

TOTAL POWER MAP TO VISIBILITIES (TP2VIS): JOINT-DECONVOLUTION OF ALMA 12M, 7M & TOTAL POWER ARRAY DATA

JIN KODA^{1,2,3}, PETER TEUBEN⁴, TSUYOSHI SAWADA^{2,3}, ADELE PLUNKETT^{5,3}, CRYSTAL BROGAN⁶, ED FOMALONT^{6,3}

¹Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA

²NAOJ Chile Observatory, National Astronomical Observatory of Japan, Joaquín Montero 3000 Oficina 702, Vitacura, Santiago 763-0409, Chile

³Joint ALMA Office, Alonso de Córdova 3107, Vitacura, Santiago 763-0355, Chile

⁴Department of Astronomy, University of Maryland, College Park, MD 20742-2421

⁵European Southern Observatory, Alonso de Córdova 3107, Vitacura, Santiago 763-0355, Chile

⁶National Radio Astronomy Observatory, 520 Edgemont Road. Charlottesville, VA 22903

ABSTRACT

This is the final report of the ALMA study project “Total Power Map to Visibilities (TP2VIS) – Joint-Deconvolution of ALMA 12m, 7m & Total Power (TP) Array Data”. This study developed software to convert a TP map into visibilities, which can be jointly deconvolved with ALMA 12m and 7m array data on the CASA platform. The TP2VIS procedure is based primarily on the one discussed in [Koda et al. \(2011\)](#) with some modifications. The products from this study, software and documentation, are distributed through the GITHUB repository:

<https://github.com/tp2vis/distribute>

The script “tp2vis.py” is a package that includes four functions: TP2VIS, TP2VISWT, TP2VISPL, and TP2VISTWEAK. The TP2VIS function generates a Gaussian visibility distribution, whose inversion, i.e., the synthesized beam, reproduces the primary beam of TP telescopes under natural weighting. The sensitivity-based weighing scheme is adopted as the default, but the TP2VISWT function provides several ways to manipulate the weights. The TP2VISPL function plots and visualizes the TP weights with respect to those of ALMA 12m and 7m array data. After the joint deconvolution of TP, 7m, and 12m data, the residual map should be re-scaled with the TP2VISTWEAK function. This rescaling is required due to the typical disparity between the areas of the synthesized beam and convolution beam, which is discussed in this report. The TP2VIS development team often encountered some issues in CASA, which sometimes became major hindrances. In the last section, we list some of the unresolved issues of CASA.

1. CONCEPT

Conceptually, the joint deconvolution of interferometer and single-dish data is fairly simple. The two sets of data are added *before* deconvolution (e.g., CLEAN), so that the deconvolution routine can take advantage of the better *uv* coverage. Deconvolution algorithms fill data-absent (unfilled) parts of the *uv* space; by using the data-present parts as guidance, they make guesses for the unfilled parts. The better *uv* coverage permits more educated guesses.

In practice, a joint deconvolution can be implemented in different ways (e.g., [Vogel et al. 1984](#); [Cornwell 1988](#);

[Stanimirovic et al. 1999](#); [Stanimirovic 2002](#); [Takakuwa 2003](#); [Rodríguez-Fernández 2008](#); [Kurono et al. 2009](#); [Pety & Rodríguez-Fernández 2010](#)). Most of them require fairly major adjustments in the existing CASA package and will likely be implemented in the official CASA development in the future. TP2VIS intends to provide an easy alternative, which maximally takes advantage of the existing CASA tasks with minimal modifications. In the CASA platform, TP2VIS converts a TP map into TP visibilities, which can be passed on to the existing deconvolution routines (CLEAN/TCLEAN). In addition to this report, some more details of the TP2VIS procedure are discussed in [Koda et al. \(2011\)](#).

The TP2VIS package provides four functions in the CASA platform. The key functions, TP2VIS, generates

a CASA measurement set (MS) –visibilities including weights– from a TP map. The weights are calculated based on the root-mean-square (RMS) noise from the TP map. This MS is ready for joint-deconvolution, though in some cases one may wish to manipulate the

weights using the supplementary function, TP2VISWT. An accessory function, TP2VISPL, plots the weights of ALMA 12m, 7m, and TP visibilities for comparison. Another function, TP2VISTWEAK, fixes the problem of beam-size mismatch in the image space after deconvolution (Section 4.2).

Table 1. Beam Terminology

Number	Beam Name	Symbol
1	Primary beam of Total Power (TP) telescopes	Ω_{TP}
2	Primary beam of Virtual Interferometer (VI) telescopes	Ω_{vir}
3	Dirty beam (output from clean/tclean with niter=0)	Ω_{dirty}
	Synthesized beam	Ω_{syn}
	Deconvolution beam	Ω_{dec}
	Point spread function	Ω_{psf}
4	CLEAN beam (typically derived from Gaussian fit to Ω_{dirty})	Ω_{clean}
	Convolution beam	Ω_{conv}
	Restoring beam	Ω_{res}

NOTE—Horizontal lines separate different beams. The third and forth beams have a few names: $\Omega_{\text{dirty}} = \Omega_{\text{syn}} = \Omega_{\text{dec}} = \Omega_{\text{psf}}$, and $\Omega_{\text{clean}} = \Omega_{\text{conv}} = \Omega_{\text{res}}$.

2. THE TP2VIS PROCEDURE

The TP2VIS function takes a sky brightness distribution (TP map) and simulates observations with a *virtual* interferometer (as defined below). Figure 1 shows the flowchart of steps in the TP2VIS function. The procedure can be separated to three parts: first, it converts the TP map into the sky brightness distribution, which the virtual interferometer observes (steps A and B in the figure). Second, it converts the brightness distribution into visibilities (steps C and D). And third, the weights of the TP visibilities are set so that they represent the RMS noise of the original TP map (step E).

Different types of beams are involved in our discussions. Hence, we list the beams in Table 1 to avoid confusion.

2.1. Step A: Deconvolution with TP Beam Ω_{TP}

A map from TP observations represents a sky brightness distribution convolved with a TP telescope beam (Ω_{TP}). Hence, the map needs to be de-convolved with Ω_{TP} . We approximate Ω_{TP} with a Gaussian with a full-width half maximum (FWHM) of 56.6'' at 115.2 GHz and assume that it scales linearly with 1/frequency. We note that the definition and handling of the TP telescope beam may be changed in future, when the planned beam manager (called “vpmanager”) is implemented properly

in CASA. With vpmanager in future, we should be able to convert data from other single-dish telescopes into a CASA measurement set.

2.2. Step B: Apply Virtual Primary Beam Ω_{vir}

In interferometer observations, a sky brightness distribution is attenuated by the primary beam (PB) before signals are detected. Therefore, the PB pattern of the virtual interferometer (Ω_{vir}) should be multiplied by the sky brightness distribution from Step A at each pointing position. The TP2VIS function takes pointing center coordinates of the virtual interferometer from an ascii list set by the “ptg=” option.

