Radio Telescope Design for the Observation of 21 Cm Neutral Hydrogen Emission

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Abstract - The detection of the global 21 cm hydrogen signal from the early Universe presents significant challenges due to the extremely faint nature of the signal compared to foreground emissions. This project focuses on the design and analysis of a radio antenna system developed for the REACH (Radio Experiment for the Analysis of Cosmic Hydrogen) initiative. By leveraging a quantitative, figure-of-merit-driven methodology, we explore how antenna geometry, impedance matching, and beam chromaticity affect the system's ability to distinguish the cosmological signal from foreground noise. Various candidate antenna designs, including wide-beam dipoles and high-gain structures, are evaluated through electromagnetic simulations and mock detection pipelines. We assess their performance based on spectral smoothness, calibration feasibility, and compatibility with Bayesian data analysis techniques. The final design prioritizes simplicity and spectral stability while maintaining a broad operational bandwidth, aiming to enhance the robustness and reliability of global 21 cm hydrogen signal detection.

Key Words **:** 21 cm Cosmology, REACH Experiment, Radio Antenna Design, Sky-Averaged Signal, Antenna Beam Chromaticity, Electromagnetic Simulation, Partial Sky Mapping, Impedance Matching, Wideband Dipole, Chromaticity Correction, Foreground Modeling, Bayesian Calibration, CST Microwave Studio, Figure of Merit Optimization, Global Signal Detection, Low-Frequency Radiometry, Ground Plane Effects, Balun Design, Spectral Smoothness, Signal Injection Pipeline.

1.INTRODUCTION

Understanding the early Universe requires decoding the faint cosmic signals that have traveled billions of years to reach us. Among these is the global 21 cm hydrogen line — a key spectral signature from the Cosmic Dawn and the Epoch of Reionization (EoR). However, detecting this signal presents a substantial challenge: the target signal is extremely weak, buried beneath foreground radiation that can be up to five orders of magnitude stronger. This project focuses on the design and analysis of a radio antenna system developed for the REACH (Radio Experiment for the Analysis of Cosmic Hydrogen) initiative, a global 21 cm experiment that aims to provide a definitive detection of this elusive signal.

In global 21 cm experiments, a single antenna integrates sky signals over time and across the visible sky. These measurements are represented as variations in antenna temperature across frequency, but the system's response is influenced not just by the sky but also by the antenna's beam pattern and impedance characteristics. Therefore, a significant aspect of successful detection involves the careful design of the antenna structure, ensuring spectral smoothness, low reflection coefficients, and predictable beam chromaticity. Previous experiments like EDGES, SARAS2, and BIGHORNS have demonstrated the importance of these properties, with varying levels of success and challenges in calibration.

The REACH project adopts a quantitative figure-of-merit (FoM) approach to antenna design, using extensive electromagnetic simulations in CST Microwave Studio to refine both the electrical and spatial characteristics of candidate antennas. Key metrics such as impedance matching, bandwidth, beam chromaticity, and ease of calibration are used to evaluate antenna performance. Both low-resolution (wide-beam) and high-resolution (narrow-beam) antenna architectures are assessed, each with distinct trade-offs in complexity, modeling requirements, and susceptibility to chromatic distortions. In particular, wide-beam dipoles are favored for their simplicity and spectral stability, despite their greater dependence on accurate sky modeling.

To ensure that the antenna designs remain robust against systematic errors, the project incorporates Bayesian calibration techniques and mock signal injection pipelines. These tools help evaluate how different designs respond to sky-averaged signals and foreground models, including spatial variations in spectral index. The integration of simulations with data analysis workflows ensures that the final design is not only physically feasible but also optimized for real-world observational conditions.

The rest of this report is organized as follows: Section 2 presents a comparison of various antenna architectures and their influence on foreground modeling and beam chromaticity. Section 3 details the figure-of-merit driven design process, including simulation methodologies and scaling techniques. Section 4 discusses the implementation and refinement of the REACH dipole antenna. Finally, Section 5 concludes the report and outlines future directions for improving antenna performance and expanding the REACH observational campaign.

