Improving Image Fidelity on Astronomical Data

Radio Interferometer and

Single-Dish Data Combination

Preliminary program
Improving Image Fidelity on Astronomical Data

Monday 12 August 2019

09:00 – 10:00	Registration/ Coffee
10:00 – 10:15	Welcome by the Lorentz Center
10:15 – 10:30	Welcome by the Organizers
10:30 – 12:30	Introduction of workshop objectives. Explanation of working groups. Brief introduction of all participants (names and affiliations)
12:30 – 14:00	Lunch
14:00 – 15:00	Invited talk: Overview and state of the art of different data combination methods I (Ed Fomalont)
15:00 – 15:30	Coffee Break
15:30 – 16:30	Invited talk: Overview and state of the art of different data combination methods II (Urvashi Rau)
16:30 – 17:00	Discussion/presentations
17:00	Wine and cheese party

Tuesday 13 August 2019

09:00 – 09:45	Technical talk: "The feathering technique" (Adam Ginsburg)
09:45 – 10:15	Coffee break
10:15 – 11:00	Technical talk: "The joint deconvolution technique" (Peter Teuben)
11:00 – 11:45	Technical talk: "The steer cleaning technique" (Jens Kauffmann)
11:45 – 12:30	Group setup
12:30 – 14:00	Lunch
14:00 – 17:00	Group sessions
17:00 – 17:30	Reporting from groups

Wednesday 14 August 2019

09:00 – 09:45	Technical talk: "Data combination at low frequencies" (Pedro Salas)
09:45 – 10:15	Coffee break
10:15 – 11:00	Technical talk: "Data combination in extragalactic studies" (Tokashi Saito)
11:00 – 11:45	Technical talk: "How to apply the different methods, and what is missing" (Sandra Burkutean)
11:45 – 12:30	Group sessions
12:30 – 14:00	Lunch

14:00 – 16:00	Group sessions
16:00 – 16:30	Reporting from groups/presentations
16:30 – 17:00	Coffee and tea break
17:00 – 17:30	Departure by bus to the boat
17:30 – 21:30	Workshop diner on the boat
21:30 – 22:00	Departure by bus to Lorentz Center, Central station and hotel Van der Valk.

Thursday 15 August 2019

09:00 – 09:45	Invited talk: "Galactic studies, and the need of combining data" (Alvaro Hacar)
09:45 – 10:15	Coffee break
10:15 – 11:00	Invited talk: "Extragalactic studies, and the need of combining data" (Cynthia Herrera)
11:00 – 11:45	Discussion/presentations
11:45 – 12:30	Group sessions
12:30 – 14:00	Lunch
14:00 – 17:00	Group sessions
17:00 – 17:30	Reporting from groups

Friday 16 August 2019

09:00 – 09:45	Working sub-groups prepare (drafts) of workshop proceedings (completed remotely during following weeks)
09:45 – 10:15	Coffee break
10:15 - 12:30	Working sub-groups continue working on (drafts) of proceedings
12:30 – 14:00	Lunch
14:00 – 15:00	Summary of workshop

All materials for this workshop are posted at
https://github.com/teuben/dc2019

Relevant papers, resources: /tree/master/papers
Workshop talks: /tree/master/talks

Datasets for the hands-on working sessions (groups):

1. **M100** (ALMA 12m + 7m + TP) #m100

2. **NGC346 in the SMC** (ALMA 7m + TP) #ngc346

3. **GMC fractal/powerspectrum model** (synthetic observations) #skymodel

4. **Gaussians model** (synthetic observations) #wg_simulations-sky_is_gaussian

5. **Protostellar outflows** (ALMA 12m + 7m + TP) #lupusoutflow_workgroup

6. **HI observations** (GBT + WSRT / LOFAR) #hi_working_group

Some History of Imaging Extended Objects

Högbom, J. A. 1974, A&AS, 15, 417: CLEAN ALGORITHM
1967-68: I was Post Doc In Leiden: Oort, vdHulst, vdLaan, Brouw, Hogbom

Cornwell, T.J., Holdaway, M.A. & UsonJ.M., 1993, Radio-interferometric imaging of very large objects: implications for array design, A&A 271,697.
Analysis of TP and arrays with same antenna size. Excellent error analysis

Holdaway. M.A., 1999, Mosaicing with Interferometer Arrays, ASP Conference series 180, 401. NRAO summer school. Good introduction.

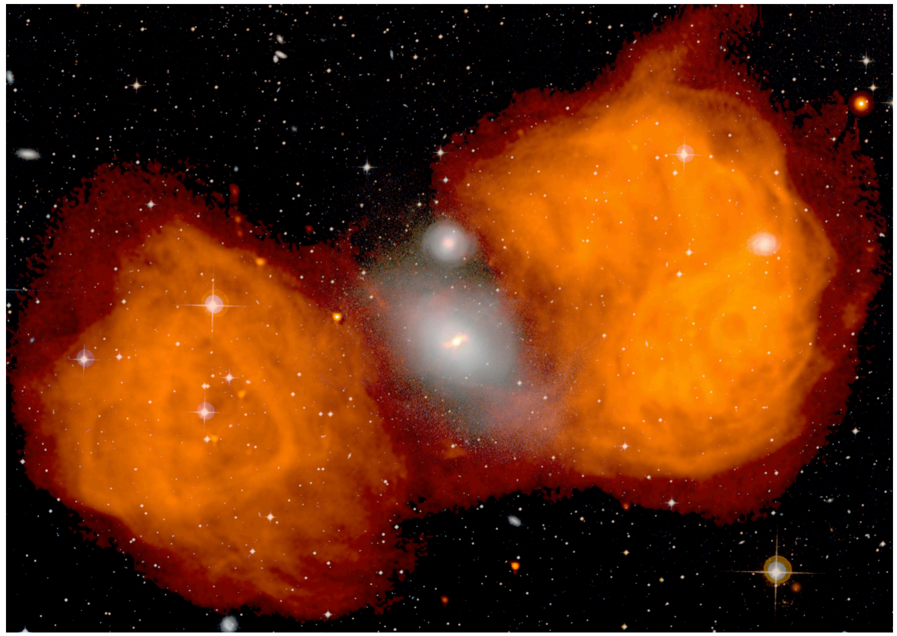
Greisen, E.W.,2002, Wide Field Imaging in Classic AIPS since 1970
Gluing each field together. Has some advantages.

