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Title of the research project

Automated design of reflector feed antennas

Broad area of research:

Engineering

Academic level of research project:

Doctoral

Primary supervisor's details:

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Abstract of research project

Radio astronomy relies heavily on reflector antennas to provide the high-quality beams required for high-fidelity imaging and the associated science. Sometimes systems (including the associated reflector optics) get developed from scratch, like MeerKAT, SKA, ngVLA, and the DSA-2000 at present, but in many other cases an ad-hoc design of a feed antenna is needed to replace/upgrade the feeds on existing reflectors. This project will leverage the recent advances in feed technology, electromagnetic simulation, mathematical modelling, and machine learning on large data sets, to develop an automated design tool for reflector feed antennas. The goal of the tool is to synthesize near-optimal feed geometry from a set of input specifications (like operating frequency, bandwidth, reflector geometry main beam pattern constraints, etc), with minimal intervention from the user. The extent to which this can be achieved is unclear at present, but at least some level of automation is certainly possible, including for commercial applications outside of radio astronomy.

Details of Research Project

1. *Engineering merit:*

This project falls squarely in the first focus area for engineering postgraduate research for 2026, since it directly addresses skills needed to design antennas for radio astronomy – using (and expanding) the latest design technology.

The overarching strategy will be to develop fast forward models of the antenna response, and then to use these to train a machine learning model or Bayesian parameter estimators to solve an optimization problem. In principle, if we have a fast enough forward model it is easy to evaluate it as many times as we need to find the optimum (in some measure). To make the strategy viable in a multi-objective or variable measure situation, it is best to model radiation patterns and input impedance levels completely instead of specific derived quantities (like aperture efficiency or sensitivity). In this context, a few objectives can be identified:

1. **Develop Fast Forward Models for Feed and Reflector Antenna Response Prediction**

- Construct computationally efficient models for predicting feed impedance, radiation patterns and the corresponding reflector antenna response.
- These models will be based on a limited set of feed antenna classes (octave-band corrugated horns and wide band Quad-ridge flared horns to start with).
- Implement a modelling approach that exploits reference reflector system data, requiring only the modelling of pattern deviations between the reflector at hand and a well-characterized reference system (as was recently shown to work well in a PhD by Mariet Venter).
- Evaluate trade-offs between full wave/asymptotic electromagnetic simulations, surrogate models, and analytical approximations in terms of accuracy and computational efficiency.

2. **Train Machine Learning Models or Bayesian Estimators for Feed and Reflector Optimization**

- Utilize the fast forward models to generate training data for machine learning algorithms or Bayesian parameter estimation methods.
- Investigate optimization techniques (e.g., Bayesian optimization, evolutionary algorithms, neural networks) for efficiently navigating the design space while accounting for both feed and reflector performance.

3. **Formulate and Solve a Multi-Objective Feed and Reflector Design Optimization Problem**

- Define an optimization framework that considers multiple performance metrics, such as reflection coefficient, main beam efficiency, sidelobe levels, spillover, and cross-polarization.
- Ensure flexibility by allowing the user to specify custom design goals while maintaining an automated workflow.

4. **Evaluate and Validate the Automated Feed and Reflector Design Approach**

- Compare the machine-learning-based designs against traditional manually designed systems.
- Validate the approach using electromagnetic simulations and, where possible, experimental measurements.
- Assess the impact of using reference reflector data to speed up design convergence and improve prediction accuracy.

These objectives align closely with critical questions in modern reflector antenna design:

- **Can fast forward models replace expensive full-wave simulations in feed design optimization?**
Efficient surrogate models could significantly reduce computation time, making real-time or large-scale optimization feasible.
- **How well can machine learning and Bayesian methods navigate complex antenna design spaces?**
This research will test whether these approaches can outperform traditional iterative design methods in speed and performance.
- **How should multi-objective optimization be formulated for reflector feed design?**
Instead of optimizing derived quantities (e.g., aperture efficiency), this project focuses on direct modelling of radiation patterns and impedance characteristics, potentially leading to more flexible and general solutions.
- **How adaptable is the automated tool to different antennas and application domains?**
The developed methods should be robust enough to generalize across various reflector geometries and use cases beyond radio astronomy.

