Phase-Retrieval for Beam Mapping with Transition Edge Sensors

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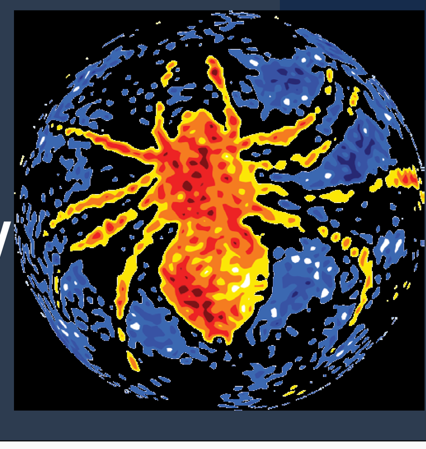
22-26 JULY 2019 MILANO LTD 18 LOW TEMPERATURE DETECTORS



Abstract

We aim to address beam characterization of small-aperture telescopes with a wide FOV in the microwave band between 90 and 300GHz, specifically focusing on Transition Edge Sensors (TESs), a baseline detector choice for upcoming ground Cosmic Microwave Background (CMB) experiments such as the Small Aperture Telescope (CMB-S4) or the balloon-borne SPIDER polarimeter.

Far-field beam characterization is often impractical for these kinds of telescope: the far field (FF) could be located hundreds of meters away and such observatories are often in remote and inaccessible sites like the Atacama Desert in Chile or the South Pole. Balloon-borne experiments have additional mechanical complications from their restricted pointing capabilities. Because of these issues, a robust and reliable technique to reconstruct the far field beam from holographic measures of the near field (NF) beam is necessary.

This in itself is challenging, for two reasons: first, this frequency range requires a positioning accuracy of a fraction of the radiation wavelength; second, the TES detectors have a typical time constant of a few milliseconds, meaning the radiation may travel several wavelengths in one time constant.

To overcome those difficulties, we designed a custom automated frame to hold and move the probes with the required precision and developed two independent pipelines to reconstruct the phase information from scalar measures of the electromagnetic field.

Introduction

The two pipelines for phase reconstruction are as follows:

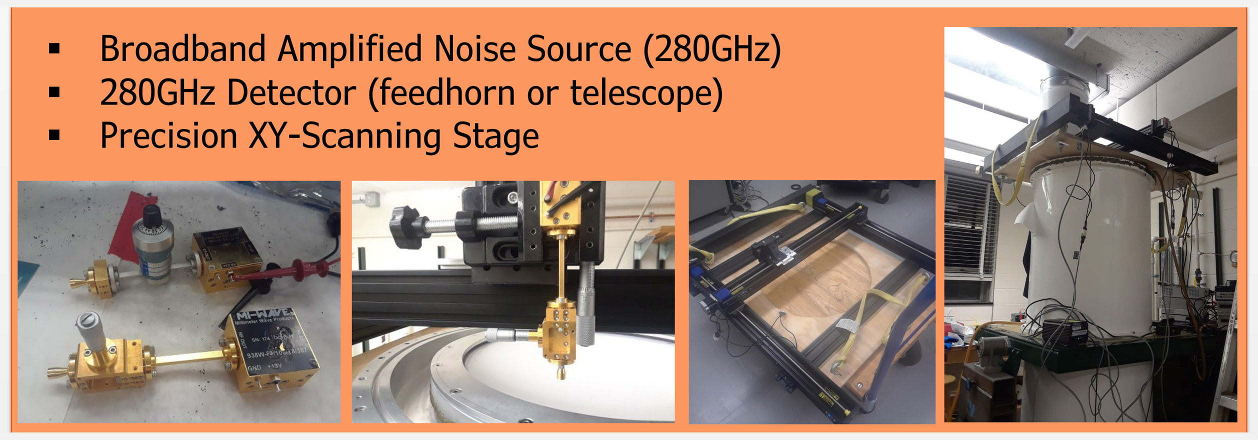
The first method requires mapping the intensity signal from at least two planar scans of the NF beam with a probe source. This source is modulated at a given reference frequency chosen to trigger the acquisition system. An initial random phase is generated and fed into a minimization algorithm that updates the phase at each iteration. Using this method, we can reconstruct the phase information for any small aperture telescope using conventional beam mapping techniques. [1,4,5]

The second method reconstructs the phase information by means of a probe signal generated by mixing two slightly offset monochromatic sources. The resultant intermediate frequency (IF), falls in the detector's band and can be measured. The detector's response is then modulated at the same IF and the signal is reconstructed with a synchronous demodulation technique. [2,3]

Planar Intensity Mapping (Pipeline 1)

Instrumentation

- Broadband Amplified Noise Source (280GHz)
- 280GHz Detector (feedhorn or telescope)
- Precision XY-Scanning Stage



Methodology

To develop our phase retrieval pipeline for use with CMB telescopes, we first train the algorithm in the lab by using smaller room temperature detectors. These have the advantage that we can measure both the NF and FF beams with relative ease.

