Imaging & Deconvolution:
II. Mosaicking

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Towards Higher Resolution: Limited Instantaneous Field of View

Measurement equation \( I_{\text{meas}} = D \ast (B_{\text{prim}} \ast I_{\text{source}}) + N \).

One pixel detector

- Single Dish: one image pixel/telescope pointing;
- Interferometer: numerous image pixels/telescope pointing
  - Field of view = Primary beam size;
  - Image resolution = Synthesized beam size.

Wide-field imaging \( \Rightarrow \) mosaicking.
Observing setup: I. Interferometry

- Stop-and-go mosaicking setup:
  - Loop around field positions ⇒ similar uv coverage per field;
  - Contiguous time per field: Compromise between
    * Need of consistency between fields;
    * Minimization of dead times due to acceleration/deceleration.

- Example (setup during 8 hours)
  - 7 fields observed 3 minutes per fields in each loop;
  - Calibrator observed every 21 minutes;
  - Pointing and focus checked every hour.

Imaging & Deconvolution: II. Mosaicking

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Imaging: Dirty beams

- One dirty beam per field (directly the final image size): \( I_i = D_i \ast (B_i \cdot I_{source}) + N_i. \)
Imaging: Dirty image and noise

- One dirty image per field (directly the final image size): \( I_i = D_i \star (B_i \cdot I_{source}) + N_i \).

- Linear combination (optimal from signal-to-noise ratio point of view):
  
  - Signal:
    \[ S(\alpha, \beta) = \frac{\sum_i B_i(\alpha, \beta) I_i(\alpha, \beta)}{\sum_i B_i^2(\alpha, \beta) \sigma_i^2} ; \]
  
  - Noise:
    \[ N(\alpha, \beta) = \frac{1}{\sqrt{\sum_i B_i^2(\alpha, \beta) \sigma_i^2}} ; \]
  
  - Signal-to-Noise Ratio:
    \[ \text{SNR}(\alpha, \beta) = \frac{S(\alpha, \beta)}{N(\alpha, \beta)} . \]
• Same as single field except:
  
  – The CLEAN components are searched on the SNR map;
  
  – The residual and SNR maps are iterated as:

\[
S_k(\alpha, \beta) = S_{k-1}(\alpha, \beta) - \frac{\sum_i \frac{B_i(\alpha, \beta)}{\sigma_i^2} \gamma I_k}{\sum_i \frac{B_i^2(\alpha, \beta)}{\sigma_i^2}}
\]

with \( I_k = B_i \ast \{ B_i(\alpha_k, \beta_k) \cdot I_k \cdot \delta(\alpha_k, \beta_k) \} \) and \( \gamma \sim 0.2; \)

* \( \text{SNR}(\alpha, \beta) = \frac{S_k(\alpha, \beta)}{N(\alpha, \beta)}. \)
Deconvolution: II Practice
Results: Signal, Noise, and Signal-to-Noise Ratio

- Clean Image [K]
- Noise [K]
- Signal-to-Noise Ratio
Comparison **without and with short-spacings**
A radio-interferometer is a multiplicative interferometer

**Avantage** all offsets are irrelevant ⇒ Much easier;

**Inconvenient** Radio interferometer = bandpass instrument;
⇒ Low spatial frequencies are filtered out.

Image 

Imaging & Deconvolution: II. Mosaicking  
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Importance of Short-Spacings:

II.1 A CO diffuse thick disk in M51

\( \sim 50\% \) of the flux is resolved at scales \( \geq 36'' \sim 1.3 \text{kpc} \)
(PAWS collaboration, Pety et al., 2013)

**Hybrid synthesis**

**PdBI-only**

**Hybrid synthesis – PdBI-only**

**Integrated emission [K.km.s\(^{-1}\)]**

**PdBI-only component**

- **Bright**  From 2 to 16 K with a median of 2.5 K.
- **Compact** It fills only \( \sim 2\% \) of the surface.

**Filtered component**

- **Faint**  From 0.07 to 1.36 K with a median of 0.14 K.
- **Extended** It fills \( \sim 30\% \) of the surface.
Importance of Short-Spacings:
II.2 A CO diffuse thick disk in M51

A dense and diffuse components of very different vertical scale heights, which probably mix in the galactic plane.
(PAWS collaboration, Pety et al., 2013)

Relative linewidths

Fact The filtered component has a velocity dispersion at least twice as large as the compact component.

