Large-field imaging

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Large-field imaging

The problems

- The field of view is limited by the antenna primary beam width
  Solution: observe a mosaic = several adjacent overlapping fields

- The field of view is limited because of the "2D approximation"
  Solution: use appropriate algorithm if necessary

- The largest structures are filtered out due to the lack of the short spacings
  Solution: add the short spacing information

- Deconvolution algorithms are not very good at recovering small- and large-scale structures
  Solution: try Multi-Scale CLEAN...
Measurement equation of an interferometric observation:

$$ F = D \ast (B \times I) + N $$

- $F$ = dirty map = FT of observed visibilities
- $D$ = dirty beam (→ deconvolution)
- $B$ = primary beam = FT of transfer function
- $I$ = sky brightness distribution = FT of “true” visibilities
- $N$ = noise distribution

• An interferometer measures the product $B \times I$

• $B \sim$ Gaussian → primary beam correction possible (proper estimate of the fluxes) but strong increase of the noise
Mosaics
Primary beam width

Gaussian illumination $\implies B \sim \text{Gaussian Beam of } 1.2 \frac{\lambda}{D} \text{ FWHM}$

Plateau de Bure
$D = 15 \text{ m}$

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (mm)</th>
<th>Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>3.5</td>
<td>58”</td>
</tr>
<tr>
<td>100</td>
<td>3.0</td>
<td>50”</td>
</tr>
<tr>
<td>115</td>
<td>2.6</td>
<td>43”</td>
</tr>
<tr>
<td>150</td>
<td>2.0</td>
<td>33”</td>
</tr>
<tr>
<td>230</td>
<td>1.3</td>
<td>22”</td>
</tr>
<tr>
<td>345</td>
<td>0.8</td>
<td>15”</td>
</tr>
</tbody>
</table>
Mosaics
Mosaicing with the PdBI

Mosaic:

• Field spacing = half the primary beam FWHM = 11″ at 230 GHz

Observations:

• Fields are observed in a loop, each one during a few minutes → similar atmospheric conditions (noise) and similar uv coverages (dirty beam, resolution) for all fields

Calibration:

• Procedure identical with any other observation (only the calibrators are used)
• Produce one dirty map per field
Mosaics
Mosaic reconstruction

• Forgetting the effects of the dirty beam:

\[ F_i = B_i \times I + N_i \]

• This is similar to several measurements of \( I \), each one with a “weight” \( B_i \)

• Best estimate of \( I \) in least-square formalism (assuming same noise):

\[ J = \frac{\sum_i B_i F_i}{\sum_i B_i^2} \]

• \( J \) is homogeneous to \( I \), i.e. the mosaic is **corrected for the primary beam attenuation**
Mosaics

Noise distribution

\[ J = \frac{\sum_i B_i F_i}{\sum_i B_i^2} \Rightarrow \sigma_J = \sigma \frac{1}{\sqrt{\sum_i B_i^2}} \]

The noise depends on the position and strongly increases at the edges of the field of view.

In practice:

- Use **truncated primary beams** \((B_{\text{min}} = 0.1 - 0.3)\) to avoid noise propagation between adjacent fields.
- **Truncate the mosaic**
Mosaics

Mosaic deconvolution

- **Linear mosaicing**: deconvolution of each field, then mosaic reconstruction

- **Non-linear mosaicing**: mosaic reconstruction, then global deconvolution

- The two methods are not equivalent, because the deconvolution algorithms are (highly) non-linear

- **Non-linear mosaicing gives better results**
  - sidelobes removed in the whole map
  - better sensitivity

- Plateau de Bure mosaics: **non-linear joint deconvolution based on CLEAN**
Mosaics
Example

H$_2$ + CO(2–1) EHV + continuum 1.3 mm in HH211

(Gueth & Guilloteau 1999)
Mosaics Example

\[ \text{H}_2 + \text{CO}(2-1) \text{ EHV} + \text{continuum 1.3 mm in HH211} \]
TT Cyg  CO(1–0)  v=-28.5 to -26.5 km s^{-1}