2.3. Step C: Generate Gaussian Visibility Distribution

A visibility distribution (and MS) is generated so that its Fourier transformation (called the synthesized beam Ω_{syn}) reproduces Ω_{TP} . Assuming a Gaussian TP beam on the sky, the visibility distribution also follows a Gaussian distribution. Hence, we generate random numbers to make a Gaussian visibility distribution in the uv space. The standard deviations of the Gaussians in the sky σ and in the uv space σ_{F} have the relation of $\sigma_{\text{F}} = 1/2\pi\sigma$. The full width at half maximum (FWHM) is calculated as $\text{FWHM} = 2\sqrt{2\ln 2}\sigma$ ($\approx 2.355\sigma$).

2.4. Step D: Fill Visibility Amplitudes and Phases

By now, we have the sky brightness distribution with the PB of the virtual interferometer applied (from step B) and the Gaussian visibility distribution in the uv space (step C). The sky distribution is Fourier-transformed into the uv space, which is used to fill the AMPLITUDE and PHASE columns of the visibilities in the MS.

These visibilities are already *internally* consistent. CLEAN/TCLEAN with the natural weighting produces a synthesized beam Ω_{syn} similar to the TP telescope beam Ω_{TP} . The brightness distribution also reproduces the observed TP brightness distribution.

2.5. Step E: Set Weights of TP Visibilities

The TP2VIS function sets visibility weights according to the RMS noise in the TP map. The RMS value is set manually by the “rms=” option. [Note that in the current implementation, the RMS is set by hand, because it is not always trivial to find emission-free channels using an algorithm.] The RMS is converted to the weight of individual visibilities. The equation for this conversion is in Section 5. This sensitivity-based weight is a proper representation of the quality of the TP data.

One may wish to adjust the weights of TP visibilities with respect to those of ALMA 12m and 7m data. The supplementary TP2VISWT function provides several options to manipulate the weights. An accessory TP2VISPL function plots the weight distributions of ALMA 12m, 7m, and TP visibilities for comparison, so that user can decide how the TP visibilities need to be weighted with respect to 12m and 7m data.

3. A SCHEMATIC CODE

The TP2VIS package takes advantage of functions in the CASA Toolkit. Here, we present a skeleton PYTHON code and show how some of the functions are used in TP2VIS. A typical reader of this report may skip this section entirely, but it may be useful for those who intend to develop similar or better software.

In the CASA Toolkit, the “sm.predict” function in the SIMULATOR module is the key. It takes a sky image and visibilities, and swaps the visibility amplitudes and phases with respect to the image. Hence, we generate a visibility distribution that represents the Ω_{TP} shape, and run “sm.predict” to generate TP visibilities.

The steps here are straightforward: (1) create a new measurement set (MS) with a specified number of empty visibilities, (2) replace their (u,v,w) coordinates with those following a Gaussian distribution (with $w = 0$), and (3) run “sm.predict” with a single-dish image as input to replace the visibility amplitudes and phases. The following shows the skeleton code.

```
# Open measurement set file
```

```
# -----

sm.open("ms file")

# Setup observational parameters
# -----

sm.setconfig() # observatory, antenna pos.
sm.setspwindow() # spectral window
sm.setfeed() # polarization
for "loop over pointings":
    sm.setfield() # pointing centers
sm.setlimits() # shadowing, el. limit
sm.setauto() # weight of auto-corr. = 0
sm.settimes() # integ. time per vis.

# Generate measurement set
# -----

# Set # of vis. by adjusting start/end time,
# integ. time, and # of antenna pairs.

sm.observemany() # generate "box" of vis.

# Replace uvw coordinates
# -----

tb.open("ms file") # open MS file as table
uvw = tb.getcol('UVW') # get uvw

# Generate gaussian distributions for (u,v),
# including (u,v)=(0,0). w=0.

tb.putcol('UVW',uvw) # put uvw back
tb.close()

# Replace amplitude/phase
# -----

sm.setdata() # all pointings
sm.setvp() # primary beam
sm.predict("image name") # replace amp/pha

# Close measurement set
# -----

sm.done()
```

4. BEAM DISPARITY AND FLUX PROBLEM

Four different beams are involved in this report (Table 1). The first two beams were used in Section 2; the primary beam of the TP telescopes (Ω_{TP}) and that of the virtual interferometer (Ω_{vir}). The third and fourth beams are from visibilities, i.e., a synthesized beam

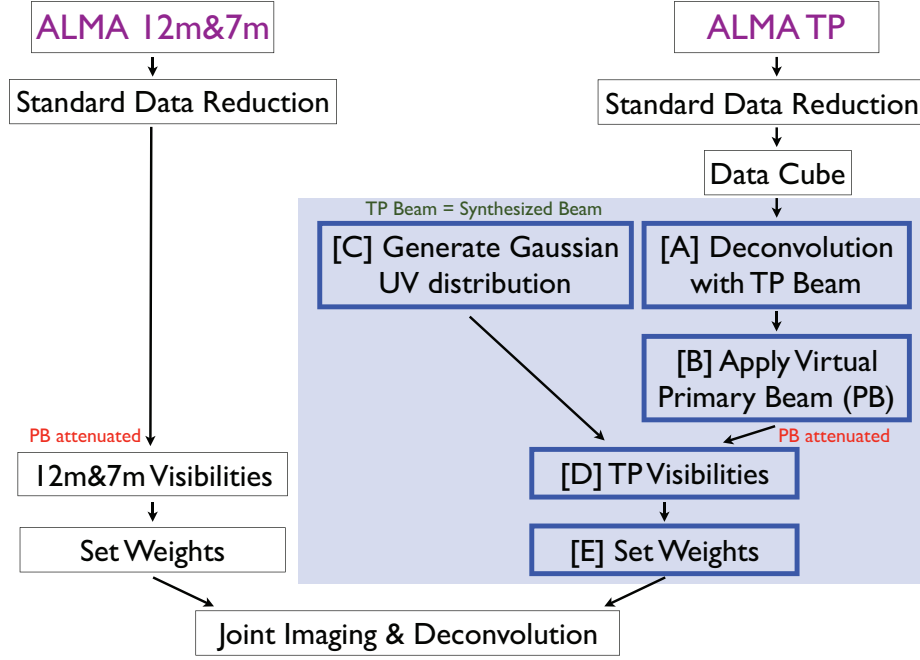


Figure 1. Flow chart of the TP2VIS procedure. TP2VIS processes the functions shaded in blue: taking a calibrated TP data cube from CASA, converting it into a set of visibilities (i.e., a measurement set), and passing it to a deconvolution task in CASA, together with the ALMA 12m and 7m interferometer visibilities.

(Ω_{syn}) and convolution beam (Ω_{conv}). The Ω_{syn} is also called a dirty beam (Ω_{dirty}), deconvolution beam (Ω_{dec}), or point spread function (Ω_{psf}). The Ω_{conv} is also called a clean beam (Ω_{clean}) or restoring beam (Ω_{res}). As they are needed in later sections, we describe the definitions of Ω_{syn} and Ω_{conv} in Section 4.1.

