Antenna array optimization for radio interferometry: towards a machine learning-guided approach

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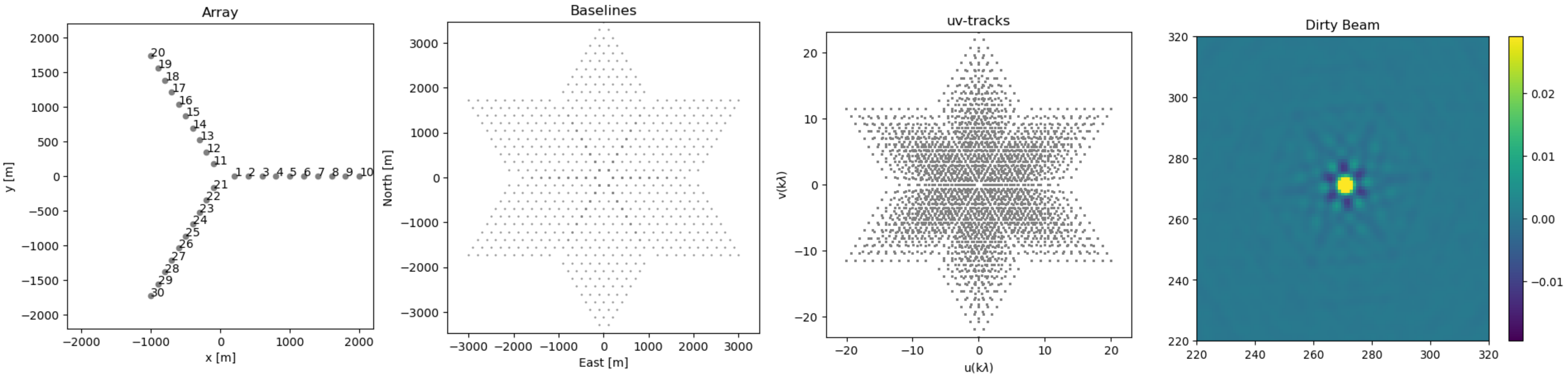
Context and scientific motivation

- Radio astronomy : high angular resolution for detailed observations.
- ARGOS project : design of a next generation interferometric array.
- Performance depends on :
  - Antenna placement.
  - UV plane coverage.
  - Beam shape and quality.

- Key challenge : optimize antenna configuraion for specific science cases.

Radio interferometry



- Each antenna pair defines a baseline, which corresponds to a sampled spatial frequency in the uv-plane.
- The uv-plane coverage directly impacts the synthesized beam (PSF) and image quality.
- In Fourier space :

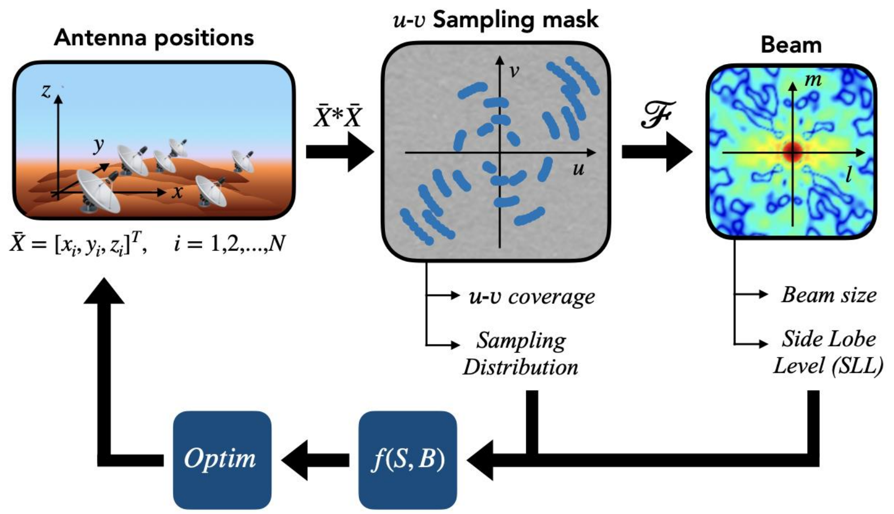
$$\widehat{O}(u,v) = \hat{S}(u,v)\,.\,M(u,v)$$

- In real space :

$$o(x,y) = s(x,y) * b(x,y)$$

- Goal: Improve uv-coverage and beam quality by optimizing the antenna layout.

