Testing current and future instruments for CMB polarization

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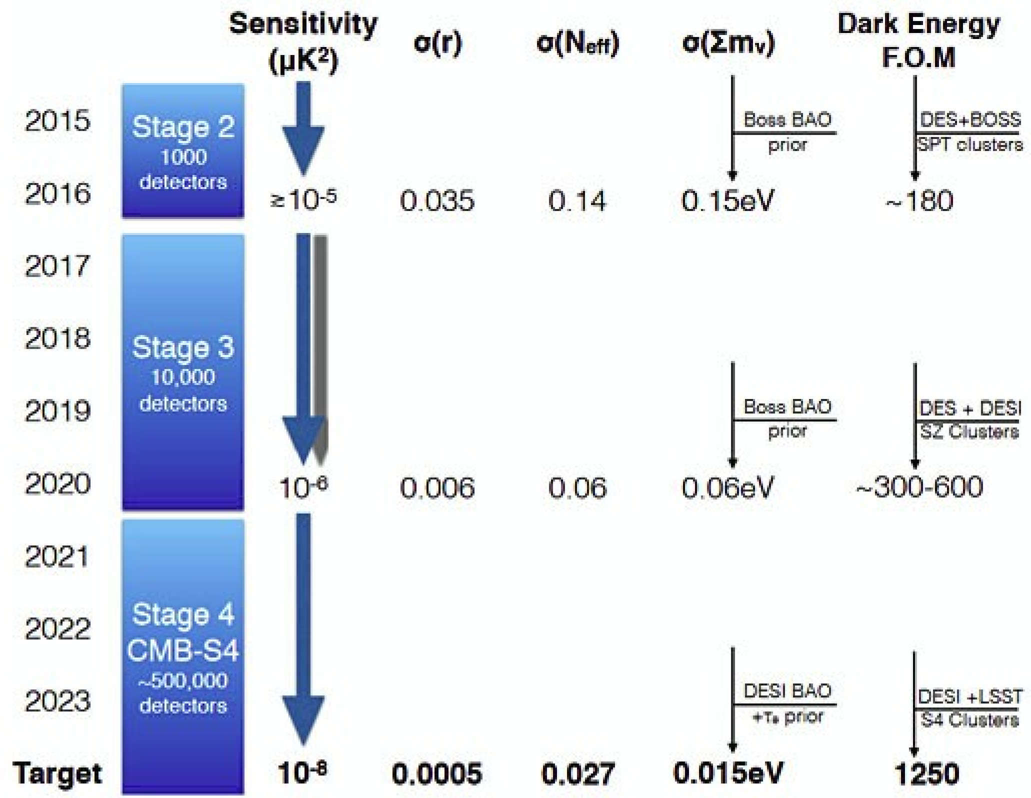
The big challenge



- CMB B-modes are a challenging quest (sensitivity, systematic effects, foregrounds).
- Required sensitivity ⇒ 10^4 - 10^5 detectors
- Foreground control ⇒ 1 - 2 decades in frequency coverage
- Systematic effect control ⇒ instrument knowledge, i.e. THOROUGH TESTING

The big questions

- Must we test each component for all detectors?
  - If not, how we deal with the missing information?
  - If yes, how can we perform the tests, store the data and do the analysis with reasonable time and effort?

Any clear answers?

Any clear answers?

- Unfortunately not (at least from me).

- Dealing with testing of several thousands of detectors is poorly charted territory, *detailed information difficult to find in the literature*

- Let's see a few examples from existing experiments

SPTpol

Performance and on-sky optical characterization of the SPTpol instrument

E.M. George[h], P. Ade[b], K.A. Aird[r], J.E. Austermann[c], J.A. Beall[d], D. Becker[d], A. Bender[f], B.A. Benson[a,s], L.E. Bleem[a,q], J. Britton[d], J.E. Carlstrom[a,e,q,s,t], C.L. Chang[a,e,s], H.C. Chiang[a,s], H-M. Cho[d], T.M. Crawford[a,t], A.T. Crites[a,t], A. Datesman[g], T. de Haan[f], M.A. Dobbs[f], W. Everett[a], A. Ewall-Wice[a,q], N.W. Halverson[c,p], N. Harrington[h], J.W. Henning[c], G.C. Hilton[d], W.L. Holzapfel[h], S. Hoover[a,q], N. Huang[a,s], J. Hubmayr[d], K.D. Irwin[d], M. Karfunkle[a,q], R. Keisler[a,q,s], J. Kennedy[f], A.T. Lee[h], E. Leitch[a], D. Li[d], M. Lueker[j], D.P. Marrone[o], J.J. McMahon[k], J. Mehl[a,s], S.S. Meyer[a,q,s,t], J. Montgomery[a,q], T.E. Montroy[m], J. Nagy[m], T. Natoli[a,q], J.P. Nibarger[d], M.D. Niemack[d], V. Novosad[g], S. Padin[a], C. Pryke[l], C.L. Reichardt[h], J.E. Ruhl[m], B.R. Saliwanchik[m], J.T. Sayre[m], K.K. Schaffer[n], E. Shirokoff[j], K. Story[a,q], C. Tucker[b], K. Vanderlinde[f], J.D. Vieira[j], G. Wang[e], R. Williamson[a,s], V. Yefremenko[e,g], K. W. Yoon[d], E. Young[h]

Proc. of SPIE Vol. 8452, 2012

SPTpol

ABSTRACT

of both of these detector technologies, and is one of the first deployed instruments using DfMUX readout technology. We present the details of the design, commissioning, deployment, on-sky optical characterization and detector performance of the complete SPTpol focal plane.

The complete focal plane consists of 1536 TES bolometers (1136 at 150 GHz and 360 at 90 GHz)

SPTpol

- Detector properties
  - Detector biases
  - Uniformity in det. parameters

- Optical properties
  - Time constants
  - Linearity (gain stability)
  - Beams
  - Sidelobes
  - Bandpassess
  - Optical efficiency
  - Polarization properties
  - Optical yield

- Noise

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The paper doesn't state explicitely if each parameter was measured for **all** detectors, but it appears that a large number of them (if not all) was tested. Let's see some examples

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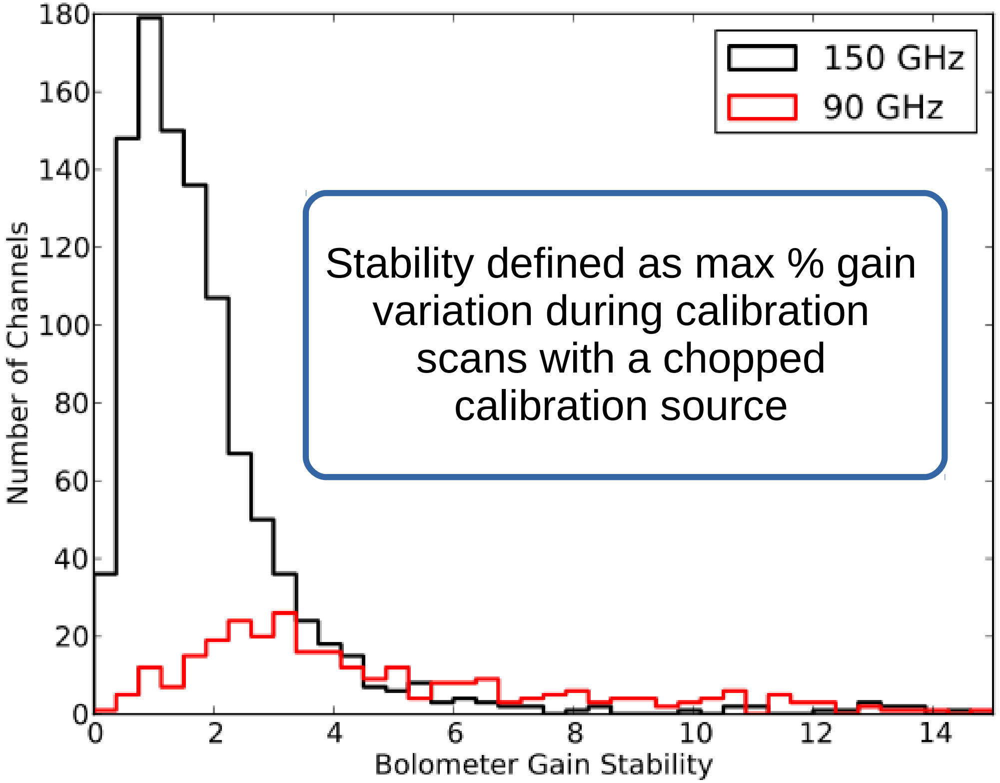