2. *Feasibility: outline the methods that will be used to achieve the objectives.*

To achieve the research objectives, a combination of electromagnetic modelling, machine learning, and optimization techniques will be employed. First, efficient forward models will be developed to predict both feed radiation patterns and reflector antenna responses. Instead of relying solely on computationally expensive full-wave simulations, surrogate modelling techniques such as Radial Basis Function Interpolation, Gaussian Process Regression, and neural networks will be explored. In particular, the reflector pattern modelling will leverage reference system data, focusing only on the deviations between the given reflector and a well-characterized reference model, significantly reducing computational effort. For both impedance and pattern models the feature space will be represented compactly by numerical basis function weights to reduce the forward modelling dimensionality.

The optimization process will be formulated as a multi-objective problem, balancing key performance metrics such as beam efficiency, spillover, sidelobe levels, and impedance matching. A range of optimization strategies will be investigated, including Bayesian optimization, genetic algorithms, and reinforcement learning, to efficiently explore complex and high-dimensional design spaces.

The developed framework will be validated through high-fidelity electromagnetic simulations. Benchmarking against existing manually designed feeds will ensure that the automated approach meets or exceeds current performance standards. The adaptability of the tool across different reflector configurations and application areas, including radio astronomy, satellite communications, and radar systems, will be assessed by comparison with the state-of-the-art. By integrating these methods, this research aims to develop a robust and efficient automated design tool that can significantly enhance the speed and quality of feed and reflector antenna optimization.

3. *Skills development*

The candidate will develop skills in antenna design and simulation, as well as in mathematical modelling and inference.

4. *Details of the availability of required infrastructure/equipment*

Most of the work will be simulation driven, so physical infrastructure required is mainly computers and simulation software – all of which are available in the research group. Specifically access to CST, GRASP and MATLAB will be needed.

5. *Milestones*

Y1S1: Literature study, and initial implementation of forward models of feed antennas. Start data generation of feed antennas.

Y1S2: Complete and test forward models of the feeds. Start data generation of reflector patterns.

Y2S1: Complete and test forward model of reflector patterns. Write a conference paper on forward modelling strategy.

Y2S2: Build optimization framework and start generating optimized designs.

Y3S1: Complete optimized designs and compare them to literature. Evaluate the efficacy of the method and write journal paper.

Y3S2: Write dissertation.

6. This project is most suited to a student with an interest in both mathematical modelling as well as antenna design. Experience in radio astronomy related projects would be helpful.

PUBLICATIONS

INTERNATIONAL JOURNAL PAPERS

1. (2026) D.I.L. de Villiers, Z. du Toit and R. Lehmensiek, 'Tri-Ridge Flared Horn Antennas as a Trapped Mode Free Alternative to Quad-Ridged Flared Horns in Wideband Reflector Feed Applications', *IEEE Transactions on Antennas and Propagation*, submitted.
2. (2026) G.V.C. Allen, S. Pegwal, D.I.L. de Villiers, and the REACH collaboration, 'Circuit Modeling for In Situ 21 cm Radiometer Calibration', *Journal of Astronomical Instrumentation*, submitted.
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8. (2024) R.-M. Weideman, A. Cuyt and D.I.L. de Villiers, "Characterizing the Electric Field Ripple in Reflector Antennas Using Sub-Sampled Exponential Analysis", *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 7, pp. 5511 – 5519, Jul. 2024.
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11. (2022) D.I.L. de Villiers and R. Lehmensiek, "Multi-level Approximations for Fast and Accurate Antenna Noise Temperature Calculation of Dual-Reflector Antennas", *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 6, pp. 4784-4793, Jun. 2022.
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 19. (2021) F. Mokhupuki and D.I.L. de Villiers, "Efficient optimisation of wideband reflector feed antennas for optimal receiving sensitivity", *Wiley International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 34, no. 3, 2021; pp. e2849.
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INTERNATIONAL CONFERENCE PROCEEDINGS