Jorsater & van Moorsel (1995) extensively discussed the problem of flux conservation when there is a disparity between the areas of Ω_{syn} and Ω_{conv} . The problem becomes more apparent when the TP visibilities are included (Section 4.2). We introduce two ways to resolve/mitigate this problem, by adjusting the weights of the TP visibilities (Section 5.2), and/or by scaling the residual map (Section 6).

Note that we use the symbols, Ω_{syn} and Ω_{conv} , to represent the synthesized and convolution beams, respectively, but also to denote their areas.

4.1. The Synthesized and Convolution Beams

The synthesized beam Ω_{syn} , equivalently Ω_{dirty} or Ω_{dec} , represents the distribution of visibility weights in uv space. Its 2-dimensional pattern, $B(l, m)$, is a Fourier transformation of the weight distribution $W(u, v)$. With the normalization of $\iint W(u, v) du dv = 1$,

$$B(l, m) = \iint W(u, v) e^{+2\pi i(ul + vm)} du dv. \quad (1)$$

The area of Ω_{syn} is the beam solid angle and is given as an integration over space,

$$\Omega_{\text{syn}} = \iint B(l, m) dl dm = W(0, 0). \quad (2)$$

This area depends only on $W(0, 0)$, the weight of visibility at $(u, v) = (0, 0)$. This is just $W_{\text{TP}}(0, 0)$ when ALMA 12m, 7m, and TP visibilities are combined. Only the weight of the TP visibility matters, because the interferometer data have zero weight at $(u, v) = (0, 0)$.

The convolution beam Ω_{conv} , equivalently Ω_{clean} or Ω_{res} , is typically defined by a Gaussian fit to the central peak in the $B(l, m)$ pattern. Hence, it depends on the full weight distribution, $W(u, v)$; but in practice, the outer, long-baseline part of the visibility weight distribution is often the determining factor.

4.2. Beam Disparity and Flux Problem

For simplicity, we use CLEAN as an example here, but it applies to other image deconvolution schemes as well. In each iteration, the CLEAN task identifies a peak in a dirty map, fits the 2-dimensional pattern of Ω_{syn} to the peak to determine its position and amplitude, subtracts it from the dirty map, and puts a δ -function at that position in a clean-component map. The CLEAN task then convolves the clean-component map with Ω_{conv} to produce a model map, which has brightness units of $\text{Jy}/\Omega_{\text{conv}}$. There is typically leftover emission after CLEAN iterations. These unidentified emissions are stored in a residual map, whose units remain $\text{Jy}/\Omega_{\text{syn}}$. The CLEAN task *naively* adds the model and residual maps to produce a final map, whose units are often denoted as Jy/beam , and for the “beam” in

the denominator, Ω_{conv} is typically adopted. Therefore,

$$\left[\frac{F}{(Jy/\Omega_{\text{conv}})} \right] = \left[\frac{M}{(Jy/\Omega_{\text{conv}})} \right] + \left[\frac{R}{(Jy/\Omega_{\text{syn}})} \right], \quad (3)$$

where F , M , and R stand for the final, model, and residual maps, respectively.

The areas and patterns of Ω_{syn} and Ω_{conv} could be very different, as they depend on different parts of the weight distribution in uv space (Section 4.1). In particular, if their areas are not equal, $\Omega_{\text{syn}} \neq \Omega_{\text{conv}}$, the brightness of R in eq. (3) is calculated incorrectly. For example, if $\Omega_{\text{syn}} \gg \Omega_{\text{conv}}$, the brightness in R is overestimated by $\Omega_{\text{syn}}/\Omega_{\text{conv}}$ ($\gg 1$), leading to an overestimation of flux in F . This happens when the ALMA 12m, 7m, and TP visibilities are combined.

In case $\Omega_{\text{syn}} \ll \Omega_{\text{conv}}$, the brightness in R is underestimated. The impact of this on F may not be as noticeable as in the opposite case, since R typically has much less flux than M . This happens when 12m and 7m visibilities are imaged without TP, since $\Omega_{\text{syn}} = W_{\text{TP}}(0,0) = 0$ (hence, $\ll \Omega_{\text{conv}}$). This flux problem did not attract much attention in the past, as single-dish data were typically not included.

5. WEIGHTS

An optimal weighting scheme for TP visibilities is a topic of debate. TP2VIS provides some implementations of weighting schemes, as well as providing a framework for testing other schemes that may be suggested in future. It may be worth noting that in the history of radio interferometry it has been very common to manipulate visibility weights, e.g., using natural, uniform, or robust weightings. No matter what weights are used, the final map should be usable for scientific applications, as long as the same weights are used consistently for both map and beam in the imaging process.

Our main function, TP2VIS, sets the weights so that their sum represents the RMS noise of the original TP map. The supplementary function, TP2VISWT, provides several options to manipulate the weights. Currently, it has five modes:

- *mode='statistics'*: output statistics of the current weights in MS(s).
- *mode='constant'*, *value=*: set the weights of all visibilities to a constant value specified by the "value=" option.
- *mode='multiply'*, *value=*: multiply a constant value specified by the "value=" option to the current weights.
- *mode='rms'*, *value=*: use the sensitivity-based weight for all visibilities (Section 5.1). An RMS

value from TP map should be set with the "value=" option.

- *mode='beam'*: use the beam size-based weight for all the TP visibilities (Section 5.2).

5.1. The Sensitivity-Based Weight

One of the most intuitive weighting schemes is the one that represents the quality of TP data, namely the root-mean-square (RMS) noise of the TP map. The TP2VISWT function with the *mode='rms'* sets the weights to the sensitivity-based one. This is the default weighting scheme used by the TP2VIS function as well. Section 5.1.1 discusses the conversion of the RMS noise of a TP map into the weights of individual visibilities. For a joint deconvolution of ALMA 12m, 7m, and TP visibilities, the weights of 12m and 7m data should be set consistently. Section 5.1.2 shows the corresponding weights of 12m and 7m data. [Note that CASA version 5 uses this definition of 12m and 7m weights by default. Prior versions, however, did not set the 12m and 7m weights properly.]

5.1.1. Weights for TP Visibilities

With the natural weighting, the sensitivity of a map, or the RMS noise of the image (ΔS^i), is a simple summation over all visibility sensitivities (ΔS_k^v),

$$\left(\frac{1}{\Delta S^i} \right)^2 = \sum_k \left(\frac{1}{\Delta S_k^v} \right)^2 = N_{\text{vis}} \left(\frac{1}{\Delta S^v} \right)^2, \quad (4)$$

where N_{vis} is the number of visibilities. All visibilities are assumed to have the same sensitivity ($\Delta S_k^v = \Delta S^v$). The weight of each TP visibility is

$$w_k \equiv \left(\frac{1}{\Delta S_k^v} \right)^2 = \frac{1}{N_{\text{vis}}} \left(\frac{1}{\Delta S^i} \right)^2. \quad (5)$$