Argosim simulation package



- Argosim : tool used to simulate the radio interferometry imaging process, developed at CosmoStat.

  Input : antenna positions.

  Output : uv coverage, beam, sky reconstruction and metric values.

  Used for evaluation and optimization.

- My contribution : integrated new beam metrics, submitted as Pull Request to the main Argosim repository.

Evaluation metrics

- UV metrics :

  Number of filled uv-cells.

  Uniformity.

  Redundancy (duplicate uv sampels).

- Beam metrics :

  FWHM (Full Width at Half Maximum).

  Eccentricity.

  SLL (Side Lobe Level) in dB.

- Image metrics :

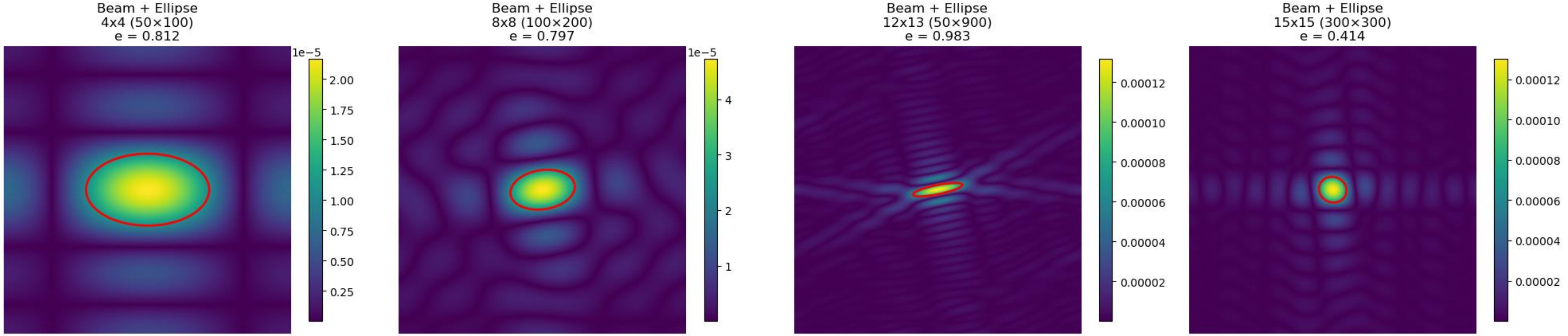
  MSE = Mean Squared Error between sky model and output image.

  RMSE = Relative Mean Squared Error (normalized version).

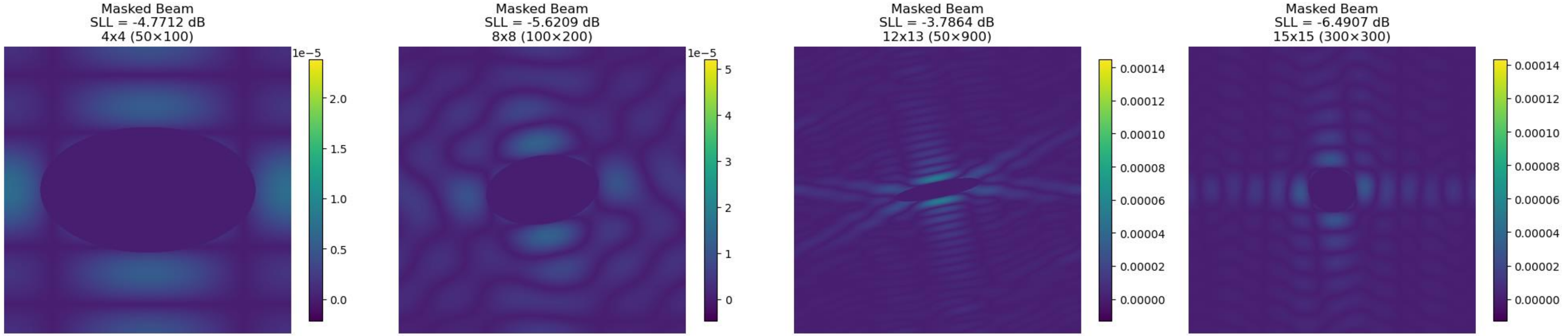
  SSIM = Structural Similarity Index.