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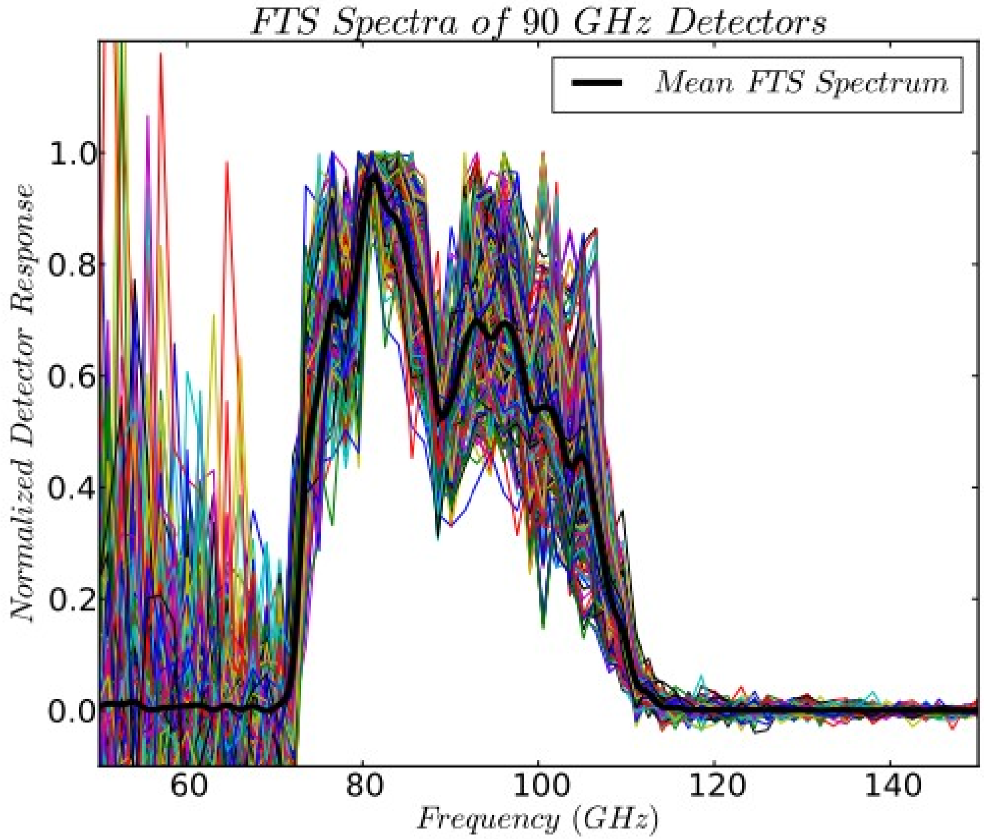


Sayre et al, Proc. of SPIE Vol. 8452, 2012

SPTpol

- Detector properties
  - De
  - Ur
- Opti
  - Ti
  - Li
  - Be
  - Si
  - Ba
  - Optical efficiency
  - **Polarization properties**
  - Optical yield
- Noise

response of 0.3%. At 150 GHz, the two polarizations are not prone to alignment rotations as the alignment is defined lithographically on a common plane.[3]

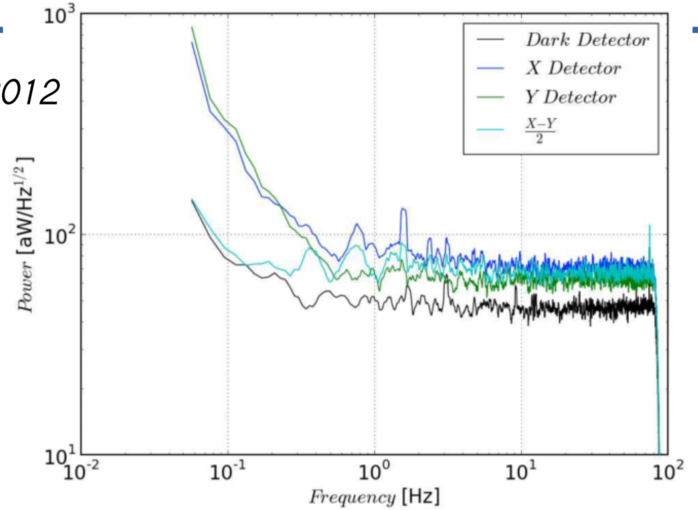
To measure the polarization angles of the complete array as installed in the telescope, a polarization calibration source placed 3 km from the telescope is employed. The polarization calibration source consists of a chopped blackbody at $\sim 1000°$C with a fixed polarized grid and a rotating polarized grid to define and vary the polarization. The source is placed in a hole cut in the center of a 24' x 24' reflector angled at 60° to the horizon, such that when the telescope is scanned over the reflector, most of the beam is reflected to the sky. For each pixel position, the rotating grid steps through a set of discrete angles spaced at 15° to measure the polarization angle of the two bolometers. A preliminary analysis suggests that the polarization angles are measured with a precision of $\sim 1°$ using this technique. Analysis of the polarization calibration is ongoing, and further details about the polarization calibration can be found elsewhere in these proceedings.[2,15]

SPTpol

- Det
  - D
  - U
- Opt
  - T
  - Linearity (gain stability)
  - Beams
  - Sidelobes
  - Bandpassess
  - Optical efficiency
  - Polarization properties
  - Optical yield
- **Noise**

We have also measured detector noise between field observations while on the telescope. Figure 11 (Right) shows the noise for three detectors in a single representative 150 GHz pixel. Detectors "X" and "Y" are optically coupled and looking at the sky, while the "Dark" detector is not optically active. Given in-lab calibration factors with systematics at the 10 - 20% level, the white noise levels of all the devices are consistent with expectations, 47 aW/$\sqrt{\mathrm{Hz}}$ with no optical loading and 76 aW/$\sqrt{\mathrm{Hz}}$ with nominal optical load. Additionally, differencing optically loaded detector timestreams removes correlated long time scale atmospheric fluctuations. As a result, the power spectral density of the differenced timestreams shows a significant reduction in the 1/f knee, increasing the frequency range that can be used for extracting relevant science.

Henning et al, Proc. of SPIE Vol. 8452, 2012



Spider, BICEP2/Keck

Microfabrication and Device Parameter Testing of the Focal Plane Arrays for the Spider and BICEP2/Keck CMB Polarimeters

J.A. Bonetti[*], A.D. Turner[*], M. Kenyon[*], A. Orlando[†], J.A. Brevik[†], A. Trangsrud[†], R. Sudiwala[†], H.G. LeDuc[*], H.T. Nguyen[*], P.K. Day[*], J.J. Bock[*,†], S.R. Golwala[†], J. Sayers[†], J. M. Kovac[†], A.E. Lange[†], W.C. Jones[**] and C.L Kuo[‡]

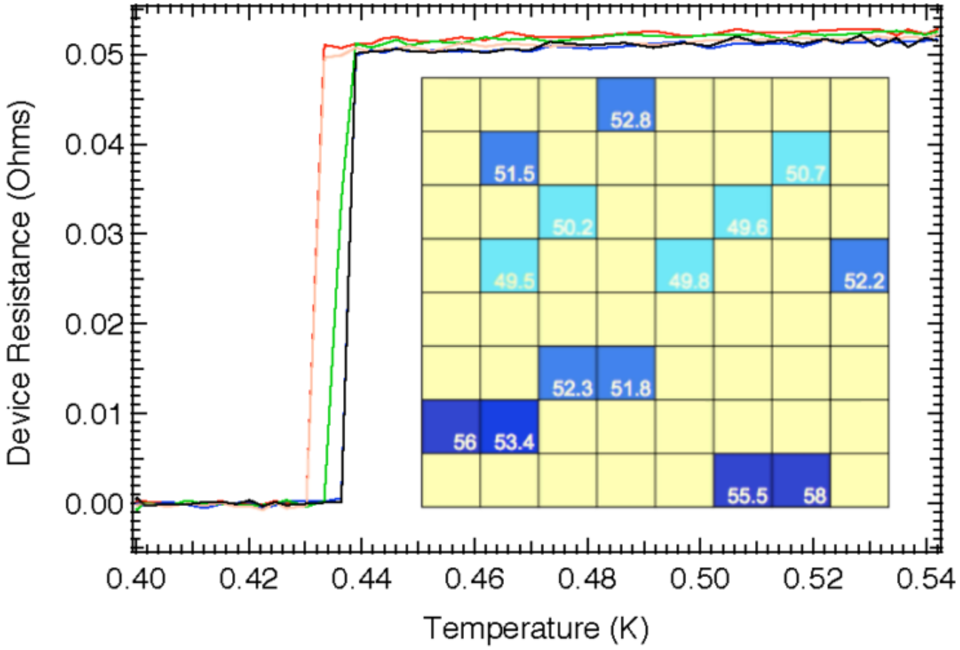
2009, AIP Conference Proceedings 1185

Spider, BICEP2/Keck

- Testing was conducted in two phases

Pre-screening Tests

After processing, selected tiles are tested in a quick-turn-around, cryogen-free, ^{3}He fridge. These tests are considered "pre-screening" because afterwards, entire focal planes (4 tiles at a time) are fully characterized in a more sophisticated crysostat equipped with SQUID based time-domain multiplexing. The pre-screening test