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2. (2025) G.V.C. Allen, D.I.L. de Villiers and S. Pegwal, "Balun Circuit Modelling for Global 21-cm Experiments", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Palermo, Italy, September, 2025, pp. 437-442.
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9. (2022) R. Lehmensiek and D.I.L. de Villiers, "Faster optimization of quadruple-ridged flared horns using geometric feasibility parameters", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Cape Town, September 2022.
10. (2021) R. Lehmensiek and D.I.L. de Villiers, "A tolerance study of the 18 m offset Gregorian dual reflector antenna for the ngVLA", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Honolulu, HI, August 2021.
11. (2021) F.T.T. Mokhupuki and D.I.L. de Villiers, "Fast Surrogate-Based Optimization of Wideband Quad-Ridge Flared Horn Feeds for SKA and ngVLA", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Honolulu, HI, August 2021.
12. (2021) D.I.L. de Villiers, E. De Lera Acedo, J.M. Cumner, Q.D. Gueuning on behalf of the REACH collaboration, "Antenna Design for the REACH Global 21cm Experiment", *URSI General Assembly*, Rome, Italy, August 2021.
13. (2021) E. De Lera Acedo and D.I.L. de Villiers on behalf of the REACH collaboration, "Exploring the sky-averaged 21-cm line from the South African Karoo using REACH", *URSI General Assembly*, Rome, Italy, August 2021.
14. (2021) R. Lehmensiek and D.I.L. de Villiers, "On the design of the 18 m offset Gregorian dual reflector antenna for the ngVLA" *URSI General Assembly*, Rome, Italy, August 2021.
15. (2019) D.I.L. de Villiers, R. Louw, R. Weideman, A. Cuyt, et al., "Practical Performance of Regular Sparse Array Direction of Arrival Estimation in 1-D", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Grenada, Spain, September 2019.
16. (2019) B. Klopper, D.I.L. de Villiers and E. de Lera Acedo, "Antenna Design and Optimisation of the Radio Experiment for the Analysis of Cosmic Hydrogen", *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Grenada, Spain, September 2019.
17. (2017) R. Lehmensiek and D.I.L. de Villiers, "On the performance limits of the SKA1-mid reflector system", 32nd URSI General Assembly, Montreal, Canada, August, 2017.
18. (2013) M. H. Volkmann, C. J. Fourie, D.I.L. de Villiers, D.B. Davidson, W.J. Perold, and T. Ortlepp, "Improving the Square-Kilometre Array with Superconductor Electronics", *European Conference on Applied Superconductivity (EuCAS)*, Genova, Italy, September, 2013.
19. (2011) M.H. Volkmann, C.J. Fourie, W.J. Perold, D.B. Davidson, H.C. Reader and D.I.L. de Villiers, "Superconducting circuits in the Square Kilometre Array radio telescope", *European Conference on Applied Superconductivity (EuCAS)*, The Hague, The Netherlands, September, 2011.

NATIONAL CONFERENCE PRESENTATIONS

1. (2018) D.I.L. de Villiers, 'The SARChI Chair in Antenna Systems for the SKA at Stellenbosch University' *South African IEEE AP/MTT/EMC Conference*, Stellenbosch, South Africa, August, 2018.
2. (2016) N. Mutoenkole, D.I.L. de Villiers, 'Parametric Modelling of Antenna Responses' *South African IEEE AP/MTT/EMC Conference*, Stellenbosch, South Africa, July, 2016.
3. (2014) D.I.L. de Villiers, R.D. Beyers, 'Recent Advances in Conical Transmission Line Power Combiner Design' *South African IEEE AP/MTT/EMC Conference*, Pretoria, South Africa, May, 2014.
4. (2011) D.I.L. de Villiers, R. Lehmensiek, E. Knox-Davies and I.P. Theron, 'Preliminary Reflector Design of the MeerKAT Radio Telescope' *South African IEEE AP/MTT/EMC Conference*, Stellenbosch, South Africa, April, 2011.
5. (2009) D.I.L. de Villiers, 'Ultra Wideband Reflector Antenna Feeds' *South African SKA Postgraduate Bursary Conference*, Stellenbosch, South Africa, December, 2009.
6. (2009) D.I.L. de Villiers, 'Development of a Wideband Ortho-Mode Transducer' *South African IEEE AP/MTT Conference*, Stellenbosch, South Africa, March, 2009.
7. (2008) D.I.L. de Villiers, 'Development of a Wideband Ortho-Mode Transducer' *South African SKA Postgraduate Bursary Conference*, Stellenbosch, South Africa, December, 2008.
8. (2007) D.I.L. de Villiers, P. Meyer and P.W. van der Walt, 'Design of a Ten-Way Conical Transmission Line Power Combiner' *South African IEEE AP/MTT Conference*, Stellenbosch, South Africa, March, 2007.

