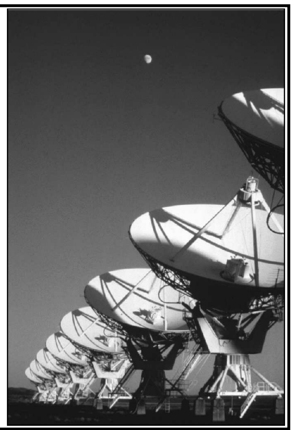


Mosaicing

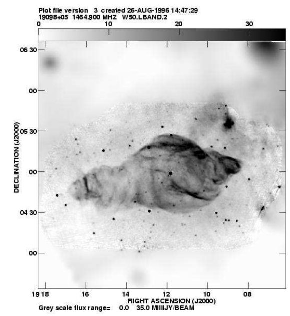
Tim Cornwell

Ninth Synthesis Imaging Summer School
Socorro, June 15-22, 2004

Imaging mosaic

2

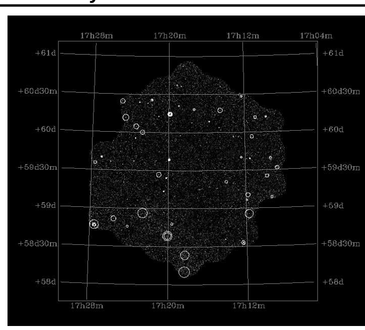
- •VLA mosaic of W50 (Dubner et al 1998)
- •See entire structure of the remnant, not just the fine scale features



Survey mosaics

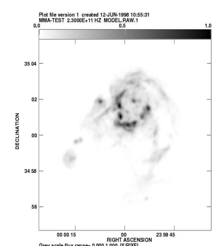
3

- •Spitzer First Look Survey - VLA image
- •A mosaic of 35 VLA pointings taken over 240hrs
- •Hundred brightest sources marked
- •3565 catalog sources > 110 microJy/beam
- •The average rms noise is about 23 microJy/beam.



A simulation of VLA mosaicing

4



Model brightness distribution

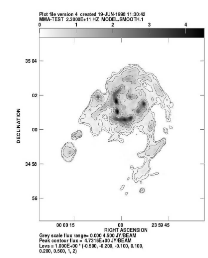
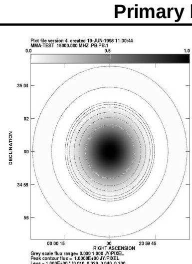


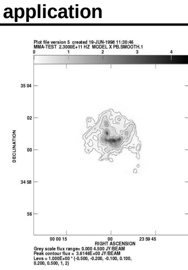
Image smoothed with 6" Gaussian (VLA D config. resolution at 15 GHz)

Primary beam application

5



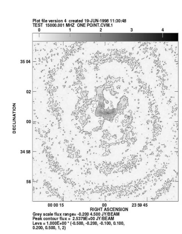
Primary beam used for simulations



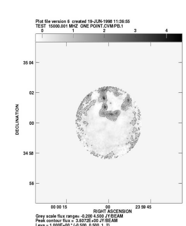
Model multiplied by primary beam & smoothed with 6" Gaussian. Best we can hope to reconstruct from single pointing.

Single field imaging

6



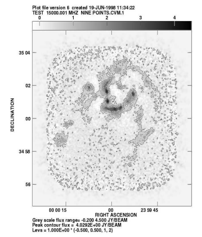
Visibilities constructed with thermal Gaussian noise. Image Fourier transformed & deconvolved with MEM



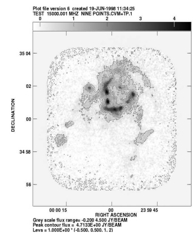
Primary beam-corrected image. Blanked for beam response < 10% peak. Need to Mosaic!

Joint deconvolution of all 9 pointings

7



Nine VLA pointings deconvolved via a non-linear mosaic algorithm (AIPS VTESS). No total power included.



Same mosaic with total power added.

Mosaicing - the math

8

$$V(u,v) = \int I(l,m)\cdot e^{j.2\pi.(ul+vm)}dl.dm$$

This relationship must be modified to include the power receptivity of the antennas

$$V_p(u,v) = \int A(l-l_p, m-m_p) I(l,m)\cdot e^{j.2\pi.(ul+vm)}dl.dm$$

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A single pointing

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$$V_p(u,v) = \int A(l-l_p, m-m_p) I(l,m)\cdot e^{j.2\pi.(ul+vm)}dl.dm$$

Inverse Fourier transform, then divide by primary beam

$$I^{\text{single}}(l,m) = \frac{\int V_p(u,v)\cdot e^{-j.2\pi.(ul+vm)}du.dv}{A(l-l_p, m-m_p)}$$