5.1.2. Corresponding Weights for 12m & 7m Visibilities

For consistency, the 12m and 7m data should also use the sensitivity-based weights. Theoretically, a visibility sensitivity, for a single visibility k between antennas i and j , is given by (Taylor et al. 1999; Thompson et al. 2007)

$$\Delta S_k^v = C_{ij} \sqrt{\frac{T_{\text{sys},i} T_{\text{sys},j}}{B \cdot t_{\text{vis}}}} = C_{ij} \sqrt{\frac{T_{\text{sys}}^2}{B \cdot t_{\text{vis}}}}, \quad (6)$$

where $T_{\text{sys},i}$, $T_{\text{sys},j}$, and B , t_{vis} are the system temperatures of i and j , bandwidth, and integration time of the visibility, respectively. For simplicity, we assume $T_{\text{sys},i} = T_{\text{sys},j} = T_{\text{sys}}$. The coefficient C_{ij} is

$$C_{ij} = \frac{2k_B}{\sqrt{(\eta_{a,i} A_i)(\eta_{a,j} A_j)}} \frac{1}{\sqrt{2\eta_q}}, \quad (7)$$

where $\eta_{a,i}$, $\eta_{a,j}$, A_i , A_j , and η_q are the aperture efficiencies and areas of antenna i and j , and the quantum

efficiency of correlator, respectively. With the natural weighting, the RMS sensitivity of final map is

$$\Delta S^i = C_{ij} \sqrt{\frac{T_{\text{sys}}^2}{B \cdot t_{\text{tot}}}}, \quad (8)$$

where t_{tot} is the total integration time $t_{\text{tot}} = N_{\text{vis}} t_{\text{vis}}$. The weights of 12m and 7m visibilities should be set to $w_k = (1/\Delta S_k^v)^2$ with eq. (6).

5.1.3. Supplementary Note for Internal Consistency

This step is not necessary in practice, but is discussed for consistency among all data columns in MS. It might become important in some future CASA development. TP2VIS fills the WEIGHT and SIGMA columns. Only the WEIGHT column is used by CLEAN in CASA; other columns do not matter in practice. For the consistency, however, one could also make the EXPOSURE column (i.e., integration time of each visibility) consistent.

The sensitivity equations for TP, corresponding to eqs. (6), (8), and (7), are

$$\Delta S_k^v = C_{\text{TP}} \sqrt{\frac{T_{\text{sys}}^2}{B \cdot t_{\text{vis}}}} \quad (9)$$

and

$$\Delta S^i = C_{\text{TP}} \sqrt{\frac{T_{\text{sys}}^2}{B \cdot t_{\text{tot}}}}, \quad (10)$$

where

$$C_{\text{TP}} = \frac{k_B}{\eta_a A} \frac{1}{\eta_{\text{mb}}} \frac{1}{\eta_q}, \quad (11)$$

and η_{mb} is the main beam efficiency of the TP antennas. T_{sys} , ΔS^i , and B are measured during observations. With eq. (10) we can derive t_{tot} , using T_{sys} and ΔS^i from the MS and TP maps, respectively. Equation (5) gives $t_{\text{vis}} = t_{\text{tot}}/N_{\text{vis}}$.

5.2. The Beam Size-Based Weight

Section 4.2 explained the problem in flux conservation due to the disparity between the areas of Ω_{syn} and Ω_{conv} . The beam size-based weighting scheme discussed here is an attempt to adjust the weights of TP visibilities to equalize their areas. Note again that we use the symbols, Ω_{syn} and Ω_{conv} , to represent the areas of the beams as well as to refer the beams themselves.

5.2.1. The Synthesized and Convolution Beams from Combined INT+TP Visibilities

The pattern of the synthesized beam Ω_{syn} , denoted by $B(l, m)$, is given by eq. (1), where the weight is normalized as $\iint W(u, v) du dv = 1$. For the visibilities from interferometer (hereafter INT; e.g., ALMA 12m and 7m) and TP, the synthesized beam patterns, $B_{\text{INT}}(u, v)$ and $B_{\text{TP}}(u, v)$, are derived with their normalized weights, $W_{\text{INT}}(u, v)$ and $W_{\text{TP}}(u, v)$, respectively.

By using a relative weight parameter β , a combined weight distribution of INT and TP visibilities can be defined as

$$W(u, v) = \frac{W_{\text{INT}}(u, v) + \beta W_{\text{TP}}(u, v)}{\iint [W_{\text{INT}}(u', v') + \beta W_{\text{TP}}(u', v')] du' dv'} \quad (12)$$

$$= \frac{1}{1 + \beta} [W_{\text{INT}}(u, v) + \beta W_{\text{TP}}(u, v)]. \quad (13)$$

The corresponding synthesized beam pattern is

$$B(l, m) = \frac{1}{1 + \beta} [B_{\text{INT}}(l, m) + \beta B_{\text{TP}}(l, m)]. \quad (14)$$

The area of the synthesized beam is derived from eqs. (2)(13),

$$\Omega_{\text{syn}} = W(0, 0) = \frac{\beta}{1 + \beta} W_{\text{TP}}(0, 0), \quad (15)$$

where we used $W_{\text{INT}}(0, 0) = 0$, as INT has no contribution at zero spacing. Note that $W_{\text{TP}}(0, 0)$ is equal to the area of the synthesized beam of TP visibilities.

The convolution beam Ω_{conv} is typically derived by a 2-d Gaussian fit to the central peak in $B(l, m)$. Using the major and minor axis diameters, b_{maj} and b_{min} , from the fit, the area of Ω_{conv} is

$$\Omega_{\text{conv}} = \frac{\pi b_{\text{maj}} \times b_{\text{min}}}{4 \ln 2}. \quad (16)$$

5.2.2. Setting Up Weights for TP Visibilities

This weighting scheme attempts to achieve $\Omega_{\text{syn}} = \Omega_{\text{conv}}$. Equation (15) gives β as

$$\beta = \frac{\Omega_{\text{syn}}}{W_{\text{TP}}(0, 0) - \Omega_{\text{syn}}} = \frac{\Omega_{\text{conv}}}{W_{\text{TP}}(0, 0) - \Omega_{\text{conv}}}. \quad (17)$$

$W_{\text{TP}}(0, 0)$ is equal to the area of the synthesized beam of TP visibilities alone, which, by construction, is the same as that of the Gaussian primary beam of the TP antennas. Hence, $W_{\text{TP}}(0, 0) = \pi b_{\text{TP}}^2 / 4 \ln 2$ (as in eq. 16) using the beam size of the TP antennas, b_{TP} . The Ω_{conv} should be calculated from INT+TP visibilities, but in practice it depends primarily –and almost solely– on the longest baselines. Hence, for simplicity, we derive Ω_{conv} from INT visibilities alone. We now obtain β from eq. (17).

Using β , we adjust the TP visibility weight distribution from W_{TP} to βW_{TP} , by scaling the weights of individual visibilities (w_k^{INT} and w_k^{TP} for INT and TP visibilities in MSs, respectively).

