Complex beam mapping and Fourier optics analysis of a wide field Microwave Kinetic Inductance Detector camera

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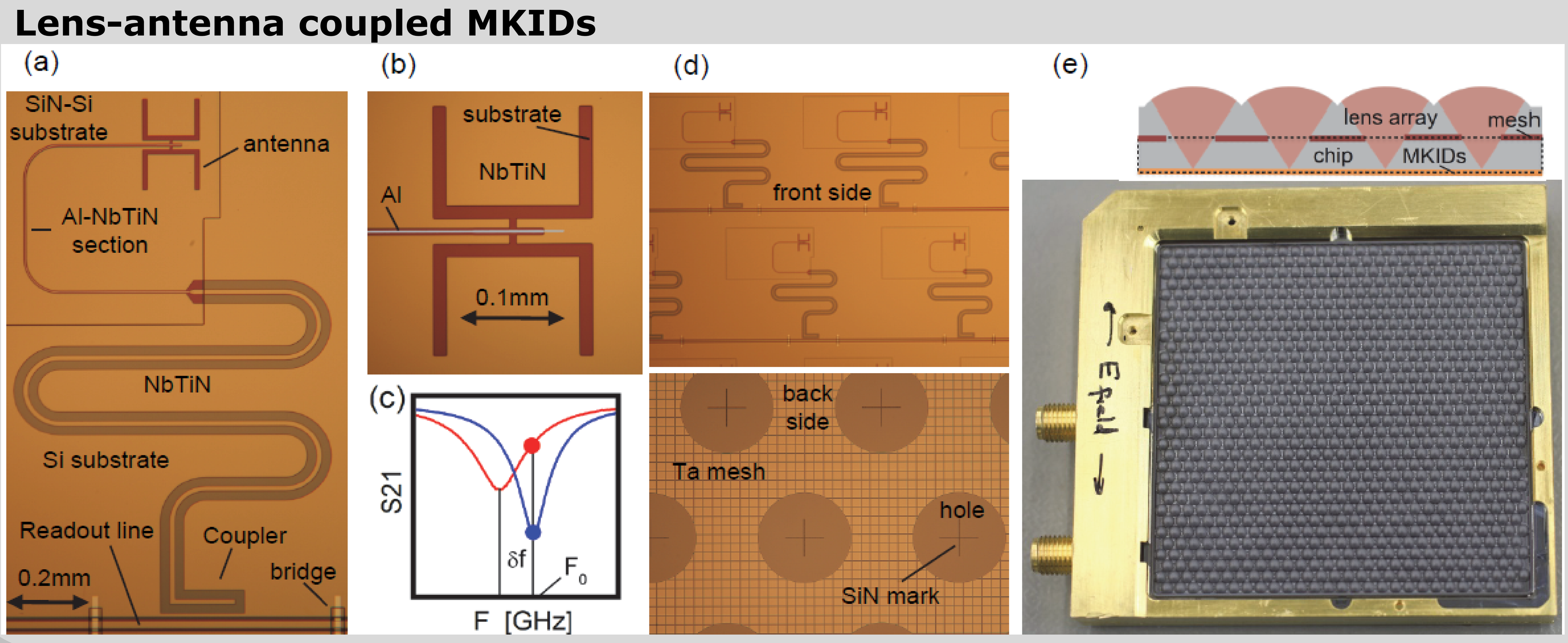
A full optical system is described by the angular and position dependent optical response of the receiver, its beam pattern which is a vector with both amplitude and phase. With the full complex beam pattern, you can numerically propagated the measured beam in either direction to investigate the optics or the optical coupling between components. This allows measurements at an arbitrary (or the most accessible) position, for testing at the sub-component level or in the near field of a full instrument which can then be used to determine and understand the final deployed on sky performance. This is the typical technique used for phase sensitive heterodyne spectrometer instruments, such as ALMA, Herschel HIFI and IRAM. Complex beam pattern measurements have only recently been shown to be possible with direct, power only sensitive, detector arrays: the lack of an intrinsic phase response, high pixel count and low detector speed make it difficult. As an exercise, we apply a Fourier analysis to measurements from a lab based large field MKID camera to calculate how the system would integrate with a telescope and calculate the on sky beam pattern and coupling efficiency. A similar analysis was used recently to explain the on first light sky beam pattern and coupling efficiency for the MKID based DESHIMA spectrometer.

