Designing an Optimised Phased Antenna Array

The Synthetic Aperture Microwave Imager (SAMI-2) is a diagnostic that uses microwave radiation to probe various properties of the plasma edge on MAST-U, an experimental fusion facility in Culham, UK. SAMI-2 uses phased antenna array technology which allows 2D images to be digitally reconstructed [1]. This project focuses on determining the best antenna layout possible to maximize the performance of the array.

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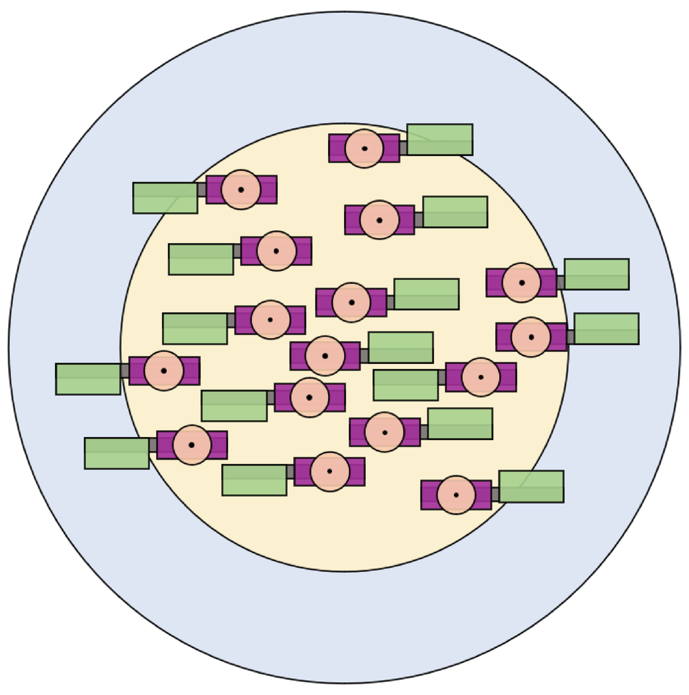

Figure 1: Example 16-element phased antenna array with the circular antenna elements shown in ***orange***

1 Introduction

- **Monitoring plasma** properties using a diagnostic such as SAMI-2 not only provides insights into new physics but also informs plasma control systems such as current drive and magnetic confinement [1]
- **The accurate identification** of turbulent plasma phenomena necessitates high-resolution imaging, both spatial and temporal, to distinguish genuine turbulence from mere image artefacts.
- **The focus of this project** is increasing the accuracy and resolution of the SAMI-2 diagnostic by optimising the arrangement of antennas

2 Objective

- **This project aimed** to develop methods of automatically arranging antenna elements on a phased array such that its performance is maximized
- What is meant by "**performance**"?
  - **Minimal image artefacts** –> Truer to life images
  - **Minimal beamwidth** –> Higher spatial resolution
- **Lower** side-lobe powers mean **weaker** image artefacts which means a more **accurate** image!

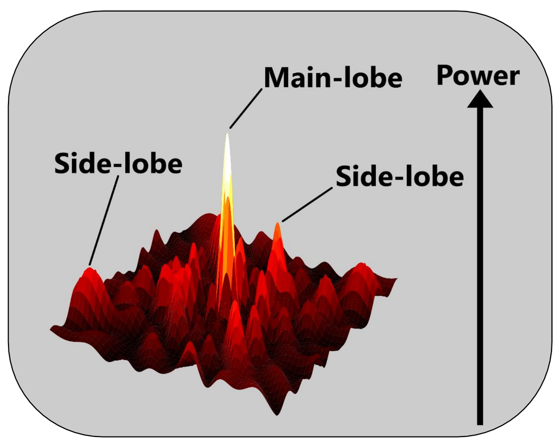

Figure 2: Example interference pattern

3a Methodology

Stochastic Optimisation

- Each antenna is sequentially nudged, and if the below objective function is increased and if the new position doesn't result in any overlaps with other antennas, then the new position is kept