For the following, we use the notation \bar{W} for an unnormalized weight distribution. The ratio of the two

terms in the numerator of eq. (13) is

$$\begin{aligned} W_{\text{INT}}(u, v) : \beta W_{\text{TP}}(u, v) \\ = \frac{\overline{W}_{\text{INT}}(u, v)}{\iint \overline{W}_{\text{INT}}(u, v) dudv} : \beta W_{\text{TP}}(u, v) \\ = \overline{W}_{\text{INT}}(u, v) : \beta \left[\iint \overline{W}_{\text{INT}}(u, v) dudv \right] W_{\text{TP}}(u, v). \end{aligned} \quad (18)$$

The unnormalized $\overline{W}_{\text{TP}}(u, v)$ and w_k^{TP} are related as $\iint \overline{W}_{\text{TP}}(u, v) dudv = \sum_k w_k^{\text{TP}} = N_{\text{vis}}^{\text{TP}} w_k^{\text{TP}}$. Thus, for the normalized $W_{\text{TP}}(u, v)$, we set $w_k^{\text{TP}} = 1/N_{\text{vis}}^{\text{TP}}$. Also, the term in the bracket is simply, $\iint \overline{W}_{\text{INT}}(u, v) dudv = \sum_k w_k^{\text{INT}}$. Therefore,

$$w_k^{\text{TP}} = \frac{\beta}{N_{\text{vis}}^{\text{TP}}} \sum_k w_k^{\text{INT}}. \quad (19)$$

The weights of TP visibilities are set in this way, to satisfy $\Omega_{\text{syn}} = \Omega_{\text{conv}}$ for the combination of INT and TP visibilities. The weights of INT visibilities (7m and 12m) are kept as delivered from the ALMA observatory.

5.3. Notes on Visibility and Weight Distributions

The weight distribution of TP visibilities can be controlled, either by changing the distribution of TP visibilities in uv space, and/or by adjusting the weights of individual visibilities of any given distribution. TP2VIS takes the former approach, generating a Gaussian visibility distribution with a constant weight for all the visibilities.

The latter approach could be useful in future. For example, generating a grid distribution, instead of the Gaussian distribution, and changing the visibility weights as a function of uv distance so that the weight distribution follows a Gaussian. This way, one could avoid shot noise due to the randomly-distributed discrete visibilities. In the end, the CLEAN task puts the visibilities onto a grid. If the grid spacing is controlled consistently between TP2VIS and CLEAN, we can test grid-based approaches in future. Of course, the weight distribution can be realized on a grid without visibilities, however, its implementation requires an update of the CLEAN task in CASA. It cannot be achieved by a supplementary package such as TP2VIS.

6. THE RESIDUAL SCALING

The flux problem in Section 4.2 is due to the disparity between the areas of Ω_{syn} and Ω_{conv} in eq. (3). The residual part of the final image from CLEAN is added incorrectly with an inconsistent unit of brightness. Hence, its surface brightness needs rescaling. To solve this, we simply scale the residual map by a factor of $\Omega_{\text{syn}}/\Omega_{\text{conv}}$ and add it to the model map to generate a new final

map. The TP2VISTWEAK function does this operation.¹

In theory, $\Omega_{\text{syn}}/\Omega_{\text{conv}}$ can be calculated mathematically, but it turns out not to be that simple. The estimation of $\Omega_{\text{syn}} = W(0, 0)$ depends on how the visibilities are gridded in imaging process. The integration of the synthesized beam, $\Omega_{\text{syn}} = \int B(l, m) dl dm$, requires an unrealistically large image size as its tiny responses at the far outskirts add up as their area is cumulatively large.

Instead, Jorsater & van Moorsel (1995) suggested a more practical approach by taking advantage of detected emissions. In parallel to eq. (3), we can write a similar equation for the dirty map D ,

$$\left[\frac{D}{(\text{Jy}/\Omega_{\text{syn}})} \right] = \left[\frac{I}{(\text{Jy}/\Omega_{\text{syn}})} \right] + \left[\frac{R}{(\text{Jy}/\Omega_{\text{syn}})} \right], \quad (20)$$

where I denotes a map of the emissions that will be identified in CLEAN. We should note that the brightness unit is $\text{Jy}/\Omega_{\text{syn}}$ for all terms, and that M and I in eqs. (3) and (20) represent exactly the same emissions in different units. The D , F , and R are given by CLEAN in CASA, and hence, we can calculate the scaling factor as

$$\frac{\Omega_{\text{syn}}}{\Omega_{\text{conv}}} = \frac{F - R}{D - R}. \quad (21)$$

We multiply the R map by this factor and add it to M to construct a new F as in eq. (3), but with consistent brightness units (consistent beam areas). This residual scaling method is included in the AIPS task IMAGER and was used recently by Ianjamasimanana et al. (2017).

In principle, this method can be applied on a pixel-by-pixel basis, as long as the emissions are significantly detected across the map. In practice, this is not always the case. In addition, different spillovers of the beam patterns of Ω_{syn} and Ω_{conv} degrade the accuracy of the calculation on a pixel-by-pixel basis. Hence, TP2VIS integrates the part of map with significant detections and calculates a single beam ratio with eq. (21). Currently, TP2VIS uses a single ratio even for mosaic, which may be modified in future as the synthesized beam may vary among mosaic pointings.

7. TESTS WITH ALMA DATA

We apply TP2VIS to two sets of ALMA data.

7.1. The Spiral Galaxy M100

The first example is a mosaic of the nearby spiral galaxy M100 in CO(1-0). The data are conveniently readily available from a science verification project

¹ One should keep it in mind that the patterns of Ω_{syn} and Ω_{conv} are still not the same, even though their areas are the same.

(2011.0.00004.SV; Preben Grosbol and Catherine Vlahakis) and are discussed in the CASA guide on the combination of ALMA 12m, 7m, and TP data with the FEATHER method.² Calibrated data were downloaded from the website in the CASA guide. The galaxy is covered in a 47-point mosaic with the ALMA 12m array, a 23-point mosaic with the 7m array, and mapped with the TP array. In the following, we describe the steps for combination.

First, we pre-prepare two inputs for TP2VIS: (1) the RMS noise of the TP map, and (2) a text-format list of mosaic pointing coordinates around which visibilities are generated. The RMS is derived with the IMSTAT task in CASA. The list of pointing coordinates is manually created, based on an output from the LISTOBS task on the ALMA 12m data. Here, we adopt the set of the mosaic pointings of the 12m, though it could be any set of coordinates within the TP map.

Second, we run the TP2VIS function with three inputs and one option: (1) and (2) from the previous step, (3) the TP map in CASA image data format, and (4) the “nvgrp=20” option. TP2VIS generates visibilities as a batch of 1,035 visibilities (called “a visibility group”). The “nvgrp” parameter controls the number of visibility groups to generate. In this case, it generates 20 visibility groups, and hence, 20,700 visibilities per mosaic pointing. This second step creates a MS of the TP data.

The TP2VIS function uses the sensitivity-based weighting scheme (Section 5.1). The relative weights among TP, 7m, and 12m visibilities can be visualized with the TP2VISPL function. Figure 2 is an example. The weight density appears to transition smoothly from TP to 7m, and to 12m. There may be a flux calibration issue on the 7m data with respect to the 12m and TP (the top-right panel), which should have been dealt with in the calibration prior to the TP2VIS steps. We ignore this calibration issue, since it is not in the scope of this report.