Wright, M. 2012, ALMA Single Dish and Array Combination Workshop: Heterogeneous Array Imaging:
http://w.astro.Berkeley.edu/~wright/ALMA/SingleDishandArrayCombinationWorkshopDec17-19.pdf

Rau, Naik, Braun, 2019, AJ 158,3,1: A joint Deconvolution …
Discussed in next talk, and throughout workshop.

ALMA imaging/deconvolution 'relatively easy' because of little large field problems where sky curvature is important.

VLA image at 1.4 GHz of Fornax-A with 20” resolution



Three VLA pointing mosaic plus Parkes SD.
Each field imaged and then overlap combined,
Smooth to Parkes resolution and scale.
“A SIMPLE FEATHER”

Combination	Fourier domain	Image domain
Before Deconvolution	*Generate psuedo visibilities* • Vogel et al. 1984 • Rodriguez-Fernandez 2008 • Kurono et al. 2009 • Pety & Rodriguez-Fernandez 2010 • Koda et al. 2011 • Koda et al. 2019 (TP2VIS)	*Combine dirty map/beam* • Stanimirovic et al. 1999 • Urvashi Rau, in prep.
During Deconvolution	*Single dish map as initial model* • Cornwell 1988 • Dirienzo et al. 2015	
After Deconvolution	*"Feather" and its predecessors* • Herbstmeier et al. 1996 • Weiβ et al. 2001 • Blagrave et al. 2017	*"Feather" in image domain* • Faridani et al. 2018

From Teuben

Adam Ginsberg

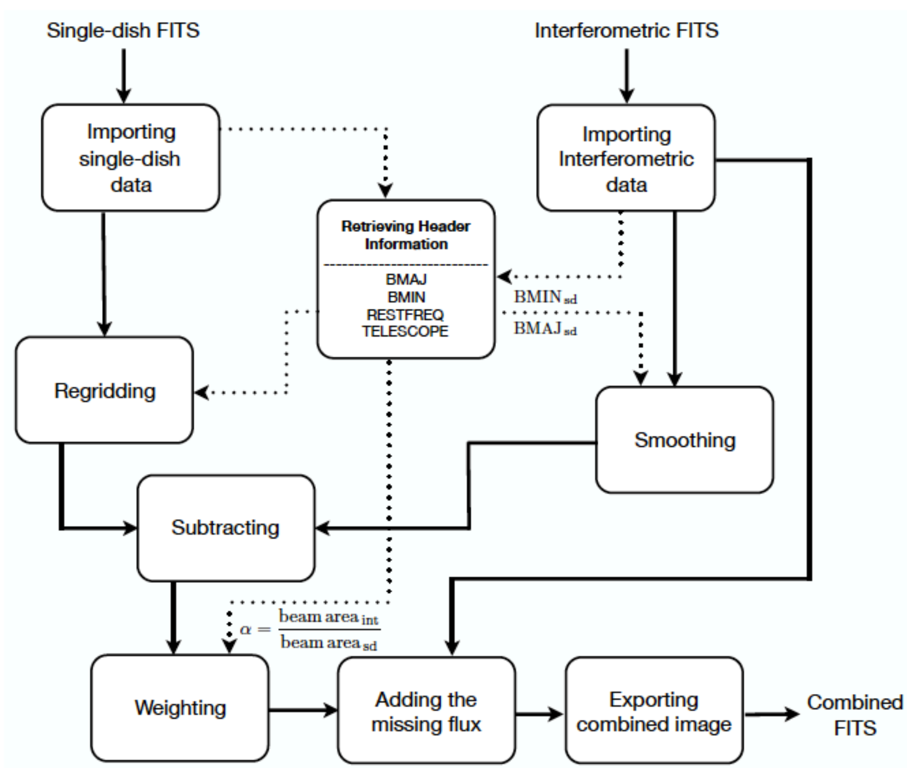
Adam's talk is not available in the github repository. I assume the content included feathering in both the Fourier and image domains. The appeal of feathering techniques is their simplicity.

