maintained throughout the discussion, the results can also be interpreted for extended sources under some simplifying assumptions on the source structures. Understanding the way CRUSH modifies the calibration, through it myriad of configuration options, is only half way to good calibration. Compiling an adequate set of pointing and calibration data, as well as understanding their implications on the science targets, is the responsibility of the careful astronomer.

Quick κ Lookup for Point Sources

Scenario	default or `-extended`	`-compact`	`-deep`
Source Map Follows...			
Row Polynomials	—	1/16	1/12
MUX Offsets	—	1/16	1/12
Regional Correlations (`-regionSize=R`)	—	—	$(9/R)^2$
Map Smoothing `-smooth=final:S`)	$S^2/(9^2+S^2)$		
Single Scan	—	0-0.05	0.03-0.05

Table 1: Approximate point source flux reduction factors (κ) for various scenarios. The default reduction remains unaffected by the pipeline ordering as extended reduction mode is assumed. Regional Correlations are normally disabled, unless the `-deep` option is used. The different reduction factors under `-compact` and `-deep` are because the latter excludes 4 pixels both sides of every row, effectively reducing the number of pixels per row to 24 from 32. Map smoothing affects peak fluxes (unless the appropriate renormalization is already taken into account) but will leave aperture fluxes unchanged as long as a large enough aperture is chosen. If maps are cast in $Jy/beam$ units, the smoothing effect will be already accounted for, and no additional correction will be necessary.