Third, we concatenate TP, 7m, and 12m MSs with the CONCAT task to generate a single MS. This CONCAT step should not be necessary in theory, but is required to avoid issues in data headers in CASA. We then run the TCLEAN task and obtain dirty and clean maps. For this demonstration, we use the natural weighing, which gives the same weights for TP data as those in FEATHER with respect to the 7m and 12m data. The power of TP+7m+12m combination with TCLEAN can be appreciated more with other weighing schemes, such as robust (Briggs), uniform weightings, etc. FEATHER allows only the one weighting scheme, but TP2VIS is flexible. In

addition, the TP2VIS approach combines the data before TCLEAN, providing better uv coverage for better imaging.

Forth, we apply the residual scaling method (Section 6) with the TP2VISTWEAK function. This generates a final map for science. Figure 3 presents a channel map, showing a part of the molecular gas disk in this galaxy. It compares clean maps with 7m+12m data alone (left panel) and with TP+7m+12m data (right). Negative sidelobes appear clearly around significant emissions in the map without TP (left), while they are absent in the map with TP (right).

7.2. A Giant Molecular Cloud in LMC

This example makes a map of a giant molecular cloud (GMC) in the Large Magellanic Cloud (LMC). The data were taken as part of the ALMA Cycle 1 project (2012.1.00641.S; PI T. Sawada) with the ALMA 12m, 7m, and TP arrays. Each data set was reduced and calibrated separately using the data reduction scripts distributed through the ALMA data archive. The individual weights of the 7m array visibilities were adjusted by following the instruction in the CASA guide.³ The data covers a $\sim 2.5' \times 2.5'$ region at the heart of Cloud 197 in the LMC in the CO $J=1-0$ transition. The region is observed with a 27-point mosaic with the 12m array, a 10-point mosaic with the 7m, and mapped with the TP array.

The calibrated TP cube is converted into visibilities using TP2VIS in the same way as in Section 7.1. We used the 27 pointings of the 12m as the pointings of the virtual interferometer. The sensitivity-based weighting scheme is used first. We then plot the weight density in Figure 4. In the two lower panels, the TP weights appear to be lower than those of the 12m by a factor of about 4-10. The 7m weights are also lower, but in this paper we do not manipulate the weights of the 7m and 12m [though of course, we can]. We made a map of TP+7m+12m with this sensitivity-based weight, but the effect of TP was only marginally recognizable. Hence, we increased the TP weights by a factor of 4 with the the TP2VISWT function.

Figure 5 compares three cleaned channel maps with TP data (left panel) and without TP data (right). Clearly, the TP data is critical for this object. The emission at large scales, seen clearly on the right panels, is missed in the left panels. The uv space is not filled very well without the TP data (Figure 4 top-left), and the CLEAN process without TP data left substantial negative side-lobes around the emission (Figure 5 left).

² https://casaguides.nrao.edu/index.php/M100_Band3_Combine_4.3

³ <https://casaguides.nrao.edu/index.php/DataWeightsAndCombination>

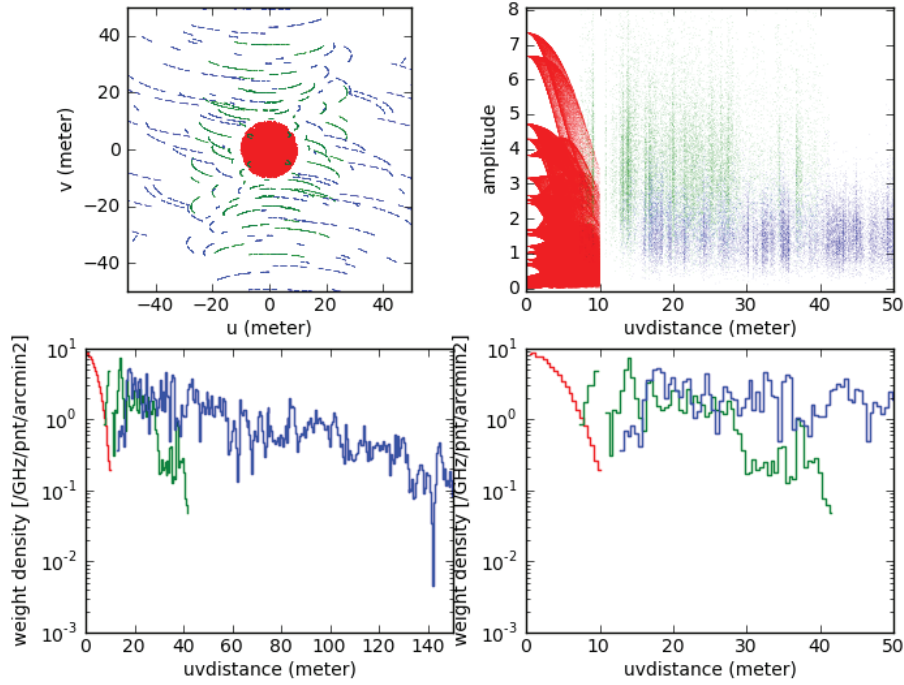


Figure 2. A plot generated by the TP2VISPL function for the spiral galaxy M100. The red, green, and blue correspond to the TP, 7m, and 12m visibilities. Top-left: uv coverage. Top-right: amplitude as a function of uv distance. Bottom-left: weight density as a function of uv distance. Bottom-right: the same as the bottom-left panel, but for a smaller range of uv distance.

8. OPEN CASA ISSUES

During the development of TP2VIS we encountered several problems that sometimes were caused by problems in CASA. We typically filed those as a helpdesk ticket, or if clear enough, a JIRA ticket, or if not clear enough, consulted with NRAO staff.

Here is a few noteworthy issues which are still open as of the date of this final report.

(1) The TCLEAN task does not generate a correct synthesized beam image (or .psf image) in case of mosaic. This is very clear when we map a single field of a mosaic with “field=” option. The synthesized beam pattern appears distorted and does not show the expected 180 deg-rotation symmetry. This effect becomes even more severe when the field is farther from the phase/map center.

For example, when we map a single field near the center of a mosaic with TP visibilities, its synthesized beam is a nice round with the 40'' size, but in the mosaicked field, the combined PSF becomes as large as 60'' and is also not round. Since we generate the uv distribution, we have a control of its size and shape. This result was a surprise.

When we then map the individual fields, it became clear that the synthesized beam patterns in the outer fields are very distorted, non-gaussian. It is not a surprise that the mean of these distorted synthesized beams

becomes 60'' and not the expected 40''. However, when we map them with phasecenter=field-center, we do get nice 40'' beams for each field.

It is still not clear if this problem affects the clean operation and final map. At very least, the part that generates a .psf image does not handle the phase shift properly.

(2) The TCLEAN task does not handle the POINTING table in MS properly. The primary beam shape varies unexpectedly when a POINTING table exists, and subsequently, the final image also suffers from this problem.