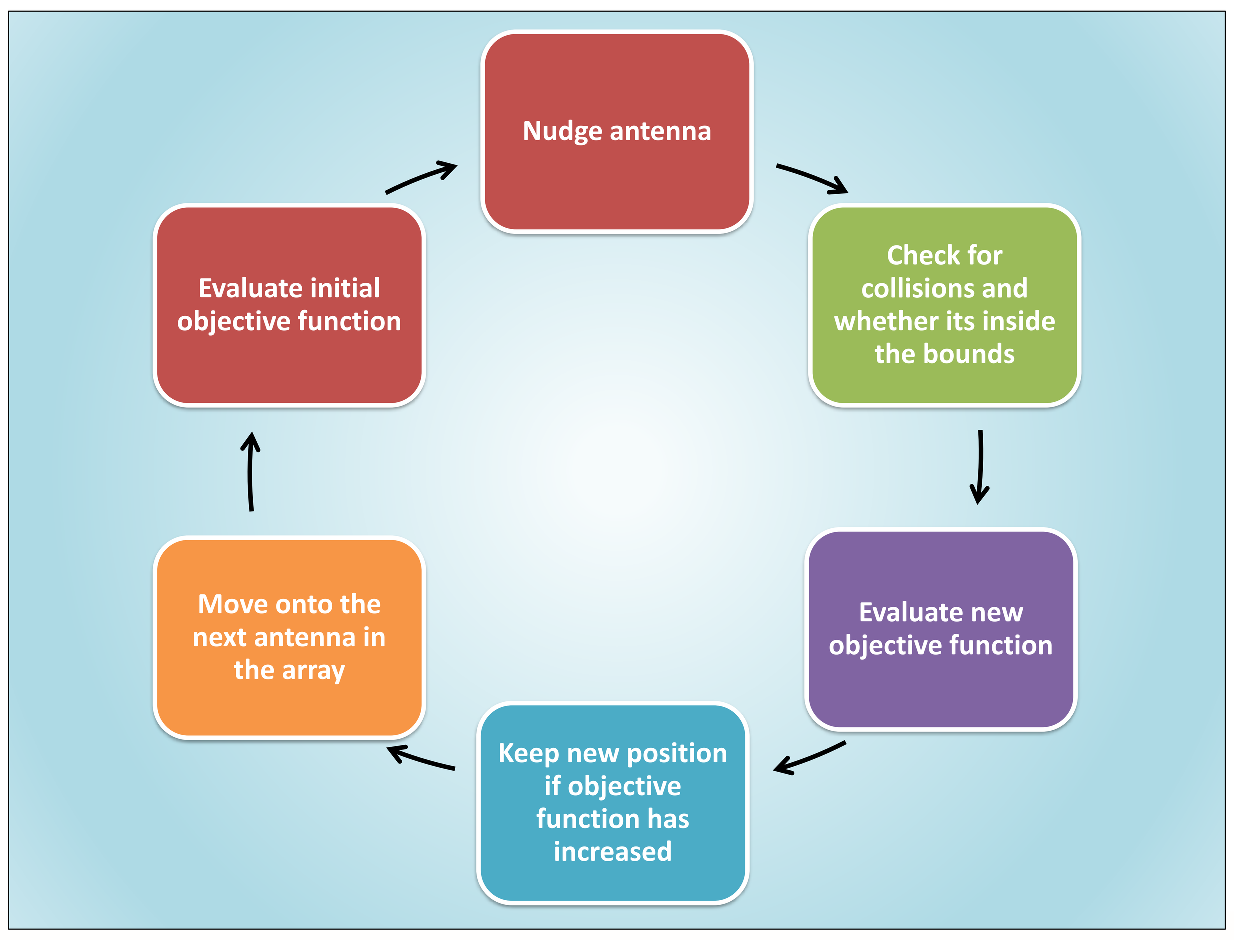

Figure 3: Flow chart for a single iteration of the optimisation process. This loop is completed once for every antenna in the array

- **Objective function**:
  - **Computational efficiency** was critical, so a simple process is used to approximate the side-lobe power
    1. The interference pattern is created
    2. Then a central circle just bigger than the main-lobe is cut out from the pattern
    3. The ratio of power between outside and inside the circle is found:
       a) Measured in *dB*, this value is referred to as the "side-lobe rejection" [3]
    4. This method is faster than a full 2D peak search and as a benefit, penalises large beamwidths whenever the main-lobe impinges on the circle
- More thorough **performance analysis** was undertaken such as full theoretical image reconstruction and beamwidth determination

3b Methodology

It is important to clarify **what** the "**interference pattern**" is and **why** we use it.

