Short-Spacings Correction From the Single-Dish Perspective

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VLA: FWHM>1″

+

Arecibo: FWHM~3′

`Black magic' for bringing the best of both worlds:
short-spacings correction, or
combination of single-dish and interferometer data

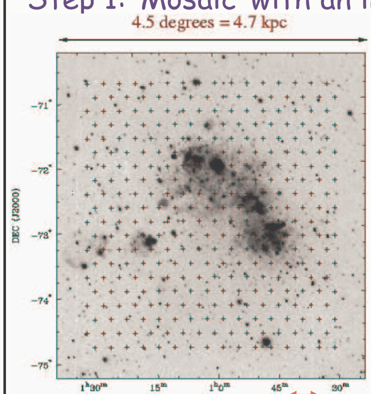
A Recipe for Observing Extended Objects:

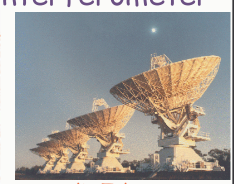
- **Ingredients:**
  1. an extended object (e.g. Small Magellanic Cloud)
  2. an interferometer (e.g. VLA, ATCA, BIMA, ATA)
  3. a single-dish (e.g. Arecibo, GBT, Parkes, 12m)
- **Procedure:**
  1. observe with an interferometer
  2. observe with a single-dish
  3. take advantage of both worlds: combine !
- **This recipe makes:**
  1. pretty pictures: lots of resolution elements, no image artifacts
  2. high resolution images with the TOTAL POWER information (accurate fluxes, masses etc.)
  3. images sensitive to a wide range of spatial scales.

Outline:

- Breath and depth of combining interferometer and single-dish data …
- A recipe for observing extended objects (with detours):
  1. the briefest possible intro to interferometry
  2. demonstration of the short-spacings problem
  3. what can we do about the short-spacings problem ?
  4. different methods for data combination
- Some recent examples
- Future directions….

Step 1: 'Mosaic' with an interferometer





Australia Telescope Compact Array (ATCA) mosaic of the Small Magellanic Cloud at 1.4 GHz.

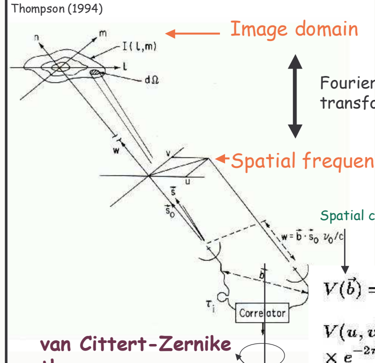
Mosaic of 320 different pointings.

Single-dish and interferometer data frequently need to be combined …

- when observing **EXTENDED** objects (larger than λ/b_{min} or interferometer's primary beam) [you'll see why exactly]
- when **MOSAICING**: if you need to mosaic, you'll need to add single-dish data.
- especially at mm wavelengths where **TOTAL POWER** info is almost always needed.

How does an interferometer actually work ?

Thompson (1994)

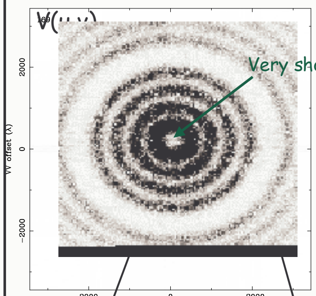


$$V(\vec{b}) = \int_{src} A(\vec{\sigma}) I(\vec{\sigma}) e^{-2\pi i \vec{b}.\vec{\sigma}/\lambda} d\Omega$$

$$V(u,v) = \int\int A(l,m) I(l,m) \times e^{-2\pi i (ul+vm)} \frac{dl dm}{\sqrt{1-l^2-m^2}}$$

van Cittert-Zernike theorem:

More baselines, more u-v tracks!



Australia Telescope Compact Array (ATCA), an E-W linear array.