Prescreening conducted on subset of detectors, checking for critical temperature behaviour

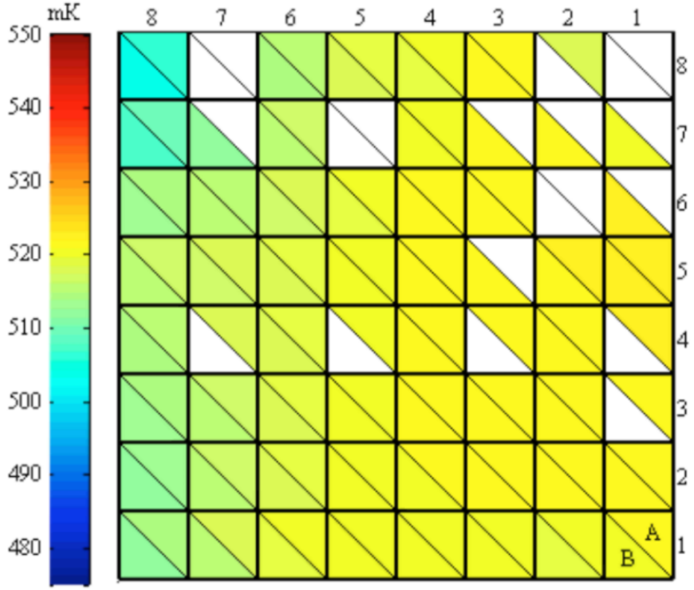
Spider, BICEP2/Keck

- Testing was conducted in two phases

Full Characterization with SQUID Multiplexing and Readout

After at least one tile is pre-screened via methods described above, entire focal planes (4 tiles) are fully characterized. The tiles chosen for these tests include one that was pre-screened and others which were processed in parallel. The full focal planes are tested in a different ^{3}He fridge in which the TES devices are measured by SQUID readout and SQUID multiplexing [7]. This system allows every device in the focal plane to be tested.

(A) T_c Tile Map



Full focal plate characterized (transition temperature, shown above for one tile)

Spider, BICEP2/Keck

- Testing was conducted in two phases

512 devices

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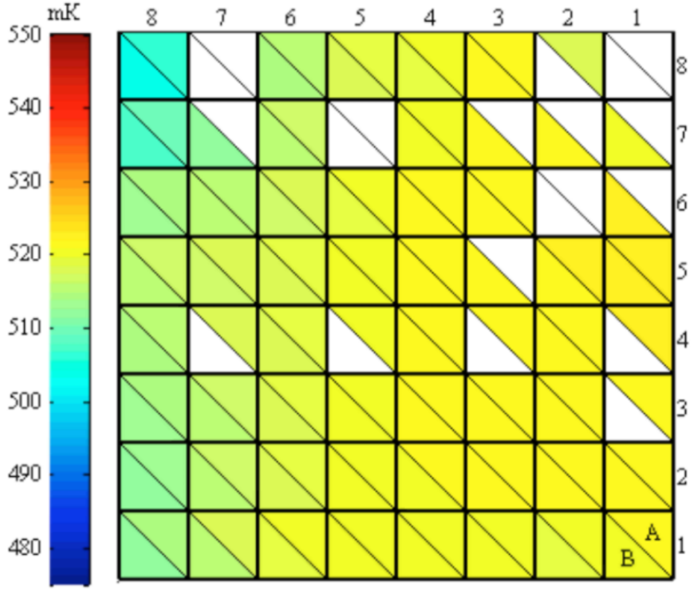

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Full Characterization with SQUID Multiplex

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Also in this case apparently all detectors were tested

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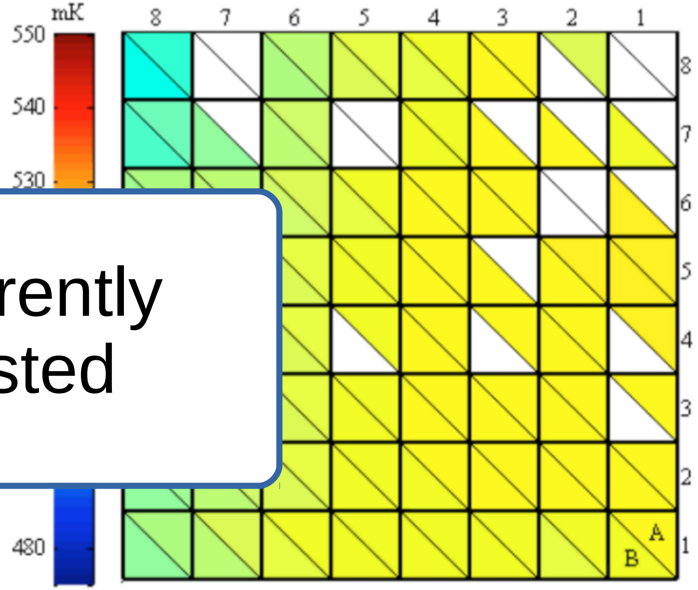


Full focal plate characterized (transition temperature, shown above for one tile)

BICEP2 bias tuning

- Another interesting example from BICEP2 bias tuning

Initial performance of the BICEP2 antenna-coupled superconducting bolometers at the South Pole

J. A. Brevik[†a], R. W. Aikin[a], M. Amiri[d], S. J. Benton[e], J. J. Bock[f,a], J. A. Bonetti[f], B. Burger[d], C. D. Dowell[f,a], L. Duband[g], J. P. Filippini[a], S. R. Golwala[a], M. Halpern[d], M. Hasselfield[d], G. Hilton[h], V. V. Hristov[a], K. Irwin[h], J. P. Kaufman[i], B. G. Keating[i], J. M. Kovac[j], C. L. Kuo[b,c], A. E. Lange[a], E. M. Leitch[k], C. B. Netterfield[e], H. T. Nguyen[f,a], R. W. Ogburn IV[b,c] A. Orlando[a,f], C. Pryke[l], C. Reintsema[h], S. Richter[j], J. E. Ruhl[m], M. Runyan[a], C. Sheehy[k,l], Z. Staniszewski[a,f], R. Sudiwala[n], J. E. Tolan[b,c], A. D. Turner[f], P. Wilson[f], and C. L. Wong[j]

Proceedings of the SPIE, Volume 7741 (2010).

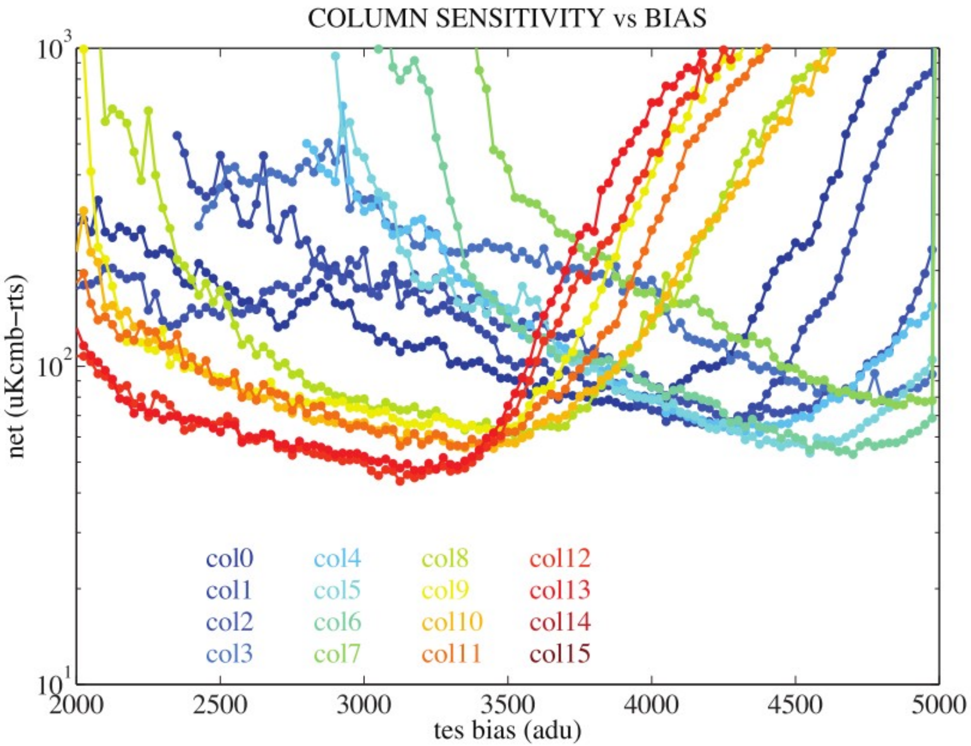
BICEP2 bias tuning

3. DETECTOR OPTIMIZATION & YIELD

Detector biases have been selected in order to minimize the instrumental noise-equivalent temperature (NET), while ensuring stability of the detector responsivities. To determine the bias that minimizes a column's NET, we have combined measurements of current noise for each detector with an estimate of its optical responsivity.

