Some thoughts on readout

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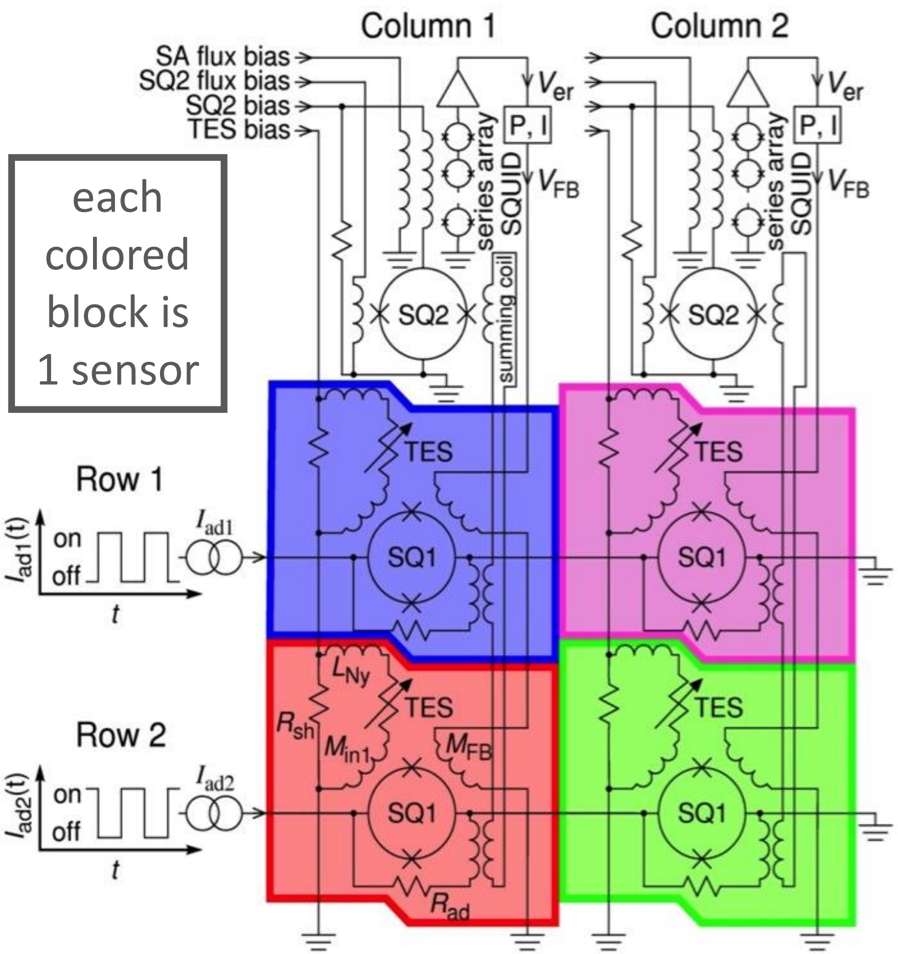
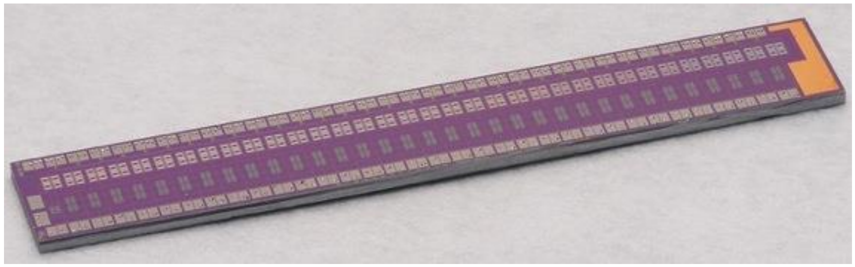
Time Division SQUID multiplexing (TDM): concept



