GBT Memo #300: Correcting ALMA 12-m Array Data for Missing Short Spacings Using the Green Bank Telescope

Melissa Hoffman and Amanda Kepley

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Contents

1 Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA) offers astronomers high resolution and exceptional point source sensitivity via its main array of fifty 12-m antennas that can be configured on baselines as long as 16.2km. These capabilities come at the cost of reduced sensitivity to extended emission and an inability to measure total power. The Atacama Compact Array (ACA) component of ALMA is designed to capture extended emission and measure the total power via an array of eleven 7-m antennas and four 12-m total power antennas.

The total power antennas in ACA are designed to measure the total flux from a source; their resolution is comparable to the primary beam of the 12-m array. The 100 m Green Bank Telescope (GBT) offers a complementary way to obtain short-spacing and total power data for ALMA observations for observations within their overlapping sky coverage ($\delta = -40°$ to $\delta = +40°$) and frequency ranges (84GHz to 116GHz).[1] Since the GBT has a diameter ∼10 times greater than the ALMA total power antennas, it has more overlap in u-v space with the ALMA 12-m baselines than the total power antennas, as illustrated in Figure 1. These characteristics may provide improved reconstruction of the large-spatial scales in the images.

The goal of this memo is to answer two questions:

- Can we map out a way in CASA to use the GBT in place of the Total Power (TP) array when combining with ALMA interferometric data?
- How does the flux reconstruction of a GBT+ALMA combination compare to TP+ALMA combination?

2 Data

2.1 Observations of Per-Bolo 58

For this study, we focused on observations of $NH_2D(1_{1,1}-1_{0,1})$ ($\nu_{\rm rest} = 85.92626$GHz) in Per-Bolo 58, a potential candidate of a first hydrostatic core. Key for our purposes, however, is that this source has a declination of $+31:28:16.6°$, which falls within the region of overlapping sky coverage of ALMA and the GBT, and the line of interest lies within the GBT 4 mm receiver tuning range, W-Band.

Per-Bolo 58 was observed by ALMA in Cycle 1 (2012.1.00394.S, PI: D. Mardones). Four 0.5 GHz, high spectral resolution spws were arranged over $85.92626 - 89.18853$GHz. The lines of interest included HCN, HCO^+, $H_{13}CO$, and our focus in this memo, NH_2D, with a spectra resolution of 20.518kHz (0.16km/s). The data included 23 12-m antennas and 12 7-m antennas with a total time on source of 38.28 minutes. The final 12m+7m image had an RMS of 35.0mJy/beam with a resolution of 6.28 x 3.2 arcsec.

Unfortunately, the ALMA total power data for Per-Bolo 58 was never taken. To provide the necessary short-spacing data, we observed this source using the 2-pixel 4 mm receiver on the GBT (GBT/15B-375, PI: Amanda Kepley). The observing and data reduction strategy follows that of Kepley et al. (2014). We briefly outline the relevant details below. The data were taken over three observing sessions on 2015 November 12, 21, and 25. The total on-source time was ∼ 6hr. The observation was centered one 187.5MHz spectral window with 5.7kHz channels on the rest frequency of $NH_2D(1_{1,1} - 1_{0,1})$. and was mapped a 1.75arcmin square region using on-the-fly mapping, alternating maps in the

[1] The frequency coverage will overlap even more once ALMA bands 1 and 2 are included in the array.