BICEP2 bias tuning

3. DETECTOR OPTIMIZATION & YIELD



the instrumental noise-equivalent temperature (NET),
› determine the bias that minimizes a column's NET,
ı detector with an estimate of its optical responsivity.

BICEP2 bias tuning

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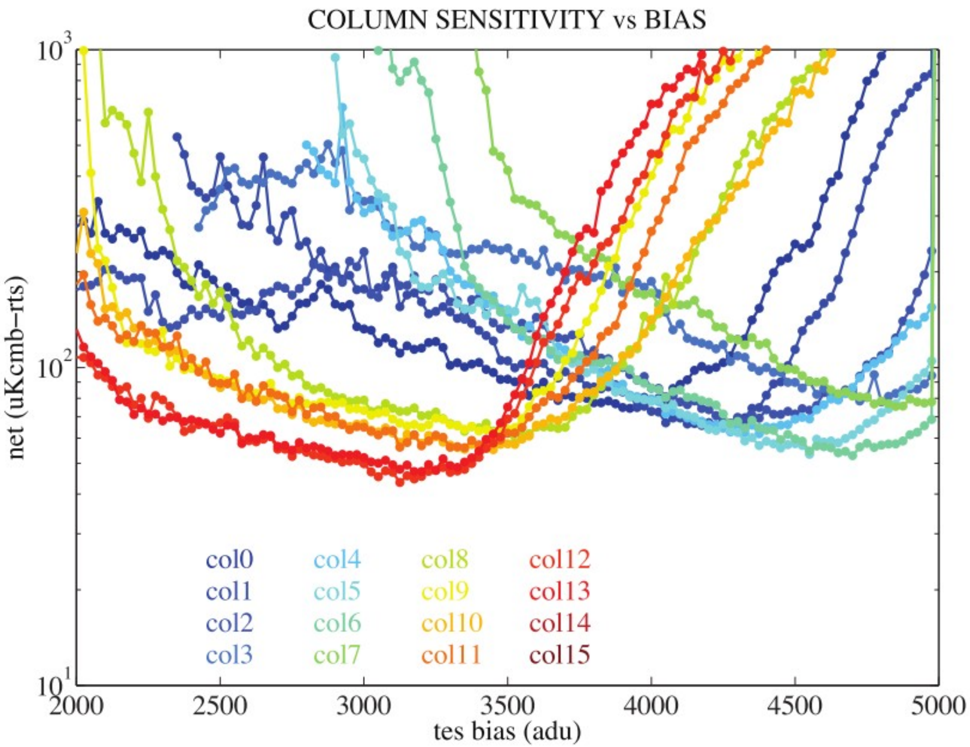


- They reduced the bias-detector correspondence by lumping detectors in groups of 32.
- This required, however, knowing noise properties of all detectors

Keck on site beam calibration

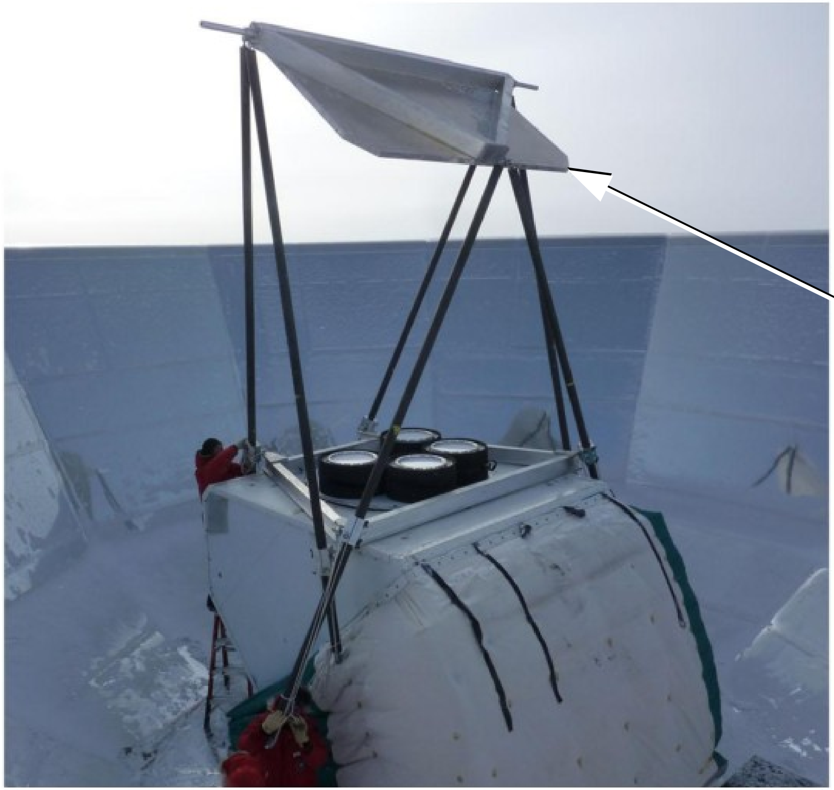
3.3 Far-Field Beam Characterization

3.3.1 Data Acquisition and Reduction

Measuring the beam pattern of each of the 2480 detectors of the Keck Array in the far field presents a challenge and requires an extensive beam mapping campaign at the South Pole. Figure 4 shows the setup used for measuring the beam pattern in the far field. With all five receivers installed in the drum, we install a 1.2×1.8 m aluminum honeycomb mirror, flat to 0.2 mm across the mirror, mounted on carbon-fiber rods. The mirror assembly was designed to be installed with no overhead crane; the entire system weighs less than 150 kg. The mirror redirects the beams over the top of the ground shield and to a chopped thermal microwave source with an aperture of 20 cm mounted on a 10 m tall mast on the Dark Sector Laboratory, 211 m away. The thermal source chops between a flat mirror directed to zenith (~ 15 K) and ambient (~ 260 K) at a tunable frequency, set to be 10 Hz.

Vieregg et al, Proceedings of the SPIE, Volume 8452, (2012).

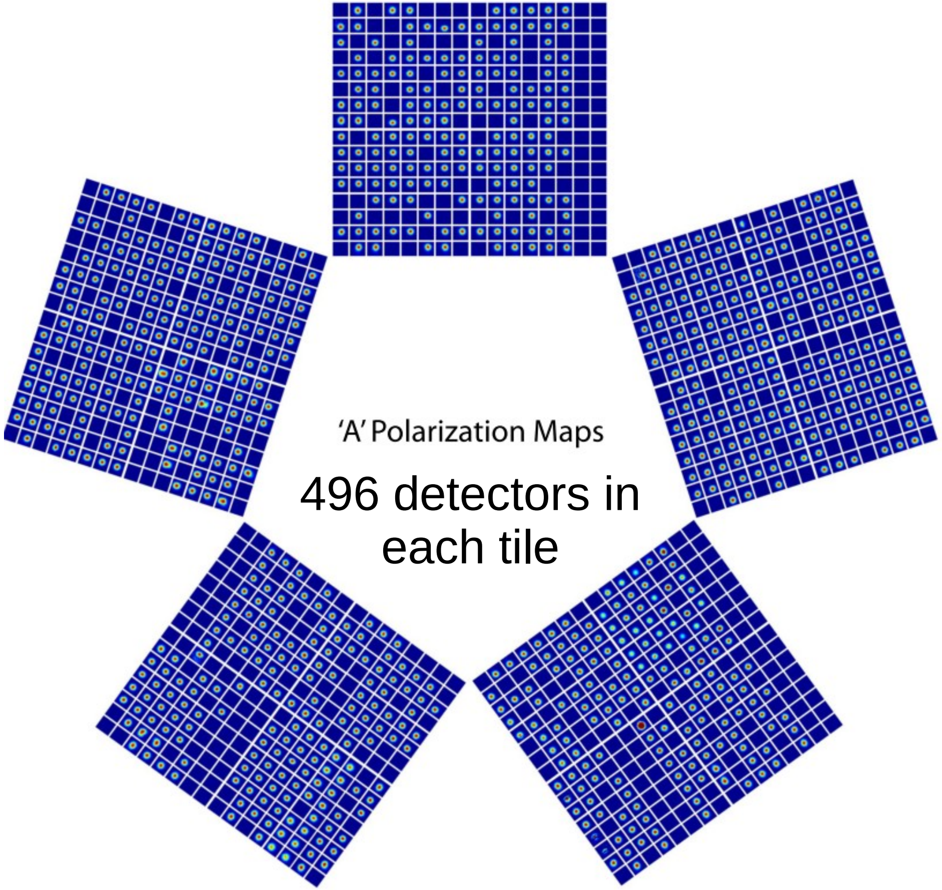
Keck on site beam calibration



Microwave source, 10 m high at a distance of 211 m from the instrument.