In particular, the primary beam is not symmetric for a symmetrically enforced mosaic from TP2VIS. In fact, some of the pointings are over- or under-weighted, which appears in the .pb image. To test this, we generated .pb images with and without the POINTING table left in MS and checked their difference. We can obviously work around this by removing the POINTING table with the textscConcat task with “coppointing=False” option.

(3) The TCLEAN task and CASA as a whole would crash when a list of MSs including one from TP2VIS was given to TCLEAN. Removing the POINTING table and DATA_CORRECTED column would fix this. For this, the CONCAT or MSTRANSFORM tasks can be used.

(4) We could not get the vpmanager to work (Helpdesk ticket # 11267; Jira ticket # CAS-10384).

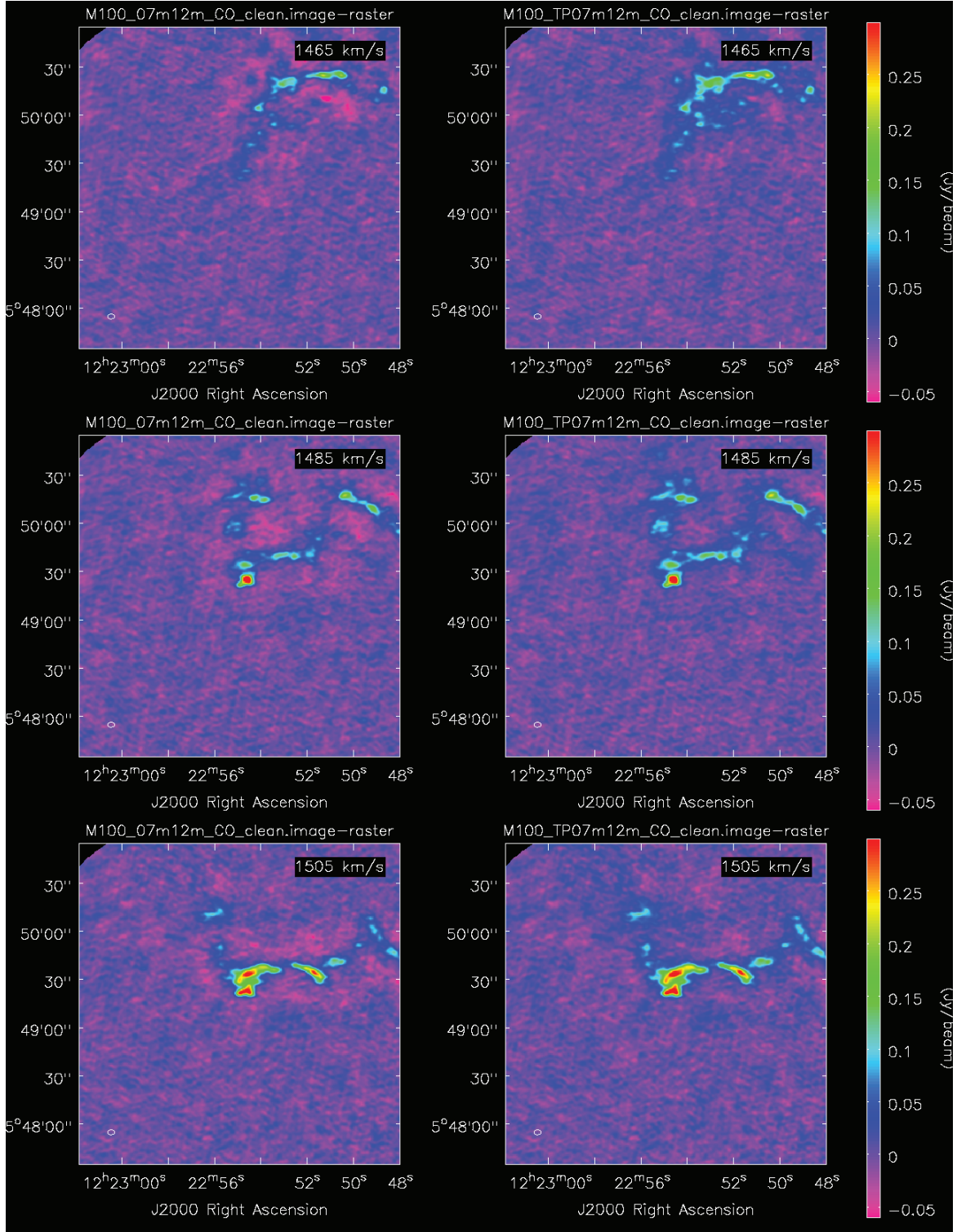


Figure 3. A comparison of cleaned channel maps of the spiral galaxy M100 in CO(1-0) with (left panels) and without (right) TP data, using the ALMA science verification data. Both left and right panels include ALMA 7m and 12m data. Negative sidelobes are apparent in the left panels, but absent in the right panels.

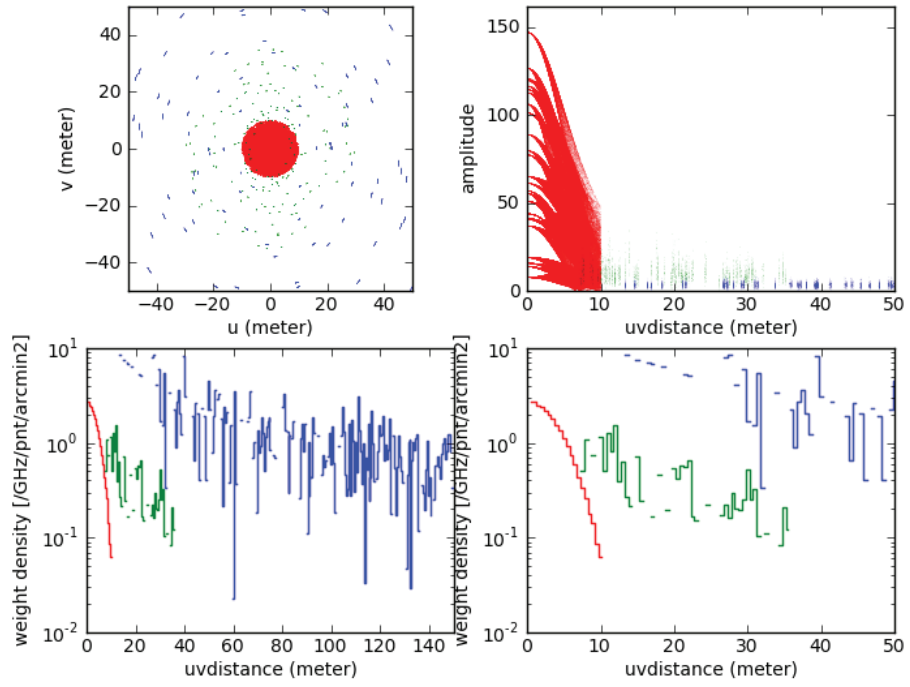


Figure 4. The same as Figure 2, but for Cloud 197 in the Large Magellanic Cloud.