We utilize a high-precision XY-scanning stage and a lock-in amplifier to map the NF beam from a chopped 280GHz amplfiied noise source. This gives us a scalar intensity map of response at a given distance from the aperture. Using multiple (at least two) maps at known distances, it is possible to iteratively reconstruct the phase of the field in these planes. This is done by first assigning a selection of random phases to one field, which are then constrained as the algorithm continuously propagates the field to generate the second map. We then confirm that the phase information is correct by using it to reconstruct the FF beam, which we can directly measure.

Once satisfied with the performance of the algorithm, we can apply it to NF maps taken directly from a complete CMB telescopes. The noise source and XY stage are mounted on top of the instrument under study (in this case, a SPIDER 280 GHz receiver) and a bolometer data are acquired during scans at different heights above the aperture. This is used to iteratively determine the phase, and therefore the characterize the FF in the exact same way.

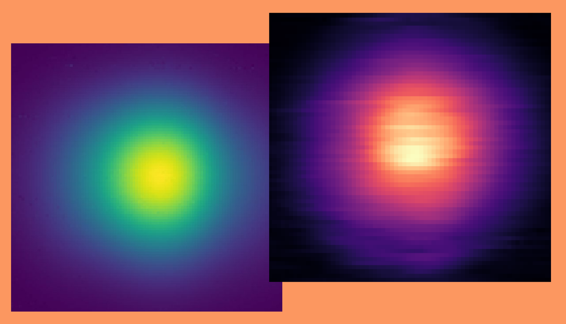


Fig 1. NF beam maps for room temperature detectors (left) and the cryogenic SPIDER TESs (right)

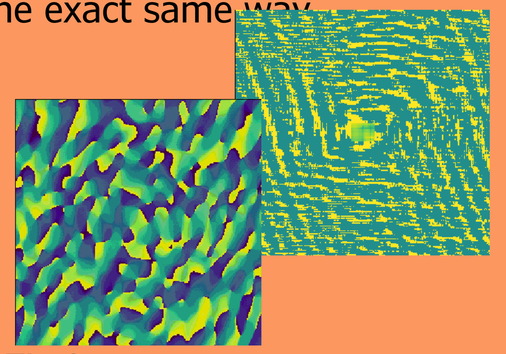


Fig 2. Frames from the phase retrieval algorithm as it converges on a selection of phases

Preliminary Results

We have already demonstrated the use of this algorithm to generate phase information for artificial data from simulated apertures, and we have successfully taken high signal-to-noise NF beam maps for both room temperature detectors and the SPIDER Telescope, both with high precision.

We are currently training the algorithm with data from the known NF and FF beam maps, and hope to apply it to unknown FFs in the near future.

Near Field Beam Propagation

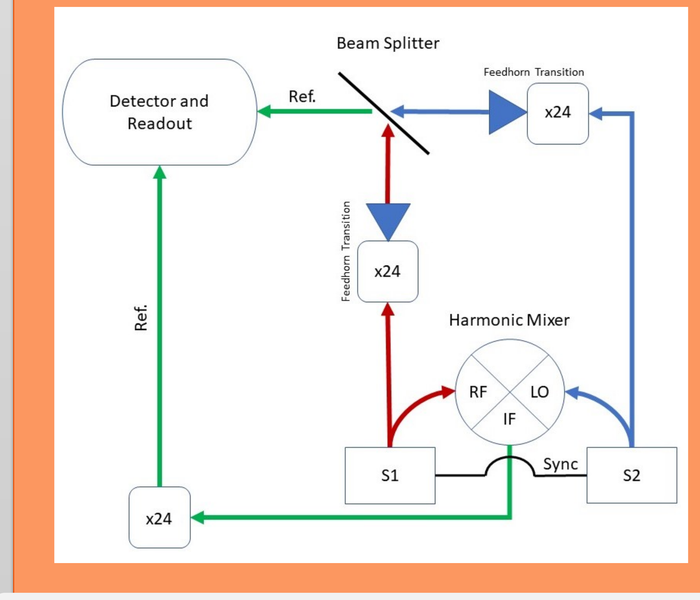
Gaussian field emanating from aperture is given by $E(x,0) = e^{-ax^2}$
Here *a* is a complex coefficient given by: $a = ar + iai$
In [1], the full forms for *ar* and *ai* can be written (using terms from another plane): $a_r = \frac{k_0^2 + d_5 - 8b_{2r}d_1d_2z_2^2 - 4b_{2r}d_1k_0z_2}{8b_{2r}z_2^2(d_1^2+1)}$