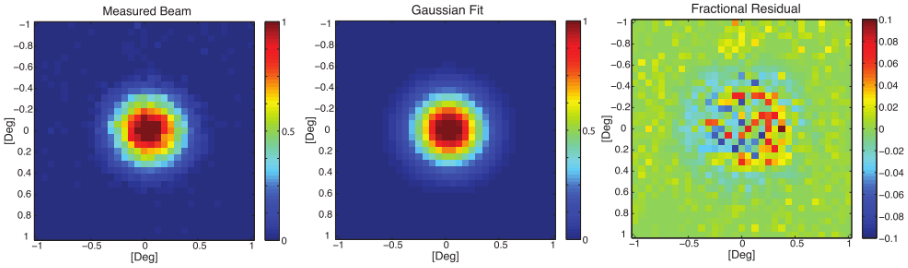
Flat mirror to redirect the signal into the focal plane. Mirror diameter allowed measurements of three detectors at a time

Keck on site beam calibration



496 detectors in each tile

- Measured beams for a single polarization.
- The full focal plane contains 2480 detectors
- Measured beams fitted with a Gaussian function



Measure Fit Residual

POLARBEAR (1274 detectors)

- An example found in the literature: polarization sensitivity measurements

4.1 Laboratory polarization tests

While in the laboratory at Berkeley, measurements of detectors in the cryogenic receiver were made by exposing the detectors to a modulated thermal source through an aperture just outside the cryostat window. To test the polarization sensitivity of the bolometers as well as the operation of the HWP, a tilted wire-grid polarizer was placed between the aperture and the cryostat. The polarizer was rotated and the response of each of the bolometers was recorded. Then the HWP rotation angle was changed, and the polarizer rotated again. Fig. 5(a) shows the previously measured polarized response of a witness pixel. The ratio of minimum to maximum response for the fit sinusoidal function is 0.02, which is likely limited by the wire-grid polarizer in the test setup. Fig. 5(b) shows the measurement in the POLARBEAR receiver, for a single pixel, at two positions of the HWP. Note that the HWP is correctly acting as a polarization modulator.

Arnold et al, 2010, Proc. of SPIE Vol. 7741

POLARBEAR (1274 detectors)

- Apparently all detectors were tested, although just an example was provided

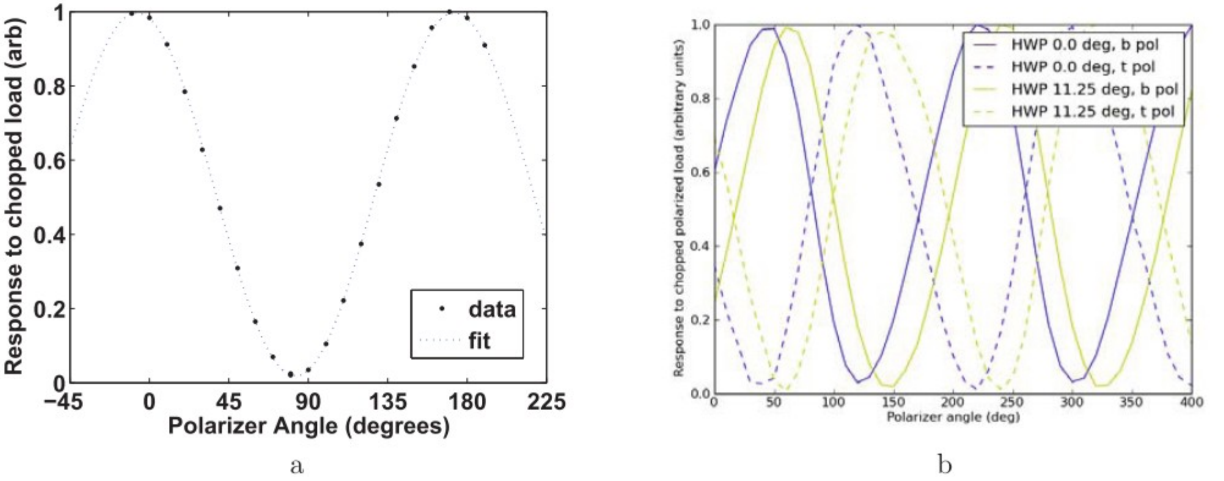


Figure 5. **(a)** Response of a single bolometer to a chopped thermal source with a rotating polarized grid between the source and the pixel. **(b)** Response of two bolometers on the same pixel in the same excitation setup as (a), with the HWP at two different positions.

Arnold et al, 2010, Proc. of SPIE Vol. 7741

ACT - MBAC (Millimeter Bolometer Array Camera)

J Low Temp Phys (2008) 151: 690–696
DOI 10.1007/s10909-008-9729-2

A Kilopixel Array of TES Bolometers for ACT: Development, Testing, and First Light

M.D. Niemack · Y. Zhao · E. Wollack · R. Thornton · E.R. Switzer · D.S. Swe
S.T. Staggs · L. Page · O. Stryzak · H. Moseley · T.A. Marriage · M. Limon ·
J.M. Lau · J. Klein · M. Kaul · N. Jarosik · K.D. Irwin · A.D. Hincks ·
G.C. Hilton · M. Halpern · J.W. Fowler · R.P. Fisher · R. Dünner ·
W.B. Doriese · S.R. Dicker · M.J. Devlin · J. Chervenak · B. Burger ·
E.S. Battistelli · J. Appel · M. Amiri · C. Allen · A.M. Aboobaker

Three 32x32 arrays of TES bolometers for a total of 3072 detectors

ACT - MBAC (dark detector measurements)

3 Dark Detector Measurements

Each column of 32 bolometers is subjected to a series of tests prior to insertion into the array. These tests are performed on every detector and include: measurements of the SQUID V-ϕ curve through the SQUID feedback and detector bias lines; TES T_c; Johnson noise spectra to extract the shunt resistance, R_{sh}, and Nyquist inductance; load curves for TES normal resistance, R_n, saturation power, P_{sat} and bias current, I_b; multiple noise measurements on the transition to measure non-multiplexed noise spectra and check for anomalies (Table 1). Based on these measurements, columns

ACT - MBAC (dark detector measurements)

3 Dark Detector Measurements

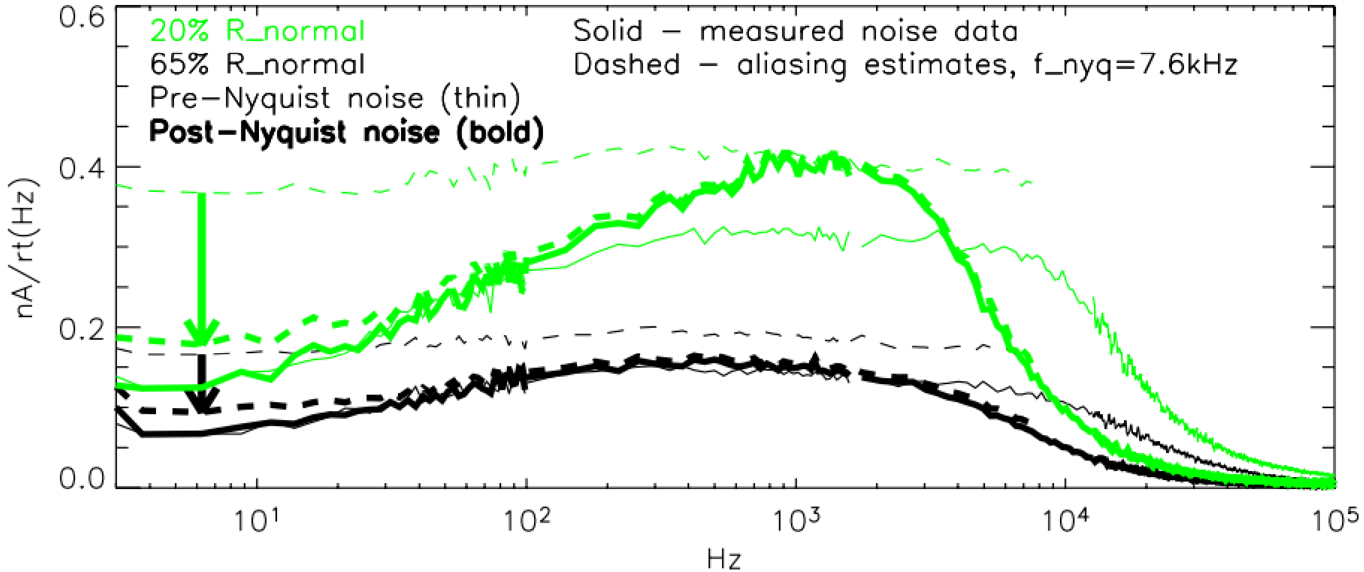
Each column of 32 bolometers is subjected to
the array. These tests are performed on every c
the SQUID V-ϕ curve through the SQUID fee
Johnson noise spectra to extract the shunt res
load curves for TES normal resistance, R_n, satu
multiple noise measurements on the transitio
spectra and check for anomalies (Table 1). Ba

These were measurements aimed at characterizing the bolometers before their installation in the array.