First phase : testing the metrics

- Evaluation of different configurations : Y-arrays, circular uniform array, random configurations.



FWHM = (296.60, 173.24)px FWHM = (156.37, 94.35)px FWHM = (121.27, 22.32)px FWHM = (67.21, 61.17) px



→Gaussian fit applied to the main lobe of the dirty beam.

→ Eccentricity and FWHM computed from the fit.

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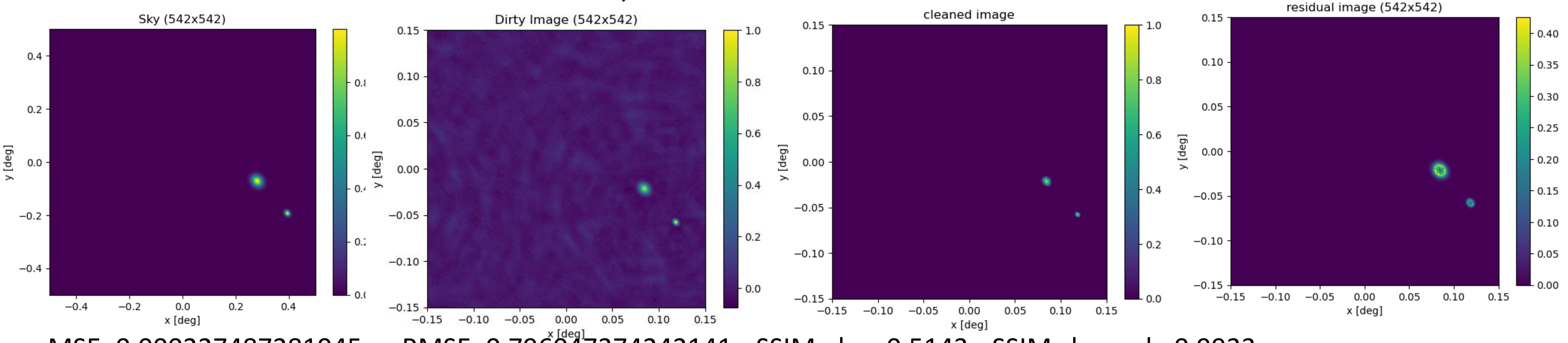
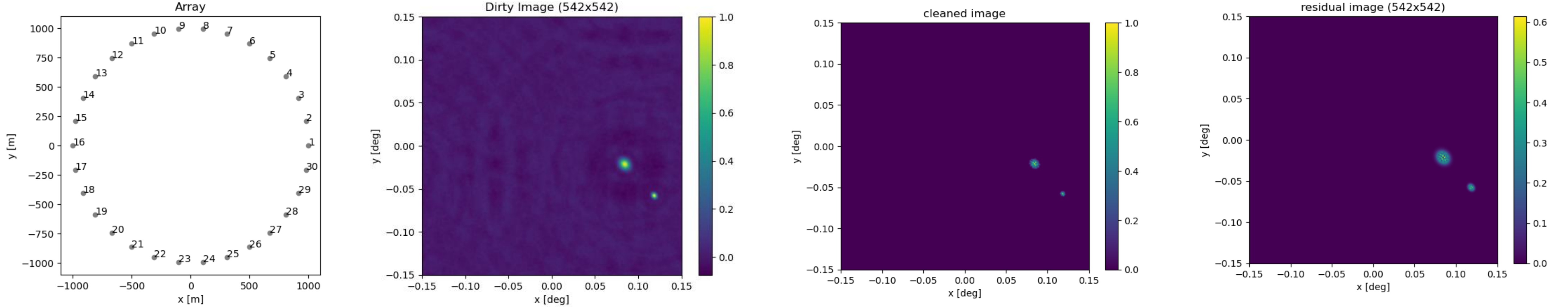
Image reconstruction metrics