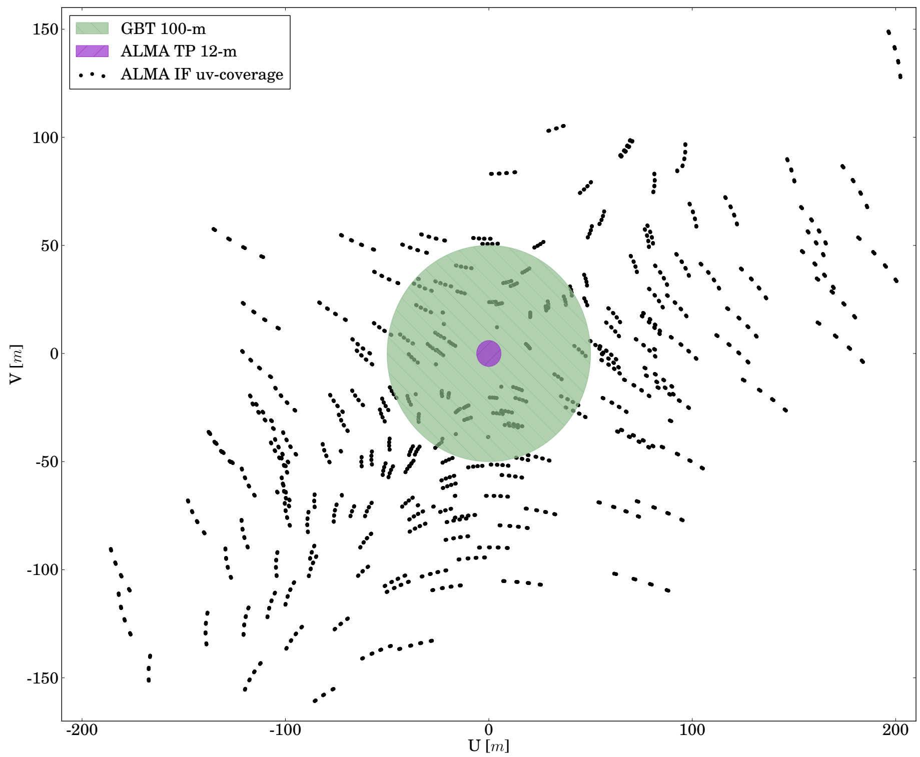

Figure 1: uv-coverage of the ALMA 12m+7m array for the data used in this memo with the GBT (green) and ALMA TP (purple) coverages overlaid. The GBT data has significant overlap with the ALMA 12-m array uv-coverage.

RA and DEC directions to reduce scanning artifacts. The map was sampled at twice Nyquist in the scanning direction and at Nyquist in the orthogonal direction. Observations of hot and cold loads were done before and after each map. For each observing session, we observed an ALMA flux density calibrator to calculate our main beam efficiency.

We note that ARGUS, a new 16-pixel focal plane array on the GBT, significantly increases mapping efficiencies with the GBT. With ARGUS, this program would have taken under an hour of on-source time to reach the same sensitivity.[2]

2.2 Calibration and Imaging

The ALMA data was calibrated manually using CASA 4.2 and 4.3.1. The data were reduced following current best practices. The calibration scripts and calibrated data are available in the ALMA archive under project code

[2]The pixels in Argus are single-polarization, so the improvement over the original 4mm receiver is a factor of $\sqrt{8}$, not a factor of $\sqrt{16}$.

2012.1.00394.S. 12-m and 7-m data were combined via `tclean`. Three outlying antennas were flagged in the final data set to improve the point spread function (PSF) of the resulting image. The resulting image has a field of view of 4.2' by 4.2' with 0.1 $\mathrm{km\,s^{-1}}$ channels and and beam size of 6.28 by 3.2". The final image RMS is 35mJy/beam.

The GBT data was calibrated via a custom GBTIDL pipeline developed for use with the 4 mm receiver as described in Kepley et al. (2014). In brief, the spectra were calibrated using the ends of the rows as an OFF position and subtracting a first order baseline fit to the line-free region of the spectra. Then they were put on the antenna temperature scale using observations of a hot and cold load taken before and after each map. The hot and cold values were 270K and 54K. Finally, they were corrected for opacity using an atmospheric model and put on the T_{MB} scale using the main beam efficiencies calculated from our flux density calibrator observations. The main beam efficiencies for each session were: 0.305, 0.226, 0.310. The opacities ranged between 0.09 and 0.14 and the system temperatures between 91 and 150K. The calibrated spectra were gridded into images using the python-based gbtgridder, which uses the algorithm described in Mangum et al. (2007). The resulting image cube is 2.0' x 2.0' with 0.1 $\mathrm{km\,s^{-1}}$ channels and a per channel noise of 0.32K on the T_{MB} scale with a final beam of 9.97".

3 Image Combination

As discussed earlier, one set of observations with a particular telescope or configuration may not be enough to recover the total emission structure at all spatial scales. To remedy this, image combination allows us to combine data to obtain an image of a source which has a greater range of spatial scales sampled. There are many different techniques for image combination, each with their own strengths and weaknesses. See Stanimirovic (2002) for a more comprehensive discussion of image combination in general. Here we use two different methods: *feathering* (Section 3.1) and a two part process which first uses the single dish as a model for `clean` and then `feather` (Section 3.2). This allows us to assess how much the combination algorithm affects the results.

Since the ALMA total power data for this project was never taken, we smoothed the GBT image using `imsmooth` to the ALMA total power resolution to create a pseudo-TP image. We use this image to compare the ALMA+GBT image combination results to what ALMA would typically do. For the 100-m GBT, at 85.9GHz, the resolution is $\sim$ 8.5", whereas for the ALMA 12-m antenna, the beam is $\sim$ 73.2".

All work was done in CASA 5.1.1-5.

3.1 Feathering

Feathering is a common way to combine single dish and inteferometer data. This method inverts the images via Fourier transform and then combines them in Fourier space (i.e. the *uv-plane*), weighting them according to the spatial frequencies of the response of each telescope. The combined image is then Fourier transformed back to the image plane. For more details, see CASA documentation. For a more comprehensive explanation of feather, see Cotton (2017).

