First AI for deep super-resolution wide-field imaging in radio astronomy:

unveiling structure in ESO 137–006

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RI imaging challenge in the SKA era

Aperture synthesis by radio interferometry

Aperture synthesis by radio interferometry provides access to high resolution high dynamic range. But forming an image $\boldsymbol{x}$ from visibility data $\boldsymbol{y}$ is an ill-posed inverse problem.

- Data model: incomplete Fourier sampling of the sky:

$$\boldsymbol{y} = \boldsymbol{\Phi} \boldsymbol{x} + \boldsymbol{n}$$

- Reconstruction algorithms are needed, leveraging a prior image model to regularise and solve the problem:

$$\boldsymbol{y} \rightarrow \boldsymbol{x}$$

- Accurate models needed for **precision**

The Square Kilometre Array

SKA will target unprecedented resolution and sensitivity regimes, leading to EB data volumes and PB wideband image sizes.

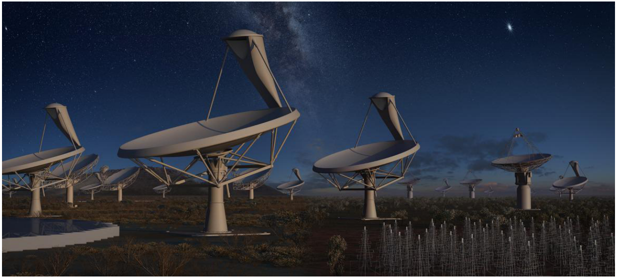


Image credit SKA organisation

- Reconstruction algorithms must be **scalable**
- CLEAN is scalable but sub-optimal and requires manual intervention

Proposed AI framework for deep super-resolution wide-field RI imaging

Terris et al., MNRAS accepted, arXiv:2202.12959

Dabbech et al., ApJL submitted, arXiv:2207.11336

Powerful optimisation framework

Convex optimisation provides a powerful framework to solve inverse problems via highly iterative algorithms.

$$\boldsymbol{x}^\star \in \operatorname*{argmin}_{\boldsymbol{x}} \Big\{ g(\boldsymbol{x};\boldsymbol{y}) = f(\boldsymbol{x};\boldsymbol{y}) + r(\boldsymbol{x}) \Big\}$$

- $f(\boldsymbol{x};\boldsymbol{y})$: data-fidelity term; $r(\boldsymbol{x})$: regularisation term

VERSATILE THEORY:

- Provides iterative algorithms with convergence guarantees
- Allows advanced regularisation for precision
- Provides parallel algorithmic structures for scalability

Forward-Backward algorithm

The Forward-Backward (FB) algorithm is a simple and flexible optimisation structure.

$$\boldsymbol{x}^\star \in \operatorname*{argmin}_{\boldsymbol{x}} \Big\{ g(\boldsymbol{x};\boldsymbol{y}) = f(\boldsymbol{x};\boldsymbol{y}) + r(\boldsymbol{x}) \Big\}$$

- $f(\boldsymbol{x};\boldsymbol{y})$: differentiable; $r(\boldsymbol{x})$: differentiable or not
- Iteration structure: (reminiscent of, but more general than, CLEAN)

$$\boldsymbol{x}^{(i)} = \mathrm{prox}_r \left(\boldsymbol{x}^{(i-1)} - \gamma \nabla f \left(\boldsymbol{x}^{(i-1)} \right) \right)$$

  - ✓ forward gradient descent data-fidelity step
  - ✓ backward regularisation step involving prox_r
  - ✓ the proximal operator prox_r is an image denoiser

Unconstrained SARA (uSARA)

Unconstrained SARA leverages FB with handcrafted regularisation for monochromatic intensity imaging.

- Data fidelity term: $f(\boldsymbol{x}, \boldsymbol{y}) = ||\boldsymbol{y} - \boldsymbol{\Phi}\boldsymbol{x}||_2^2$ (Gaussian noise)
- Regularisation term: log-sum prior (generalising ℓ_1) promoting average sparsity in a redundant wavelet dictionary

$$r(\boldsymbol{x}) = \eta \sum_{n=1}^{B} \rho \log \left(1 + \rho^{-1} \left| \left(\boldsymbol{\Psi}^\dagger \boldsymbol{x} \right)_n \right| \right) + \iota_{\mathbb{R}_+^N}(\boldsymbol{x})$$

- Iteration structure:

$$\boldsymbol{x}^{(i)} = \mathrm{prox}_r \left(\boldsymbol{x}^{(i-1)} + \gamma \boldsymbol{\Phi}^\dagger \left(\boldsymbol{y} - \boldsymbol{\Phi}\boldsymbol{x}^{(i-1)} \right) \right)$$

- SARA's proximal operator is sub-iterative

AI for Regularisation in Imaging (AIRI)

AIRI leverages FB, plugging a learned DNN denoiser in lieu of a proximal operator for monochromatic intensity imaging (plug-and-play approach).