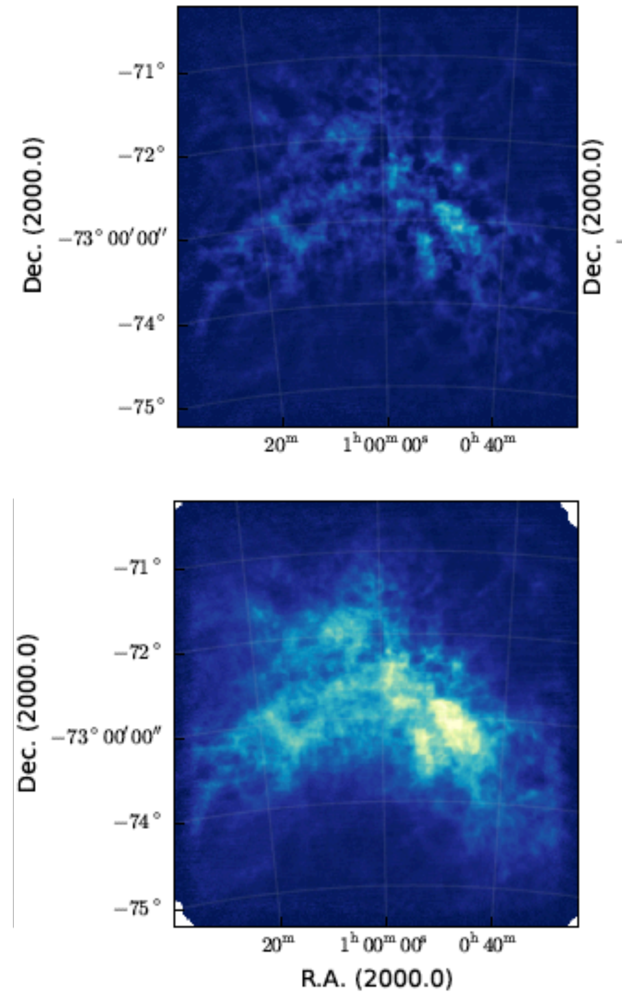
Fourier Domain

1. Grid SD and (deconvolved) INT maps appropriately (can be one or more of each)
2. Generate weighting masks for each resolution except the lowest; e.g.,
   - Take image of clean beam of a given map
   - FFT
   - Take real part and normalize to unity
   - Weight of map $w_i = 1 - w_{i+1}$ where i+1 is next lowest resolution
3. FFT each map and multiply by its corresponding weighting mask
4. Sum in FT domain
5. Perform IFT of the total
6. Normalize

Imaging Domain (SSC)

Faradani et al. (2018): "A new approach for short-spacing correction of radio interferometric data"





ATCA

+ Parkes

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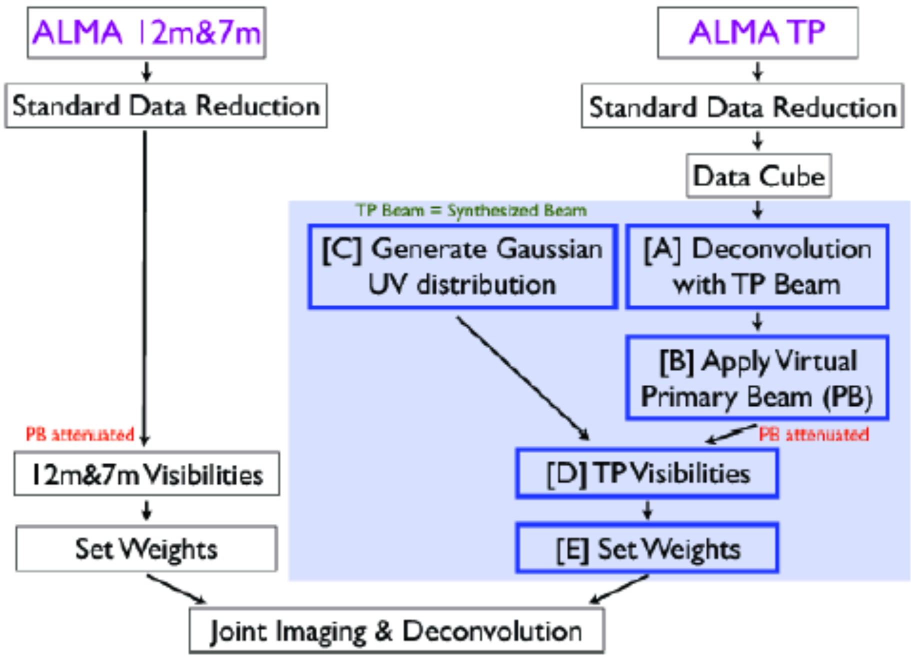
See Koda et al. (2019): “Total Power Map to Visibilities (TP2VIS): Joint Deconvolution of ALMA 12m, 7m and Total Power Array Data”. [ALMA Development Study]

