Postdoc Research

Antenna Development for Future 21cm Radio Telescopes

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Background

Up-and-coming 21cm intensity mapping experiments are highly promising probes of dark energy and have the potential to address many questions pertaining to our cosmic origins, particularly when used in conjunction with data sets from Euclid, SPHEREx, and other NASA missions. These new 21cm experiments aim to detect small signals set against bright foregrounds, and thus calibration will be a key piece of their realization. The layout and structure of these experiments bring about several calibration challenges, including antenna sensitivity and redundancy. The focus of this poster is on antenna development for HIRAX[1,2], a new radio interferometer to be built in South Africa. HIRAX will consist of 1000 stationary radio dishes, and must utilize low-cost antenna/amplifier instrumentation on each element that is well understood and highly repeatable. Early models of the HIRAX antenna demonstrate nonidealities in the beam, frequency dependent beam features, high levels of cross-polarization, and a noise performance above specifications. I am focusing on a modification of the antenna model, and in the process will develop technologies that can be broadly applied to other missions.

Fig 1: Rendering of HIRAX, a 1024 dish array to be built in the Karoo Desert, South Africa. HIRAX will operate between 400-800 MHz, with an associated redshift range of $0.8 < z < 2.5$, and is designed to constrain dark energy and its time dependence in over 1000 redshift bins by measuring the $100h^{-1}$Mpc BAO scale as a function of time.

Objectives/Design Drivers

Each of the HIRAX dishes will have a dual-polarization antenna mounted at the focus. The HIRAX antenna design is constrained by the goal of measuring baryon acoustic oscillations in the redshift range, $0.8 < z < 2.5$. It requires the following features:

Broadband
The antenna should be well-matched in the 400–800 MHz frequency range (redshift range of $0.8 < z < 2.5$), which probes the window when dark energy is beginning to influence the Universe's dynamics.

Low-Noise
For HIRAX, there is a system temperature budget of 50K, of which 30K is contributed by the LNA. This is accomplished by embedding the first-stage LNA directly into the antenna structure.

Smooth Frequency Response
21cm foreground mitigation techniques assume that foregrounds are smooth in frequency, while the 21 cm signal is expected to contain spectral structure. If the instrument has unexpected frequency structure, smooth foregrounds can no longer be differentiated and removed, as they will contain instrument artifacts.

Smooth Beam per-Frequency
An effective measurement of the BAO scale will require instrument beam effects to be well understood and then removed in the analysis. A smooth and symmetric beam at each frequency makes measurement and beam deconvolution as straightforward as possible.

Low-Cost
The antenna should be inexpensive to manufacture and build, from the raw materials to the assembly procedure, thereby enabling a large N-element array. For this reason, FR4 is chosen.

Broad-Beam
HIRAX utilizes a deep dish design, with F/D = 0.23. Illuminating such a dish requires a broad antenna beam, with low-level sidelobes to reduce spill-over.

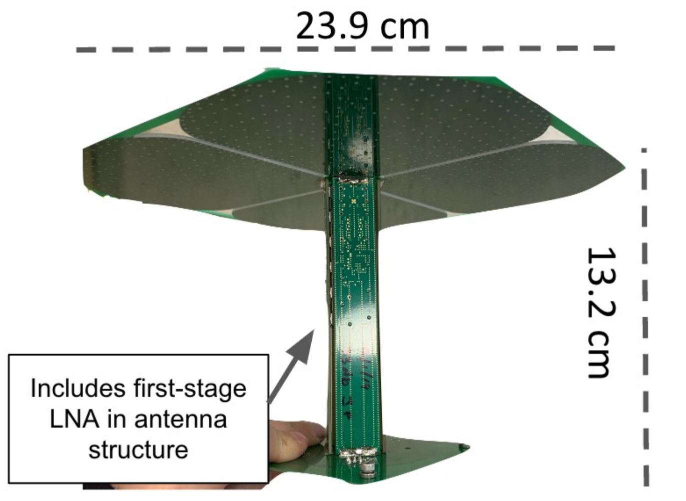

Fig 2: The current HIRAX antenna, which is the starting point for the new design.