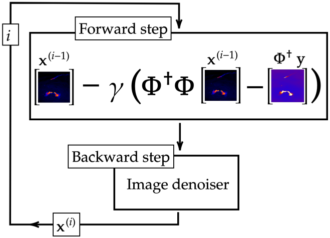
- Data fidelity term: $f(\boldsymbol{x}, \boldsymbol{y}) = ||\boldsymbol{y} - \boldsymbol{\Phi x}||_2^2$ (Gaussian noise)
- Regularisation term: implicitly defined by a learned DNN denoiser
- Requires tailored training approach to ensure algorithm convergence
- Iteration structure:

$$\boldsymbol{x}^{(i)} = \mathrm{DNN}\left(\boldsymbol{x}^{(i-1)} + \gamma \boldsymbol{\Phi}^\dagger \left(\boldsymbol{y} - \boldsymbol{\Phi x}^{(i-1)}\right)\right)$$

- Learning opens the door to powerful physical regularisation
- DNNs provide acceleration over sub-iterative proximal operators

Fully parallelised and scalable AI framework for RI

The algorithmic framework is parallelised both in its forward and backward steps, to run on high performance computing hardware.



- Parallel denoising via image faceting
- Parallel gradient step via decomposition of $\boldsymbol{\Phi}^\dagger\boldsymbol{\Phi}$ into sparse and low-dimensional blocks
- Parallelisation degree automated depending on hardware

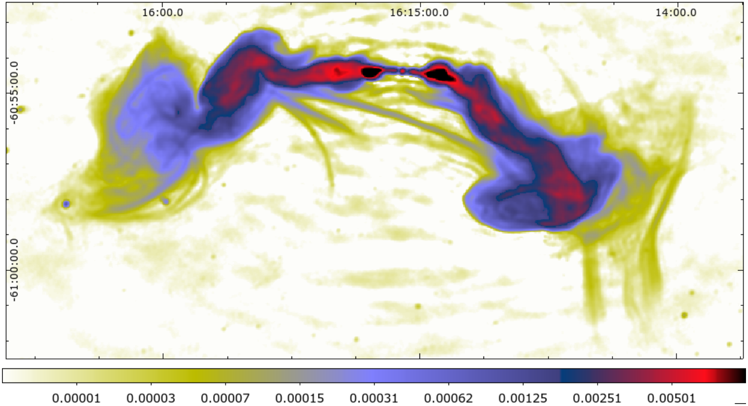
Revisiting ESO137-006 from MeerKAT data

Dabbech et al., ApJL submitted, arXiv:2207.11336

When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

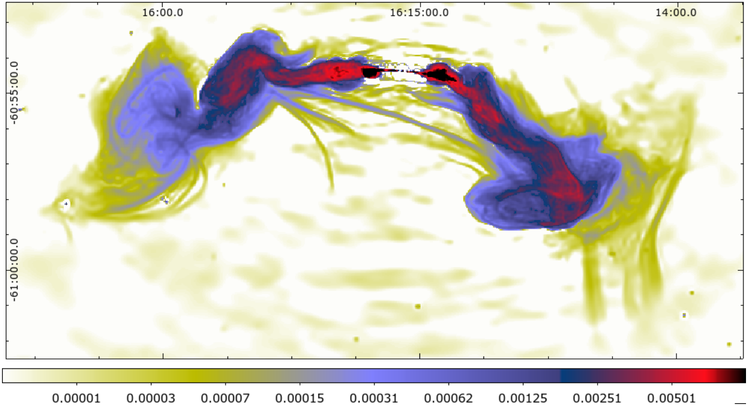
- **WSClean** (1.4GHz; 4k x 4k image; 11GB data; compute cost: 236 CoreH; precision: instrument resolution)