All bolometers were tested and a number of parameters measured

ACT - MBAC (noise measurements)

plexity of the bolometer model, we determined the inductance experimentally using a NIST multi-L chip with values between $L = 0.1$–1.4 μH. The noise on each bolometer was measured at multiple bias points before and after adding the inductor (Fig. 1). The noise level after aliasing, $N(f)$ where f is a frequency between 0 Hz-f_{Nyq},



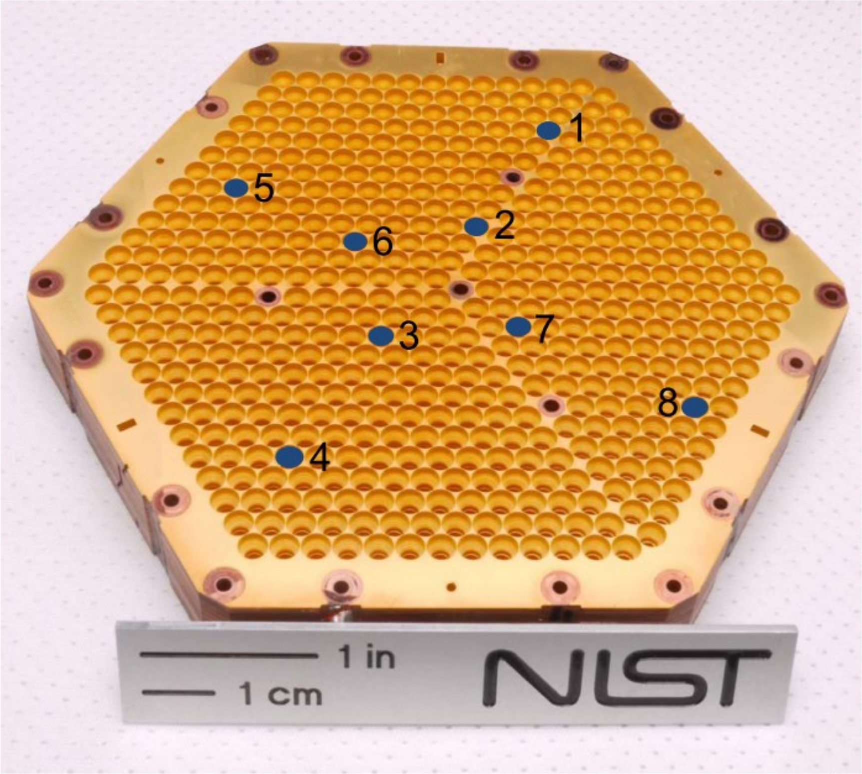
The design and characterization of wideband spline-profiled feedhorns for Advanced ACTPol

Sara M. Simon[a], Jason Austermann[b], James A. Beall[b], Steve K. Choi[a], Kevin P. Coughlin[c], Shannon M. Duff[b], Patricio A. Gallardo[d], Shawn W. Henderson[d], Felicity B. Hills[c], Shuay-Pwu Patty Ho [a], Johannes Hubmayr[b], Alec Josaitis[c], Brian J. Koopman[d], Jeff J. McMahon[c], Federico Nati[e], Laura Newburgh[f], Michael D. Niemack[d], Maria Salatino[a], Alessandro Schillaci[g], Benjamin L. Schmitt[e], Suzanne T. Staggs[a], Eve M. Vavagiakis[d], Jonathan Ward[e], and Edward J. Wollack[h]

Proceedings of the SPIE Volume 9914 (2016)

AdvACT - feedhorn measurements

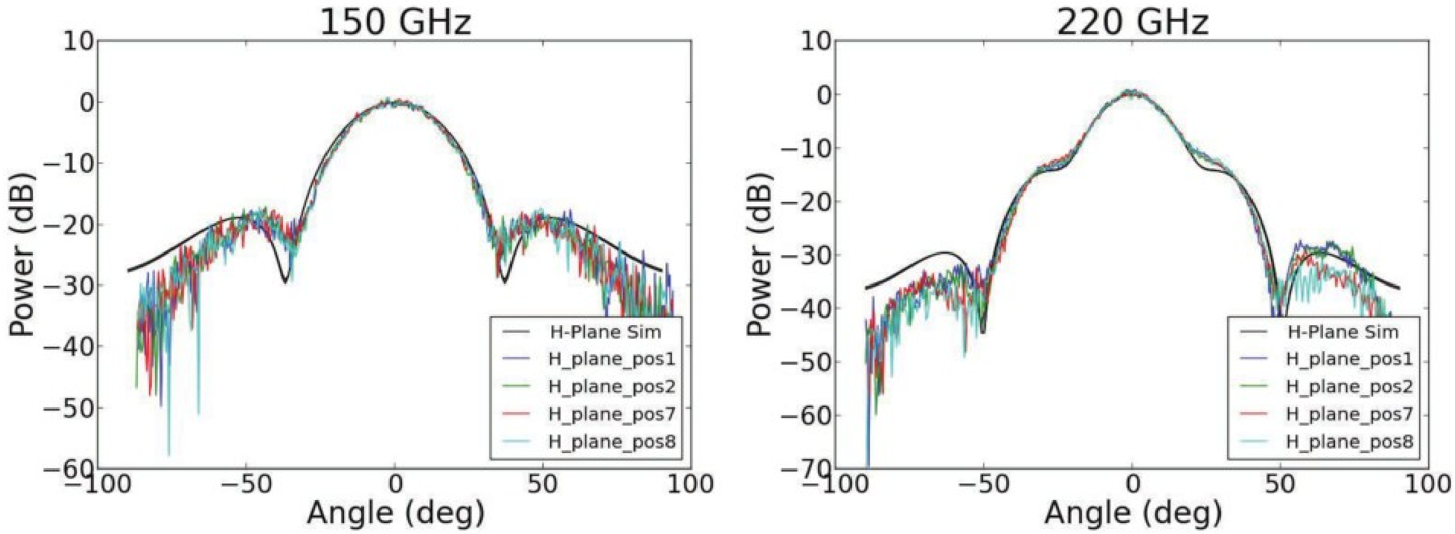
90 – 150 GHz dual-band feedhorns



- Focal plane of 507 corrugated feedhorns
- Only limited VNA measurements were performed (8 feeds, see figure)
- Results compared with simulations

AdvACT - feedhorn measurements

90 – 150 GHz dual-band feedhorns



(a) 150 GHz (b) 220 GHz

Figure 13: Measurements of H-plane beams at 150 GHz at each of the four feedhorn positions are shown above. The measurements between horns show that the feedhorns are highly uniform across the array.