2. Body of Paper

The exploration of the early Universe has driven cosmologists to develop novel techniques capable of detecting signals emitted during the Cosmic Dawn and Epoch of Re-ionization (EoR). One of the most promising signatures is the global 21 cm signal from neutral hydrogen. This sky-averaged signal, originating from the hyper fine transition of hydrogen atoms, provides invaluable insights into the formation of the first stars and galaxies. However, the extreme faintness of this signal compared to foreground emissions such as synchrotron radiation poses a significant detection challenge.

Unlike interferometric approaches, global 21 cm experiments rely on single-element radiometers with wide beam antennas that integrate signals across the sky. The antenna temperature, which reflects the combination of foregrounds and cosmological signals weighted by the antenna's beam pattern, is used as the primary observable. Any spectral structure introduced by the antenna or receiver may mimic or mask the 21 cm absorption feature, making spectral smoothness and beam calibration critical factors. The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) is one such initiative that aims to deliver a confident detection of this signal by combining robust antenna design with a Bayesian calibration framework.

To address this challenge, the REACH project adopts a figure-of-merit-based design methodology, emphasizing the interplay between electromagnetic performance and data analysis compatibility. Central to this process is the ability to model how the antenna responds to both the sky and instrumental effects, enabling accurate post-processing and foreground removal. Several antenna configurations were evaluated, including idealized dipoles, bow-tie dipoles, log-periodic designs like SKALA, large reflector-based systems like HERA, and capacitively-loaded dipole arrays (CLDA). Each design presented unique trade-offs between angular resolution, beam chromaticity, physical complexity, and calibration feasibility.

Low-angular-resolution antennas such as dipoles and SKALA offered smoother, more predictable beam responses, which are easier to model and calibrate. These antennas typically feature half-power beamwidths greater than 20°, allowing them to average out large portions of the sky and reduce sensitivity to spatial foreground fluctuations. However, even minor frequency-dependent variations in their beam patterns, often called "beam chromaticity," can significantly distort the measured antenna temperature spectrum. To assess these distortions, simulations were conducted using CST Microwave Studio, and the resulting beams were combined with realistic sky maps using both constant and spatially-varying spectral indices.

In contrast, high-angular-resolution designs like HERA and CLDA promised improved directional control and the potential to avoid bright foreground regions. However, their narrower beams came with increased chromaticity, complex mutual coupling effects, and heightened sensitivity to modeling errors. Additionally, their large physical size and structural complexity made them harder to simulate and build. While these designs could, in principle, isolate cleaner sky regions, their beam variations over frequency posed substantial risks to signal fidelity and calibration accuracy.

To quantify antenna performance, REACH employed several figures of merit (FoMs), including reflection coefficient (S11), impedance bandwidth, spectral smoothness, and beam chromaticity variance. These metrics allowed designers to evaluate the trade-offs between different antenna geometries and guide the refinement process. For example, smoother S11 curves indicate better impedance matching across the frequency band, improving calibration reliability and reducing signal distortion. Similarly, lower beam chromaticity variance correlates with a reduced risk of foreground leakage into the 21 cm signal band.

Another crucial part of the design pipeline was the use of a mock detection system. This framework simulated sky observations by injecting artificial 21 cm signals into a sky map and processing the results through the REACH Bayesian calibration pipeline. This approach allowed designers to evaluate how different antenna configurations influenced the detectability of the signal under realistic observational conditions. Variants of each antenna design were tested using this setup, revealing that even structurally similar designs could yield dramatically different levels of residual foreground contamination after calibration.

Ultimately, a wideband dipole design was selected as the baseline for REACH Phase I. This choice was driven by its balance of spectral smoothness, ease of modeling, and manufacturability. The selected dipole uses a seven-pointed blade geometry and a Roberts-style balun for impedance transformation. The geometry was defined by 14 parametric variables, including blade length, width, tapering, spacing, and balun dimensions. A Latin hypercube sampling method was used to explore the design space efficiently. Simulations were run for each candidate using CST's frequency domain solver with adaptive meshing, and results were evaluated using the defined FoMs. Designs with steep S11 transitions, poor chromaticity correction, or overly complex meshes were filtered out.

