NIST Instrumentation for CMB Observations

Joel Ullom

Silicon feedhorn arrays
TES polarimeter arrays
MKID polarimeter arrays

SQUID-based multiplexed readout
On-chip refrigeration
CMB power spectra measurement status

Figure courtesy L. Page
Developed by a large fraction of US CMB community

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Feedhorns for CMB science

U2 DMR
http://aether.lbl.gov/www/projects/u2/U2PARAMETRIC.JPG

COBE
http://muller.lbl.gov/COBE-early_history/preCOBEhistory.html

WMAP
http://wmap.gsfc.nasa.gov/media/ContentMedia/990259b.jpg

Planck
http://www.esa.int/spaceinimages/Images/2009/05/Planck_s_instruments4
Silicon feedhorn-coupled arrays

Yoon et al. *AIP* 2009
Hubmayr et al. *JLTP* 2012

**corrugation profile**
Silicon feedhorn-coupled arrays: performance

Hubmayr et al. JLTP 2012
Silicon feedhorn-coupled arrays

Yoon et al. *AIP* 2009
Hubmayr et al. *JLTP* 2012
Detection concept

- Transition-edge sensor (TES) bolometer
  - (one per polarization)

- Planar Ortho-mode Transducer (OMT) pixel

- Corrugated feedhorn

- NIST feedhorn-coupled, superconducting TES polarimeters

( Yoon et al. JLTP 2008 )
Detection concept

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"Yoon et al. JLTP 2008"

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NIST feedhorn-coupled, superconducting TES polarimeters

(Yoon et al. JLTP 2008)
TES parameters driven by $T_b$ and readout
Have produced sensors for all relevant parameter space
Space-optimized TES bolometers

Niemack et al. JLTP 2012
Multichroic polarimeters with 2.3:1 bandwidth

We believe 3:1 bandwidth is possible in the future

McMahon et al. *JLTP* 2012
Hubmayr et al. *ISSTT* 2015
ACTPol 90/150 GHz detectors

Thornton et al. 2016 in prep

TES bolometer
Lossy Au meander
SiN legs
Nb microstrip
OMT
MoCu bilayer

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ACTPol 90/150 GHz assembled focal plane

255 optical pixels

1020 TES

83% yield (includes readout, cabling, etc)

Detector yield near 100%

Observing since early 2015

Thornton et al. 2016 in prep
90/150 GHz ACTPol images

ACTPol PA3 90 GHz (0.9' Smoothed)  ACTPol PA3 150 GHz (0.6' Smoothed)

Preliminary Centaurus A
90/150 GHz ACTPol performance

- Based on observation of Saturn at PWV = 0.5mm
- Preliminary multichroic array NET < 9 uK √s with 1020 TES

Achieved instantaneous sensitivity of KECK array (2560 TES)

Bk-V: arXiv:1502.00643
Array fabrication improvements

- 150mm array fabrication now routine
- most recent wafer for Advanced ACTPol:
  - 503 pixels, 2012 sensors
  - 99.9% electrical yield
  - Saturation power within 15% of specification
  - 2% transition temperature variation
  - Optical efficiency (through feeds) 70-80% at 150 GHz and 65-75% at 230 GHz based on single pixel tests
Feedhorn-coupled, dual-polarization MKIDs

- feedhorn-coupled
- TiN/Ti multilayer superconducting material
- lumped element kinetic inductance detectors

- scalable to large detector-count cameras
- scalable in frequency
- dual-polarization sensitivity
- beam properties defined by feedhorns
- low number of focal plane interconnects

Hubmayr et al. IEEE Trans Appl Sup 2013
MKID Pixel Design

pixel schematic (not to scale)

TiN/Ti multilayer absorbers

waveguide aperture

MKID-1

MKID-2

detailed pixel design
single metal layer with no cross-overs

Dober et al. *JLTP* 2016
Dual-polarization MKID demonstration

Optical NEP

Photon-noise-limited @
P > 0.5 pW

$\eta_{opt} = 75\%$ relative to 1-1.4THz top hat band
This matches HFSS coupling simulations