Lens-antenna coupled MKIDs



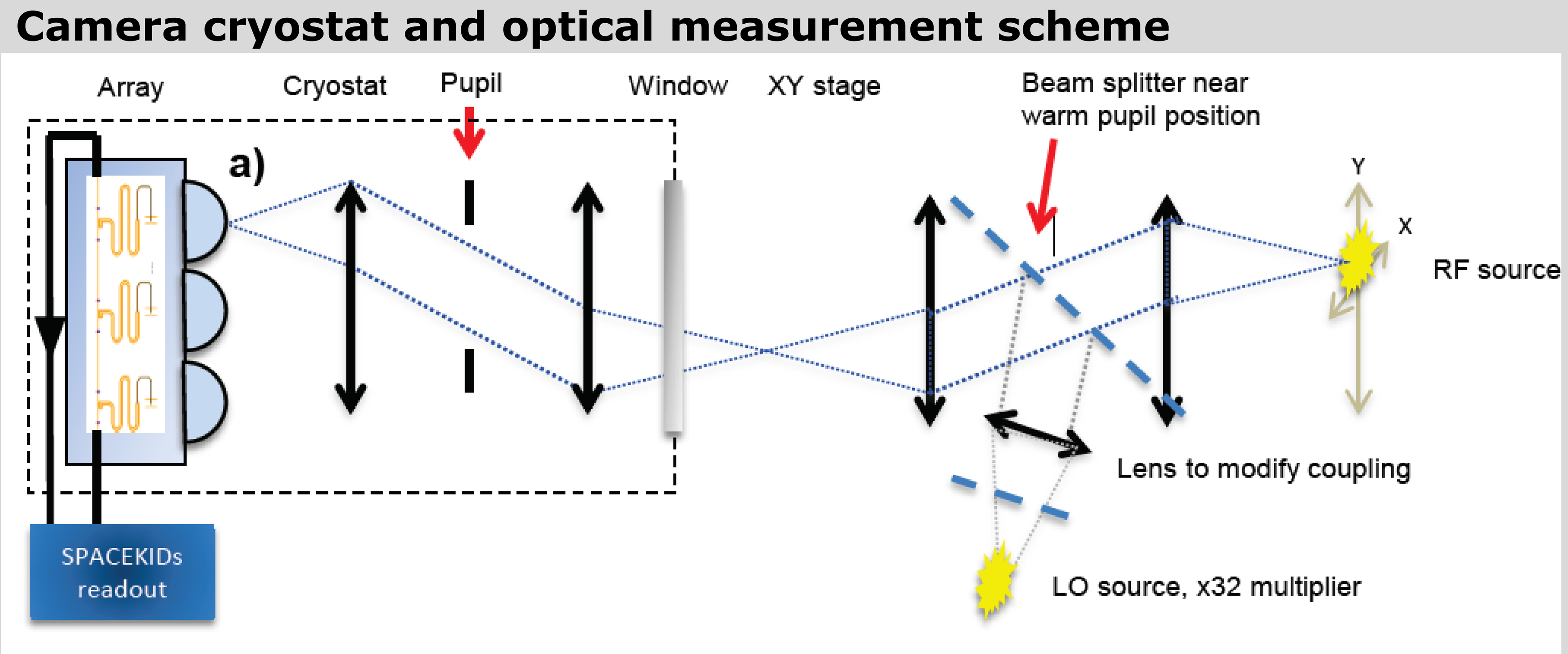
Left: from Yates et al. 2017, overview of array.