An additional consideration was ground plane configuration. Finite ground planes introduce edge reflections that produce sinusoidal ripples in the beam pattern, potentially complicating the frequency response. To minimize these effects, a 10-meter circular ground plane was simulated in combination with the dipole, striking a balance between reflection suppression and realistic deployment constraints.

Following simulation and figure-of-merit evaluation, the top candidate designs were fabricated and field-tested in the Karoo Radio Astronomy Reserve in South Africa. Environmental effects such as ionospheric variability, soil conductivity, and local radio-frequency interference were also considered during site selection and hardware testing. The final dipole antenna was integrated into the REACH system with a well-characterized receiver chain and calibrated sky models.

This body of work demonstrates that precise control over antenna geometry, beam behavior, and impedance characteristics is essential for isolating the cosmological 21 cm signal. While antenna design is only one part of the signal detection pipeline, it lays the foundation for successful calibration and analysis. The REACH project's iterative, simulation-driven design methodology—backed by electromagnetic modeling, figure-of-merit scoring, and mock detection—provides a robust framework for building antennas that are not only efficient and manufacturable but also tailored for the extreme precision required in global 21 cm cosmology.

2.1 Existing System and Drawbacks: The current generation of sky-averaged 21 cm cosmology experiments faces several limitations stemming from antenna system design. Many existing instruments, including those used in prominent experiments like EDGES, SARAS2, and BIGHORNS, are built around simple dipole-based antennas that prioritize ease of construction and broad bandwidth coverage. While these designs are effective in terms of hardware simplicity and deployment, they often overlook critical issues related to beam chromaticity, spectral smoothness, and calibration complexity.

One of the key drawbacks of such systems is their limited ability to model or control how the antenna beam interacts with the foreground sky signal. In global 21 cm detection, this interaction can significantly affect the measured system temperature, leading to contamination of the faint cosmological signal. Many conventional designs utilize wide-beam antennas without taking into account the spatial-spectral structure of the foregrounds, leading to chromatic distortions that are difficult to calibrate out. This introduces non-smooth features in the data that can mimic or mask the desired 21 cm absorption trough, making reliable detection far more challenging.

Moreover, these systems tend to lack flexibility or configurability. Once deployed, antenna geometries are fixed, and any performance shortcomings must be compensated for in post-processing. The inability to iteratively refine the design through simulation or reconfiguration prior to deployment limits the effectiveness of optimization strategies. Additionally, many earlier antenna designs do not consider the time and frequency-dependent variations in beam behavior, especially in environments with changing ionospheric conditions or RFI (radio-frequency interference) contamination. This compromises the long-term stability and repeatability of observations.

These drawbacks highlight the need for a more modernized, simulation-driven antenna design methodology—one that not only optimizes for physical performance but also prioritizes calibratability and signal extraction fidelity. The REACH approach, which this project builds upon, introduces a new paradigm. By simulating thousands of antenna variants using CST Microwave Studio and evaluating

Table -1: literature survey

Author-year	Objective	Summary	Remarks
Cumner et al., 2022	Design and evaluate antennas for detecting global 21 cm signal (REACH case)	Presented a quantitative figure-of-merit-based design method to produce wideband, spectrally smooth antennas using CST simulations for REACH.	Introduced a systematic design pipeline including chromaticity correction and Bayesian modeling for improved signal recovery
Anstey et al., 2021	Apply Bayesian inference for 21 cm signal detection in REACH	Developed a data analysis pipeline that jointly models sky signal, foregrounds, and antenna response to extract weak cosmological signatures.	Provided a robust framework for integrating antenna modeling with statistical signal extraction, enabling calibration under high foreground contamination
Liu et al., 2013	Analyze antenna resolution impact on foreground modeling	Compared wide vs. narrow beam designs; emphasized that high angular resolution doesn't always reduce foreground error due to increased chromaticity	Highlighted the trade-off between angular focus and spectral smoothness, supporting REACH's choice of low-resolution, smooth-beam antennas.
Monsalve et al., 2017	Use chromaticity correction in EDGES experiment	Introduced a correction factor for antenna beam chromaticity based on known sky models to reduce spectral ripple effects in power traces.	Informed REACH's use of chromaticity correction in antenna design evaluation using realistic sky maps.
Fialkov & Barkana, 2019	Study variability of the 21 cm absorption trough	Predicted wide variation in timing and depth of the 21 cm signal, supporting the need for wide frequency observation ranges in	Motivated REACH's broad 50–135 MHz coverage for dipole antennas to capture diverse potential signal shapes.