Approach and Results

The antenna I develop has heritage in the CHIME antenna [3] and will be a modification of the HIRAX V1-6 designs spearheaded by Kevin Bandura at WVU and Jeff Peterson at CMU. A description of characterization efforts for earlier versions can be found at [1][4][5].

For the redesign, dimensions and materials will remain the same. The following upgrades are needed:

- New LNA, which will need to be prototyped and tested in the lab. We plan to use a XXX chip, and the circuit design and verification process is underway.
- New petal geometry. Previously, opposing petals on the diagonal formed the arms of a dipole-style antenna, setting the polarization axis. The geometry of the traces was asymmetric with respect to the full antenna structure, which introduces beam asymmetries at higher frequencies (seen in measurements and verified in simulations). Various layouts, including those involving adjacent petals forming the dipole or strip lines running through the geometric center, will be tested in simulations.
- Potential upgrade: add amplifiers to all balun stems (currently, only two stems have LNAs, which asmplify differences between petals), sum signals in a helical geometry.

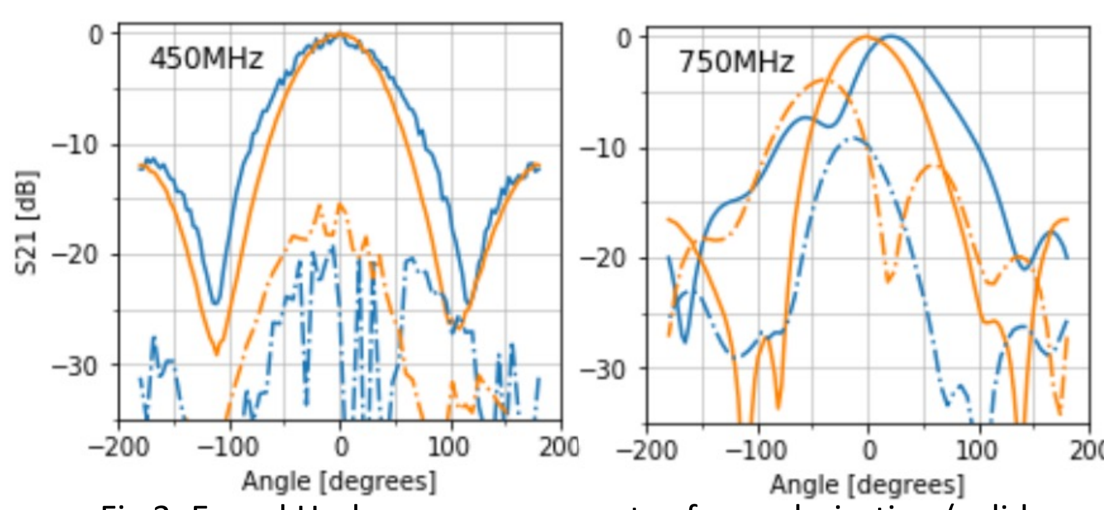

Fig 3: E- and H-plane measurements of co-polarization (solid lines) and cross-polarization (dashed lines) for the old HIRAX antenna, which show the development of beam asymmetries and high cross-polarization at high frequencies.

Significance of Results/Benefits to NASA/JPL

The results of this research program will enable HIRAX to successfully probe dark energy, supporting NASA's Cosmic Origins initiative, and will be useful to 21cm and intensity mapping experiments worldwide. The antenna and amplifier technology I develop through this project can be applied to related JPL-led missions and concepts, and will be of broad interest to NASA and their industrial partners.

Future Work

The work presented in this poster is ongoing, with work for the near future detailed in the approach/results section. Once the new antenna is built, it will be verified on antenna ranges and in the field. It will then be deployed as part of the 128-element HIRAX array that is presently under development.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Clearance Number: CL#00-0000

Poster Number: PRD-

Publications and Acknowledgements:

[1] Newburgh et al., arXiv:1607.02059
[2] Criton et al. arXiv: 2109.13755
[3] Deng, M et al, (ANTEM) 16, IEEE 2014
[4] Emily R. Kuhn, et al, SPIE 12182, 2022
[5] Emily R. Kuhn, et al, SPIE 11445, 2020

This work is the result of a collaborative effort with several members of HIRAX. The work benefitted from discussions with Jeff Peterson and hardware contributed by his group at CMU, and is based upon a design originally by Meiling Deng for CHIME.

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