Some assumptions about the data are necessary when feathering data:

- Images have overlapping, well-sampled spatial frequencies, i.e. adequate coverage of the *uv*-plane.
- Images have well-defined beams: primary beam (PB) of low-resolution image, PB_{Lo} and primary beam of the high-resolution image, PB_{Hi}.
- Images must have the same flux density normalization scale.

We use a method based on the steps outlined in the M100 Band3 Combine CASAGuide. This method requires three images:

- A low-resolution, single dish (SD) GBT image.
- A high-resolution, interferometric (IF) ALMA image.
- The primary beam of the high resolution image.

The images were then manipulated as follows:

1. The GBT image was converted from Kelvin to Jy/beam.
2. The low resolution and PB image were regridded with `imregrid` using the high resolution image as a template, so all images shared common spatial coordinate axes.
3. Any other transformations necessary, such as switching the sign of the spectral axis, or changing the order of axes were performed using `imtrans`.
4. All images were trimmed to the same size region, using `imsubimage`. The region chosen was the maximum overlapping box between the ALMA and GBT high and low resolution images.
5. The low resolution image was multiplied by the PB response, so that the high and low resolution images have a common response on the sky.
6. Finally, `feather` is used to combine the high and low resolution images.

Our method uses many of the imaging utilities found in CASA to manipulate the images, including `imtrans`, `imsubimage`, `imrebin`, `specsmooth`, and `imregrid`. An important step in our process is regridding the SD image to match the ALMA interferometric image. Although technically the task `feather` does this for us, we have had more success regridding the images prior to feathering. Note that the task `imregrid` interpolates data onto the grid provided by another image. This process does not conserve flux if the pixels

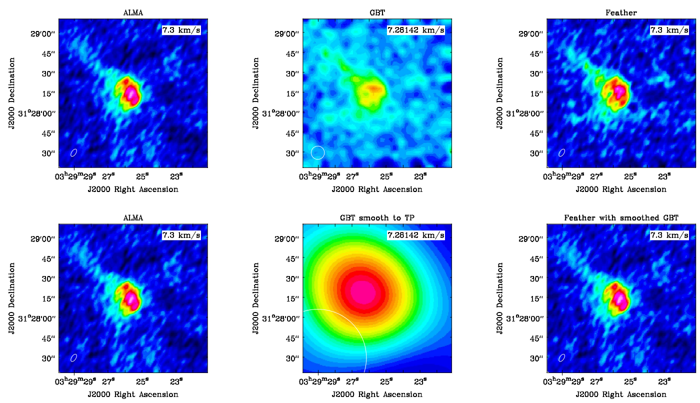

Figure 2: **Comparison of the GBT+ALMA and Pseudo-TP+ALMA Results Using Feathering:** The top row shows the ALMA *(left)* image, GBT image *(middle)* and Feathering result *(right)*. The bottom row shows ALMA *(left)*, the GBT image smoothed to simulate TP data *(middle)* and the feathering results *(right)*. All slices are at 7.3 $\mathrm{km\,s^{-1}}$ the rest frequency for NH_2D.

and channels are different sizes. It is also inaccurate when the angular resolution is poorly sampled. To remedy this, one can use the tasks `imrebin` and `specsmooth` to bin the spatial pixels and velocity channels to similar sizes to the template image and then use `imregrid` to regrid the data.

The results of feathering the GBT and ALMA data and the pseudo-TP and ALMA data are shown in Figures 2 and 3. In the feather process, we adopted `sdfactor=1.0`, i.e., the default of 'no scaling', since the feathered flux was close to the GBT image. See Figure 4 for a comparison of images made with scale factors ±20%.

3.2 Single Dish as Model for Clean Plus Feathering

This technique uses the single dish image as the model for clean when cleaning the 12m+7m data and then feathers the 12m+7m with the single dish image. See Dirienzo et al. (2015) for an example. The idea behind this approach is that clean can better extrapolate what the large scale flux should be when the single dish is used as a model. However, since clean is only extrapolating the largest scales, the single dish data still needs to be added in via feather. Dirienzo et al. (2015) found that this method yielded improved flux reconstruction over simply feathering. We note that the model input into `tclean` must be in Jy/pixel. Anecdotal evidence also suggests that using a large mask region including most of the single dish emission is important for the success of this technique.

We combined our GBT and ALMA data using this technique, and the results are shown in Figures 5 and 6.