Interpretation (using Koyama & Ostriker 2009) The extended component has a Gaussian scale height ($\sim 200$ pc) typically 5 times as large as the compact component one ($\sim 40$ pc). The Galaxy scale height is 57 pc (Ferriere 2001, Cox 2005).

Consequence The extended component average density ($1\text{H}_2 \text{ cm}^{-3}$) is one order of magnitude lower than the compact component one ($10\text{H}_2 \text{ cm}^{-3}$). The Galaxy average density is $0.29\text{H}_2 \text{ cm}^{-3}$ (Ferriere 2001, Cox 2005).
Importance of short-spacings: III.1 ALMA alone

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 $-1^\circ$
Level step: 5 mJy/beam

28-AUG-2001 09:37:46
Importance of short-spacings: III.2 ALMA + ACA + Short-spacings
Short-Spacings also help at large \( uv \) radius
Observing Setup: II. Single-Dish

• On-The-Fly setup:
  – IRAM-30m resolution at 115 GHz: 22″.
  – Raster scanning in RA and then Dec
    * Speed: 3″/second;
    * Dump time: 1 second ⇒ 7 points/beam;
  – Separation between rasters: 8″ ⇒ Nyquist sampling.

• Calibration:
  – ON-OFF switching;
  – Hot/cold/atm measurement every 15 minutes;
  – Chopper wheel method;
  – Factor from $T_A^*$ to $T_{mb}$: $F_{\text{eff}}/B_{\text{eff}}$
Short-Spacings Processing: I. Pseudo-visibilities

From \( I_{\text{meas}} = B_{30m} \ast I_{\text{source}} + N \)

To \( V_{\text{pseudo}}(u, v) = \mathcal{F} \{ B_{15m}^{\text{primary}} \ast I_{\text{source}} \}(u, v) + N \)

1. Gridding + Apodization;
2. Deconvolution of \( B_{30m} \) in \( uv \) plane;
3. Multiplication by \( B_{15m}^{\text{primary}} \) in image plane;
4. Sampling of pseudo-visibilities in \( uv \) plane.
Short-Spacings:

II.1 Merging (Amplitude cross calibration)

- Amplitude cross calibration:
  - Extremely important (wrong ⇒ distortion);
  - Difficult to achieve (no overlap).
  ⇒ Careful independent work needed.

- Outlier points have extremely low weights ⇒ No need to clip them out.
Short-Spacings:

II.2 Merging (Weight density and dirty beam shape)

- Dirty beam = FFT of weight density;

- Single-dish total weight: A free parameter (as long as it is down-weighted...)

⇒ Single-dish total weight set to get a roughly Gaussian shape for the circularly averaged weight density.

- Minimum visual change of the dirty beam;

- Dirty beam integral > 0 after addition of short-spacings.
One dirty image per field (directly the final image size): \( I_i = D_i \ast (B_{\text{primary}}^{15m}.I_{\text{source}}) + N_i \).

Linear combination (optimal from signal-to-noise ratio point of view):

- **Signal:**
  \[
  S(\alpha, \beta) = \frac{\sum_i I_i(\alpha, \beta)}{\sum_i B_i^2(\alpha, \beta)};
  \]

- **Noise:**
  \[
  N(\alpha, \beta) = \frac{1}{\sqrt{\sum_i B_i^2(\alpha, \beta)}};
  \]

- **Signal-to-Noise Ratio:**
  \[
  \text{SNR}(\alpha, \beta) = \frac{S(\alpha, \beta)}{N(\alpha, \beta)}.
  \]
Imaging: Dirty image and noise (With short-spacings)

- One dirty image per field (directly the final image size): \( I_i = D_i \star (B_{\text{primary}}^{15m} \cdot I_{\text{source}}) + N_i \).

- Linear combination (optimal from signal-to-noise ratio point of view):
  - Signal:
    \[
    S(\alpha, \beta) = \frac{\sum_i B_i(\alpha, \beta) I_i(\alpha, \beta)}{\sum_i B_i^2(\alpha, \beta) \sigma_i^2} ;
    \]
  - Noise:
    \[
    N(\alpha, \beta) = 1 \sqrt{\sum_i B_i^2(\alpha, \beta) \sigma_i^2} ;
    \]
  - Signal-to-Noise Ratio:
    \[
    \text{SNR}(\alpha, \beta) = \frac{S(\alpha, \beta)}{N(\alpha, \beta)}.\]
Deconvolution: II.1 Practice (Without short-spacings)
Deconvolution: II.2 Practice (With short-spacings)
When observing/adding the short-spacings?