5 antennas, 5(5-1)/2 diff. baselines

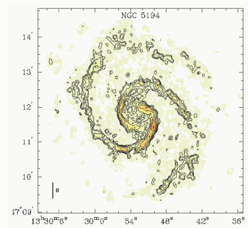
Lowest spatial frequency: ~31m/0.21m

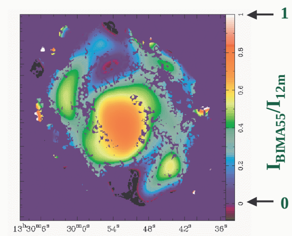
Can not see structure > 24'.

Highest spatial frequency: ~495m/0.21m

Angular resolution=1.6'

How severe the problem is ?





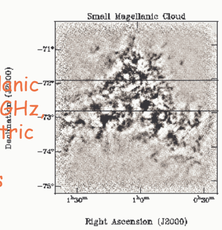
BIMA SONG CO map

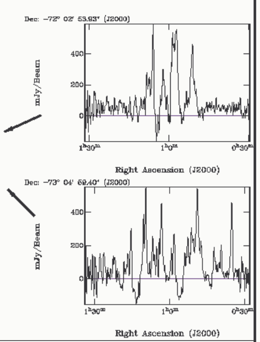
Flux recovery ratio map

Farther away from the nucleus, the less flux is recovered!

And what is the result ?

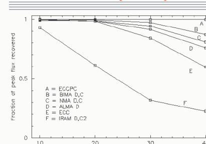
Small Magellanic Cloud at 1.4 GHz interferometric (ATCA) observations only.



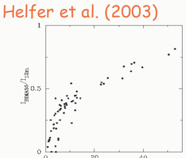


How much flux is missing ?

Simulations
Helfer et al. (2002)



BIMA SONG Data, > 30 galaxies
Helfer et al. (2003)



Large-scale flux recovery for a mosaic observation

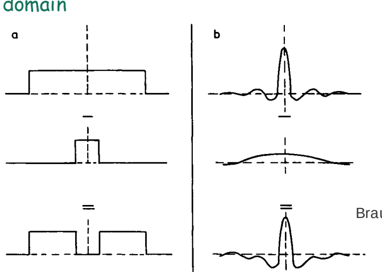
- depends on the minimum distance between the dishes, b_{min}-D
- is a function of the S/N
- varies from source to source, and spatially

→ Large-scale distribution can not be modeled, needs to be measured!

And what is the result ? WHY ?

Spatial frequency domain

Image domain



Braun & Walterbos (1985)

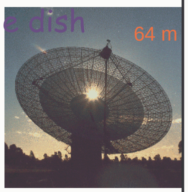
Missing short sp. frequencies

Negative bowls

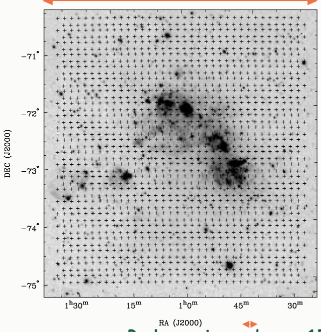
What can we do about the short-spacings problem ?

- ✓ How to provide missing short-spacings ?
  1. Homogeneous scheme = all antennas of the same size
  2. Heterogeneous scheme = different-sized antennas
- ✓ How to combine short-spacing data with that from an interferometer ?
- ✓ As few gaps in the u-v plane as possible ! Single-dish diameter > min. interferometer baseline.
- ✓ Must match flux scales of both data sets.

Step 2: 'Mosaic' with a single dish



4.5 deg = 4.7 kpc



Parkes primary beam=15'

- Point to many directions & grid all spectra.
- **1540** different pointings with the Parkes (64 m) telescope!
- Go multi-beams!

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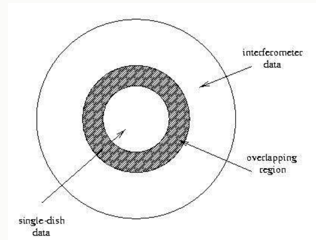
Step 3: Cross-calibration of two data sets



Interferometer and single-dish data should have the same flux density scale.