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A single pointing with limited Fourier plane sampling

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$$I^{mosaic}(l,m) = \frac{I_p^{\text{dirty}}(l,m)}{A(l-l_p, m-m_p)}$$

$$I^{mosaic}(l,m) = \frac{B(l,m) * (A(l-l_p, m-m_p) I(l,m))}{A(l-l_p, m-m_p)}$$

Two problems:

1. Convolution and division do not commute
2. The primary beam goes to zero far from the pointing center

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Multiple pointings

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Generalize by a least squares fit for a given position on the sky

$$I^{\text{linearmosaic}}(l,m) = \frac{\sum_p A(l-l_p, m-m_p)\int V_p(u,v)\cdot e^{-j.2\pi.(ul+vm)}du.dv}{\sum_p A^2(l-l_p, m-m_p)}$$

$$I^{\text{linearmosaic}}(l,m) = \frac{\sum_p A(l-l_p, m-m_p) I_p^{\text{dirty}}(l,m)}{\sum_p A^2(l-l_p, m-m_p)}$$

Weighted linear sum of dirty images

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Multiple pointings deconvolved separately

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- Deconvolve pointings separately and then combine using the least squares estimate
- Works ok if separate deconvolutions are accurate
  - As for point sources
- Deconvolution is non-linear - better to deconvolve all data together
  - "Joint deconvolution"

$$\frac{\sum_p A(l-l_p, m-m_p) I^{\text{deconvolved}}(l,m)}{\sum_p A^2(l-l_p, m-m_p)}$$

Weighted linear sum of deconvolved images

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Approximate convolution relation

$$I^{mosaic}(l,m) \approx B^{mosaic}(l,m) * I(l,m)$$

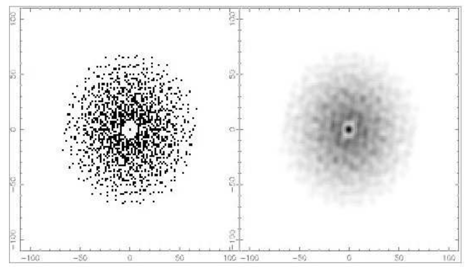
Linear mosaic image = true sky convolved with linear mosaic PSF

$$B^{mosaic}(l,m) = \frac{\sum_p A(l-l_p, m-m_p) B(l,m)}{\sum_p A^2(l-l_p, m-m_p)}$$

Linear mosaic PSF = Weighted sum of PSFs

Effective Fourier plane coverage for ALMA snapshot

$FT(B(l,m))$ $FT(B^{mosaic}(l,m))$



Joint deconvolution algorithms based on linear mosaics

- Use any suitable deconvolution algorithm to solve the approximate convolution equation
- Use alternating major/minor cycles
  - In minor cycle, solve approximate convolution equation to some level of accuracy
  - In major cycle, recalculate linear mosaic from residual images

Joint deconvolution via non-linear optimization

- Find a model image that fits all the observed data
- *e.g.* using Maximum Entropy

$$\text{Maximize } H(I) = -\int I(l,m)\log\left(\frac{I(l,m)}{I^{\text{default}}(l,m)}\right) dldm$$

$$\text{Subject to } \sum_i \frac{\left|V_p(u_i,v_i) - \int A(l-l_p, m-m_p) I(l,m) e^{j2\pi.(u_i l + v_i m)} dl.dm\right|^2}{\sigma_i^2} = M$$

When is mosaicing required?

- Bigger than the Primary Beam: λ/**D** Full Width Half Max
- Bigger than the shortest baseline can measure: θ_{LAS} = 91,000/B_{short}
- VLA short baselines can recover:
  - 80% flux on 1/5 λ/**D** Gaussian
  - 50% on 1/3 λ/**D** Gaussian
- CLEAN can do well on a 1/2 λ/**D** Gaussian
- MEM can still do well on a high SNR 1/2 λ/**D** Gaussian

➔ Lack of short baselines often become a problem before source structure is larger than the primary beam:

Mosaicing is almost always about Total Power!