CO 1–0 in TT Cygni, Olofsson et al. 2000
CO 1–0 in TT Cygni, Olofsson et al. 2000
CO in the warped galaxy NGC 3718 (Krips et al. 2005)
(Stanke et al. 2004)
(Pety et al. 2005)
Short Spacings
Lack of the short spacings

Amplitude

Radius in UV plane

Shortest baseline observed
Short Spacings
Lack of the short spacings

Amplitude

Radius in UV plane

Shortest baseline observed
Short Spacings

Lack of the short spacings

![Image of a snowy landscape with telescope arrays]

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**Graph:**

- **Y-axis:** Amplitude
- **X-axis:** Radius in UV plane

**Legend:**

- **Red Arrow:** Shortest baseline observed

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**Text Highlight:**

- "Shortest baseline observed"
Short Spacings
Lack of the short spacings
Short Spacings
Lack of the short spacings

No information on extended structures

Shortest baseline observed
Short Spacings
The problem

Missing short spacings:

- Shortest baseline $B_{\text{min}} = 24$ m at Plateau de Bure
- Projection effects can reduce the minimal baseline – but baselines smaller than antenna diameter $D$ can never be measured
- In any case: **lack of the short spacings information**

Consequence:

- The most extended structures are filtered out
- The largest structures that can be mapped are $\sim 2/3$ of the primary beam (field of view)
- Structures larger than $\sim 1/3$ of the primary beam may already be affected
Short Spacings

Example

Without short spacings

With short spacings

$^{13}\text{CO} \ (1-0)$ in the L 1157 protostar (Gueth et al. 1997)
Smoothed Object
Flux = 17.70 Jy (100%)

Simulated Observation
Flux = 17.73 Jy (100%)

cluster
hybrid (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0

Frequency: 230 GHz
Beam: 1.42 x 1.32 PA –1°
Level step: 50 mJy/beam

Difference RMS = 2.1229E-04 Jy
Fidelity Range = 3099.

-22°59'40"
-23°00'00"
-23°00'20"

10°00'00" 00" 00"

10°00'00" 00" 00"

28–AUG–2001 09:37:51
cluster
alma-only (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.35 PA -1°
Level step: 5 mJy/beam

28-AUG-2001 09:37:46
cluster
hybrid (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.32 PA -1°
Level step: 5 mJy/beam

28-AUG-2001 09:37:52
Simulations of small source + extended cold/warm layer with narrow line emission

Lack of short spacings can introduce complex artifacts leading to wrong scientific interpretation
A single-dish of diameter $D$ is sensitive to spatial frequencies from $0$ to $D$.

An interferometer baseline $B$ is sensitive to spatial frequencies from $B - D$ to $B + D$.
Short Spacings
Spatial frequencies

- A single-dish of diameter $D$ is sensitive to spatial frequencies from 0 to $D$
- An interferometer baseline $B$ is sensitive to spatial frequencies from $B - D$ to $B + D$

- An interferometer measures the product primary beam $\times$ sky
- In the uv plane: transfer function $\ast$ true visibilities
An interferometer measures the \textit{convolution} of the “true” visibility with the \textit{antenna transfert function}.
Short Spacings Measurements

No short-spacings
Short Spacings Measurements

Single-dish measurement (same antenna diameter)
Short Spacings Measurements

Interferometer with smaller antennas

Radius in UV plane
Short Spacings Measurements

Small interferometer + Single-dish measurement

Radius in UV plane
ALMA = 4 12m + 12 7 m + 50 12 m
Short Spacings Measurements

Single-dish measurement (larger antenna diameter)
Short Spacings
Short spacings from SD data

- Combine SD and Interferometric maps in the image plane

- **Joint deconvolution** (MEM or Multi-scale CLEAN)

- **Hybridization** (aka feather): Combine SD and Interferometric maps in the $uv$ plane