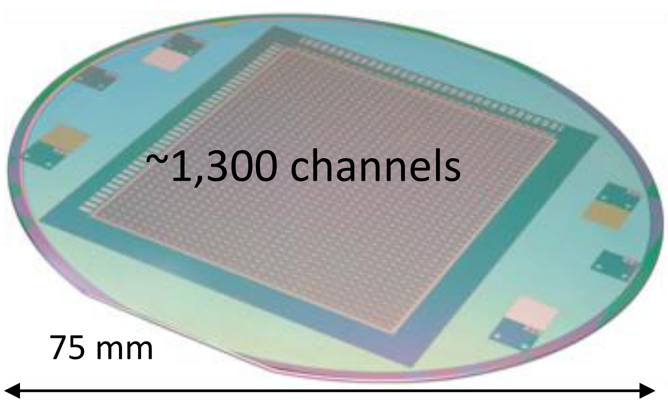
- DC biased TES
- each TES coupled to one SQ1
- rows of SQ1s turned on and off sequentially
- each SQ1 in flux-locked loop
- wire count scales as N+M, whereas detector count scales as N*M
- TRL = 6 (33 channels per column) in SPIDER balloon flight 2015

TDM: performance

33x1 SQUID multiplexer



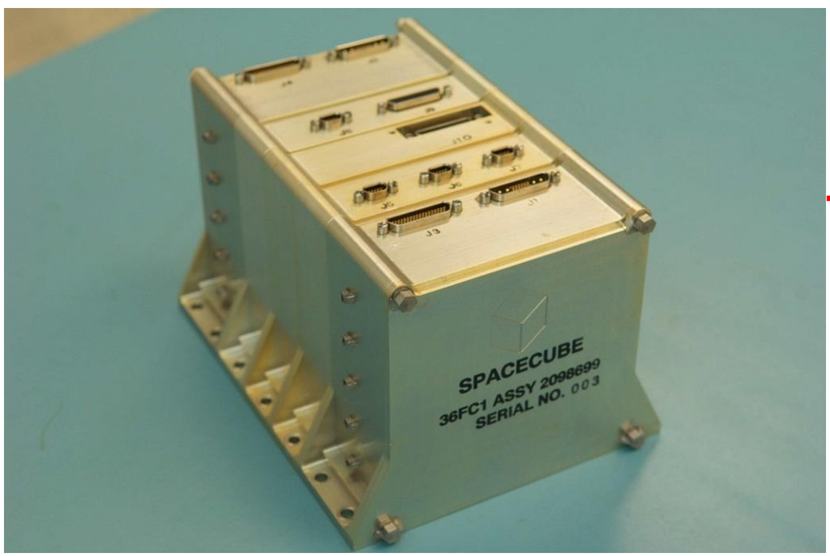
2D multiplexer



HAWC+, PIPER, SCUBA2

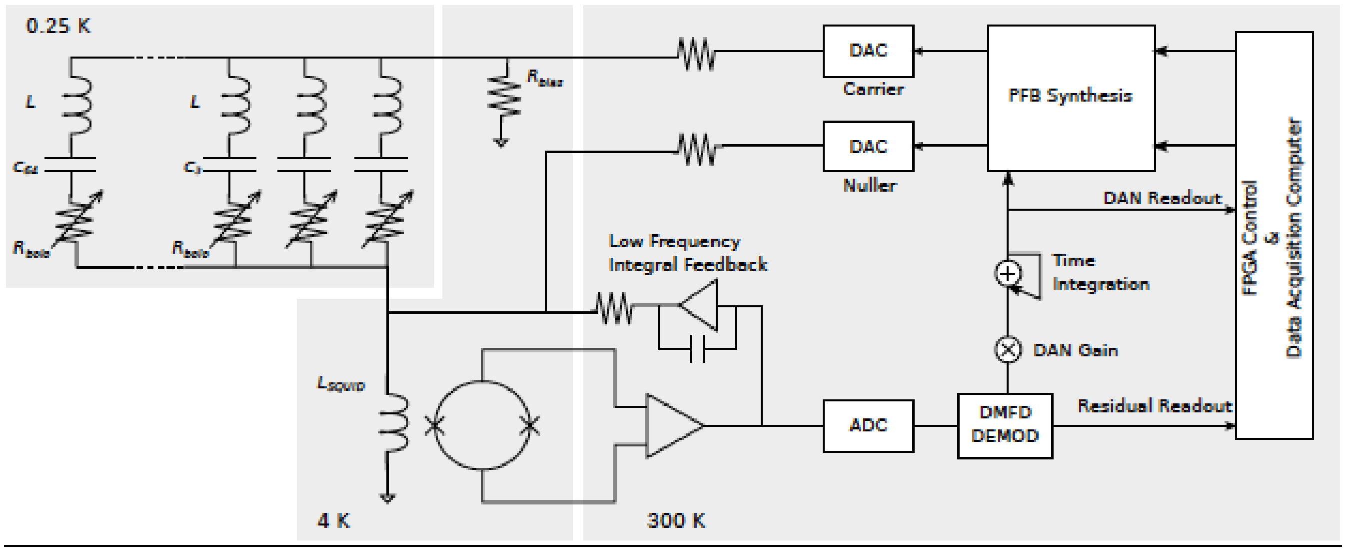
- Used in mm/sub-mm instruments: ACT, ACTPol, Advanced ACTPol, ABS, BICEP2, BICEP3, CLASS, HAWK+, PIPER, GISMO1, GISMO2, Keck Array, MUSTANG, SCUBA2, SPIDER, ZEUS2
- highest mux-factor in deployed instrument: 40 in SCUBA2
- highest mux factor under development: 64 (advanced ACTPol, Henderson et al 2016)
- highest pixel-count array demonstrated on the sky: 10,000 SCUBA2
