# Combining Single Dish and Interferometer Data

or
Seeing the Forest *and* the Trees

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# Outline

- Why combine?
- Combination methods:
  - Combination before imaging
  - Combination before, during or after deconvolution
- Concerns and practicalities
- Useful, practical references:
  - Miriad User's Manual (http://www.atnf.csiro.au/computing/software/miriad)
  - S. Stanimirović 1999, PhD Thesis (http://www.naic.edu/~sstanimi)
  - S. Stanimirović 2001, Proceedings of the AO Single Dish Summer School

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# Why Combine?

- Interferometers are inherently limited by the shortest baseline sampled
  - For the ATCA at 21 cm you aren't sensitive to structures larger than $\lambda/d_{min}$~ 23 arcmin
- As a result, they miss large-scale flux
- You may be interested in true fluxes, so you need a single dish to accurately reconstruct all of the flux, "total power"
- If you're mosaicing, you must be curious about structures larger than the primary beam (~33 arcmin at 21cm)

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# Why Combine?

- If you mosaic you can recover some of that missing baseline – up to about $\lambda/(d_{\min} - D/2)$ (~36 arcmin at 21 cm)
- There remains a hole in the center of the u-v plane
  - This is the so-called "zero-spacing problem"

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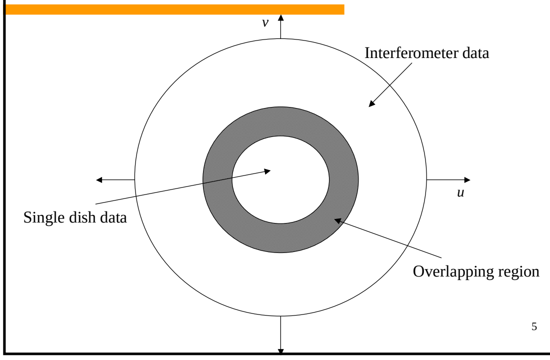
# The u-v plane

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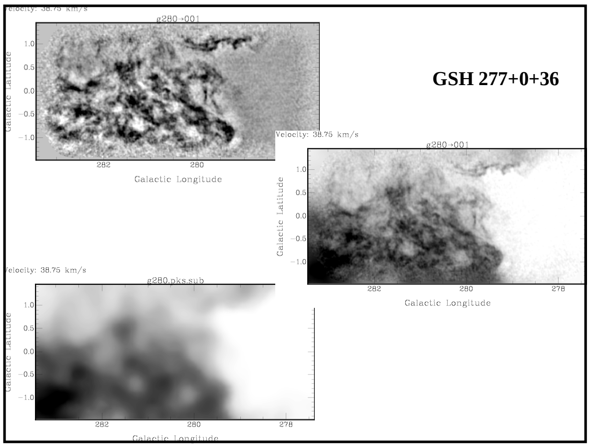


# The Answer: Combine Single Dish and Interferometer Data

- A solution to the zero-spacing problem is to combine the interferometer data with data on the same region from a single antenna
- A scanned single antenna continuously samples the *u-v* plane between zero baseline spacing and the diameter of the antenna
- This can be done in a number of ways from
  - observing with a homogeneous array and using the autocorrelations

    to

  - to observing with a separate larger antenna

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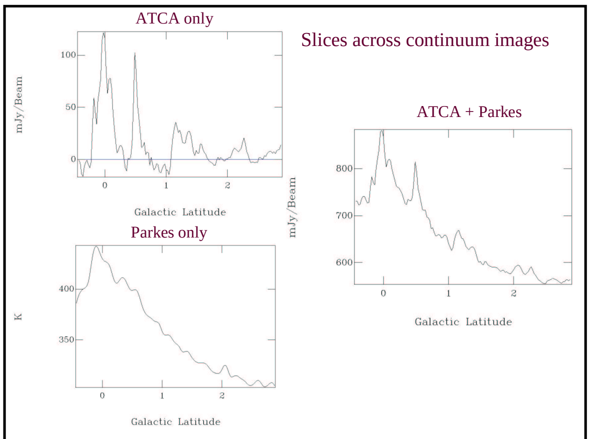

## Methods

- There are two basic ways to combine data:
  - You can combine in the u-v plane and then image,
    - This demands that you convert the single dish (s.d.) data to the u-v domain
  - You can image and then combine
    - This can require a good knowledge of the s.d. beam
- In both cases it helps if you assure that:
  - $\frac{D_{sd}}{2} \geq b_{\min}$
  - That both images, single dish and interferometer, are well-sampled

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## Methods

- The easiest, most practical methods are to image and then combine:
  - Imaging, combining and then deconvolving
  - Image then combine during deconvolution
  - Imaging, deconvolving and then combining

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## Relative Calibration

- Before adding single dish data in any manner one needs a relative calibration factor

$$f_{cal} = \frac{S_{\text{int}}}{S_{sd}}$$

by which the single dish data are multiplied

- If the calibration is perfect $f_{cal} = 1$
- If $D_{sd} > b_{\min}$ one can compare the fluxes in the overlap region to determine

$$f_{cal} = \frac{I_{\text{int}}}{I_{sd}}$$

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## Combine and then Deconvolve

- Combine the dirty images, $I^D_{\text{int}}$ and $I^D_{SD}$ according to:

$$I^D_{comb} = \frac{\left(I^D_{\text{int}} + \alpha f_{cal} I^D_{SD}\right)}{(1+\alpha)} \text{ ,}$$

  - where $\alpha = \frac{\Omega_{\text{int}}}{\Omega_{SD}}$ accounts for differences in the beam sizes
- And similarly combine the dirty beams