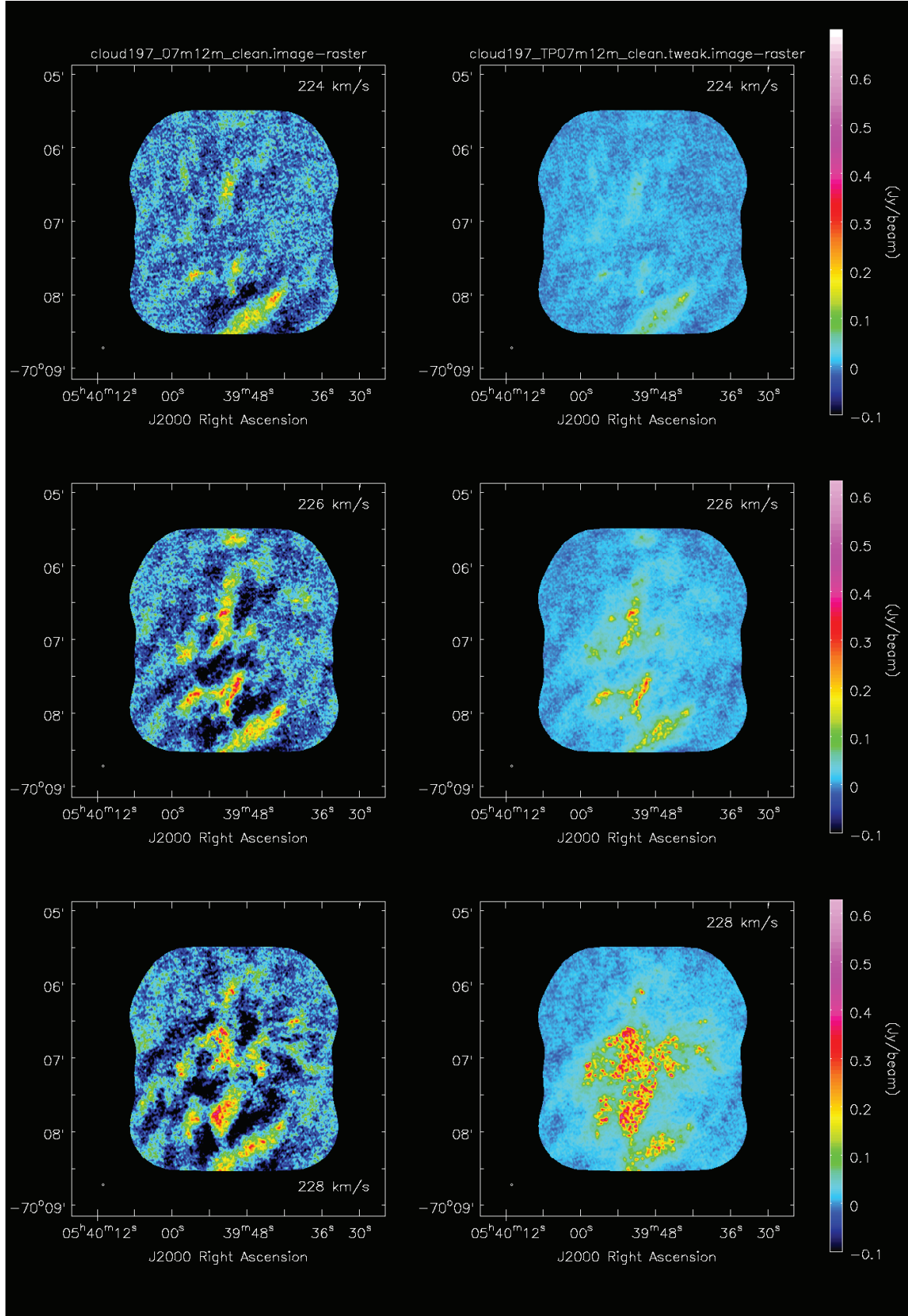


Figure 5. A comparison of three cleaned channel maps of Cloud 197 with TP (left) and without TP (right). The red, green, and blue correspond to the TP, 7m, and 12m visibilities.

Without the properly-functioning `vpmanager`, we could not implement a widely-requested option for handling other single-dish telescope data (such as GBT, LMT, Nobeyama, IRAM 30m, etc) with `TP2VIS`.

(5) There are differences (1-5%) in the result of `TCLEAN` between different `CASA` versions. Such differences often caused confusions and sometimes became a major hindrance to the `TP2VIS` development.

(6) The `IMVIEW` and `CASAVIEWER` tasks have some kind of hysteresis effect, by which png's or images on the screen cause a rescaling if you repeat them or try and write a python loop for comparison between images. This made it very hard and time consuming to interactively compare results, and we had to use both `ds9` and write a custom made `matplotlib` routine to help us.

We thank NRAO staffs, in particular, Remy Indebetouw, Kumar Golap, and Jennifer Donovan Meyer, for their helps. We also thank Kazuki Tokuda for very helpful feedback on an early version of `TP2VIS`. This report makes use of the following ALMA data: ADS/JAO.ALMA#s 2011.0.00004.SV, 2012.1.00641.S, and 2013.1.00652.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

REFERENCES

- Cornwell, T. J. 1988, *A&A*, 202, 316
- Dubinski, J., Narayan, R., & Phillips, T. G. 1995, *ApJ*, 448, 226
- Ianjamasimanana, R., de Blok, W. J. G., & Heald, G. H. 2017, *AJ*, 153, 213
- Jorsater, S., & van Moorsel, G. A. 1995, *AJ*, 110, 2037
- Koda, J., Sawada, T., Wright, M. C. H., et al. 2011, *ApJS*, 193, 19
- Kurono, Y., Morita, K.-I., & Kamazaki, T. 2009, *PASJ*, 61, 873
- Pety, J., & Rodríguez-Fernández, N. 2010, *A&A*, 517, A12
- Rodríguez-Fernández, N. 2008, Single-dish observation and processing to produce the short-spacing information for a millimeter interferometer, Tech. Rep. 2008-2, IRAM
- Stanimirovic, S. 2002, in *Astronomical Society of the Pacific Conference Series*, Vol. 278, *Single-Dish Radio Astronomy: Techniques and Applications*, ed. S. Stanimirovic, D. Altschuler, P. Goldsmith, & C. Salter, 375–396
- Stanimirovic, S., Staveley-Smith, L., Dickey, J. M., Sault, R. J., & Snowden, S. L. 1999, *MNRAS*, 302, 417
- Takakuwa, S. 2003, A Method of Combining Single-Dish Data with the Nobeyama 45 m Telescope and Interferometric Data with the Nobeyama Millimeter Array, Tech. Rep. 65, Nobeyama Radio Observatory
- Taylor, G. B., Garilli, C. L., & Perley, R. A., eds. 1999, *ASP Conference Series*, Vol. 180, *Synthesis Imaging in Radio Astronomy II* (Astronomical Society of the Pacific)
- Thompson, A. R., Moran, J. M., & Swenson, G. W. 2007, *Interferometry and Synthesis in Radio Astronomy* (John Wiley & Sons)
- Vogel, S. N., Wright, M. C. H., Plambeck, R. L., & Welch, W. J. 1984, *ApJ*, 283, 655