Y-array

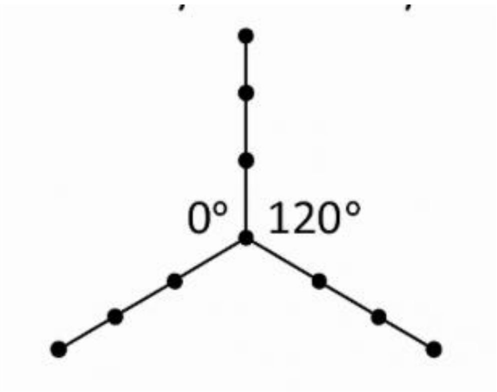


MSE: 0.000227487281945 RMSE: 0.796047374242141 SSIM obs : 0.5143 SSIM cleaned : 0.9933



MSE: 0.000229945891837 RMSE: 0.975834540958991 SSIM obs : 0.6139 SSIM cleaned : 0.9934

PSO optimization on symmetric Y-array



- Based on : Jin & Rahmat-Samii, IEEE TAP, 2008
- Configuration: 3 arms, symmetric, fixed angles (0°, 120°, 240°).
- Fitness function: maximize the number of filled u-v grid cells.

- PSO : population based algorithm inspired by swarms

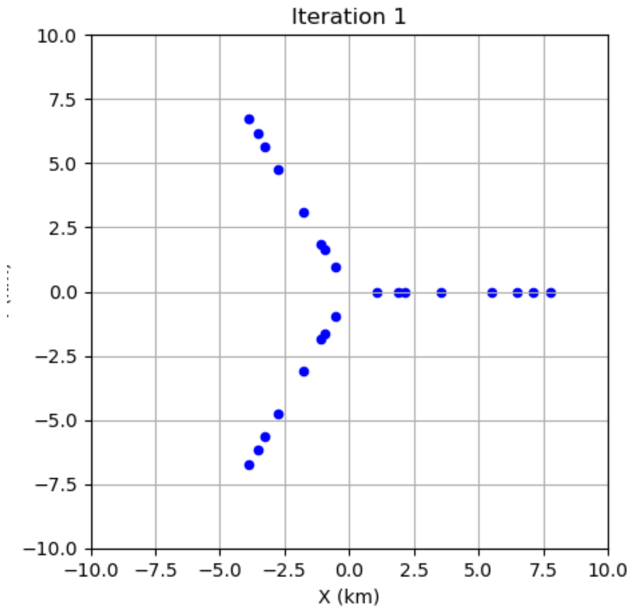
  Each particle = one Y- array configuration

  At each iteration, particles update using :

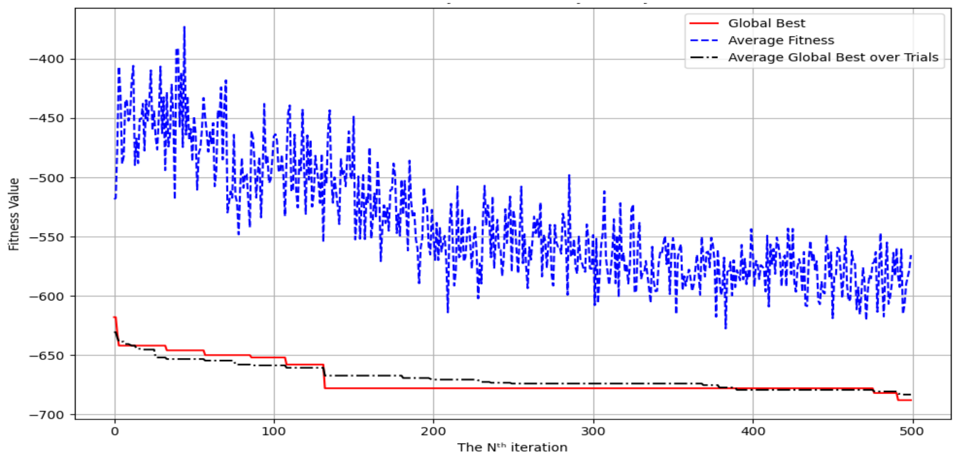
  → Their personal best (p_best)
  → The global best (g_best)
  → Velocity and position updates:

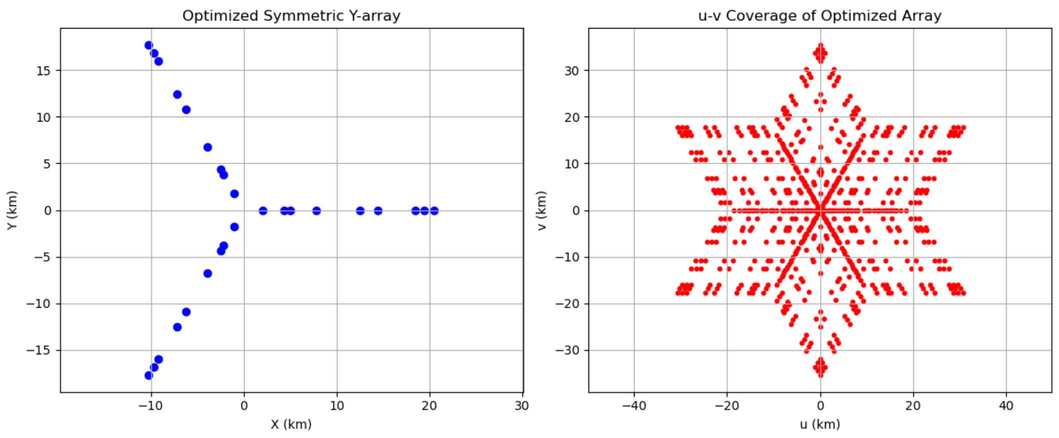
  $$v_i(t+1) = w * v_i(t) + c1 * rand * (p_{best} - x_i) + c2 * rand * (g_{best} - x_i)$$
  $$x_i(t+1) = x_i(t) + v_i(t+1)$$

PSO optimization on symmetric Y-array



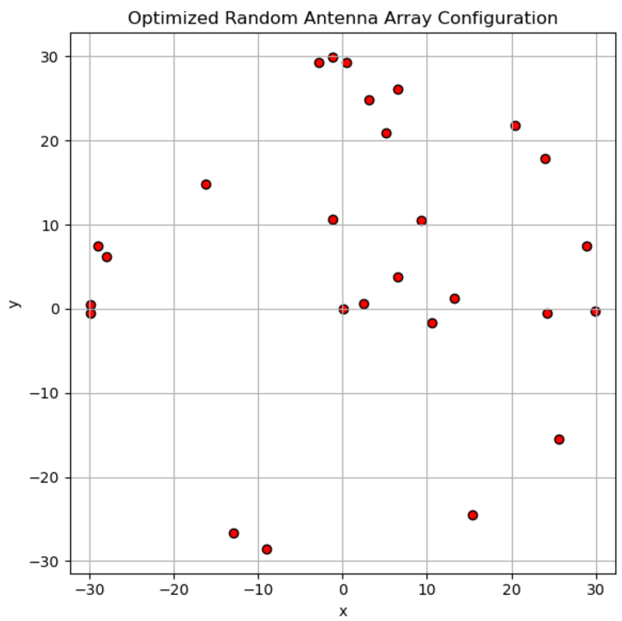
- Results:
  - Good convergence in structured space
  - Visual tracking of g_best evolution
- Limitation:
  - Fixed structure restricts optimization space.