GRADUATE SUPERVISION

COMPLETED PHD DEGREES

1. (2020-2025) Zain du Toit (Co-supervisor with Prof. Robert Lehmensiek): 'A tri-ridge horn antenna for radio astronomy applications'
1. (2024-2025) Sindhu Gaddam (Co-supervisor with Prof Kavilan Moodley, student at UKZN), 'Design, Optimization, and Characterization of a Wideband Dual Polarized Feed Antenna for the HIRAX Radio Telescope'
2. (2022-2025) Steven Ndungu (Co-supervisor with Prof Stefan Wijnholds, Prof George Azzopardi and Dr Trienko Grobler): 'CARAD: Computer-aided Analysis of Radio Astronomy Data'
3. (2021-2024) Carla Pieterse: 'Antenna Beam Pattern Modelling for Sky-Averaged 21 cm Cosmology Experiments'
4. (2020-2024) Mariet Venter (Part-time student): 'Parametric Beam Modelling for Reflector Antennas'
5. (2021-2023) Rina-Mari Weideman (Co-supervisor with Prof Annie Cuyt): 'Sub-sampled Exponential Analysis in Antenna Applications'
6. (2019-2023) William Cerfonteyn: 'Impact and Cause of Sensitivity Ripple in Radio Astronomy Reflector Antennas'
7. (2021-2022) Prof Coenrad Fourie (DEng): 'Inductance in Superconductor Integrated Circuits'
8. (2019-2022) Ridalise Raal (Co-supervisor with Prof Annie Cuyt): 'Sub-Sampled Exponential Analysis Applied to Sparse Planar Antenna Array Configurations'
9. (2020-2022) Scott Kriel: 'A Figure of Merit for the X-Band All-Sky Survey'
10. (2017-2020) Fahmi Mokhupuki: 'Efficient Optimisation of Wideband Reflector Feed Antennas'
11. (2016-2019) Jako du Toit (Upgraded from Masters in 2018): 'Partially Filled Radial Power Combiner with Port Isolation'
12. (2018-2019) Jan-Gerald Bij de Vaate: 'Expanding the Field of View: Station Design for the AAMID SKA Radio Telescope'
13. (2016-2018) Brandt Kloppe: 'Antenna Elements for Sparse-Regular Aperture Arrays'
14. (2014-2016) Ngoy Mutonkule, 'Modelling of Antenna Responses'
15. (2013-2015) Ryno D. Beyers: 'Circuit Model Design of Conical Transmission Line Power Combiners and Isolation of Reactive Combiners'

COMPLETED MASTER'S DEGREES

1. (2024-2025) Madison Crews: 'Design of a feed antenna for the HIRAX telescope'
2. (2022-2023) Raynard Swanepoel (Co-supervisor with Dr. Danie Ludick): 'Automated Synthesis of Array Antennas for Improved Accuracy in RF Safety Simulations using Spherical Wave Elements'
3. (2022-2023) Henry Johnston: 'Radio Frequency Direction Finding and the Watson-Watt Method'
4. (2020-2022) Yusuf Dhoda (Co-supervisor with Dr Werner Steyn): 'Wide-Band Radio Receiver for Radio Astronomy Applications'
5. (2020-2021) Insight Agbetsiafa (Co-supervisor with Dr Trienko Grobler): 'An RFI Simulation Pipeline to Help Teach Interferometry and Machine Learning'
6. (2020-2021) Stella Schleich: 'Design and implementation of a two-element interferometer'
7. (2020-2021) Jacques Wolmarans: 'Beam ripple modelling in wideband dual-reflector antenna systems'
8. (2017-2020) Hein Swart (Part time student): 'Wideband Axially Symmetric Power Combiners Based on Short Step Filters'

