Radio Surveys Data Analysis in the Visibility Domain

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Outline

- Galaxy catalogs from radio data analysis: image vs visibilities
- Visibility model
- Bayesian methods in the visibility domain
  - Galaxy shape measurement (for radio weak lensing)
  - Galaxy detection
- Conclusions

Data analysis: image vs visibilities

SKA extragalactic continuum surveys will allow **new scientific measurements** that will require more and more **accuracy in galaxy catalogs**.

Radio image is obtained from processing of the original data originated in the Fourier space:

- noise is highly correlated
- systematics introduced by the imaging process (due to iterative deconvolution procedure) may become too large

e.g. Radio Weak Lensing (RWL) shear measurement gives poor results w.r.t. requirements:

Patel+ 2015

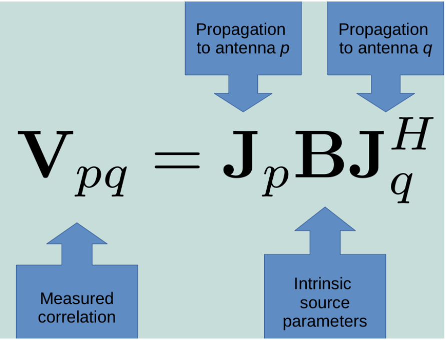
	Multiplicative Bias	Additive Bias
SKA1 requirement	0.0067	0.00082
CLEAN images	-0.265 ± 0.02	0.001 ± 0.005

Visibilities analysis is a more natural approach BUT:

- Computationally demanding (big data)
- Sources cannot be easily isolated
- Model fitting for source characterization

Radio Interferometry Measurement Equation (RIME)

Description of what happens to the radio signal from the source to the interferometer (Hamaker+ 1996, Hamaker 2000, Smirnov 2011):



Multiple propagation effects can be added by chaining up Jones matrices (e.g. antenna gains, antenna primary beam, ...):

$$\mathbf{V}_{pq} = \mathbf{J}_{p,n}(\dots(\mathbf{J}_{p,1}\mathbf{B}\mathbf{J}_{q,1}^H)\dots)\mathbf{J}_{q,n}^H$$

Galaxy Radio Surface Brightness Model

star-forming galaxies

- synchrotron radiation emitted by the interstellar medium in the *disc alone*
- Fourier Transform of optical disc model (*Sérsic profile index* 1)
- can be computed analitically! (Rivi+ 2016)

$$V(u,v) = \mathcal{F}(I \circ A)(\mathbf{k}), \quad I(r) = I_0 \exp(-r/\alpha), \quad A\mathbf{x} = \begin{pmatrix} 1-e_1 & -e_2 \\ -e_2 & 1+e_1 \end{pmatrix} \begin{pmatrix} l \\ m \end{pmatrix}$$

radio-quiet AGN

- compact radio emission within host galaxy (Guidetti+ 2017)
- 2-components model?

radio-loud AGN

- jets + lobes components
- *shapelets* model (invariant by Fourier Transform) for lobes? (Chang+ 2004)

SF Galaxy Shape Measurement for RWL

Two Bayesian approaches given the *sky catalog* (source position and integrated flux) and *calibrated visibilities*:

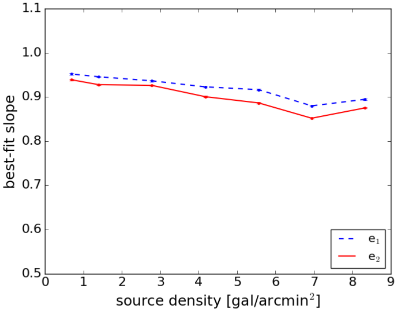
- **Single-source model**: *RadioLensfit* (Rivi & Miller 2018)
  - source extraction (sky model + faceting)
  - chi-square *fitting of a single source at a time* marginalising over position, flux and size
    $\rightarrow L = L(e_1, e_2)$, i.e. parameter space of dimension 2
  - likelihood sampling: ML + adaptive grid around the maximum

- **Multi-source model**: *BIRO - Hamiltonian Monte Carlo* (Rivi+ 2019)
  - *Joint fitting* for $e_{1,s}, e_{2,s}, \alpha_s$ parameters of all N sources in the FoV
    $\rightarrow$ parameter space of dimension $3N$
  - likelihood sampling: HMC with step size dependent on source flux and analytic likelihood gradient