\textbf{source size} < \textbf{1/3 primary beamwidth} Short-spacings are superfluous.

\textbf{1/3 primary beamwidth} < \textbf{source size} < \textbf{1/2 primary beamwidth} A single spectrum in the direction of the source is OK.

\textbf{1/2 primary beamwidth} < \textbf{source size} An OTF map is required.

\textbf{Field of view} PdBI field of view + PdBI half primary beam bandguard \implies Double the field of view for a 7 field mosaic. But there is no need to integrate on empty sky...

\textbf{Single dish integration time} Same time as the PdBI compact (D) configuration (assuming 6 antennas and similar receiver system at both observatories).

\textbf{Needed data quality} As good as possible (pay attention to data consistency, e.g., coordinate system, frequency tuning)… Don’t spoil your interferometric data with crap single-dish data.

\textbf{There is signal with PdBI but only noise at the 30m} Your source may be a collection of point sources diluted in the 30m beam. This is the case where adding the short-spacings may just add noise.
Mosaicking: A standard observing mode

An example among many: The Horsehead PDR

[Images of various astronomical data sets, including $^{12}$CO(1-0) and $^{18}$CO(2-1) distributions, H$_2$, HCO, 7.7 μm emission, and c-C$_3$H$_2$]
Mosaicking: State-of-the-art with PdBI in 2010
I. PAWS (PdBI Arcsecond Whirlpool Survey, PI: E.Schinnerer)

Past:

Present:
- Mosaic of 60 fields at 3 mm → Field of view: 3.5′ × 2.8′.
- 8 hr in D, 15 hr in C, 43 hr in B and 60 hr in A → 454 000 visibilities × 1024 channels and a final resolution of ∼ 1″.
- Imaging and deconvolution require images of 2 Mpxels (in fine: only 36 000 fully independant pixels).
  → 8 days and 14 hours to deconvolve 20 channels (320 000 components per channel).
- Mosaicking ∼ Raster mapping for a single-dish.
  → 8-9 seconds lost when moving from one field to the next one.

Future:
- Interferometric On-The-Fly.
  - New observing mode + new imaging algorithm.
Mosaicking: State-of-the-art with PdBI in 2010

II. Why/How HD TV changes your life

(a) PAWS 1"

(b) PAWS 3"

(c) PAWS 6"
Mosaicking: State-of-the-art with PdBI in 2010

III. Multi-wavelength comparison
(Schinnerer et al. 2013, Meidt et al. 2013)

SINGS Hα  Spitzer 8 μm  $^{12}$CO (J=1–0)

Molecular ring  Coincident star formation
Spiral arm, inside spiral corotation  Suppressed star formation.
Spiral arm, outside spiral corotation  Offset star formation.

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Mosaicking: ALMA in 2014
Orion Bar PDR (Goicoechea et al. 2016)
Mosaicking: ALMA in 2014
Orion Bar PDR (Goicoechea et al. 2016)

HCO⁺ J=3-2 (ALMA+IRAM-30m), [Oii] 6,300 Å (VLT/MUSE), [Sii] 6,731 Å (VLT/MUSE)

Imaging & Deconvolution: II. Mosaicking
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Mosaicking: State-of-the-art with NOEMA in 2016

$10' \times 10'$ on IC 342 (PI: A. Schruba)
Mosaicking: State-of-the-art with NOEMA in 2016
941 fields in 6 tracks
Next step: Mapping wide fields over wide bandwidths, e.g., Orion B

Integration time 133 hours.
Field of view 5 × 7 pc at a distance of 400 pc.
Spatial resolution 50 mpc or 10^5 AU ⇒ images of 315 × 420 pixels.
Bandwidth 32 GHz from 84 to 116 GHz.
Spectral resolution 200 kHz resolution.
Number of channels ⇒ 160,000 channels, i.e., at 24 images per seconds, it makes a movies of 1h50!
Field of view × channels 144,000 channel × square degree (i.e., the equivalent of twice of the sky in 5 days!).
Median noise level 0.1 to 0.5 K (Tmb).
A sea of noise Clear signal detected in ∼ 800 channels, or 0.5% of the data (a video of about 30 seconds).
Data size 900 GB of raw data.