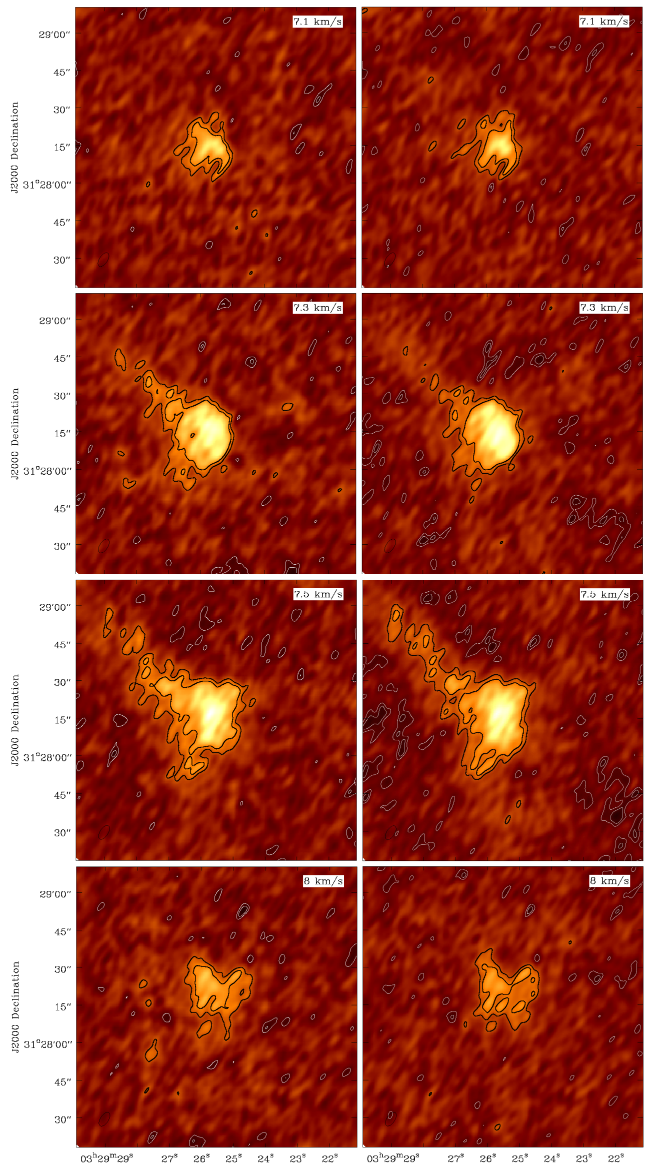

Figure 3: **Per-channel Comparison of Feathering Results:** ALMA+GBT images *(left)* and ALMA+smoothed GBT images *(right)* with contours at -2σ, -3σ in white and 3σ, 5σ in black for velocity slices $7.1^{\mathrm{kms}^{-1}}$, $7.3^{\mathrm{kms}^{-1}}$, $7.5^{\mathrm{kms}^{-1}}$, and $8.0^{\mathrm{kms}^{-1}}$. $\sigma_{\mathrm{GBT}} = 0.04$ mJy/beam and $\sigma_{\mathrm{smooth}} = 0.035$ mJy/beam. A visual inspection shows the ALMA+GBT image has lessened the amount of negative bowls while also recovering more extended emission.

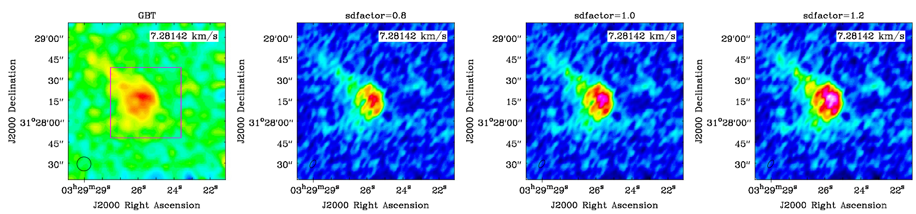

Figure 4: A comparison of the GBT image *(left)*, with various single dish scaling factors, 0.8 1.0, and 1.2 from left to right. The flux densities were computed for each image in a box 100x100 pixels, indicated in purple in the GBT image. *GBT:* 11.9 Jy, *sdfactor=0.8:* 9.5 Jy, *sdfactor=1.0*: 11.8 Jy, and *sdfactor=1.2:* 14.1 Jy. As the *1.0* factor (i.e., no scaling) is closest to the GBT flux, we did not use scaling in this project.