Calibration scaling factor:

$f_{cal}=S_{int}/S_{sd}$

Compare surface brightness of your object in the ovarlap region in the u-v plane.

Do it yourself or use Miriad's immerge

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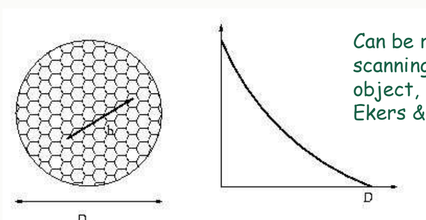
Single-dish as an interferometer!



Can be retrieved by scanning across your object, based on Ekers & Rots (1979).

'Phased array' → continuous range of baselines available from 0 to D.

Similar mathematical representation for both interferometers and single-dishes!

$$I^{D}_{int}(x,y) = I(x,y) * B_{int}(x,y)$$
$$V'_{int}(u,v) = V(u,v) \times b_{int}(u,v)$$

&

$$I^{D}_{sd}(x,y) = I(x,y) * B_{sd}(x,y)$$
$$V'_{sd}(u,v) = V(u,v) \times b_{sd}(u,v)$$

Step 4: Combination of single-dish and interferometer data

- **Data combination in the Fourier domain:**

Miriad's IMMERGE, Aips' IMERG, aips++'s IMAGER

Bajaja & Albada (1979); Vogel et al. (1984); Sault & Killen (2003)

- **Data combination in the image domain:**

1. 'Linear Combination'

a combination of tasks, Ye & Turtle (1991); Stewart et al. (1993); Stanimirovic et al. (1999)

2. 'Non-linear combination' or 'Merging during deconvolution'

Miriad's MOSMEM through either 'default image' capability or 'joint deconvolution'

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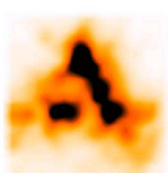
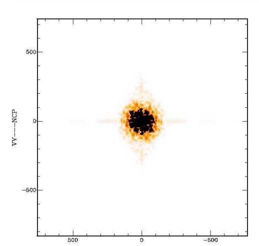
And what is the result ?

Small Magellanic Cloud at 1.4 GHz, single-dish (Parkes) observations only.



... and its Fourier transform



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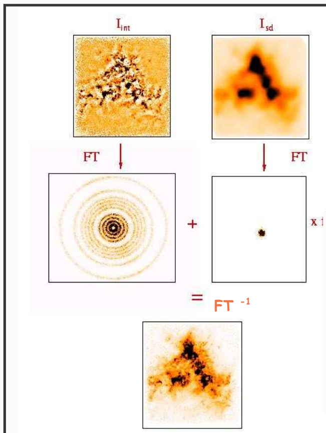
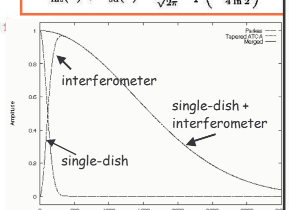
Fourier domain combination



$$V_{comb}(k) = w_{int}(k)V_{int}(k) + f w_{sd}(k)V_{sd}(k)$$

$$w_{int}(k) + w_{sd}(k) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta^2_{int}k^2}{4 \ln 2}\right)$$