- **Combine data in the uv plane before imaging**
  
  1. Use the 30–m map to simulate what would have observed the PdBI, i.e. extract “pseudo-visibilities”
  2. Merge with the interferometer visibilities
  3. Process (gridding, FT, deconvolution) all data together

This **drastically improves the deconvolution**
Short Spacings
Extracting visibilities

\[
\text{SD map} = \text{SD beam} \times \text{Sky}
\]

\[
\text{Int. map} = \text{Dirty beam} \times (\text{Int beam} \times \text{Sky})
\]

- **Image plane**
  - Gridding of the single-dish data \(\rightarrow\) SD Beam \(\times\) Sky
- **uv plane**
  - Correction for single-dish beam \(\rightarrow\) Sky
- **Image plane**
  - Multiplication by interferometer primary beam \(\rightarrow\) Int Beam \(\times\) Sky
- **uv plane**
  - Extract visibilities up to \(D_{SD} - D_{Int}\)
- **uv plane**
  - Apply a **weighting factor** before merging with the interferometer data
Weighting factor to SD data:

- Produce different images and dirty beams
- Methods are not perfect, noise → weight to be optimized
- Usually, it is better to **downweight the SD data** (as compared to natural weight)

Optimization:

- Adjust the weights so that there is almost **no negative sidelobes** while keeping the highest angular resolution possible
- Adjust the weights so that the **weight densities in 0–D and D–2D areas** are equal → mathematical criteria
Short spacings

Example

Without short spacings

With short spacings

$^{13}\text{CO} \ (1-0)$ in the L1157 protostar (Gueth et al. 1997)
$N_2H^+$ in the IRAM 04191 protostar (Belloche et al. 2004)
Short spacing
Example

CO 1–0 in the direction of NRAO 530, Pety et al. 2008
Effect of missing short spacings more severe on mosaics than on single-field images:

- Extended structures are filtered out in each field
- Lack of information on an intermediate scale as compared to the mosaic size
- Possible artefact: extended structures split in several parts
- In most cases, adding the short spacings is required
Mosaics and short spacings
Simulations

Without short-spacings
Recovered flux = 37%

With short-spacings
Mosaics and short spacings

The problem

Effect of missing short spacings more severe on mosaics than on single-field images:

- Extended structures are filtered out in each field
- Lack of information on an intermediate scale as compared to the mosaic size
- Possible artefact: extended structures split in several parts
- In most cases, adding the short spacings is required

However, mosaics are able to recover part of the short spacings information
Mosaics and short spacings

Image formation

- An interferometer is sensitive to all spatial frequencies from $B-D$ to $B+D \implies$ it measures a local average of the “true” visibilities

\[
\frac{(B+D)}{\lambda}
\]

\[
\frac{(B-D)}{\lambda}
\]

\[
\frac{B}{\lambda}
\]
Mosaics and short spacings

Image formation

- An interferometer is sensitive to all spatial frequencies from $B-D$ to $B+D \rightarrow$ it measures a **local average** of the “true” visibilities

- Measured visibilities: $V_{\text{mes}} = \text{FT}(B \times I) = T \ast V$ where $T$ is the transfert function of the antenna

- Pointing center $(\ell_p, m_p) \neq$ Phase center: phase gradient across the antenna aperture

\[
V_{\text{mes}}(u, v) = \left[ T(u, v) e^{-2i\pi (u\ell_p + vm_p)} \right] \ast V(u, v)
\]

- **Combination of measurements at different** $(\ell_p, m_p)$ should allow to derive $V$

- The recovery algorithm is a simple Fourier Transform (Ekers & Rots)
Conclusions

- Mosaicing is a **standard observing mode** at Plateau de Bure
- Adding short spacings from the IRAM 30–m is an **standard procedure** (box in proposal form)
- ALMA designed from the beginning to include the short-spacings (ACA, SD antennas) – but not for all projects
- New developments to come: on-the-fly interferometry