When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

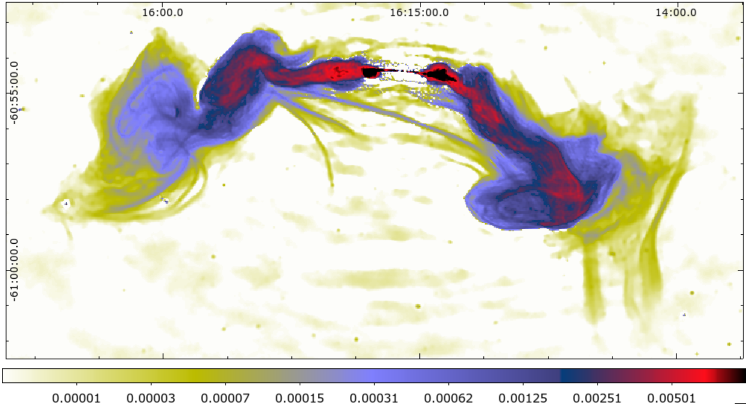
- **uSARA** (1.4GHz; 4k x 4k image; 11GB data; compute cost: 2377 CoreH; precision: super-resolved)



When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

- **AIRI** (1.4GHz; 4k x 4k image; 11GB data; compute cost: 1028 CoreH; precision: further super-resolved, improved dynamic range)



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Conclusions & future work

- **Conclusion**

  AI opens the door to further precision and scalability in RI imaging

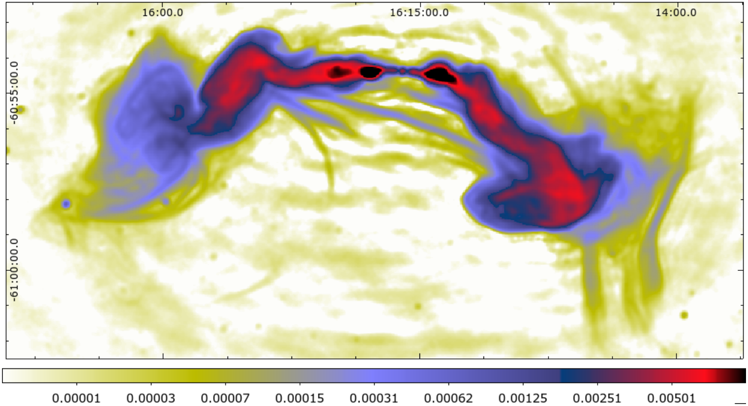
- **Ongoing evolutions beyond first uSARA & AIRI incarnations**
  - ✓ Investigate advanced denoisers: architectures, databases, losses
  - ✓ Add wideband, polarisation, calibration functionalities
  - ✓ Translate current Matlab code into C++ (Puri-Psi)
  - ✓ Application to ASKAP data (2 articles in prep.)
  - ✓ Application to EHT VLBI data

[We are hiring at PhD, postdoc., and Assist. Prof. level]

When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

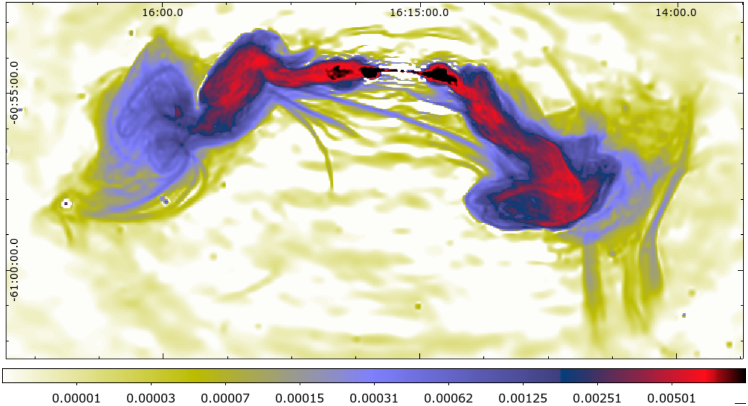
- **WSClean** (1.05GHz; 4k x 4k image; 8.2GB data; compute cost: 132 CoreH; precision: instrument resolution)



When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

- **uSARA** (1.05GHz; 4k x 4k image; 8.2GB data; compute cost: 1120 CoreH; precision: super-resolved)



When AIRI & uSARA meet the MeerKAT

Wide-field imaging of ESO137-006 with MeerKAT data *(Collab. SARAO)*.

- **AIRI** (1.05GHz; 4k x 4k image; 8.2GB data; compute cost: 480 CoreH; precision: further super-resolved, improved dynamic range)