9. (2019-2020) Rina-Mari Weideman: 'Linear Sparse Regular Array Antenna Demonstrator'
10. (2019-2020) Carla Pieterse: 'Comparison of prime focus and offset Gregorian reflector antennas for 21 cm intensity mapping' (Co-supervisor with Prof. Kavilan Moodley; Student at UKZN)
11. (2018-2019) Scott Kriel: 'Viability of UAV-based Antenna Pattern Measurements'
12. (2018-2019) Zain du Toit (Co-supervisor with Dr. Carlo van Niekerk): 'Wideband, low loss feed integration with a Pyramidal Sinuous Antenna'
13. (2018-2019) Jackline Koech (Co-supervisor with Dr. Gideon Wiid): 'Modified horn-type antennas for SKA RFI Monitoring'
14. (2017-2018) Michael Johnston (Co-supervisor with Dr. Carlo van Niekerk): 'Wideband Balun Design for the Pyramidal Sinuous Antenna'
15. (2017-2018) Shane Moyce: 'Hardware limitations of interference suppressing beamforming'
16. (2017-2018) William J. Cerfonteyn: 'A 22.2 GHz Antenna for Water vapour Radiometry'
17. (2015-2018) David Wolsky (Part time student): 'Automated Space-Mapping Framework for Electromagnetic Device Optimisation'
18. (2016-2017) Clifford Sibanda: 'Design and Optimization of Gap Waveguide Components through Space Mapping'
19. (2016-2017) Ridalise Louw: 'Surrogate Modelling of Performance Metrics of a Wideband Feed for the SKA Reflector Antenna'
20. (2016-2017) Malan A.X. Ruppert: 'A Study on Phased Array Feeds for Paraboloidal Reflector Antennas' – Co-Supervisor with Dr. Ryno Beyers
21. (2015-2017) Nicol Steenkamp: 'Design of a Wideband Sinuous Antenna for Radio Telescope Applications'
22. (2014-2015) Alex A. Vermeulen: 'The design of a dual reflector feed using surrogate modeling techniques'
23. (2014-2015) Brandt Klopper: 'Fast Design and Optimisation of One-Dimensional Microstrip Patch Antenna Arrays'
24. (2013-2014) Lukas M. van Vuuren: 'Design of a Receiver System for Use in Radio Astronomy'
25. (2012-2013) Ngoy Mutionkole: 'Study of a Wideband Sinuous Feed for Reflector Antenna Applications'
26. (2011-2013) Dewald Schoeman: 'Full Scale Low-Cost Ultra Wide Band Antenna for SKA Low Frequency Array'
27. (2011-2012) Alex Ibbotson: 'The Design and Analysis of a Rotman Lens with Reduced Conjugate Port Coupling' – Co-Supervisor with Prof Keith Palmer
28. (2010-2012) Stephanie Alphonse: 'Fast Analysis of a Compound Large Reflector Antenna' – Co-Supervisor with Prof Keith Palmer
29. (2010-2011) Shamim O. Nassar: 'An Investigation of the Equivalence Between Comblin and Evanescent-Mode Waveguide Filters & of Aspects Related to Reduction of Manufacturing Costs for Comblin Filters' – Co-Supervisor with Prof. Petrie Meyer
30. (2010-2011) David VdM. Prinsloo: 'Characterisation of L-band Differential Low Noise Amplifiers' – Co-Supervisor with Prof. Petrie Meyer
31. (2010-2011) Phillip Terblance: 'Electronically Adjustable Bandpass Filter' – Co-Supervisor with Prof. Petrie Meyer
32. (2009-2010) Karla Schoeman: 'Waveguide Antenna Feed for the Square Kilometre Array' – Co-Supervisor with Prof. Petrie Meyer
33. (2009-2010) Sunelle Otto: 'A study of radio astronomy principles and SKA pathfinder system designs with pulsar science' – Co-Supervisor with Prof. Petrie Meyer

CURRENT PHD STUDENTS

1. (2024 - 2026) Gary Allen (Upgraded from MEng end 2025)
2. (2025 - 2026) Michele Pugno (Co-supervisor with Prof. Annie Cuyt and Dr. Jacki Gilmore)
3. (2023-2026) Aiden Lötter (Upgraded from MEng end 2024)
4. (2024 - 2026) Graeme Young (Part-time student; co-supervisor with Dr. Werner Steyn)

CURRENT MASTERS STUDENTS

1. (2025-2026) Gerben Visser



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Electrical & Electronic Engineering
Elektriese & Elektroniese Ingenieurswese

26 February 2026

To whom it may concern

Confirmation of Data Collection Facilities for Postgraduate Research

This letter is to confirm that the Department of Electrical and Electronic Engineering at Stellenbosch University has the following software licences and data collection facilities available for postgraduate research.

Software Licences for Full-Wave Electromagnetic Simulations:

- Altair Feko
- CST Microwave Studio
- Ansys HFSS

Software Licenses for RF system design:

- AWR Microwave Office
- Keysight ADS

Software License for Asymptotic Electromagnetic Analysis:

- GRASP by TICRA

Software License for Data Analysis and Mathematical Modelling:

- MATLAB

RF Measurement Equipment and Facilities

- Vector Network Analysers
- Spectrum Analysers
- RF Signal Generators
- Oscilloscopes
- Anechoic Antenna Measurement Range
- Reverberation Chamber

Kind regards,

Dirk de Villiers