SF Galaxy Shape Measurement for RWL

Simulation SKA1-MID 8 hrs, $t_{acc} = 60$ s, 1 channel at 1.07 GHz → 9,266,880 visibilities
Realistic distribution of SF galaxies with SNR $\geqslant 10$

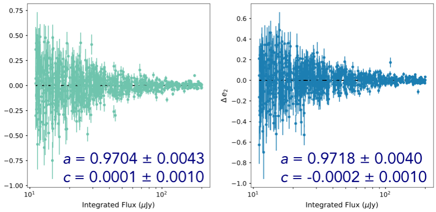
RadioLensfit (10^4 sources)



At SKA1-MID expected source density (2.7 gal/arcmin^2):

$a_1 = 0.9365 \pm 0.0017$
$a_2 = 0.9262 \pm 0.0017$

BIRO-HMC (1000 sources, 2.7 gal/arcmin^2)



Improved shape measurement **accuracy** but **computationally much more demanding**

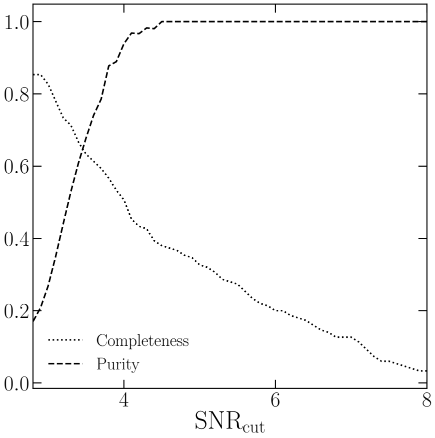
size best-fit line:
$a = 1.0048 \pm 0.0030$
$c = -0.0090 \pm 0.0051$

This two approaches can be combined to accelerate HMC convergence

Galaxy Detection in the Visibility Domain

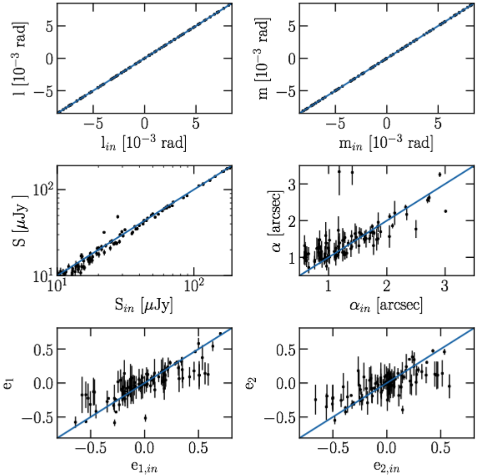
GalNest (Malyali, Rivi, Abdalla, McEwen, 2019)

- **single source model** + multimodal posterior sampler (*MultiNest*, Feroz+ 2009)
- **clustering** algorithm (SCIKIT-LEARN *mean shift*) to identify the source from clustered fake modes
- **SNR threshold** to remove remaining fake modes
- from SKA1-MID simulations of SF galaxies observation, **reliable source detection down to SNR $\sim$ 5**



Galaxy Detection: SKA1-MID simulation at 1.07 GHz

8 hrs integration time, $t_{\rm acc} = 60$ s, 1 channel → about 10^7 visibilities
realistic distribution of SF galaxies with **SNR $\geqslant$ 10**

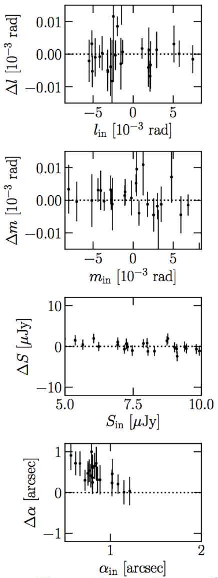


98/100 galaxy detections

Galaxy Detection: SKA1-MID simulation at 1.07 GHz

8 hrs integration time, $t_{\mathrm{acc}} = 60$ s,
single channel
realistic distribution of 50 SF galaxies with
SNR ranging 3 - 13