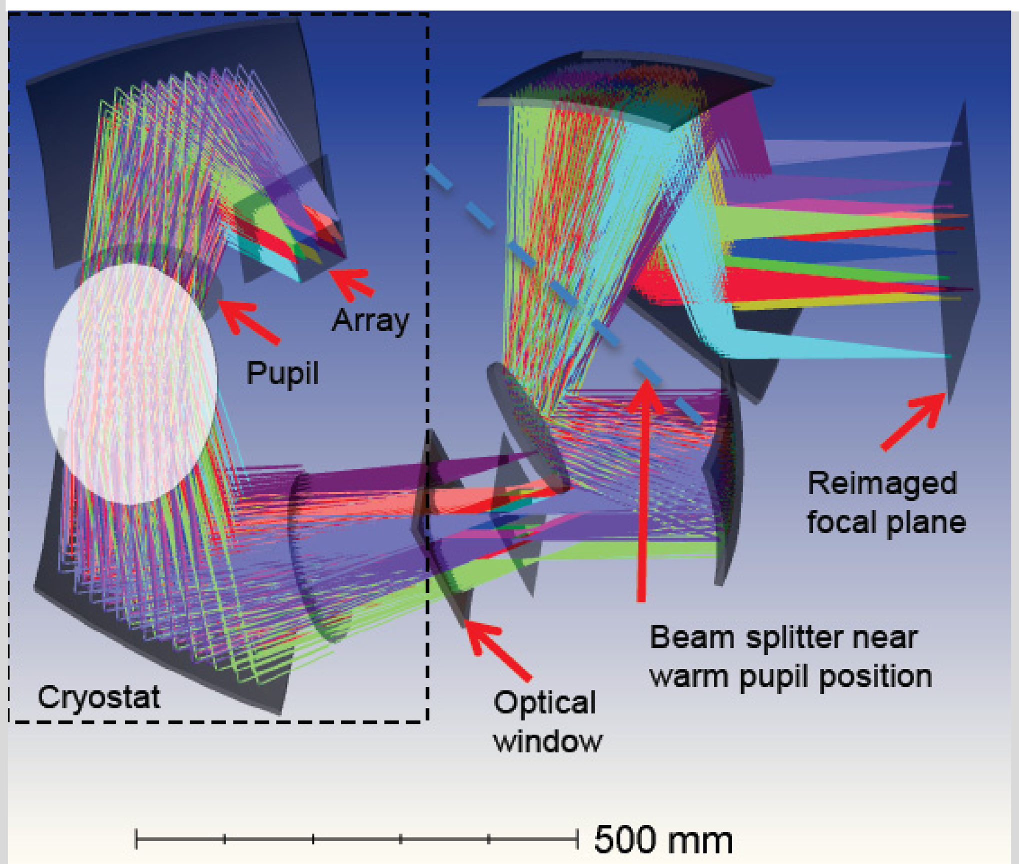
Present a large array (880 pixel) of lens-antenna coupled NbTiN/Al MKIDs (a), twinslot antenna (b) optimised for 350 GHz

Use an on-chip Ta mesh absorber to suppress in substrate stray light (d backside) and cosmic rays.

Laser machined lens array mounted to MKID array (e)