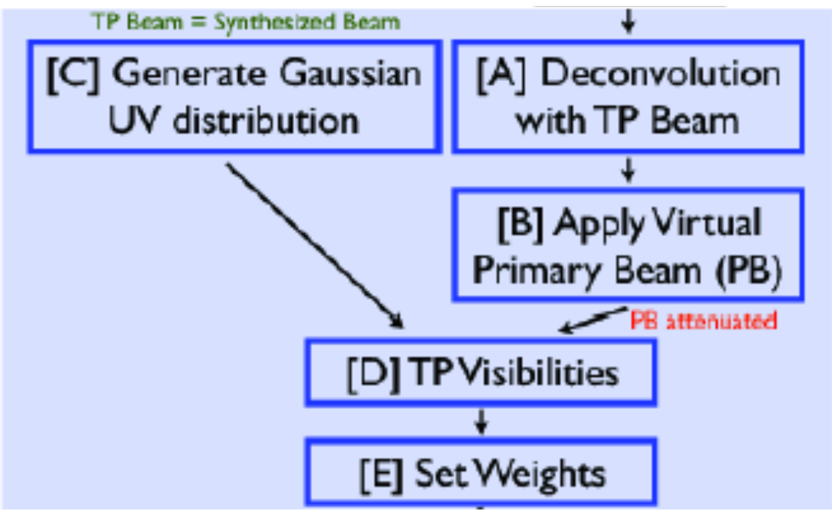
Peter Teuben

Flow Chart of the **TP2VIS** procedure



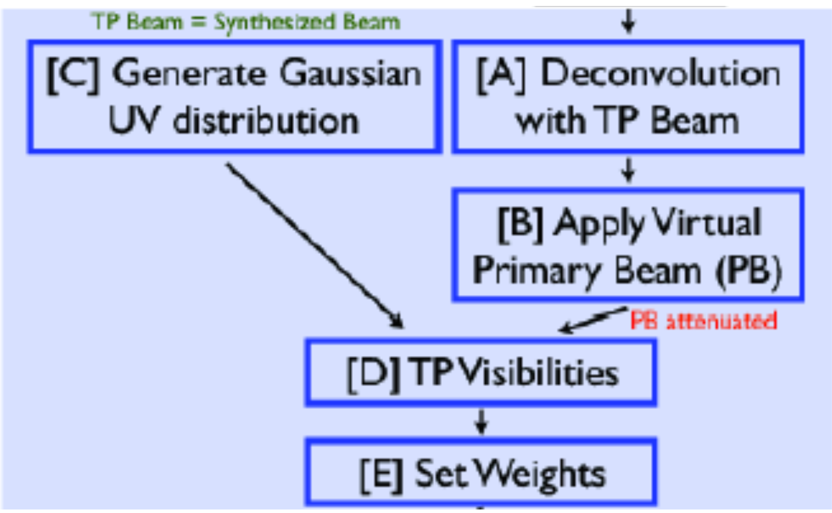
Step A:
Deconvolution with TP beam

- Input TP map is sky convolved with TP beam →
- Map needs to be deconvolved with TP beam for input to the virtual interferometer
  - ALMA: gaussian 56.6” at 115.2 GHz
    - Accurate models for PB are needed
  - Non-ALMA (e.g. GBT, VLA) can also be used
    - To the rescue: VP manager?



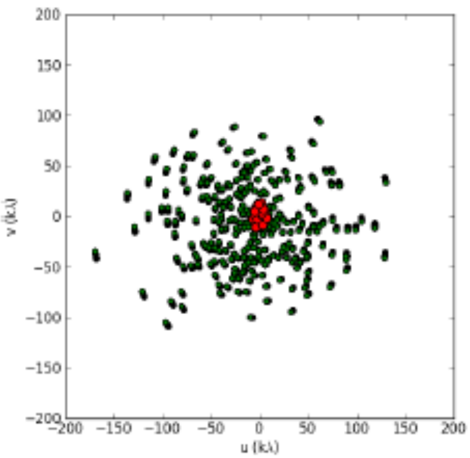
Step B:
Apply Virtual Primary Beam

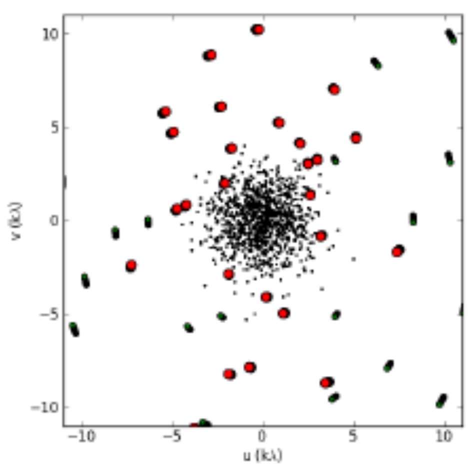
- A selected virtual primary beam is applied to all pointings selected for "observing"
- Pointings can be picked from:
  - Another (interferometric) data set (MS)
  - An ascii file with RA,DEC positions
  - An auto-filled set of pointings e.g. using hex-pattern nyquist sampling

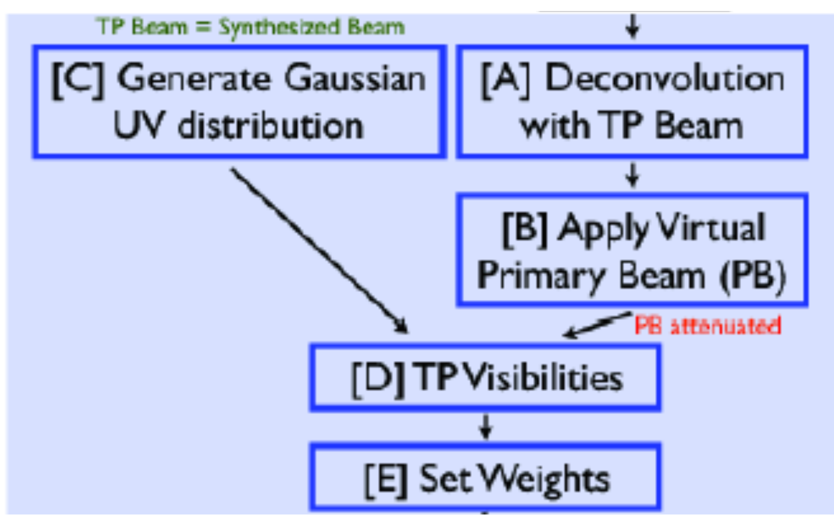


Step C:
Generate Gaussian UV Distribution

- Random gaussian distribution UV points, including (0,0) for the total flux
- Fourier transform of these points should represent the TP beam