Largest angular scales

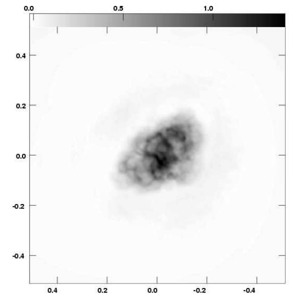
VLA	21 cm 3.6 cm 7 mm	15 arcmin 3 arcmin 40 arcsec
OVRO	2.7 mm	20 arcsec
ALMA	1.3 mm 0.4 mm	13 arcsec 4 arcsec

- **Deconvolution can make images look ok but the flux may be quite incorrect**
- **Accurate quantitative work may require mosaicing even at these sizes**

Array/Single dish combinations

Array	Number of antennas	Diameter (m)	Shortest baseline (m)	Single dish	Diameter (m)
VLA	27	25	35	*GBT*	100
ATCA	6	22	24	*Parkes*	64
OVRO	6	10.4	15	*IRAM* *GBT*	30 100
BIMA	10	6.1	7	*12m* *IRAM* *GBT*	12 30 100
PdBI	6	15	24	*IRAM*	30

VLA + VLBA antenna



Crab Nebula at 8.4 GHz. (Cornwell, Holdaway, & Uson 1993).

VLA + Total power from a VLBA antenna

Mosaic without total power looks quite reasonable but is missing half the flux

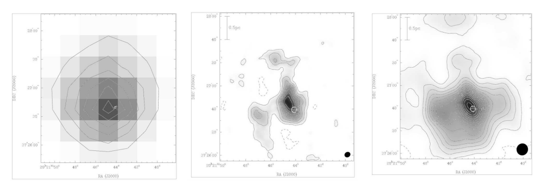
Addition of total power

- Conceptual + practical problem
  - Conceptual - what are we trying to do?
  - Practical - synthesis and single dish have been two separate worlds
- Three approaches
  - Make single dish data look like synthesis data
  - Add synthesis and single dish images after deconvolution
  - Add synthesis and single dish data during deconvolution

Adding synthesized interferometer data

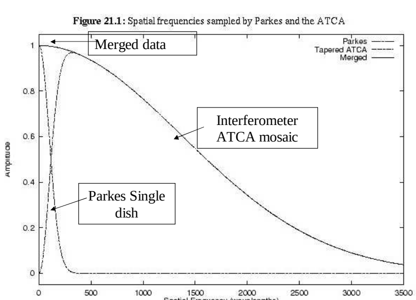
Kitt Peak 12m image convolved with BIMA primary beam, converted to ***uv*** data with sampling density similar to BIMA ***uv*** coverage, scaled & combined with BIMA data, inverted with a taper, joint deconvolution (MIRIAD).

Kitt Peak 12m BIMA 12m + BIMA



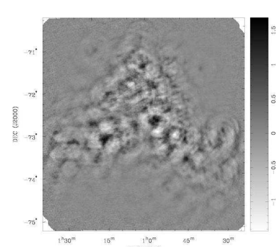
Shepherd, Churchwell, & Wilner (1997)

Merging of separate images

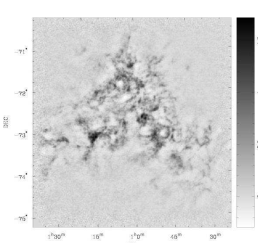


If there is significant overlap in ***uv***-coverage: images can be "feathered" together in the Fourier plane.

ATCA merged data



ATCA observations of HI in the SMC. Dirty mosaic, interferometer only.



Deconvolved mosaic, interferometer only. Stanimirovic et al. (1999).

ATCA merged data

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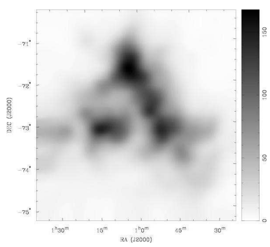
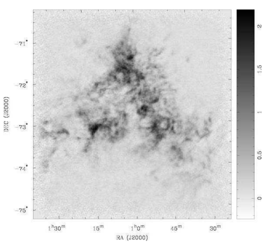


Total power image from Parkes.



Interferometer plus single dish feathered together (**immerge**).
Stanimirovic et al. (1999).

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OVRO merged data

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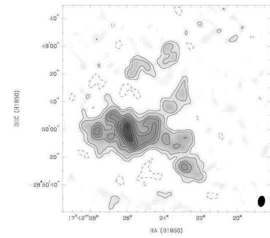
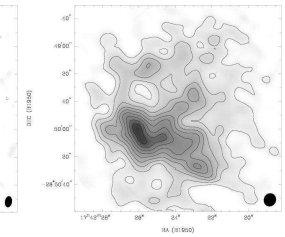


OVRO mosaic, 4 fields. Deconvolved with MEM.



OVRO+IRAM 30m mosaic using MIRIAD: immerge feather algorithm.
Lang et al. 2001.

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VLA + GBT merged data

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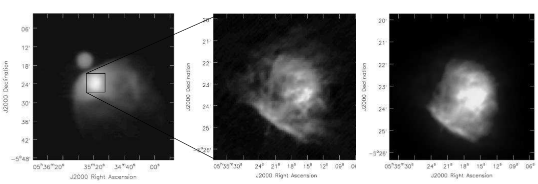

GBT On-the-fly map of the large field, (AIPS++). 90" resolution.