Polarization response

$\text{Dober et al. } \textit{JLTP} \ 2016$
BLAST-TNG Implementation

- Balloon mission with reflight planned for 2017
- Three 100 mm diameter arrays: 250, 350 and 500 micron bands
- ~3000 total MKIDs
- MKID arrays for flight presently under development; two weeks for layout, fabrication, and start of testing
Possible CORE MKID architecture

- Substitute MKIDs for TESs in designs shown earlier
- Feedhorns and OMTs for optical coupling: allows smaller volume MKIDs with lower NEPs

(a) MKID diagram

(b) MKID diagram with additional labels
• NIST fabricates SQUID circuits for Time and Frequency Division SQUID Multiplexing (TDM and FDM)

• These are widely used: ACT, ACTPol, ABS, Keck, SPIDER, BICEP2, BICEP3, SCUBA2, SPTPol, SPT3G, Polar Bear, EBEX, …

• TDM and MHz FDM provide ~10 MHz of analog bandwidth so multiplexing factors are similar: 64 to 1 in upcoming experiments

• GHz readout provides 1-4 GHz of analog bandwidth but it isn’t used as efficiently. Still, multiplexing factors > 1,000 are realistic.

• GHz readout works for both MKIDs and TESs, the latter via microwave SQUIDs

more on readout on Thursday
NIS cooling

- cooling to 300 mK is “easy”
- cooling to 100 mK is substantially harder and more expensive
- local cooling embedded in the detector circuitry is a low-cost (no-cost?) way to cool detectors to near 100 mK
- can be done with normal-insulator-superconductor tunnel junctions
- have already shown cooling of phonon payloads from 300 mK to 154 mK (Lowell, 2014). Cooling from 300 mK to ~110 mK predicted


for a satellite:
- can bias many junction cells in series using ~1 μA
- can use for fast T regulation or for different local Ts
- power rejected to 300 mK is ~100×(P_{TES}+P_{sky})
  this is probably < 300 pW/sensor. For 2,500 sensors, rejected power = 750 nW (fine for $^3$He stage)
Why silicon feedhorns?

- metal feedhorns have long, successful heritage: COBE, WMAP, Planck
  - high quality beam patterns
  - low systematic errors
- silicon feeds are like metal, but better:
  - leverage power of modern microfabrication to manufacture large, uniform arrays
  - lighter (~300 g for 150 mm diameter stack)
  - CTE matched to detector arrays
  - novel profiles possible
- compatible with <25 GHz to 680 GHz
- can be broad-band: 2.3:1 demonstrated, 3:1 planned
- silicon feeds used successfully in several CMB experiments
  - SPTPol 150 GHz
  - ACTPol
  - ABS
- silicon feeds planned for Advanced ACTPol and SPIDER
- present TRL = 4-5. After 2017 SPIDER flight, TRL = 6
- compatible with dual polarization, multifrequency pixels
- compatible with TESs, MKIDs, and all readout schemes
Thoughts on the CORE focal plane

focal plane as conic section

expanded views of focal plane

focal plane as conic section

150 mm feedhorn stack

bent feed?

sensor wafer

Some rays are limited by the stop, some by the primary.
TESs vs MKIDs

• We are pursuing both at NIST; this provides a clear-eyed perspective on strengths and weaknesses
• Both are candidates
• TRL gap between TESs and MKIDs sometimes underestimated
  – Numerous successful TES CMB instruments in challenging environments including balloons
  – Open questions about in-band sensitivity and 1/f noise of MKIDs
• Microwave readout is attractive AND is available for both TESs and MKIDs
• Layout and construction of MKID focal planes can be easier
  – Easier fabrication? Yes for direct absorption, maybe not for indirect coupling
  – Fewer interconnects within focal plane (no bias Rs, integrated readout)

More detailed discussion of readout moved to splinter session tomorrow
Thank you
Upcoming: 280 GHz Balloon-borne array demonstration on SPIDER

16x16 polarimeter array design

feedhorn silicon platelet

Q and U pixels

low thermal conductance bolometer
Highly uniform feedhorn arrays