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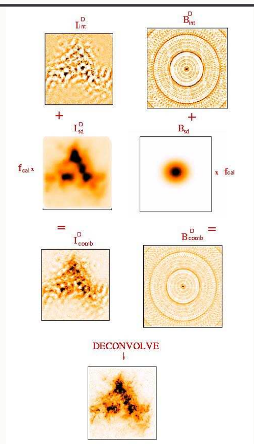
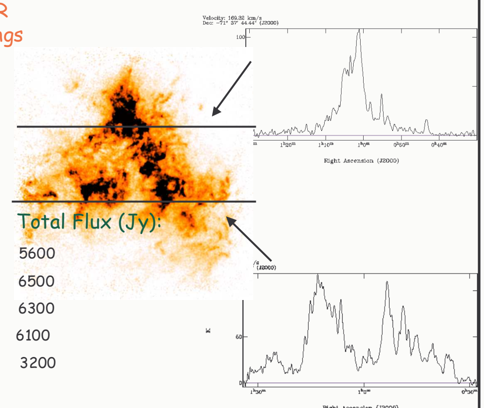


Linear combination

$$I_{\rm comb}^{D} = w_{\rm int} I_{\rm int}^{D} + w_{\rm sd} f I_{\rm sd}^{D}$$
$$B_{\rm comb} = w_{\rm int} B_{\rm int} + w_{\rm sd} B_{\rm sd}$$
$$w_{\rm int} = \frac{\Omega_{\rm sd}}{\Omega_{\rm int}+\Omega_{\rm sd}} \quad w_{\rm sd} = \frac{\Omega_{\rm int}}{\Omega_{\rm int}+\Omega_{\rm sd}}$$

Final Results:

Small Magellanic Cloud AFTER short-spacings correction.



Method	Total Flux (Jy):
1.	5600
2.	6500
3.	6300
Parkes only	6100
ATCA only	3200

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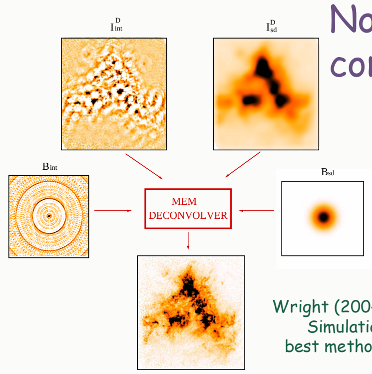

Non-Linear combination

Wright (2004): CARMA Memo27
Simulations show this as the best method, but it depends on quality of SD data.

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Remarks on different methods:

- In recent years, all methods are commonly used from small 7-point to huge >1000-point mosaics.
- All methods produce comparable results in the case of high S/N data (e.g. SMC).
- **'Feathering' method** is the fastest and the least computer intensive, great results, very robust.
- For low S/N data, as is often case at mm wavelengths, **'linear' method** seems advantageous: no need for deconvolution by the single-dish beam nor deconvolution of int. dirty maps, it is easy to implement and automate.
- **'MEM' method** is theoretically the best way but heavily dependant on the quality of the SD image.

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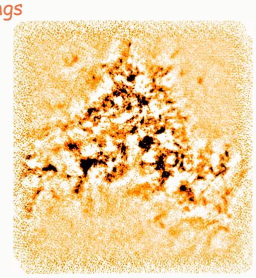
Final Results:

Small Magellanic Cloud BEFORE short-spacings correction.



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Data combination is routinely performed with a great success: examples

Array	B_{min}(m)	SD	D(m)	ν (GHz)	Method	Ref.
ATCA	25	Parkes	64	1.4	linear	Stanimirovic et al. 1999
ATCA	25	Parkes	64	1.4	immerge	McClure-Griffiths 2005
OVRO	15	IRAM	30	8.8	immerge	Lang et al. 2002
BIMA	8	FCRAO	14	115	linear	Pound et al. 2003
BIMA	8	12m	12	113	mosmem	Welch et al. 2000
BIMA	8	12m	12	115	linear	Helfer et al. 2003
VLA D	35	GBT	100	8.4	feathering, aips++	Shepherd et al. 2003
VLA D	35	AO	305	1.4	immerge	Lee et al.; Robishaw et al.