Camera cryostat and optical measurement scheme

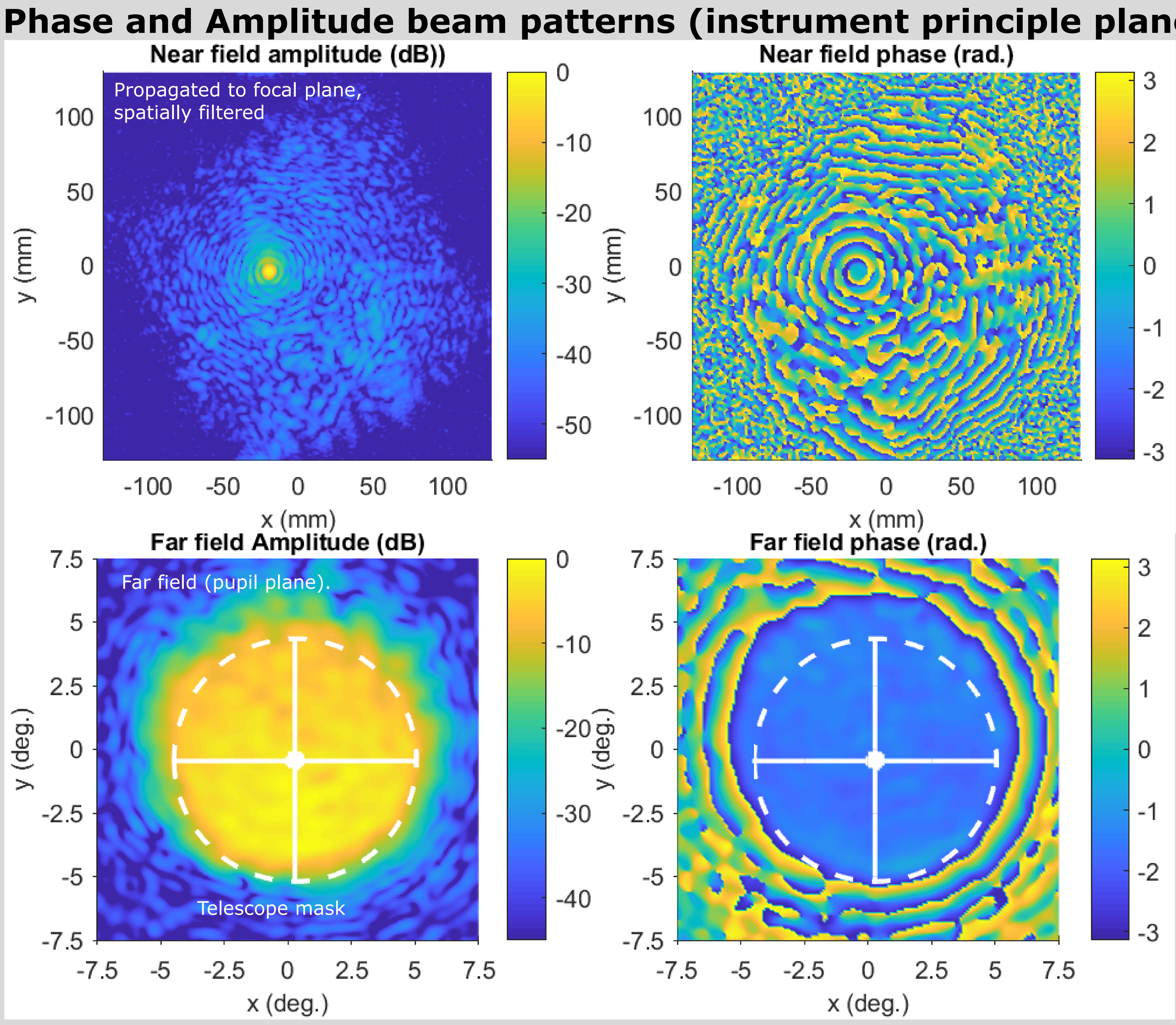




"king" cryostat, a test sub-mm camera facility. Reimage the cold focal plane (at 240mK) to the warm for full system testing, above paraxial schema, left the full ray trace.