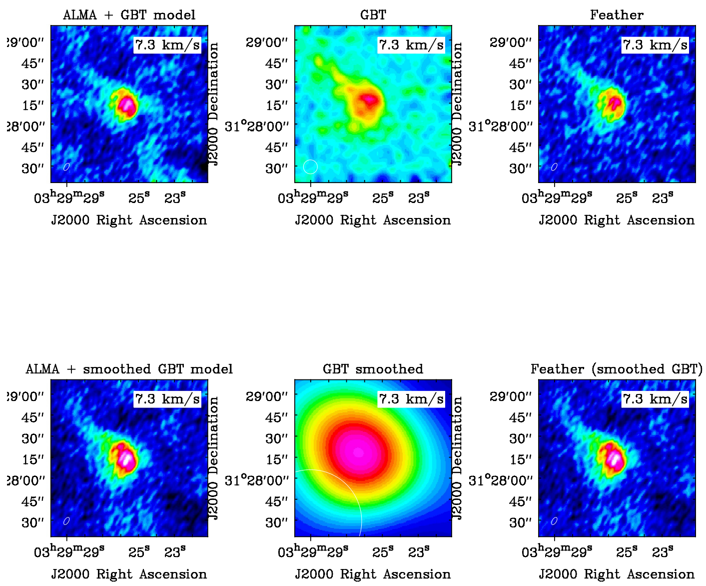

Figure 5: **Comparison of the GBT+ALMA and Pseudo-TP+ALMA Results Using The Single Dish as a Model + Feathering:** The top row shows the ALMA *(left)* image cleaned with the GBT image as a starting model, GBT image *(middle)* and Feathering result of the two*(right)*. The bottom row shows ALMA *(left)* cleaned with the smoothed GBT as a starting model, the GBT image smoothed to simulate TP data *(middle)* and the feathering results *(right)*. All slices are at 7.3 $\mathrm{km\,s^{-1}}$ the rest frequency for NH_2D.

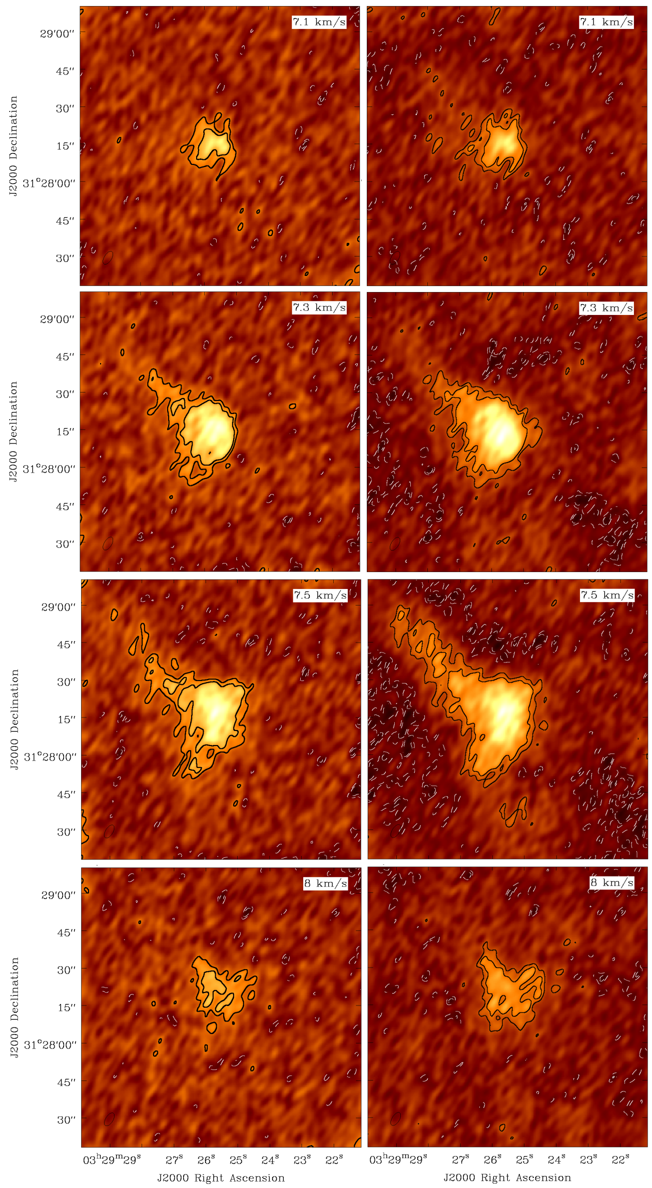

Figure 6: **Per-channel Comparison of SD as a Model Plus Feathering Results:** ALMA combined with the GBT image *(left)* and ALMA combined with the pseudo-TP image *(right)* with contours at -2σ, -3σ in white and 3σ, 5σ in black for velocity slices $7.1^{\mathrm{kms}^{-1}}$, $7.3^{\mathrm{kms}^{-1}}$, $7.5^{\mathrm{kms}^{-1}}$, and $8.0^{\mathrm{kms}^{-1}}$. $\sigma_{\mathrm{GBT}} = 0.04$mJy/beam and $\sigma_{\mathrm{smooth}} = 0.037$mJy/beam. The negative bowls in the ALMA data combined with the pseudo-TP image are much deeper and than in the ALMA combined with the GBT data.