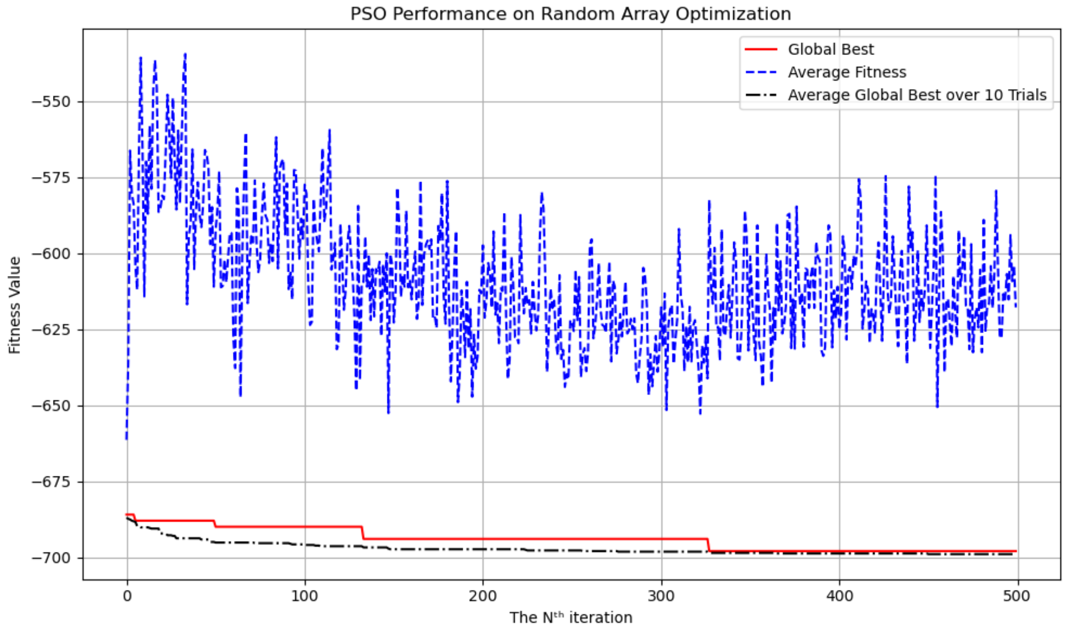




Moving to random configuration

- Each configuration is a 2D vector X = (E1,N1,… , E27,N27)
- Objective: Optimize positions to improve uv/beam metrics
- Two directions explored:
    1. PSO on 2D coordinates (slower convergence)
    2. Random Forest Regressor to predict metrics from layouts





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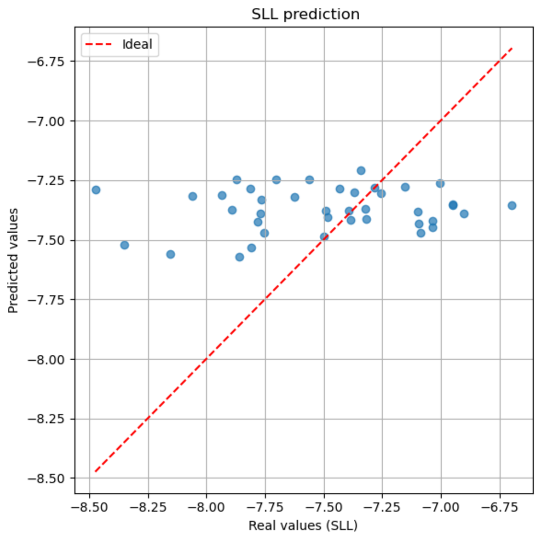
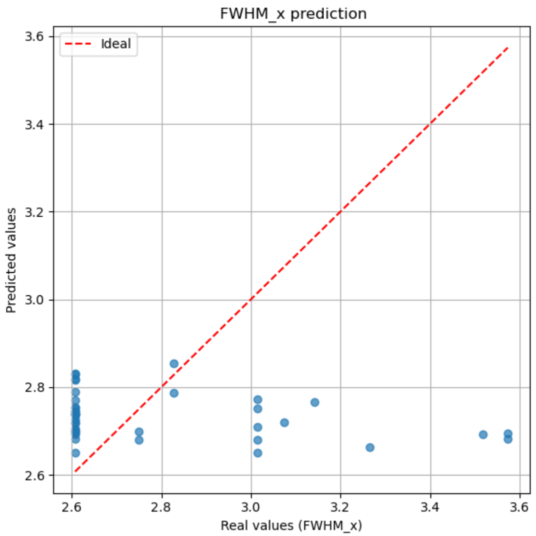
Random forest regressor