- **What is it**?
  - Each antenna is modeled as a spherically radiating point source.
  - At each grid point on a 2D virtual imaging screen, all signals are summed over, and the results is squared to get intensity. These signals are then time averaged
  - This resultant image is called the **interference pattern**
- **Why do we use it**?
  - The interference pattern represents a map of **sensitivity** or response to radiation with the array digitally steered straight ahead
  - **In an ideal** world the antenna array would only pick up signals in the direction it is steered in and ignore radiation from other directions
    - **In reality**, when the array is steered in a particular direction, the array is sensitive to signals from other directions, these other directions are called side-lobes (see Figure 2)
  - **In summary**, the interference pattern is critical in finding and quantifying the power of these unwanted side-lobes, or peripheral sensitivity areas

4 Results

This project produced a python module that successfully creates and optimises a phased antenna array and allows freedom in choice of objection function. The user can then choose from a selection of performance analysis functions such as beamwidth, directivity, sidelobe level and other common phased array metrics.

The key outcome of this research is a new array design with improved performance over the current array. This array, with 20 antennas, has been manufactured and is on track to be integrated into SAMI-2 and placed in a diagnostics port at MAST-U.

Optimisation Success

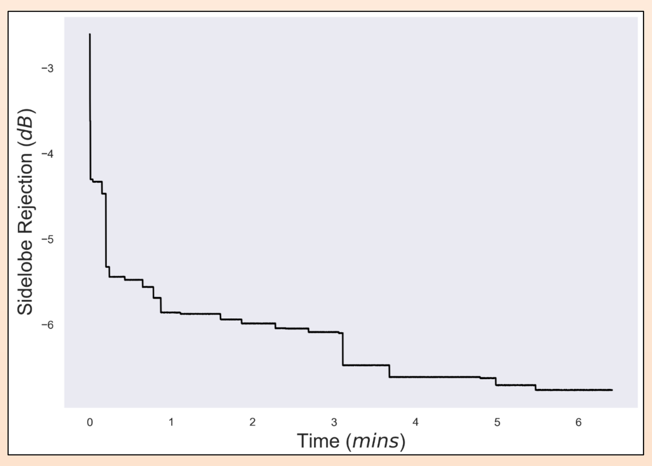

Figure 4: Optimisation progress with time as performed on a 20-antenna array

Performance Before and After

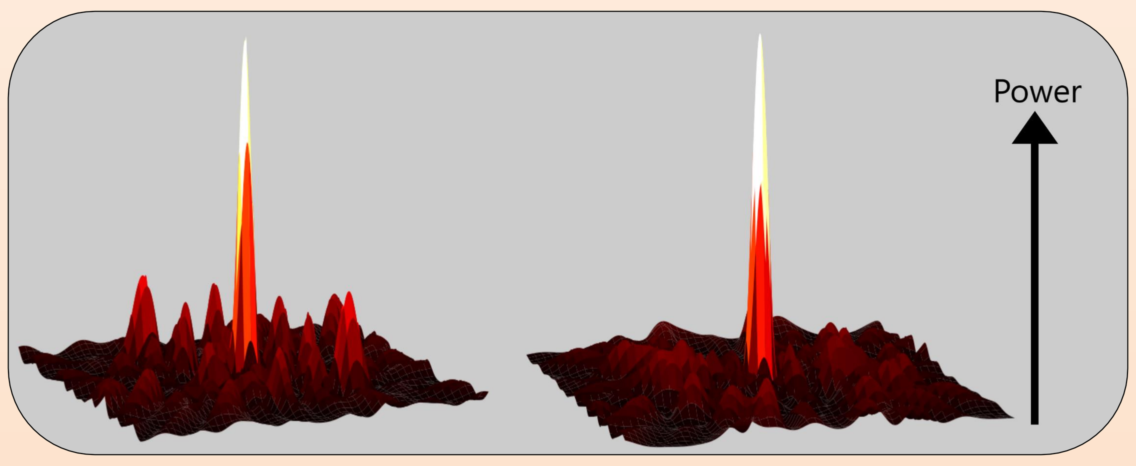

Figure 5: Visualisation of improvement: Interference pattern intensity before (***left***) and after optimisation (***right***) for an array with 20 elements