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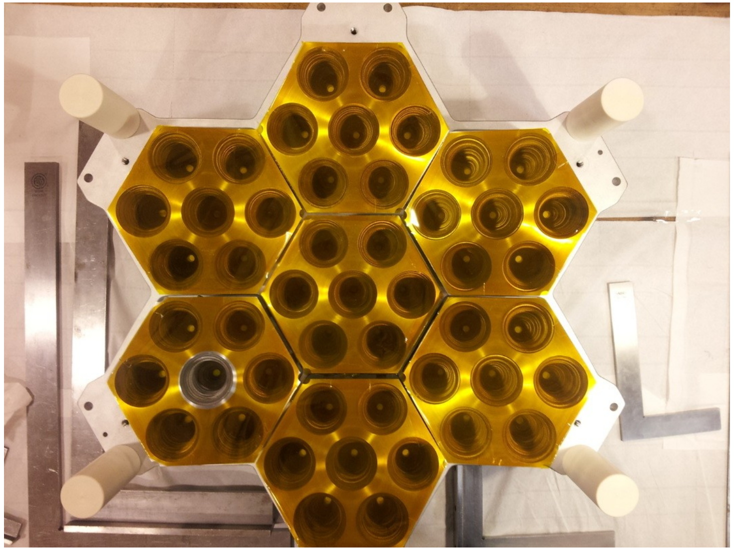
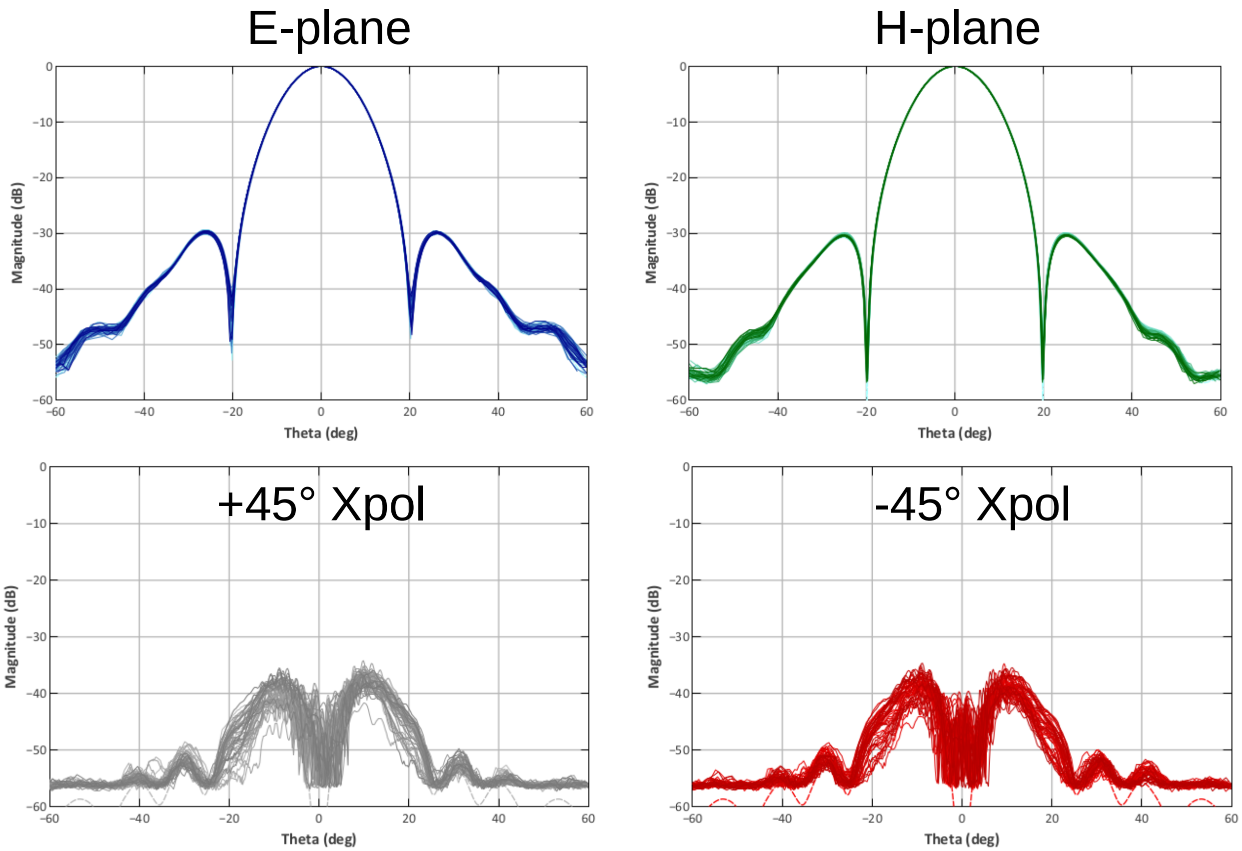
LSPE-STRIP focal plane horns measurements

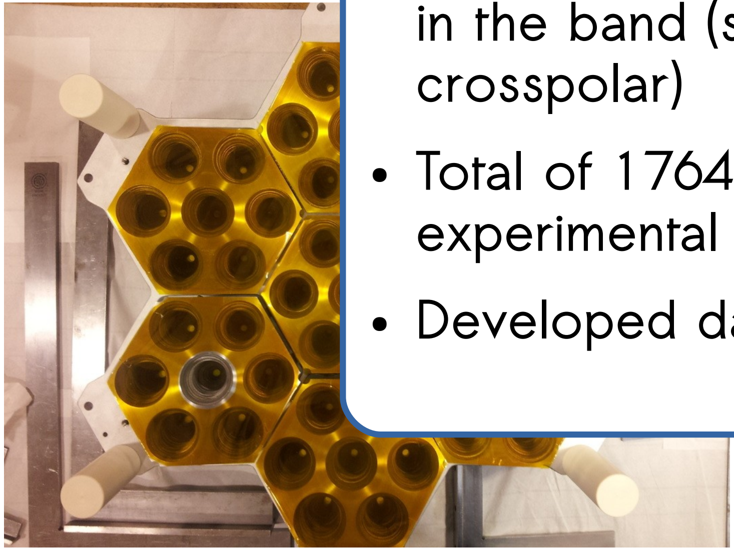
Focal plane of 49
corrugated feeds at 43 GHz

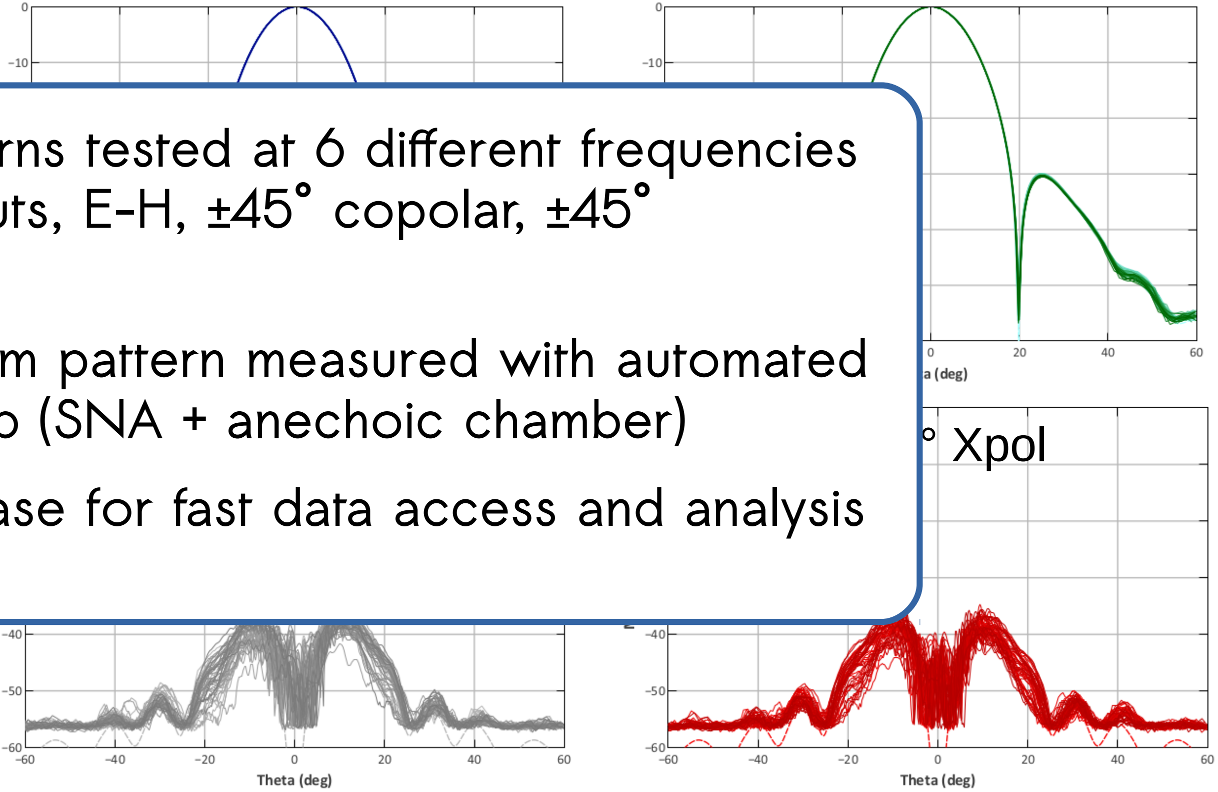




LSPE-STRIP focal plane horns measurements

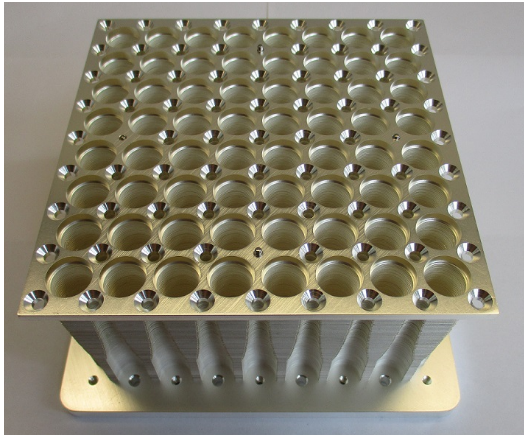
Focal plane of 49
corrugated f

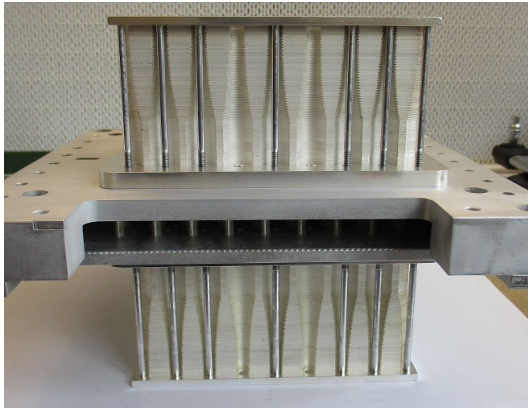




- All radiation patterns tested at 6 different frequencies in the band (six cuts, E-H, ±45° copolar, ±45° crosspolar)
- Total of 1764 beam pattern measured with automated experimental setup (SNA + anechoic chamber)
- Developed database for fast data access and analysis