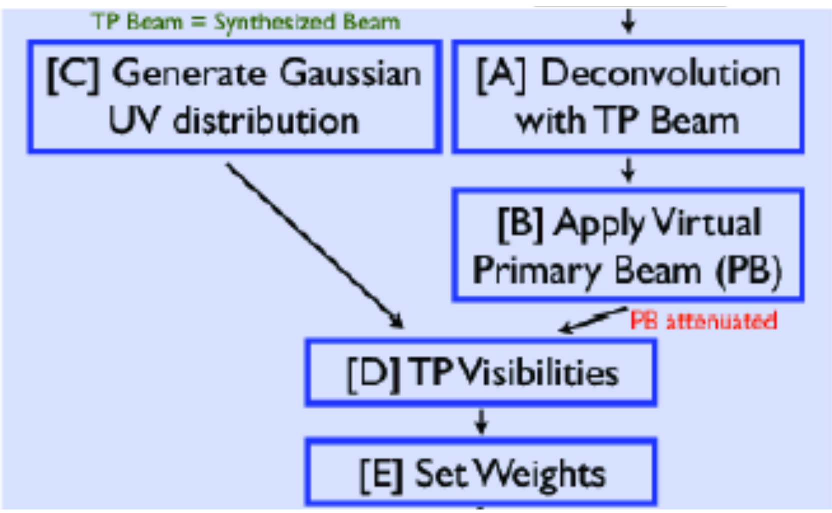






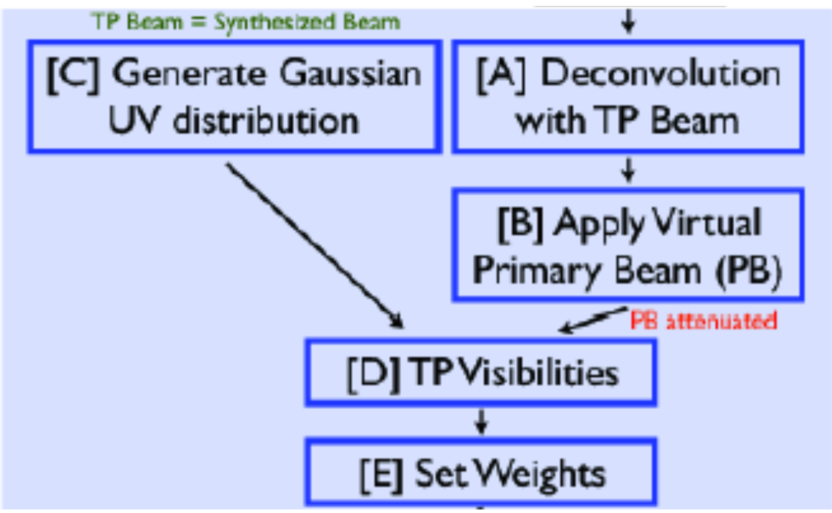
Step D:
Fill Visibility Amplitudes and Phases

- Sky brightness from step B and spacings from step C can now predict what visibilities are “observed”
- Cleaning these visibilities with a natural weighting scheme should now result in reproducing the input image
- Weights are needed to combine with 7+12m



Step E:
Set Weights of TP Visibilities

- By default weights will be set consistent with the RMS noise in the TP cube
- "**tp2viswt**" can set different weights, e.g. match dirty beam area to the beam solid angle



TP2VIS for CASA users is now simple!

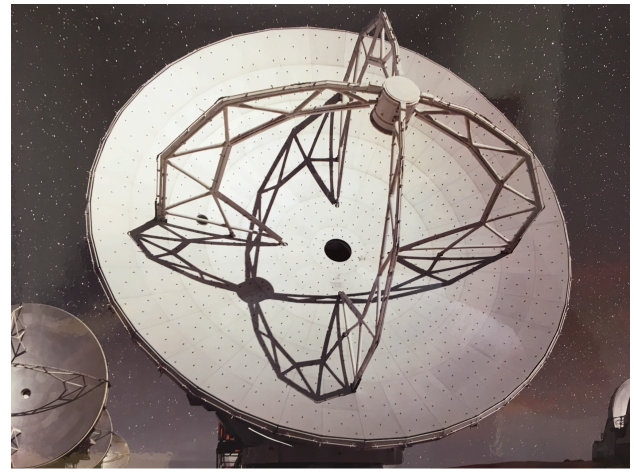
```
#  load TP2VIS  (can also use the ~/.casa/init.py trick)
execfile('tp2vis.py')

#  convert Image to Visibilities
tp2vis('alma_tp.im', 'alma_tp.ms', ptg='alma_12m.ms', rms=0.7)

#  joint deconvolution using standard CASA task
tclean(vis=['alma_7m.ms','alma_12m.ms','alma_tp.ms'], imagename='alma_all',
    niter=1000, imsize=[512,512], cell=['0.5arcsec'])
```

Note: TP2VIS and SD2VIS are available through Peter Teuben's QAC ("quick array combinations") CASA functions. See ngVLA Memo 59 for a description and https://github.com/teuben/QAC for installation.

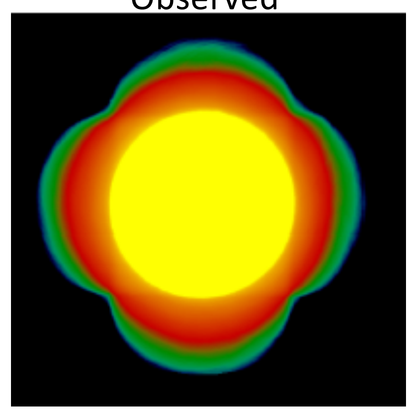
An aside:

Iwai, Bastian & White have looked at the question of deconvolution of the 12m (Melco antenna) beam from TP fast-scan maps as a means of better characterizing the center-to-limb brightness variation and to improve contrast.

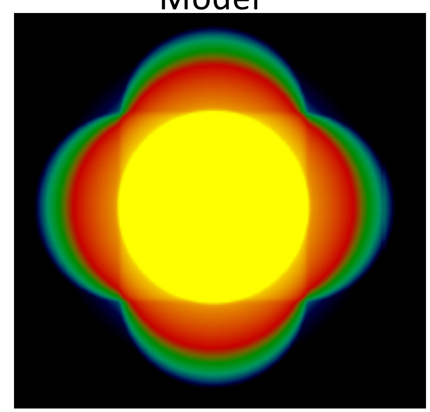
Maps were made in bands 3 and 6 of 1 deg diameter (compared with the standard 2/3 deg). These have been characterized In terms of either three Gaussians or two Gaussians and a quadrupolar component.