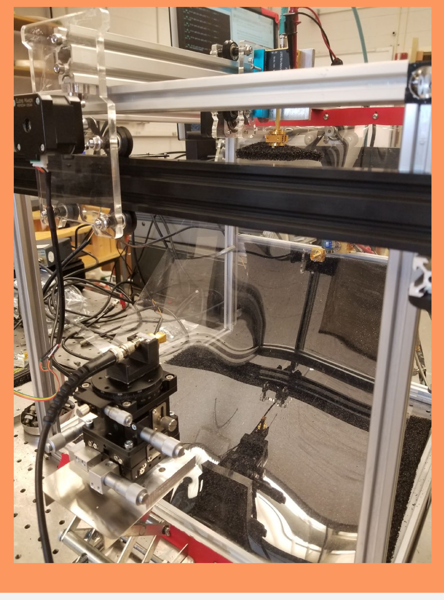
a_i is the Quadratic Phase Variation we are looking for.
z_1, z_2 are the distances to the first and second planes from the aperture
d_1, d_2, d_3, d_4, d_5 are terms defined in terms of each other, z_1, z_2 and k_0 (see [1])
b_r is the real part of a complex coefficient, $b=b_r+ib_i$. This is found by applying a Fourier transform to (1), transforming to a distance, z, performing the paraxial approximation, then performing an inverse Fourier transformation, to find the following approximation for the field at plane z: $E(x,z) = \sqrt{b/a}e^{-bx^2}$
$b_r = 4\sum|E(x,z)|^2 / \sum x^2|E(x,z)|^2$ Where *x* is the aperture co-ordinate.

Holographic Mapping (Pipeline 2)

Instrumentation

- Two frequency synthesizers, 10Mhz-20GHz
- Two active x24 multiplication chains
- Two feedhorn transitions
- Mylar beam splitter
- Diode room temperature detectors
- XY precision stage
- PLL frequency synthesizer





Methodology

The typical detector time constant for TESs for cosmological application is a few milliseconds. This means that a modulated signal could be efficiently detected if the modulation is below ~30Hz. This puts a constraint on the IF. In our case of study for the Y-band beam map, a 1Hz difference between the two beating sources with a frequency of about 12GHz has been chosen.
The first challenge is to synchronize the two sweepers with a high accuracy to keep a stable IF out of the harmonic mixer. The IF is recorded and monitored to apply eventual offline corrections. The IF is then fed to a Phase-Locked Loop synthesizer that upscales the IF to the required reference, x24 in our case. This is the second big challenge we aim to achieve since every uncertainty in the reference signal will show up in our measures as a spurious phase signal that will limit our capability of phase retrieval for the near field beam.

The two sources are frequency multiplied x24 and combined, after a feedhorn transition through a mylar beam splitter. The signal is then collimated and sent to the detector. The S2 source is then scanned on a plane perpendicular to the detector's line of sight. A synchronous demodulation technique is then applied to recover the intensity and phase of the signal. Any phase lag measured by the detector must be due to the beam.

In this very preliminary phase we aim to have a first measure at room temperature as a proof of concept using the setup show above to illuminate a room temperature detector.
The next step is to repeat the measure with a bolometer at 4K, much more sensitive but much slower than the diode.
This will help to better understand the phase noise of the measure and to debug any systematics that will arise during the process.
The final and more ambitious test will be conducted with antenna coupled TESs at 300mK in the near field of a small aperture telescope.

Conclusion and Future Work

We have described a challenging measurement that will be important to future CMB and far-IR instrumentation.
We decided to work on two independent pipelines to maximize the results and to provide cross-checks against systematic errors.
If successful this work will help present and future CMB experiments to characterize the beam pattern in the far field even without sources in the observed patch of the sky, limiting the logistics issues due to the placement of observatories in remote places.
The system we are proposing is extremely flexible and could be easily adapted at lower frequencies of interest for the CMB community: from 20GHz up to 300GHz.

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Acknowledgements

This effort is supported by internal funding at the University of Illinois, and in collaboration with the SPIDER team. The SPIDER project is supported in the U.S. by NASA under under grants NNX07AL64G, NNX12AE95G, and NNX17AC55G issued through the Science Mission Directorate and by the National Science Foundation through PLR-1043515