QUBIC prototype feedhorns

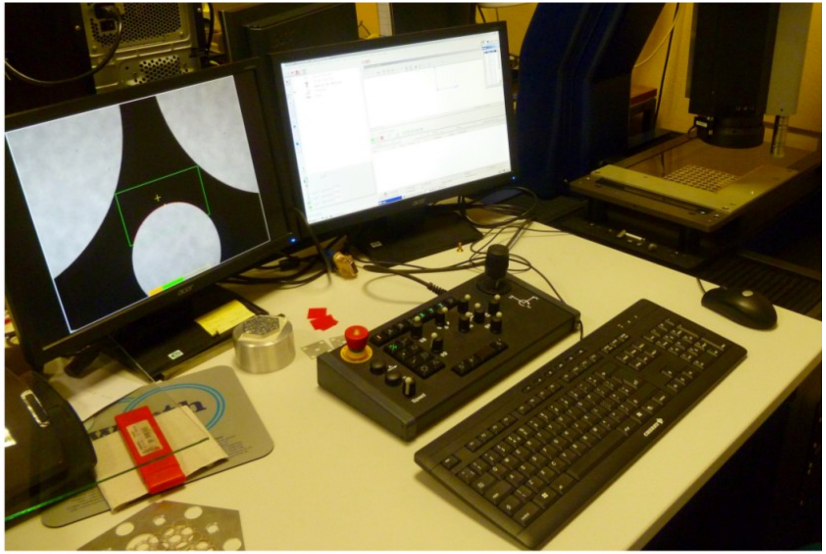


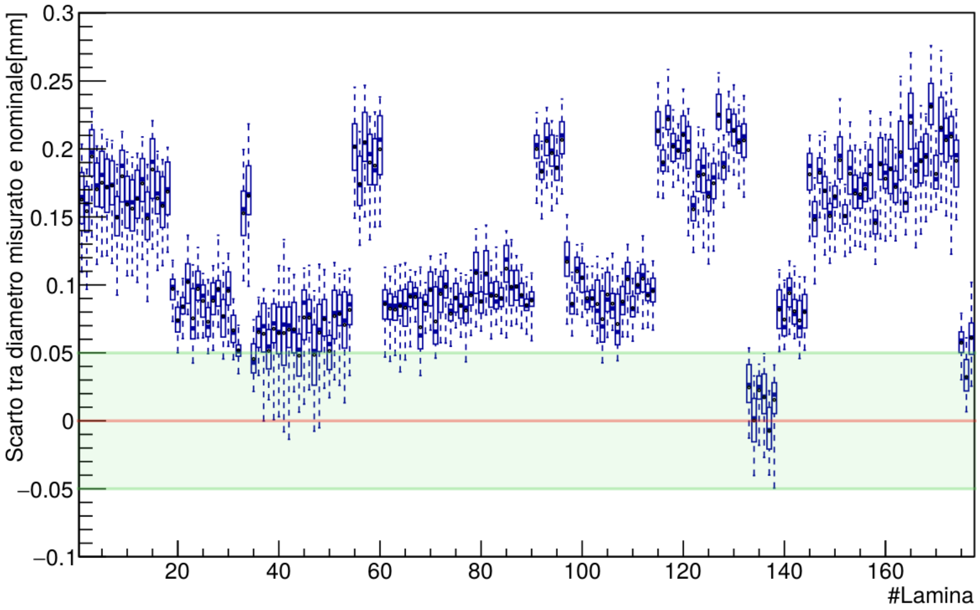


Arxiv:1609.04372

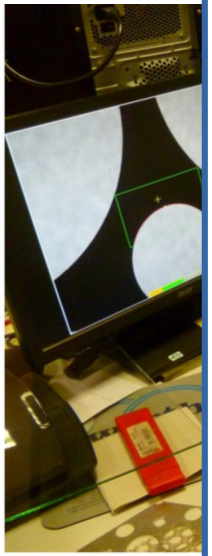
- QUBIC prototype feedhorns consist of two 64-elements feed arrays.
- The final horn array will consist of two 400-elements arrays.
- Feeds are realized from 0,3 mm Aluminium plates

QUBIC prototype feedhorns mechanical testing

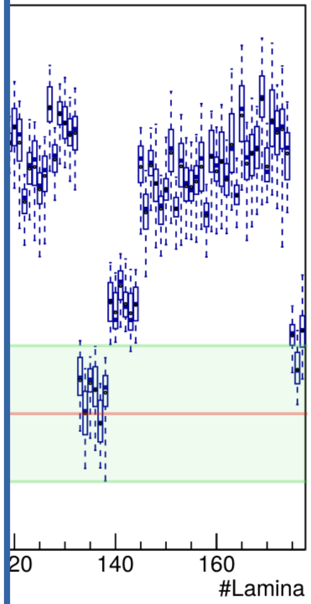




QUBIC prototype feedhorns mechanical testing



- Testing of mechanical tolerances performed on all antenna holes (22656 holes measured)
- Reconstructed real geometry of all antenna corrugations.
- Only a few antennas beam pattern will be measured (measurements in progress)
- Mechanical measurements coupled to simulations can be a means of relaxing burden of extensive e.m. tests on optical components



CMB-S4 - What do they say about testing?

CMB-S4 Technology Book First Edition

CMB-S4 Collaboration

June 9, 2017

ArXiv:1706.02464

CMB-S4 - What do they say about testing?

The cryogenic testing technology for CMB detector development is mature and well understood. The primary challenge for CMB-S4 detector development is in the sparsity of this critical resource. Investment into building up sub-Kelvin testing capabilities at universities and national labs is a high priority for CMB-S4 R&D.

CMB-S4 - What do they say about testing?

We know what must be done and how to do it, but we need a lot of resources to do the job

R&D.

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R&D.

Prospects and R&D path for CMB-S4 CMB-S4 will deploy an order of magnitude more detectors than Stage-III CMB experiments. Detector characterization throughput needs to keep up with detector fabrication. A significant amount of time for detector testing is taken up by cool down time for the test cryostat, so a robust method to shorten cool down time should be demonstrated. Automation of testing procedures allow detector characterization to be done in parallel at multiple places, and standardizing the test setup is important to be able to distribute testing to multiple institutions and still be able to compare test results. As the experiment's sensitivity increases, the requirements on detector systematic errors becomes tighter, and it becomes important to understand details such as characteristics of the attenuating filter used for testing and any reflections that happen between various optical elements in the test setup.

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Prospects and R&D path for CMB-S4. CMB-S4 will deploy an order of magnitude more detectors

1. Systematic effect requirements demand extensive testing and knowledge of details

2. Automation and standardization is key to cope with the large number of detectors

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CMB-S4 - What do they say about testing?

If the message did not get through they echo it again in the paper conclusions

Detector characterization is an essential part of detector fabrication. Timely feedback with accurate information is necessary to fabricate high performance detectors. The CMB community has many years of experience characterizing detector arrays. Development for high throughput testing is required to meet the demands of CMB-S4. New test cryostat designs, automation of testing and standardization of detector characterization will be necessary to increase detector testing throughput. Systematic error requirements on RF performance will be tighter for a more sensitive future CMB experiment and higher accuracy detector. Detector characterization will be needed to meet these requirements.

Conclusions

- The mantra "*know your instrument*" cannot be underestimated.
- Apparently there is no way out from the *hard way* of extensive testing. This must be understood and made clear to funding agencies
- The key is in *automation, standardization, parallelization*. Tests must be performed in a configured, documented, automatic and repeatable way
- Papers about testing of complex instruments are too few (at least in our field). We should publish (and cite) more, without fear to be *too technical*, or to deal with *little science*. The physics of the primeval Universe is no different from the physics of a piece of instrument.