Example Performance Analysis

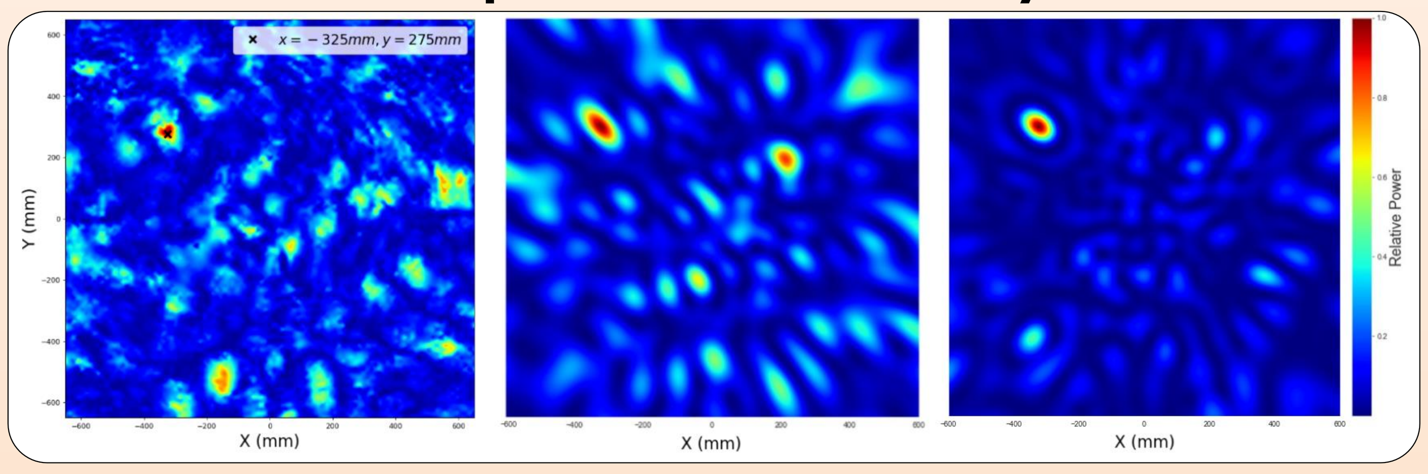

Figure 6: Image reconstructions of single source placed at a known location. Calibrated image from experimental data, taken with *a 9-antenna array* (***left***), image from virtual data using the same array (***middle***) and image from virtual data using the proposed 20-antenna array (***right***)

5 Conclusions

- The results of this study demonstrate the feasibility of using full beamforming calculations within an optimisation function when designing phased arrays
- The antenna layout of a 20-element array was successfully adjusted, reaching a final sidelobe rejection value of (-8.1±0.2)*dB*, a significant improvement over other non-optimised 20-element arrays which averaged (-5.1 ± 0.9)*db*
- It was found that in order to reconstruct accurate images using SAMI-2, a full phase-grid calibration method was required
- Next steps for this research should include determining which image reconstruction method is most suitable for SAMI-2 and improving the calibration robustness. After brief trials, neural networks showed promise in accurate image prediction and may provide an interesting area of future study

Acknowledgments and References

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[1] Thomas, D. A., Brunner, K. J., Freethy, S. J., Huang, B. K., Shevchenko, V. F., & Vann, R. G. L. (2016). 2D Doppler backscattering using synthetic aperture microwave imaging of MAST edge plasmas. Nuclear Fusion. vol. 56, no. 2.

[2] Allen, J. O. (2021). Design of the Synthetic Aperture Microwave Imager-2 for measurement of the edge current density on MAST-U. University of York, Department of Physics.

[3] Robert Mailloux, (2017), Phased Array Antenna Handbook, Third Edition, Artech.