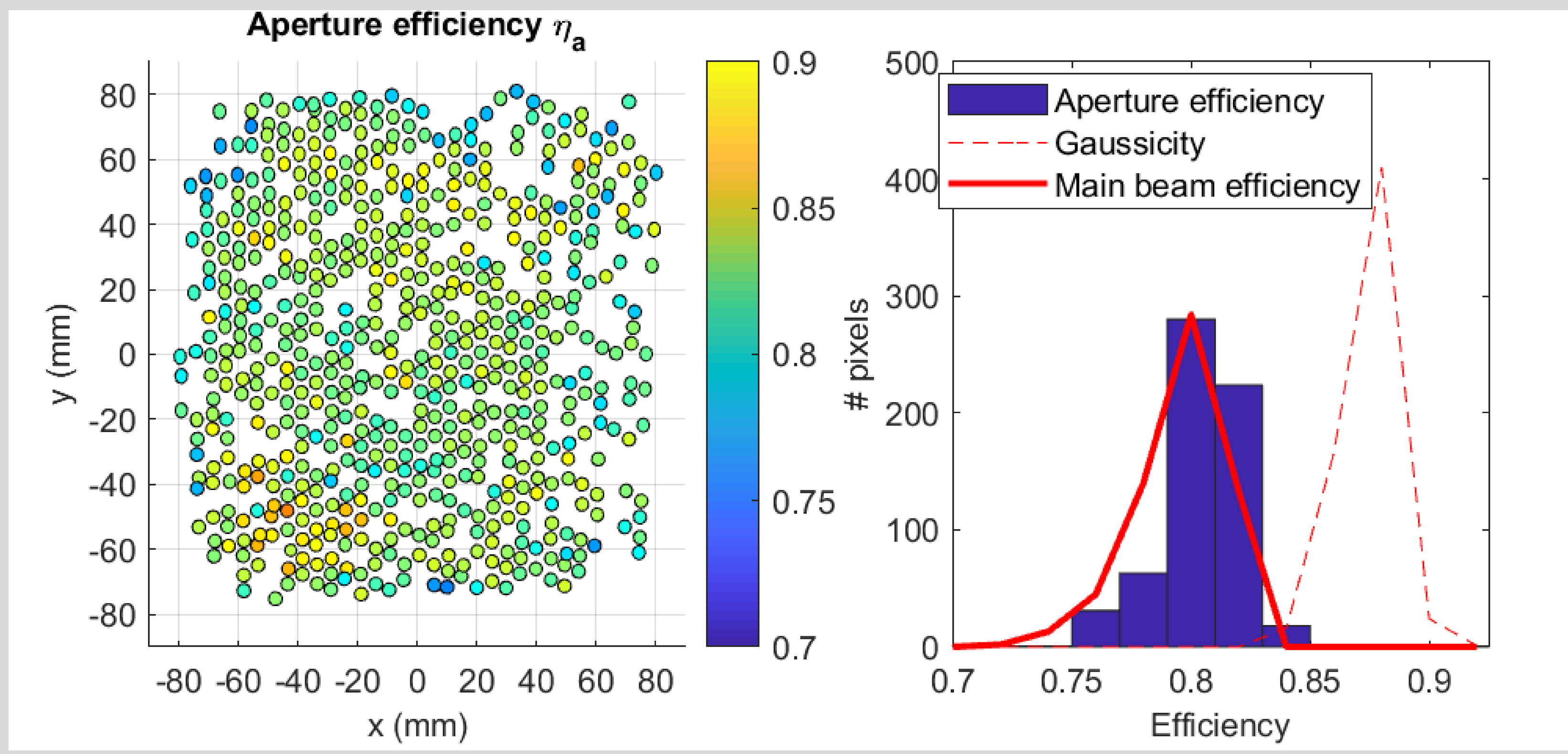
Measurement: scan one (the RF) source in the reimaged focal plane, with a second (the LO) source coupled in near the warm pupil position with a beamsplitter. Measure the optical interference (beat) between the two sources, with the phase measured relative to a reference signal, acquired as a virtual pixel.

Phase and Amplitude beam patterns (instrument principle planes)



Top: measured phase and amplitude beam patterns spatially filtered and propagated 30mm to focal plane. Bottom: far field beam pattern calculated from the measurement, an image of the system pupil. A telescope model is generated by applying a mask, indicated in white.