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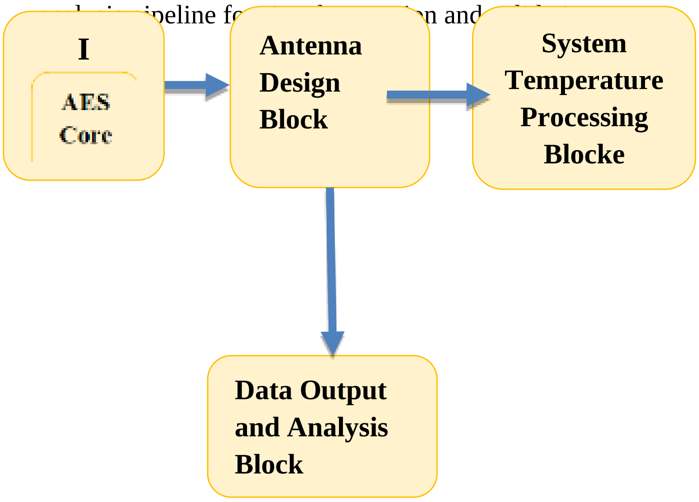
		antenna design.	
Kolitsidas et al., 2014	Propose simplified high-resolution antennas (CLDA)	Designed a capacitively loaded dipole array offering reconfigurable beam shaping for 21 cm detection with reduced chromaticity.	Inspired CLDA benchmarking in REACH for high-resolution comparison; showed beam shaping can lower leakage but increases complexity.
de Lera Acedo et al., 2017	Examine chromaticity in SKA-low antennas	Found that design features in log-periodic antennas induce sidelobe and beam chromaticity that interfere with 21 cm signal extraction.	Validated the need for beam smoothness in REACH antenna selection, as complex structures introduce spectral leakage.
Price et al., 2018	Describe large-aperture array concepts for Dark Ages detection	Proposed using a sparse aperture with interferometry for higher angular resolution detection of early-universe signals.	Reinforced REACH's contrast as a single-antenna, sky-averaged experiment prioritizing calibration over angular resolution.
Yang et al., 2016	Design bow-tie dipole antennas for wideband performance	Developed a tapered dipole with improved impedance and smoother frequency response using geometric shaping.	Informed REACH's dipole blade geometry tuning for better match and lower spectral ripple.

Existing Block Daigram

Sky Signal Input Block:
Represents the incoming sky-averaged radio signal, including the 21 cm line and dominant foreground emissions. .

Antenna Design Block: This block consists of the physical antenna structure and ground plane configuration. It captures the radio signal and introduces a specific beam response depending on geometry, materials, and layout. **System Temperature Processing Block:**Combines antenna beam response with sky models to compute the effective system temperature. This includes contributions from the foreground, instrument reflections, and the 21 cm signal. **Calibration and Chromaticity Correction Block:**Applies correction factors to account for beam chromaticity and impedance mismatches. Helps isolate the cosmological signal by smoothing spectral features and aligning the antenna model with real-world performance. **Data Output and Analysis Block:**Outputs the calibrated temperature data, which is then passed to the REACH Bayesian ipeline fo … n and



Existing Methodology

The conventional approach to detecting the global 21 cm signal in radio cosmology follows a standard system structure:

Antenna Design: A wide-beam dipole or monopole antenna captures incoming radio signals across a broad frequency band (typically 50–150 MHz **Beam-Sky Interaction Modeling:** The antenna's spatial beam is combined with sky models to estimate the received system temperature, including foregrounds and potential 21 cm signals. **Signal Integration:** The signal is time-averaged over long periods to reduce noise and extract the sky-averaged temperature spectrum. **Post-Processing Calibration:** Basic chromaticity correction is applied using pre-defined sky maps and beam models to mitigate spectral artifacts.