Method	Total Flux (Jy)	Min (JyBeam^{-1})	Max (JyBeam^{-1})	RMS Noise (JyBeam^{-1})
A	11.81	-0.10	0.54	0.16
B	10.72	-0.11	0.58	0.16
C	11.6	-0.16	0.50	0.14
D	14.3	-0.13	0.65	0.18
GBT	11.96	-0.24	2.18	0.73

Table 1: Total flux density, minimum and maximum JyBeam^{-1} and RMS at $7.3^{\mathrm{kms}^{-1}}$ for the four methods discussed in this memo: A) ALMA and GBT feathering, B) ALMA and pseudo-TP feathering, C) GBT as a starting model for ALMA and D) Pseudo-TP as a starting model for ALMA. The GBT total flux density is 11.96 Jy.

4 Results

Our results in Figures 2 through 6 show that GBT data can be successfully used to correct ALMA 12-m data for missing short spacings. However, the overall performance of the image combination appears to depend more on the image combination method used than on the resolution of the single dish data used to correct the short spacings. To demonstrate this, we compare all four reconstructions in Figure 7 and Table 1. Of the four, we prefer the image combination using feather with the GBT data because it has the fewest artifacts and recovers the most extended emission (Method A in Table 1). However, there are significant differences between the feather and the SD as a model + feather combinations of the GBT+ALMA data as well as between the TP+ALMA and GBT+ALMA combinations for both methods. We note that the SD as a model + feather combination shows signs of some negative bowls around the source indicating that the final image is still missing some extended flux.

The above result conflicts with our expectations that the GBT data would provide a more accurate reconstruction of the extended emission because of its greater overlap with the ALMA 12-m data in uv-space (Figure 1). However, we note that other image combination methods, like the joint deconvolution method, may benefit from the higher resolution and surface brightness sensitivity of the GBT data to provide a better reconstruction of the extended emission. This technique transforms the single dish cube into a visibility set and then jointly deconvolves the total power, 12m, and 7m data. This is related to the above technique which uses single dish as a model for clean, but differs in that it includes the single dish data in the deconvolution as visibilities rather than combining it with the 12m+7m data in the image plane via feather. This approach is being implemented in CASA via a external software package `tp2vis`.