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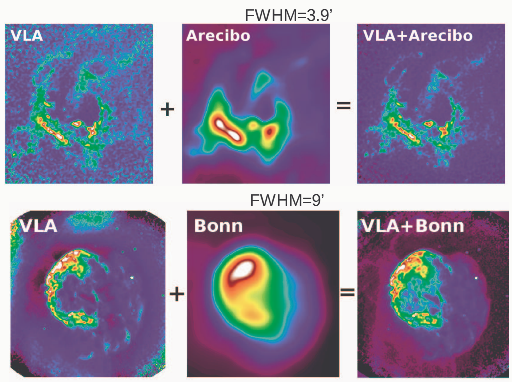
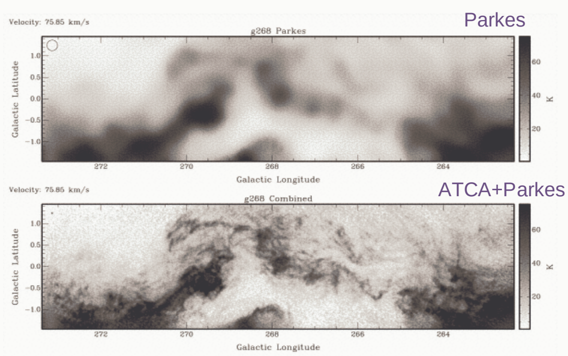
Recent Examples: IC443 Lee et al. (2005)



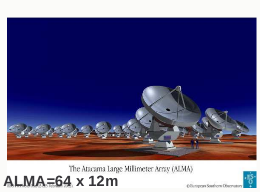
Recent Examples: SGPS = ATCA+PKS



McClure-Griffiths et al. (2005): **>300 deg^2**

Future Telescopes (arrays of small antennas):

Array	B_{min}(m)	SD	D(m)	ν (GHz)	Method	Ref.
CARMA	4	OVRO	10.4	115, 230, 345	provide OTF capability for OVRO	
ALMA	15	ACA	7-12	30-950	short spacings high priority!	
ATA	~8	ATA	6.1	1.4-11.12	homogeneous array!	



ALMA=64 x 12m

Future Telescopes (cont):

- Future trend: **heterogeneous arrays** with **small dishes**.
- Smaller dishes have lower systematic errors and larger field of view so are faster than large single dishes (Holdaway & Helfer 1999).
- Data combination has been the key driver for recent antenna designs and array configurations (CARMA, ALMA, ATA).
- Shadowing effects for closely packed antennas (Subrahmanyan & Deshpande 2004)
- Data combination (joint deconvolution) depends greatly on the quality of SD data (pointing errors, thermal noise, ground pick up, atmospheric fluctuations).

Particular (practical) single-dish needs:

- A large enough area must be covered with single-dish observations (edge-effect issue).
- Nyquist sampling is important to avoid aliasing during deconvolution (Vogel et al. 1984).
- S/N ratio of interferometer and single-dish data should be comparable.
- In general, and especially for the cross-calibration a very good knowledge of the single-dish beam is required (can start with a Gaussian first).
- At mm wavelengths main issues are: pointing and calibration accuracy.

Summary:

- **Single-dishes have a huge role in providing information that complements interferometric observations.**
- Short-spacings correction is a MUST in most of observations at mm wavelengths and may soon become a part of a general observing scheme (e.g. ALMA).
- **Easy combination of single-dish and interferometer data available and frequently done** for different telescopes and for sources of greatly varying sizes.
- 3 discussed methods work fine and with comparable results.
- Overlap of spatial frequencies is crucial for cross-calibration.

Bibliography:

- Stanimirovic 2002, ASP Conf. Ser. 278 + REFERENCES THERE
- Holdaway 1999, ASP Conf. Ser. 180
- Holdaway & Helfer 1999, ASP Conf. Ser. 180
- Helfer et al. 2002, PASP, 114, 350
- 'Interferometry and Synthesis in Radio Astronomy' Thompson, Moran & Swenson (2001)
- 'Synthesis Imaging in Radio Astronomy' Taylor, Carilli & Perley (1999)
- Sault & Killeen 2003, Miriad Users Manual