Existing Techniques

1) **Static Dipole Implementation:** Most systems use fixed dipole antennas with simple geometry and minimal calibration-aware design considerations.

2) **Basic Chromaticity Correction:** Corrections are applied using average spectral indices and generic sky

maps, without accounting for time or spatial variation, limiting accuracy in signal recovery..

2.1 Problem statement:

Detecting the global 21 cm signal requires highly sensitive and spectrally smooth antenna systems. However, conventional antenna designs often introduce beam chromaticity, impedance mismatches, and poor modeling alignment, which distort the faint signal and reduce detection reliability. The REACH project aims to address these challenges by systematically evaluating antenna design strategies using physically accurate simulations and quantitative figures of merit.

Key Vulnerabilities:

1. **Beam Chromaticity:** Frequency-dependent beam patterns distort foreground signals, complicating signal separation.
2. **Impedance Mismatch:** Poor matching leads to signal reflections, degrading system temperature accuracy.

Design Considerations in CST-style Simulation Flow: Implementation Strategies:

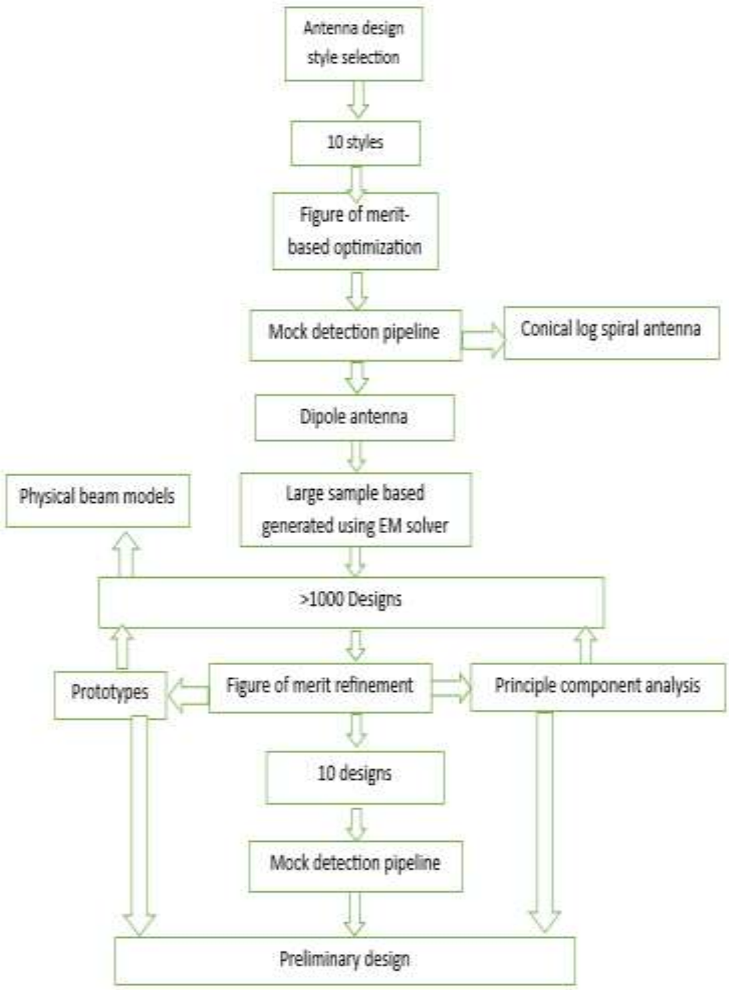
- **Geometric Variants:** Small physical changes in dipole arms, ground plane size, or balun structure affect chromaticity.

- **Broadband Performance:** Antennas must perform consistently across 50–135 MHz without introducing spectral features.

- **Simulation-Based Evaluation:** Metrics like reflection coefficient (S11) and chromatic correction factor variance are used to rank designs.

This project adopts a CST-based antenna design workflow that emphasizes low beam chromaticity and high impedance match. Antenna variants are evaluated through figures of merit tailored for 21 cm cosmology, ensuring that selected designs support REACH's Bayesian inference pipeline for robust signal recovery.