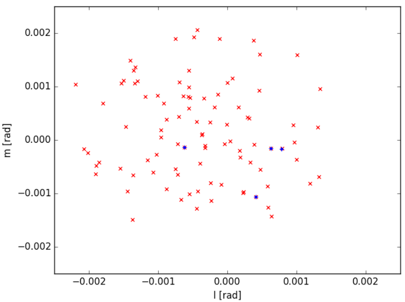
- NO fake modes at SNR $\geqslant 4.5$
- 58% detections of the population with SNR $\geqslant 5$
- still accurate position and flux measurements

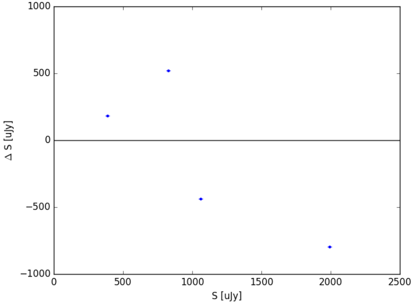


Galaxy Detection: JVLA Observations

7 pointings of the GOODS-N Field, VLA A-configuration 14 hrs, B-configuration 2.5 hrs
$t_{acc} = 1$ s, 16 adjiacent 64×2 MHz channels at a central frequency 5.5 GHz

Image Catalog: 94 sources with SNR $\geqslant 5$ (80% are AGN) Guidetti+ 2017





Using a **reduced dataset** (single pointing and single spectral window):

- all the 4 visible (brightest) sources are detected!
- flux discrepancy: source model and signal contamination, primary beam

work in progress!

SKA Data Challenge

Phase 1 SKA-MID Medium-Deep Band 2 Survey:
5000 $\deg^2$ to a depth of 2μJy RMS (10,000 hrs, $z < 0.4$)

SKA Cosmology SWG, Red Book 2018

Continuum **radio weak lensing survey requirements**:
$\sim 10^4$ pointings of ~ 1 hour each ($\Delta t = 0.5$ s sampling),
~ 6000 frequency channels at a resolution of $\Delta\nu = 50$ kHz,
necessary resolution for smearing-induced ellipticity to be acceptable.
Very large data volume for a continuum survey (**order of PBytes** per pointing)
but directly **comparable to that expected by HI line galaxy surveys**.

SKA ECP150007 v2, Brown & Harrison 2015

Possible solutions:
- *work on gridded visibilities*
- *dedicated RWL pipeline at the SKA SDP?*

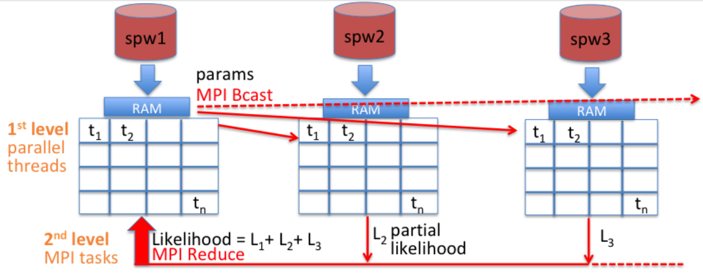
Parallelization strategy for analysis and simulation tools

The most computing intensive part is the **visibility model computation:** visibility function must be evaluated

- at each point (baseline, frequency, time) of the uv coverage
- at each iteration of the parameter space sampler

Massively embarassing parallelization along with uv points
⇒ exploitation of both multi-core CPUs and GPUs.

Large datasets may be split by spectral windows to be distributed on different computing nodes: **hierarchical parallelization**



Conclusions

- SKA will allow **new scientific measurements in the radio band**, e.g. *radio weak lensing*, for which analysis from radio images may not be accurate enough.
- **Methods in the visibility domain** may be more accurate but are computationally very challenging because of the big data.
- **Bayesian methods** in the visibility domain for **SF galaxy shape measurements** allow to reduce noise bias.
  - *RadioLensfit* working well for SKA1 source density and it is very fast
  - *HMC* more accurate but much slower for large number of sources
  - The two approaches may be combined for higher source density regions
- **Radio galaxy detection** in the visibility domain is possible, e.g. with a *Multimodal Nested Sampling* approach.
- All these approaches require **code parallelization** to exploit clusters for SKA data processing (and/or simulation).