Observed



Model



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Urvashi Rau

Several approaches to data combination are classified and discussed: “image combination”, “starting model”, “joint reconstructions”. I’ll touch on the last one here.

Joint Reconstructions

Combine constraints from SD and INT data (or images) during deconvolution

MOSMEM :

– Image-domain chi-square constraint with separate terms for the INT and SD images within a Maximum Entropy algorithm (narrow-band imaging only). Has auto-scaling.

TP2VIS :

– Construct pseudo SD visibilities by sampling the FT of the deconvolved SD image according to the UV-sensitivity envelope of the SD measurement. Match meta-data with INT observation.

– Append SD pseudo visibilities to INT dataset and reconstruct together.

Wideband SDINT :

– Combine SD and INT images and PSFs via feathering prior to minor cycle deconvolution, but keep the data (and major cycles) separate. Simple/flexible implementation.

Joint Reconstructions

– A joint sky model is constructed using information from all scales at once

=> Errors from INT-only reconstructions are not burnt in at any stage.

– The SD beam is also deconvolved from the SD observed image

=> Better resolution than just the SD observed image

– Merge Images and PSFs (feathering as a weighting scheme for deconvolution)

=> Robust to a wide range of choices of scale factors and UV-weighting functions.

– Potentially better handling of high relative error in SD data

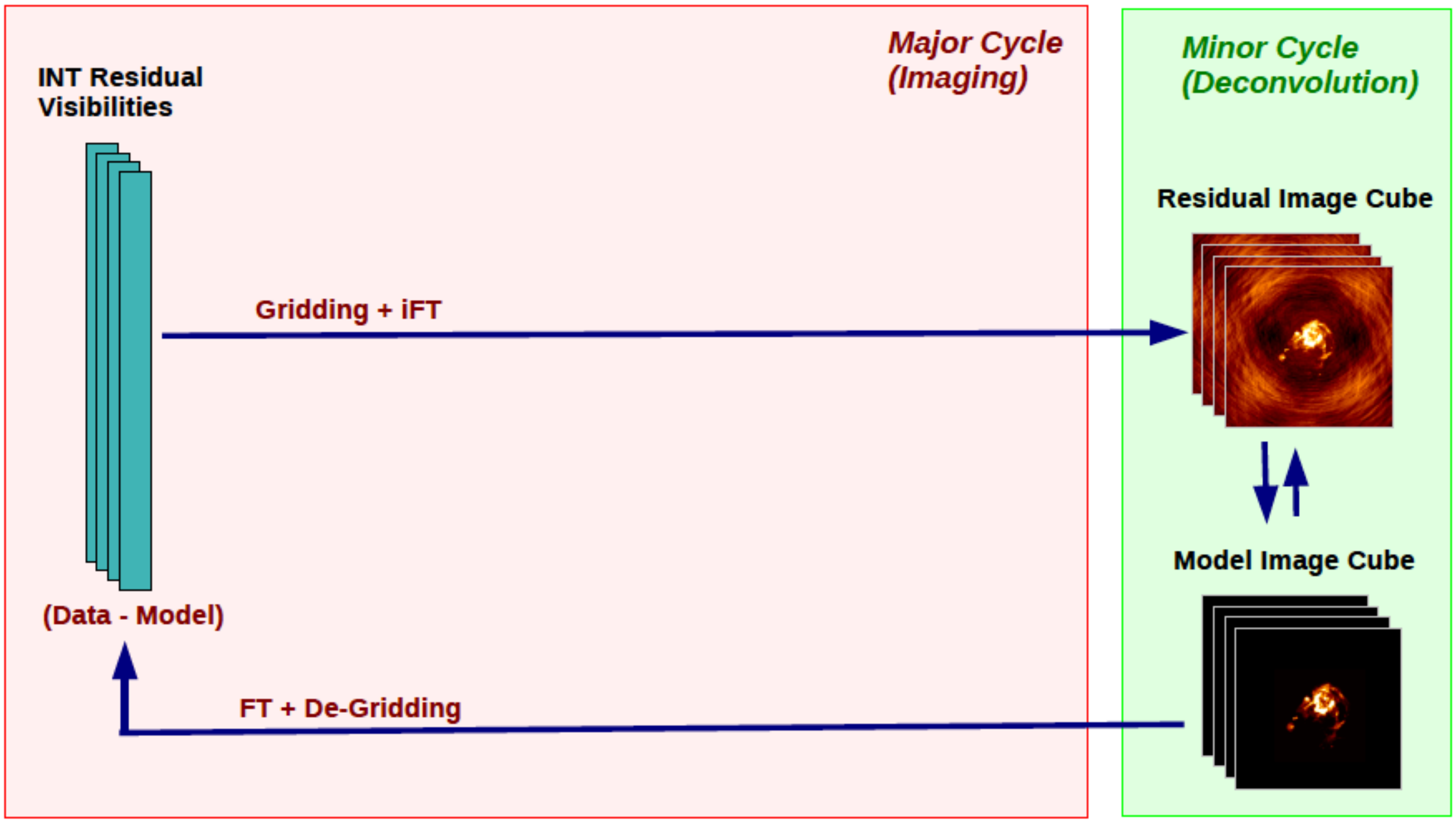
=> Less of a trade-off between noise suppression and flux accuracy.