- readout area per channel at mK stage = $3.6 mm^2$
- wire-count for 6000 sensors
  - 300K to 4K: 530 twisted pair
  - 4K to mK: 439 twisted pair
  - (assumes x64 and 1 detector bias pair per column)
- cross-talk
  - 0.25% nearest neighbor, <0.03% for rest (deKorte 2003, B2 instrument paper)
- when bias circuit optimized, negligible noise degradation due to readout
- dissipates ~1.8 nW/column at coldest stage

TDM: readout



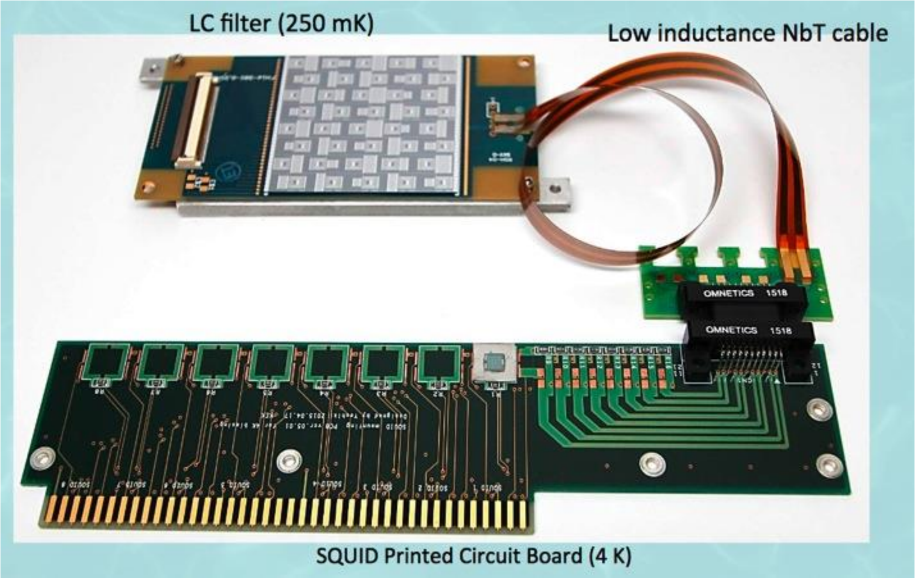
- Multi Channel Electronics (MCE) developed at University of British Columbia
- 37 mW/channel
  - 2048 channels/crate (assuming 64 rows per column)
  - 75 W/crate
- SCUBA2, ACT, ACTPol, ABS, SPIDER, NIST THz imager
- TRL=6 (SPIDER 2015)
- Also, SPACECUBE implementation under development at GSFC; TDM electronics in space-qualified framework; about 100 mW/channel