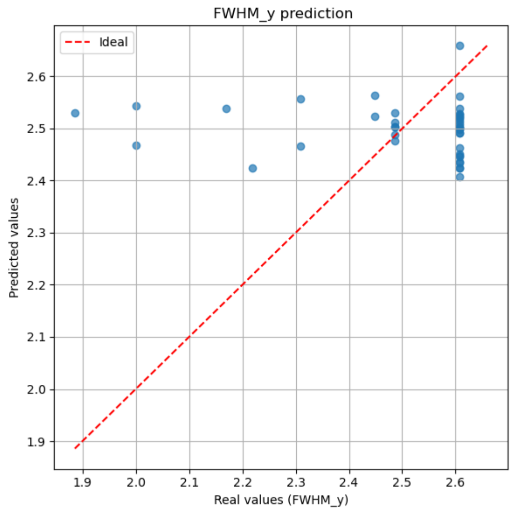
- Task: Predict beam metrics (eccentricity, SLL, FWHM) from antenna configurations.
- Dataset: Generated using Argosim (X = positions, y = metric).
- Benefits:
  - Very fast prediction after training
  - Useful for pre-evaluation and filtering

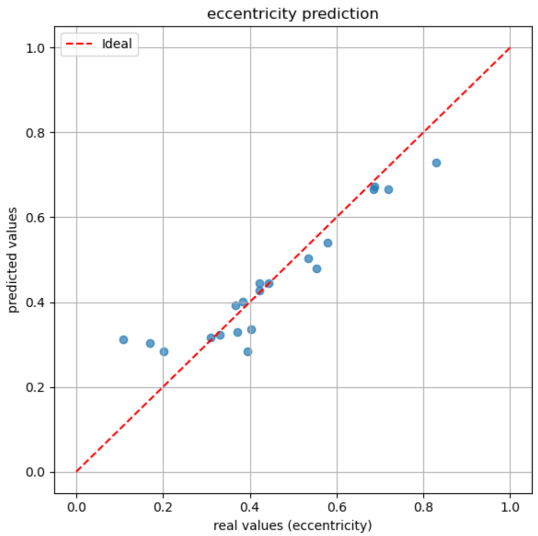
Random forest regressor

- Number of antennas : 30 (freely placed within a 2km * 2km area)
- Training data : 100 configurations









Metric	Mean Absolute Error	R^2 Score	Interpretation
SLL	0.3418	-0.0773	Poor prediction (weak correlation)
FWHM_x	0.2243	-0.1752	Low accuracy
FWHM_y	0.1478	-0.1269	Similar behavior as FWHM_x
Eccentricity	0.0529	**0.8408**	Very good prediction

Neural network for objective approximation

- Problem: $f(X)$ from Argosim is non-differentiable.
- Solution: Approximate $f(X)$ with a neural network.
- Once trained, compute gradients: $\partial f/\partial X$.
- Enables gradient-based optimization:
  - $X_{new} = X - \gamma \nabla f(X)$
- Current status:
  - Dataset preparation in progress

Summary and next steps

- **What has been done:**

  Implemented uv and beam metric computation

  Evaluated structured and random arrays

  Applied PSO on Y-array configurations

  Started ML modeling (Random Forest)

- **Next steps:**

  Train a neural network to learn f (X)

  Perform gradient descent using NN

  prediction → optimization

Thank you