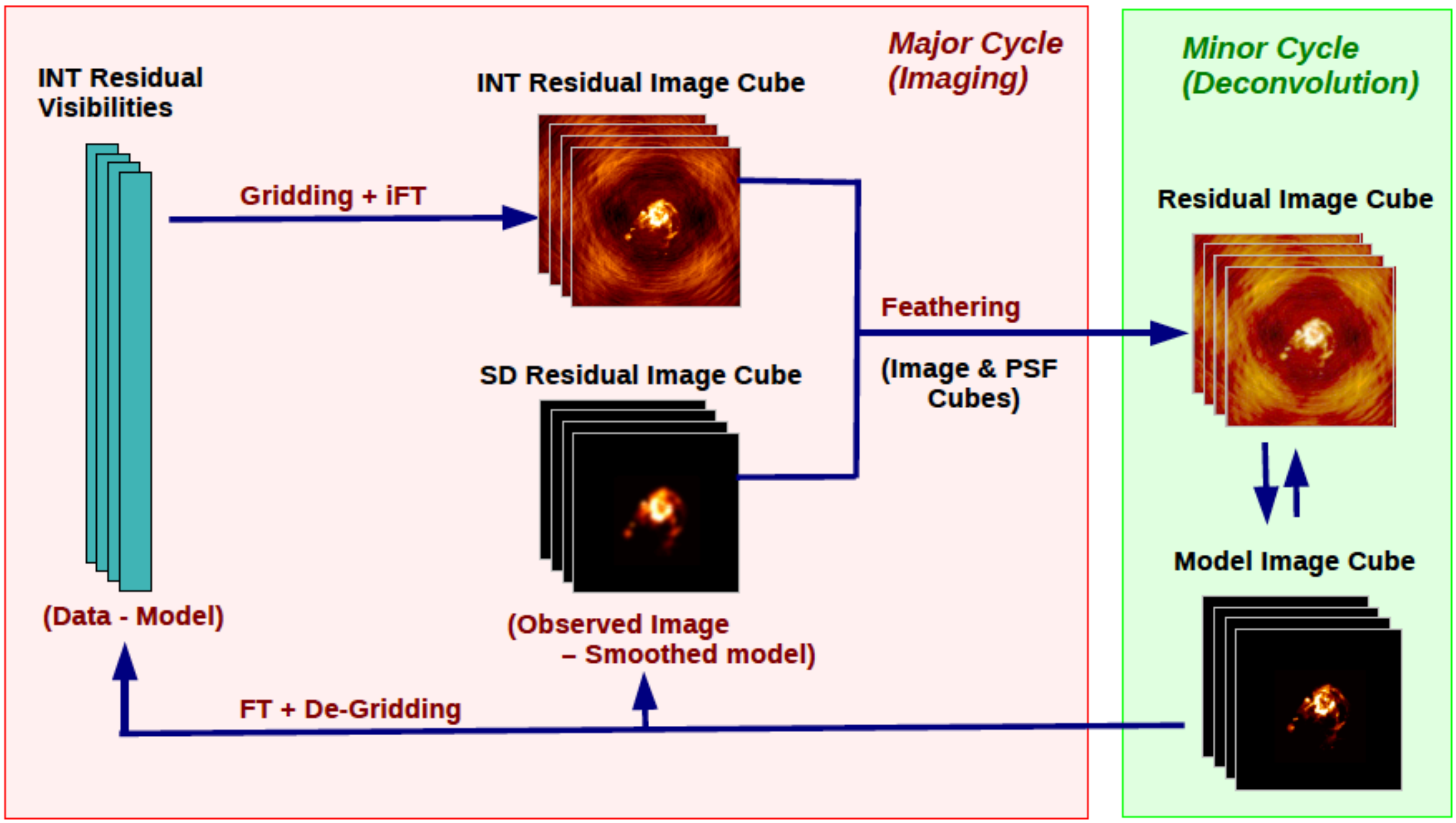
SDINT

- Uses PySynthesisImager scripting interface
- Modular design for generic data combination
- Scripts and examples : https://github.com/urvashirau/WidebandSDINT
- A CASA task is being designed and evaluated

  (Suggestions for features and validation tests are welcome)

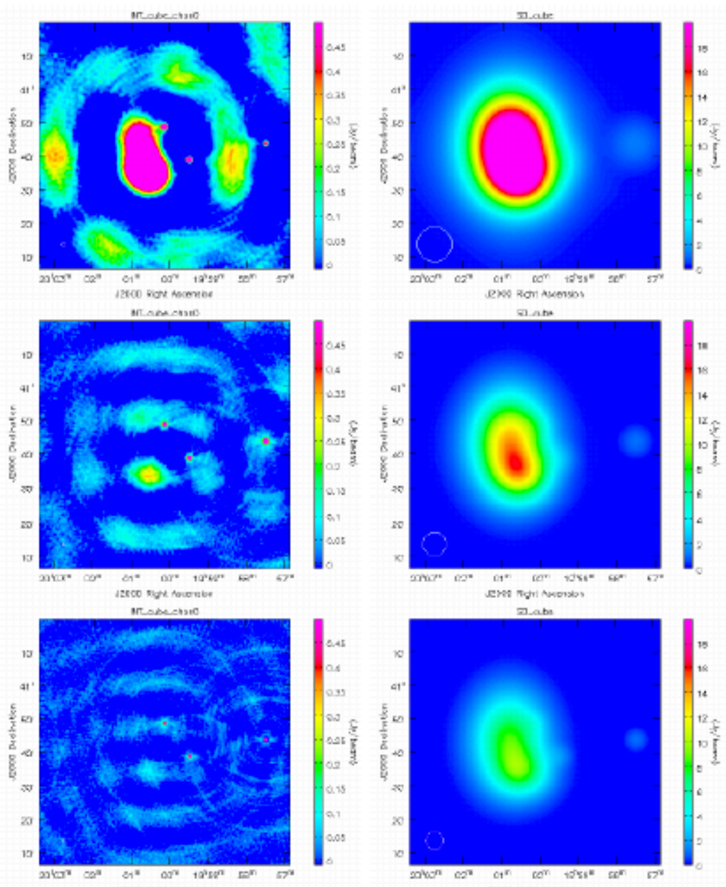
See Rau et al. (2019): “A Joint Deconvolution Algorithm to Combine Single Dish and Interferometric Data for Wideband Multi-term ad Mosaic Imaging”