VLA mosaic of central region, 9 fields. Deconvolved with MEM in AIPS++. 8.4" resolution.

GBT+VLA mosaic using AIPS++ image.feather. Shepherd, Maddalena, McMullin, 2002.

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Joint deconvolution

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- What's the big deal?
  - Just treat the single dish data same as synthesis data
- Linear mosaic algorithms
  - Include single dish data in summations
- Joint deconvolution
  - Include single dish data as additional constraints in the optimization

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An example of joint deconvolution

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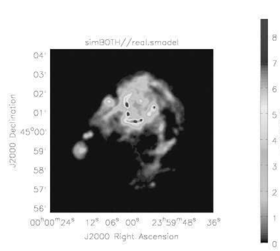
- Simulation of VLA D-configuration mosaic plus GBT raster
  - Uses AIPS++ simulator tool to generate data
  - 5 by 5 VLA mosaic
  - 21 by 21 GBT raster



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Best MEM images

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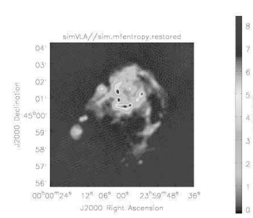
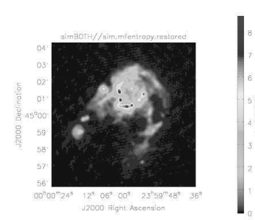


VLA mosaic only



VLA mosaic + GBT OTF

Images are visually similar but the VLA only image has significantly less flux

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Error in reconstruction of model

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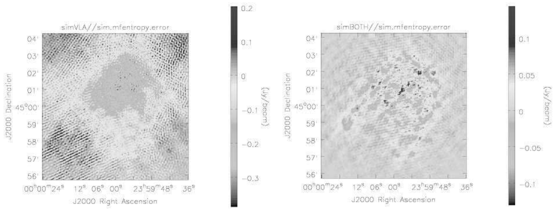


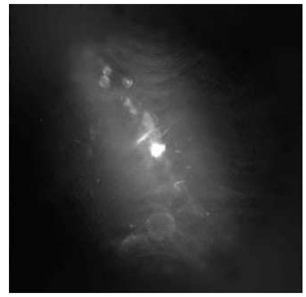
VLA mosaic only VLA mosaic + GBT OTF

Still some errors in reconstruction on intermediate scales – a good illustration of the need for the proposed VLA E-configuration

VLA single field + GBT image

32

- Often need to add single dish image to a single pointing
- *e.g.* 327MHz VLA observations of Galactic Center
  - Added GBT image during multiscale Clean deconvolution



AIPS Mosaicing algorithms

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Task names	VTESS, UTESS, LTESS
Data required	Collection of dirty images and PSFs on same coordinate system
Primary beam specification	A limited number of standard models or Gaussian primary beam
Deconvolution methods	Linear mosaic of dirty images, Maximum Entropy, Maximum Emptiness

AIPS++ Mosaicing algorithms

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Tool name	`imager`
Data required	MeasurementSet containing multiple pointings
Primary beam specification	Any of a wide range of models - standards for various telescopes, analytical forms, images
Deconvolution methods	Linear mosaic of dirty images, Clean, Multiscale Clean, Maximum Entropy, Maximum Emptiness
Self-calibration	Supported
Non-coplanar baselines	W projection and faceted imaging supported

Mosaic observations

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- Nyquist sample the sky: pointing separation $\frac{\lambda}{2D}$
- Observe extra pointings in a guard band around source.
- Get total power information. Have good ***uv*** overlap between single dish and interferometer (big single dish w/ good pointing/low sidelobes & short baselines).
- Observe short integrations of all pointing centers, repeat mosaic cycle to get good ***uv*** coverage and calibration until desired integration time is achieved.
- For VLA: Either specify each pointing center as a different source or use //OF (offset) cards to minimize set up time.

Causes of errors in mosaic images

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- Missing total power information
  - Still need to get total power observations
- Calibration inconsistency between synthesis and total power observations
  - Look carefully at overlap region in Fourier plane
- Lack of a guard band
- Insufficient image or Fourier plane sampling
- Errors in primary beam model

$$\text{Dynamic range} \approx \frac{1}{(\text{RMS PSF sidelobe level})(\text{Uncertainty in Beam})}$$

- Pointing errors
  - Especially important at high frequencies

Things we need to work on

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- Faster algorithms
- Streamlined VLA + GBT combination
- VLA polarization mosaicing
  - Need to understand antenna beams
- Pointing error self-calibration