2.2 Proposed Block Diagram



Block Diagram Components:

Antenna Design Style Selection: The process begins by selecting 10 candidate antenna styles suitable for global 21 cm signal detection.

- These include geometries like dipoles, conical log spiral, and others based on prior research and feasibility.

Figure of Merit-Based Optimization

Each antenna style is evaluated using quantitative figures of merit (FoMs), such as beam chromaticity, impedance match, and spectral smoothness.

This helps in narrowing down designs that are most promising for clean signal recovery.

Mock Detection Pipeline

- A simulation framework tests how each antenna performs in signal detection, using realistic sky and foreground models.
- This ensures only designs with good observational behavior are considered for further development.

Antenna Type Selection (e.g., Dipole Antenna)

- The dipole antenna is selected as the primary candidate due to its wide beam, smooth response, and modeling simplicity.
- Other options like the conical log spiral are evaluated but deprioritized due to complexity or subpar performance.

Electromagnetic Simulation (EM Solver)

- A large dataset of >1000 antenna variants is generated using CST or similar EM solvers, simulating physical and spectral behavior
- These variants are used to explore the design space and identify optimal configurations.

Principal Component Analysis (PCA)

- Statistical reduction techniques like PCA are used to understand the key contributors to design performance.
- This simplifies comparison and clustering of high-performing variants..

Figure of Merit Refinement

- The top-performing designs are further refined based on a detailed FoM analysis.
- This step reduces the candidate set to 10 highly optimized designs.

Physical Beam Models

- Electromagnetic beam profiles of the top designs are modeled to evaluate real-world performance, including beam–sky interactions.

Prototyping

- Selected antenna designs are physically built to validate the simulation results.
- Ensures fidelity between simulated and real-world performance.

Final Mock Detection and Evaluation

- The 10 final designs are passed through the mock detection pipeline again to verify signal extraction capability under realistic conditions.

Preliminary Design Selection

- Based on all the above steps, a single optimized antenna design is chosen for deployment in the REACH experiment.

2.3 Software used / IDE used :: ANSYS HFSS

- Primary tool used for 3D electromagnetic simulation of antenna structures.
- Enabled full-wave analysis of dipole variants, including return loss (S11), impedance, radiation patterns, and chromaticity behavior.

MATLAB/Python(optional)
Used for post-processing simulation data such as impedance plots, reflection coefficients, and beam model comparisons.

Assisted in computing figures of merit like chromatic correction factors and visualizing frequency-domain results.

REACH Signal Analysis Toolkit (Internal)
Used for integrating antenna models with Bayesian foreground modeling and mock signal injection pipelines.

Enabled validation of design performance in realistic observation scenarios.

Sky Model Tools (e.g., Haslam Map Processing Scripts)
Provided foreground inputs for sky-beam interaction simulations and chromaticity assessments.

Excel / Data Analysis Suites
Used to organize and rank antenna designs based on simulation outputs and statistical performance metrics.

2.4 Practical setup

The practical setup for this project involved simulating, analyzing, and optimizing dipole antenna designs using **ANSYS HFSS** for application in sky-averaged 21 cm cosmology (REACH case). The workflow began with parameterized modeling of multiple antenna variants within HFSS. These designs were analyzed for electromagnetic performance over a 50–135 MHz frequency range, focusing on key parameters such as reflection coefficient (S11), bandwidth, and beam spectral smoothness.

Simulated antenna patterns were then exported and processed using MATLAB or Python to compute figures of merit and assess beam chromaticity when interacting with realistic sky models. These figures were used to rank designs and inform design refinement.

The top-performing variants were further tested in a **mock detection pipeline**, where sky signals—including foregrounds and hypothetical 21 cm absorption troughs—were passed through the simulated antenna beams. Signal recovery performance was evaluated using REACH's internal Bayesian modeling tools to assess the calibration accuracy and foreground separation capability of each design.

The entire simulation and evaluation process was conducted on a workstation running ANSYS HFSS and MATLAB, supporting high-performance EM solving and data visualization. The setup enabled detailed analysis of antenna behavior prior to physical prototyping, ensuring designs meet REACH's stringent performance criteria.