MHz Frequency Division SQUID multiplexing: concept

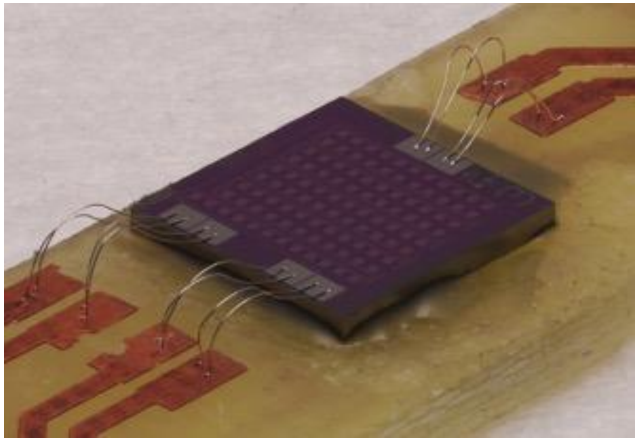


- AC biased TES
- LC for each sensor (~300kHz – few MHz)
- N sensors coupled to one SQUID series array (N_mux)
- wire count from 4K to mK stage: 2 x N_tes/N_mux
- Two separate development efforts/architectures: UC Berkeley/McGill and SRON
- TRL = 6 (N_mux = 16, EBEX flight 2013)
- Baseline readout for LiteBIRD