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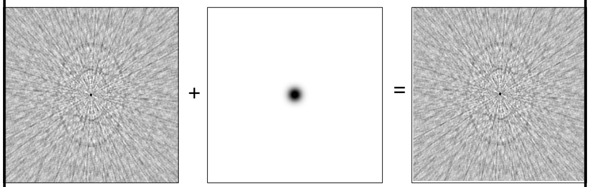
## Beam Combination




$$B_{comb} = \frac{(B_{\text{int}} + \alpha B_{sd})}{(1+\alpha)}$$

## Combine and then Deconvolve

- Using the combined beam you deconvolve the combined image
- The deconvolution isn't very dependent on the single dish beam because the single dish image isn't deconvolved on its own

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## Combining During Deconvolution: I

- Use the S.D. image as a default in the deconvolution
  - Implemented in AIPS VTESS and Miriad's mosmem
- In a maximum entropy technique we maximize the quantity $\aleph = -\sum_i I_i \ln\left(\frac{I_i}{M_i e}\right),$
- $I_i$ is the image at the i-th pixel and $M_i$ is the default image at the i-th pixel
- And minimize $\chi^2_{\text{int}} \le N\sigma^2_{\text{int}}$
- In the absence of interferometer info the image resembles the S.D. image

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## Combining During Deconvolution: II

- Or you can simultaneously deconvolve both images with a MEM technique
- In this case we must simultaneously satisfy:

$$\aleph = -\sum_i I_i \ln\left(\frac{I_i}{e}\right)$$

$$\sum_i \left\{I^D_{\text{int}} - B_{\text{int}} * I\right\}_i^2 < N\sigma^2_{\text{int}}$$

$$\sum_i \left\{I^D_{sd} - \frac{B_{sd} * I}{f_{cal}}\right\}_i^2 < M\sigma^2_{\text{int}}$$

  - Implemented in MIRIAD's mosmem

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## Deconvolve then Combine

- Alternately, one can deconvolve the images first and then combine them
- In this case, we let $V_{int}(k)$ be the F.T. of the deconvolved interferometer image and $V_{sd}(k)$ is the F.T. of the S.D. image
- We combine according to:

$$V_{comb}(k) = \omega'(k)V_{int}(k) + f_{cal}\,\omega''(k)V_{sd}(k) \ ,$$

  - where $\omega(k)$ and $\omega''(k)$ are weighting functions, such that $\omega'(k)+\omega''(k) =$ Gaussian of FWHM=$\theta_{int}$

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## Deconvolve then Combine

- Method:
  - Fourier transform both images
  - Weight them
  - Add the weighted images
  - Fourier transform back to the image plane
- Advantage of simplicity
  - Implemented in MIRIAD's immerge, AIPS' IMERG, and the aips++ image tool

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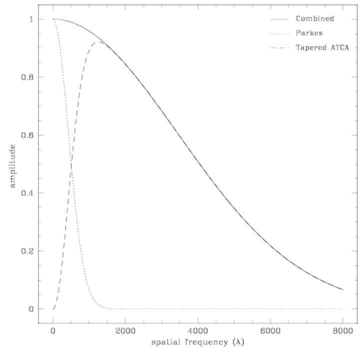
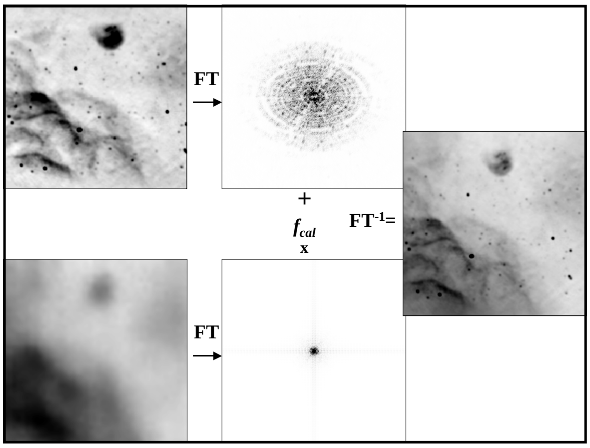
## Weighting functions



## Concerns and Practicalities

- Joint deconvolution seems to require a good knowledge of the S.D. beam
  - That's difficult, particularly with a multibeam
- Deconvolving then combining is rather roubust
- And it seems less sensitive to the S.D. beam deconvolution
  - But, the deconvolution involves initial "guesswork" on the short spacings
- All methods require the relative calibration factor $f_{cal}$

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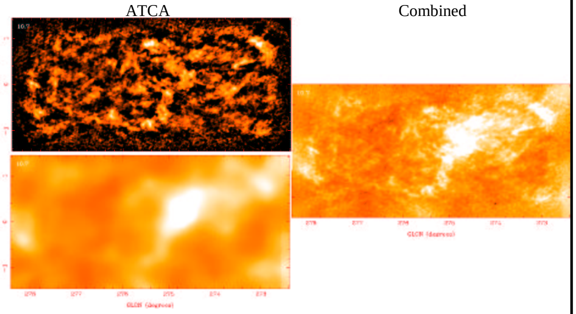
## Results: Combined HI Cube

ATCA

Combined



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## Concerns and Practicalities

- Don't forget about the calibration factor or the beam size factor!
  - If you're using immerge the data are expected in Jy/Bm and the beam sizes will be taken into account
    - Beware if your data is in K!
- The resolution of the combined image should be the same as the interferometer image and the total flux should be the same as the total flux in the single dish image.

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## Conclusions

- If you're mosaicing you probably need to think about combining with single dish data, too.
- Combining is easy!
- You have a variety of choices, all of which give fairly consistent results:
  - Combine prior to imaging
  - Combine after imaging:
    - Combine before deconvolution
    - Combine during deconvolution
    - Combine after deconvolution

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