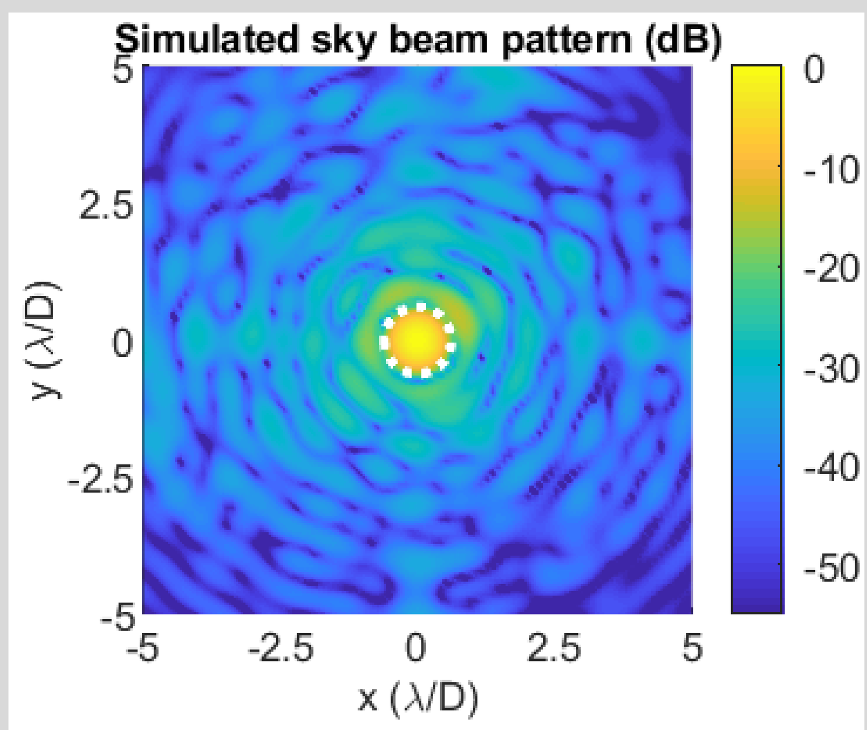
Telescope coupling: aperture efficiency from lab measurements



The aperture efficiency is the plane wave coupling at telescope, point source on sky.
Gaussicity is the coupling to an ideal Gaussian beam, in plane of measurement.
The main beam efficiency (extended source) is calculated from the on sky beam pattern overlap integral, using a source of radius 1.22λ/D.
Yield ~80% of pixels measured.

On sky beam pattern:

Calculate the on sky beam pattern using the measured instrument beam pattern, from a FFT of the masked far field data.



Efficiency comparison to simulation

Efficiency	Simulated	Measured
Gaussicity	0.91	0.87 ± 0.02
Aperture η_a	0.9	0.80 ± 0.03
Taper η_t	0.9	0.91 ± 0.02
Spillover η_f	1	0.88 ± 0.024
Main beam pattern η_{mbp}	0.89	0.90 ± 0.01
Main beam η_{mb}	0.89	0.79 ± 0.03

Compare to physical optics, see good agreement for entire array.
See slight increased spillover, this is pupil aperture defocus visible as power outside of the f#6 angle in far field aperture.
Wave front error from far field phase is 28±6μm, or weight by beam amplitude gives 10±2μm. Surface error half this. Implies optics works to ~2.3 THz.

Conclusion

Phase information opens up a whole new way to characterise direct detector sub-mm instruments with a single measurement, allowing analysis previously only available to heterodyne (phase sensitive) instruments. Advantages include:

- Beam propagation and Fourier optics analysis, forwards as shown here: can determine coupling efficiency; spillover; pointing and alignment to telescope; on sky beam pattern.
- Propagate into instrument: to investigate optical illumination and alignment of components
- Phase errors gives a direct measure of surface accuracy and alignment of optics
- Allows near field full characterisation of full instruments or telescopes: useful for pre-deployment full verification of balloon, satellite or ground based telescopes
- Signal to noise is the square of normal amplitude only measurement

Further information: proceedings this conference, or for more details on the technique please see:
K. Davis et al., *"Complex Field Mapping of Large Direct Detector Focal Plane Arrays"*, IEEE Trans. THz Sci. Tech. vol. 9, 67-77 (2019),
Additional information on arrays:
S.J.C. Yates et al., *"Surface wave control for large arrays of microwave kinetic inductance detectors"*, IEEE Trans. THz Sci. Tech. IEEE Trans. THz Sci. Tech. vol. 7, 789-799 (2017),
On camera cryostat:
L. Ferrari et al., *"MKID large format array testbed"*, IEEE Trans. THz Sci. Tech. vol. 8, 572-580 (2018),
A similar analysis was done to explain the on sky beam pattern and efficiency for DESHIMA:
A. Endo et al., *"First light demonstration of the integrated superconducting spectrometer"* arXiv:1906.10216 (2019)
Also, authors would like to acknowledge the support and help of Lorenza Ferrari, Akira Endo, Kotaro Kohno, Chris Groppi, Vignesh Murugesan, David J. Thoen, Ronald Hesper, Jan Barkhof, Andrey Khudchenko and the NOVA ALMA group.