2.4 Implementations:

1. Design and model antenna variants in ANSYS HFSS.
2. Simulate radiation patterns, impedance, and S-parameters across target frequency band..
3. Export simulation data for analysis in MATLAB/Python.
4. Compute figures of merit such as chromaticity variance and return loss.
5. Evaluate designs using mock signal injection and Bayesian modeling.
6. Refine and select optimal designs for potential prototyping.

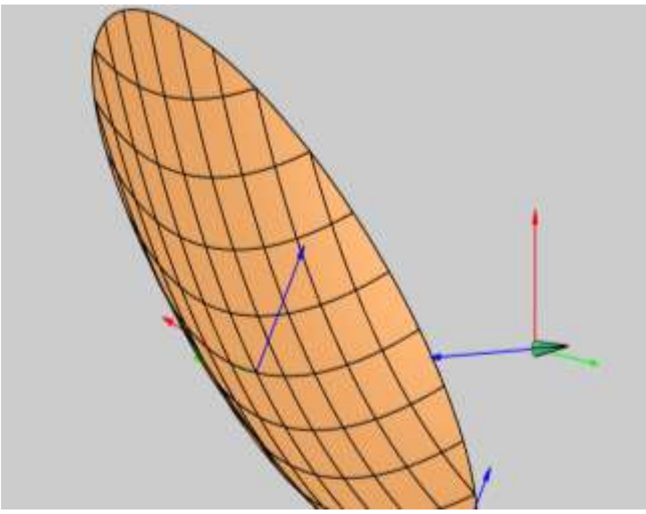


Fig 1- **Design and implementation of antenna**

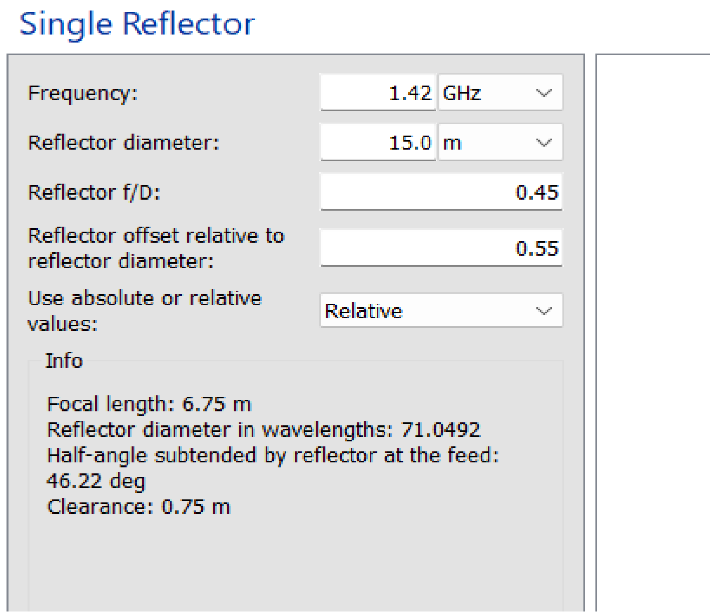


Fig - 2 **Parameters for antenna**

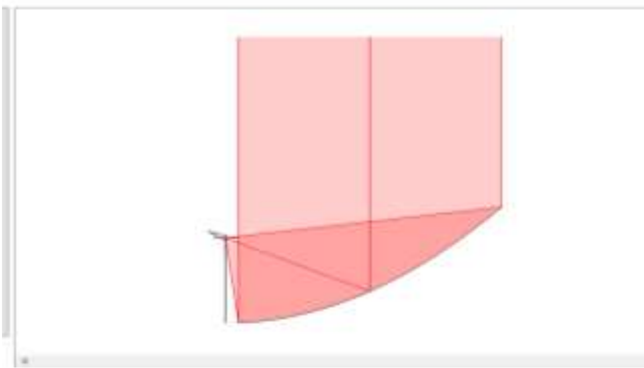


Fig 3 – Single reflector

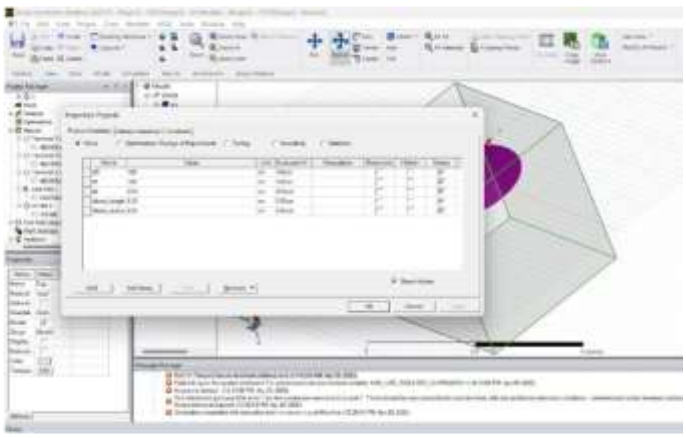
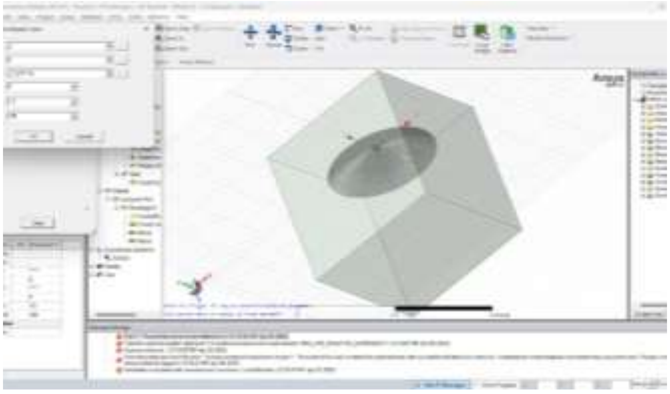


Fig 4 – HFSS antenna parameters



Simulation results:

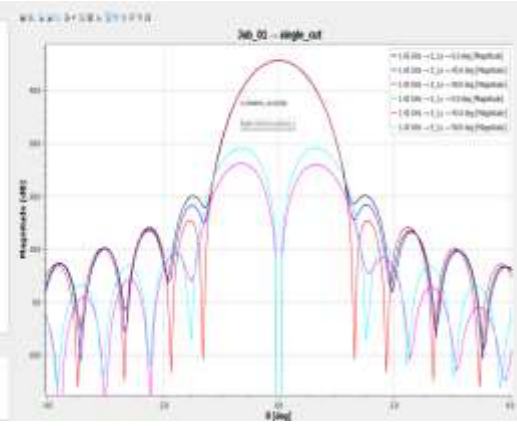


Fig 6 – Result.

3.CONCLUSIONS

This project focused on the simulation-driven design and optimization of wideband dipole antennas for detecting the global 21 cm signal, within the framework of the REACH experiment. Using ANSYS HFSS, we explored how electromagnetic design choices—such as antenna geometry, ground plane configuration, and impedance characteristics—affect the antenna's ability to minimize beam chromaticity and ensure spectral smoothness, both of which are critical for accurate signal recovery in global 21 cm cosmology.

By simulating over 1000 antenna variants and refining them using quantitative figures of merit, the work illustrates how systematic design, physical modeling, and statistical evaluation pipelines can be effectively combined to identify optimal antenna structures. These simulations were further integrated into mock detection pipelines to validate the ability of each design to isolate the cosmological signal from dominant foregrounds.

The results emphasize that even small design changes can significantly influence beam response and calibration complexity. Furthermore, the use of a structured workflow—beginning with physical simulation and culminating in statistical modeling—demonstrates a scalable method for antenna selection in precision cosmological measurements.

In conclusion, this work highlights the importance of integrating electromagnetic simulation, figure-of-merit analysis, and mock signal evaluation in antenna design for 21 cm experiments. The findings validate the REACH methodology and offer a reproducible approach for designing antennas that are both spectrally smooth and physically realizable, contributing directly to the field of observational cosmology. This project paves the way for future physical prototyping and deployment of optimized antennas aimed at unlocking insights into the early universe.

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Ms. Ganga Bhavani, who is specializing in Systems and Signal Processing and also pursing her doctoral research, has been a consistent source of motivation, provided practical direction, and contributed a lot toward the successful implementation of our project.

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