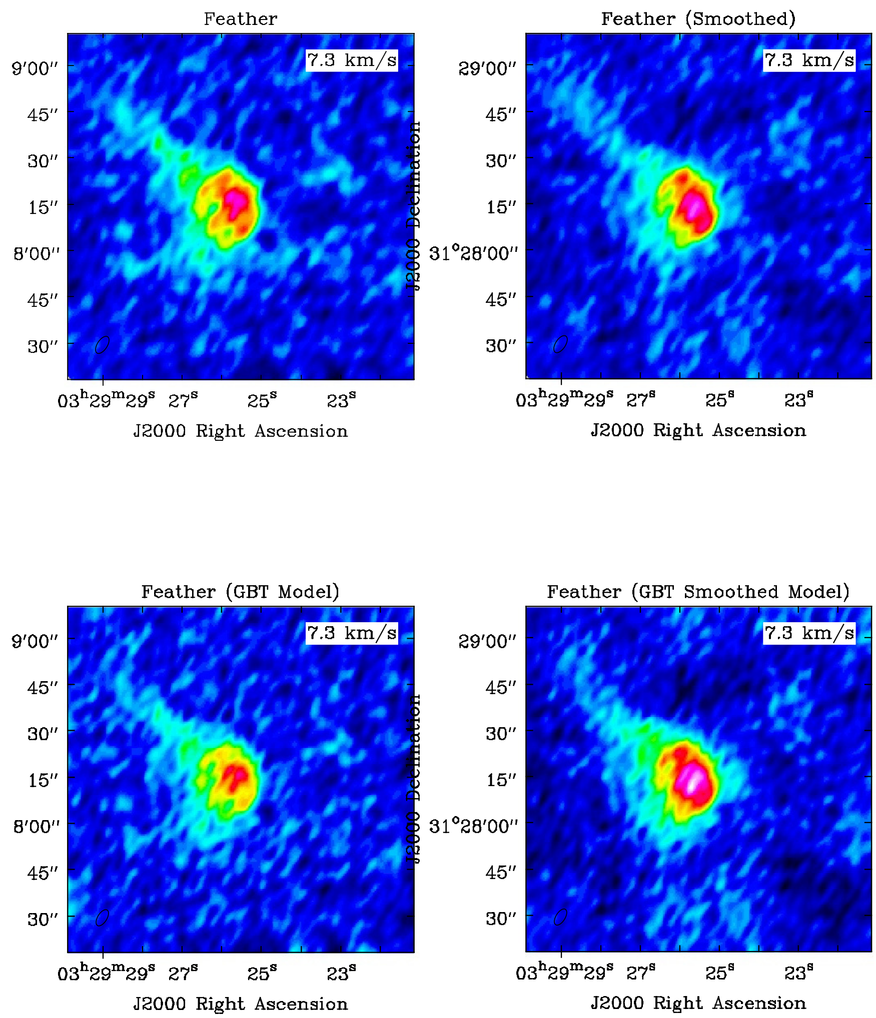

Figure 7: **A comparison of the final results of both combination methods and both SD images.** The GBT images were smoothed to represent ALMA TP images and will be referred to as TP for the sake of brevity. ALMA + GBT *(top left)*, ALMA + pseudo-TP *(top right)*, ALMA cleaned with GBT starting model + GBT *(bottom left)*, ALMA cleaned with pseudo-TP as a starting model + pseudo-TP *(bottom right)*. The choice of combination method matters to the final results.

5 Limitations

The ALMA data (including the pseudo-TP image) presented here do not correspond exactly to those that are currently produced by ALMA in full operations. The two primary differences are:

- An ALMA TP image was not available for this source at this frequency, so we had to simulate this image by smoothing the GBT image to what the resolution of the ALMA total power data would have been. The noise in the smoothed GBT image could be achived by the ALMA TP data, but it would require a long observation.
- The data are from Cycle 1, so only 23 12-meter antennas were used in the interferometric observations. This is only slightly more than half what is guaranteed in Cycle 5, 43 12-meter antennas. Therefore, the intrinsic uv-coverage is much less than what could be achieved today (typically between 40-50 antennas).

This was the only data currently available that fit the constraints of an ALMA project with frequency and location on the sky that would also be observable by the GBT. Therefore, we proceeded with the study despite these limitations to provide a proof of concept. Observations are currently being taken by ALMA and the GBT data as part of two separate projects that could be used to further explore combining ALMA and GBT data.

References

Cotton. 2017, Publications of the Astronomical Society of the Pacific, 129, 094501