Major Cycle
(Imaging)
INT Residual
Visibilities
Gridding + iFT
(Data - Model)
FT + De-Gridding
Minor Cycle
(Deconvolution)
Residual Image Cube
Model Image Cube

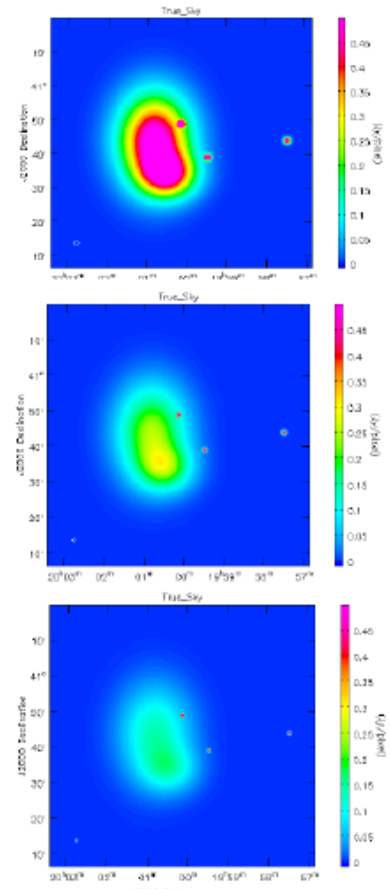


SDINT mplementation supports both wide-band and mosaic imaging.

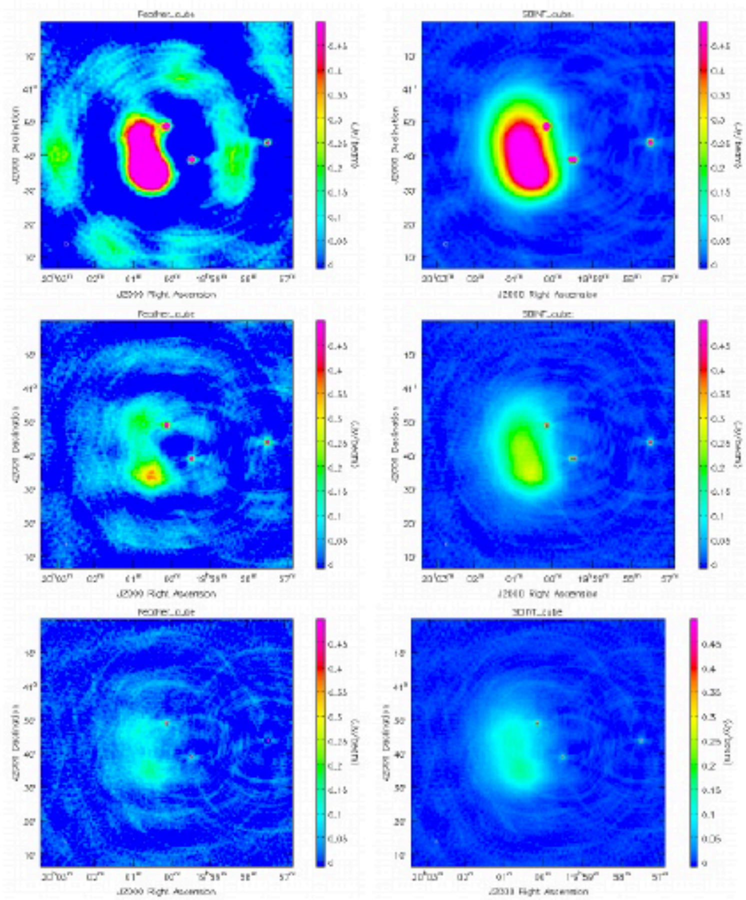
INT Cube SD Cube

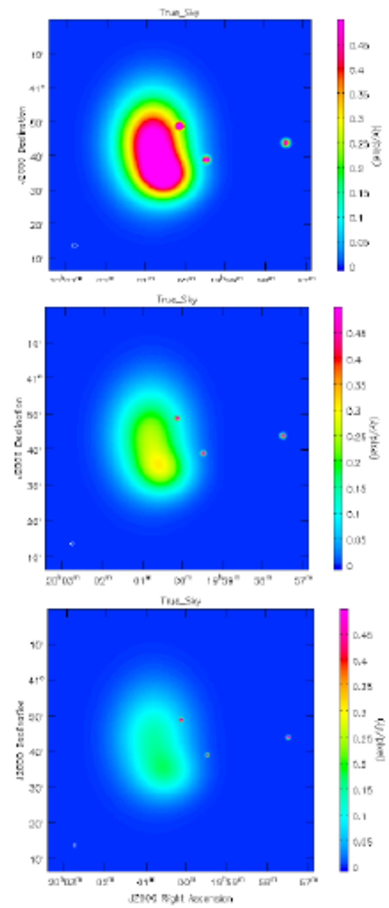


True Sky



Feather Cube SDINT Cube True Sky





Where does this leave us?

- No need to reinvent the wheel: a lot of effort has been expended on recovering the information content on short spacings
- The Sun is a but different from other ALMA imaging problems in that the background emission is very bright with low-contrast complexity superposed
- The tools are largely available to perform the task, but
- A sober-minded and systematic evaluation of various approaches is needed to assess which one(s) are best matched (using what criteria?) to the solar imaging problem:
  - Feathering in either the Fourier or image domain may be fine for single pointings
  - Mosaics may need to pursue TP2VIS or SDINT but here, too, simplicity may rule the day