Dirienzo+. 2015, AJ, 150, 159

Kepley+. 2014, ApJL, 780, L13

Mangum+. 2007, A&A, 474, 679

Stanimirovic. 2002, 375–396

Appendices

A Combination Script

This script can be found on github at mhoffies/GBT_ALMA_Combination

```
# Combination script for GBT + ALMA Data
# At the end we smooth ALMA to GBT and feather that to
# simulate a regular TP+ALMA combination

# Use imhead to determine what need to be regridded/transformed
import glob

myfiles=[]
myfiles=glob.glob('*image*')
mykeys=['cdelt1','cdelt2','cdelt3','cdelt4','restfreq']

for f in myfiles:
     print(f)
     print('------------')
     for key in mykeys:
         q = imhead(f,mode='get',hdkey=key)
         print(str(key)+' : '+str(q))
'''
flagged_image_r_2.0.image
------------
cdelt1 : {'value': -2.42406840554768e-06, 'unit': 'rad'}
cdelt2 : {'value': 2.42406840554768e-06, 'unit': 'rad'}
cdelt3 : {'value': 1.0, 'unit': ''}
cdelt4 : {'value': -28661.91616821289, 'unit': 'Hz'}
restfreq : {'value': 85926263000.0, 'unit': 'Hz'}
PerBolo58_NH2D_gridder_v2_cube_Jybeam.image
------------
cdelt1 : {'value': -9.696273622190623e-06, 'unit': 'rad'}
cdelt2 : {'value': 9.69627362219071e-06, 'unit': 'rad'}
cdelt3 : {'value': 28610.43197631836, 'unit': 'Hz'}
cdelt4 : {'value': 1.0, 'unit': ''}
restfreq : {'value': 85926260000.0, 'unit': 'Hz'}
flagged_image_r_2.0.pb
------------
cdelt1 : {'value': -2.42406840554768e-06, 'unit': 'rad'}
cdelt2 : {'value': 2.42406840554768e-06, 'unit': 'rad'}
cdelt3 : {'value': 1.0, 'unit': ''}
cdelt4 : {'value': -28661.91616821289, 'unit': 'Hz'}
restfreq : {'value': 85926263000.0, 'unit': 'Hz'}

'''

# In your headers, there are three things to note:
# 1. Axes
# 2. Order of Axes
# 3. Rest Frequency
# As long as these match, or as long as we can make them
# match we shouldn't run into any problems when feathering.

# Regrid GBT Image to match ALMA image
```

```
imregrid(imagename='PerBolo58_NH2D_gridder_v2_cube_Jybeam.image',
         template='flagged_image_r_2.0.image',
         axes=[0,1,2],
         output='GBT.image.regrid')

# Reorder the axes of the GBT to match ALMA/pb

imtrans(imagename='GBT.image.regrid',
        outfile='GBT.image.regrid.ro',
        order='0132')

'''
# (OPTIONAL) RECLEAN ALMA DATA W. GBT AS MODEL

# If you would like to first clean the ALMA data using the GBT image
# as a model, use the following tclean command after regridding and
# reordering, paying attention to the names in the ALMA subimage
    command.
# After cleaning, continue the feathering process.

# Before cleaning, we have to convert the GBT image from Jy/beam to Jy/
    pixel

bmaj = 9.976
bmin = 9.976 # Note: these are in " so we will include our pixel of
    0.5" in our conversion

toJyPerPix = 0.25 / (1.1331 * bmaj * bmin ) # Gaussian to pixel
    conversion

fluxExpression = "(IM0 * %f)"%(toJyPerPix)
immath(imagename='GBT.regrid.ro/',
       outfile='GBT.Jyperpix',
       mode='evalexpr',
       expr=fluxExpression)

hdval = 'Jy/pixel'
dummy = imhead(imagename='GBT.Jyperpix',
               mode='put',
               hdkey='BUNIT',
               hdvalue=hdval)


myvis='perbol58_nh2d_comb_withflags.ms'
modelvis='GBT.Jyperpix'                   # GBT image in Jy/pixel

tclean(vis=myvis,
       imagename='ALMA_w_GBT_model',
       field='0,1,2,3,4,5,6,7,8,9,10',
       spw='0,1,2,3,4,5,6,7,8,9,10,11,12',
       phasecenter=3,
       specmode='cube',
       start='-6km/s',
       width='0.1km/s',
       nchan=200,
       outframe='lsrk',
```

```
        veltype='radio',
        restfreq='85.926263000GHz',
        niter=1000,
        threshold='0.0mJy',
        interactive=True,
        cell='0.5arcsec',
        imsize=[512,512],
        weighting='briggs',
        robust=0.5,
        gridder='mosaic',
        pbcor=True,
        restoringbeam='common',
        chanchunks=-1,
        startmodel=modelvis)
'''

# Trim all images to the same size
# Note: This step is not necessary

imsubimage(imagename='GBT.image.regrid.ro',
           outfile='GBT.image.regrid.ro.subim',
           box='143,143,366,366')

imsubimage(imagename='flagged_image_r_2.0.image',
           outfile='ALMA.image.subim',
           box='143,143,366,366')

imsubimage(imagename='flagged_image_r_2.0.pb',
           outfile='pb.subim',
           box='143,143,366,366')


# Multiply the flux by the GBT image to get the same response

immath(imagename=['GBT.image.regrid.ro.subim',
                  'pb.subim'],
       expr='IM0*IM1',
       outfile='GBT.multiplied')


# Feather together the GBT*pb and ALMA images

feather(imagename='Feather.image',
        highres='ALMA.image.subim',
        lowres='GBT.multiplied')

###############################################################
# Copy & smooth GBT image to look like TP
# for 85.9 GHz and 12-m dish size, TP beam will be ~73"

os.system('cp -r PerBolo58_NH2D_gridder_v2_cube_Jybeam.image GBT.image'
    )
mybeam = {'major': '73.2arcsec', 'minor': '73.2arcsec', 'pa': '0deg'}
imsmooth( imagename='PerBolo58_NH2D_gridder_v2_cube_Jybeam.image',
    kernel='gauss', beam=mybeam, targetres=True,outfile='GBT.smooth')

# Regrid to ALMA image, as before
```

```
imregrid(imagename='GBT.smooth',
         template='flagged_image_r_2.0.image',
         axes=[0,1,2],
         output='GBT.smooth.regrid')

# Still gotta fix that pesky axis...

imtrans(imagename='GBT.smooth.regrid',
        outfile='GBT.smooth.regrid.ro',
        order='0132')


# Trim cube to correct size

imsubimage(imagename='GBT.smooth.regrid.ro',
           outfile='GBT.smooth.regrid.ro.subim',
           box='143,143,366,366')


# Multiply by primary beam response

immath(imagename=['GBT.smooth.regrid.ro.subim',
                  'pb.subim'],
       expr='IM0*IM1',
       outfile='GBT.smooth.multiplied')

# Delete the telescope info from the header

imhead('GBT.smooth.multiplied',mode='del',hdkey='telescope')

feather(imagename='Feather.smooth.image',
        highres='ALMA.image.subim',
        lowres='GBT.smooth.multiplied')
```

B CASA Feather Wishlist

Having used `feather` extensively during the development of this memo, we have two requests that would improve the overall usability of this task:

1. The effective dish diameter being used should be printed to the logger or terminal.

2. The creation of diagnostic plots such as those seen in the *casafeather* GUI. These would be especially helpful for determining whether or not `sdfactor` is necessary and what value is appropriate if it is.