MHz FDM: performance



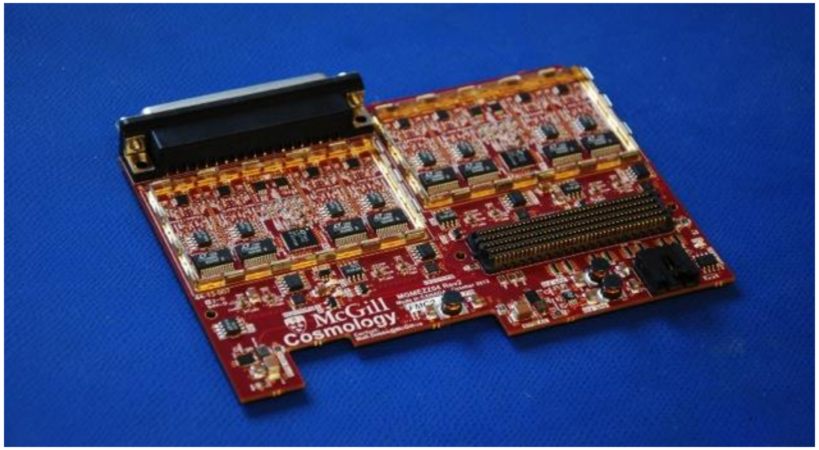
Hattori LTD16

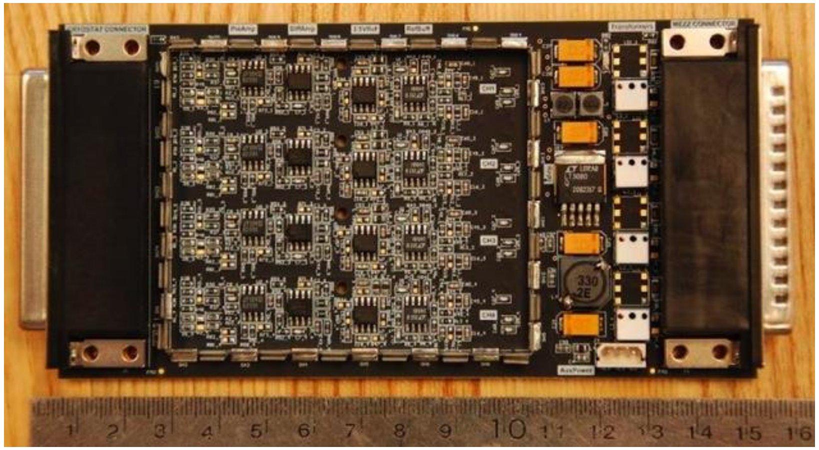


SQUID Series Array

- Used in mm/sub-mm instruments APEX-SZ, EBEX, PolarBear/Simon's Array, SPT, SPTpol, SPT-3G
- highest mux factor achieved in deployed instrument: 16 (EBEX, McDermid 2014)
- highest mux factor under development: 64 (SPT-3G)
  - lab demonstration (Bender et al 2014)
- highest pixel-count array demonstrated on the sky: 1,536 (SPTpol, Austermann 2012)
- Readout area per channel at mK stage = 60 mm^2 (silicon LC chips only)
- wire count for 6000 sensors
  - 300K to 4K: 375 twisted pairs
  - 4K to mK: 94 low inductance pairs
  - assumes x64 multiplexing
- Xtalk: <1% is the goal (Hattori 2016)
- When bias circuit optimized, negligible noise degradation due to readout
- Demonstrated systems used surface mount capacitors and lithographed inductors .Fully lithographed circuits possible.
- Depending on SQUID array location, no dissipation at focal plane

MHz FDM: readout

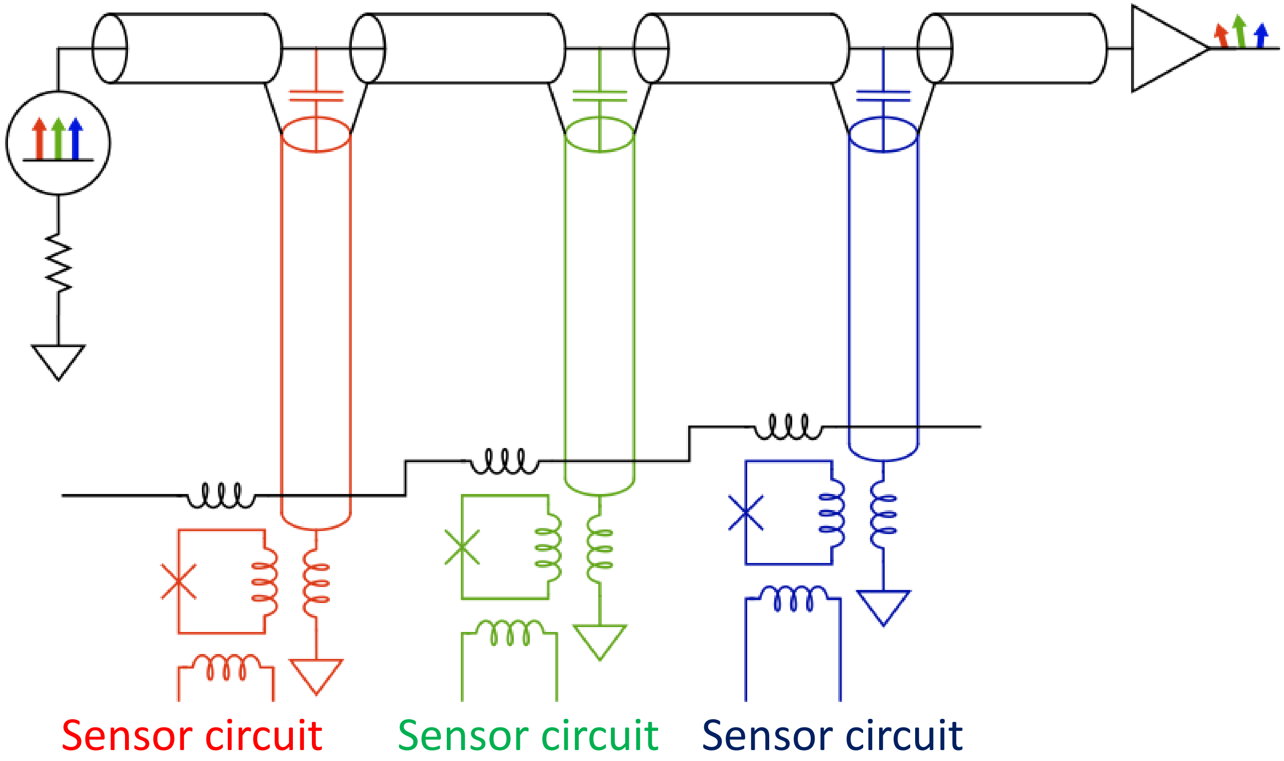




- Developed at McGill University and SRON
- Power consumption
  - 330 mW/channel (x16 MUX, EBEX 2013, McDermid 2014)
  - 49 mW/channel with new FPGA chips and x64 MUX (Bender et al. 2014)
- EBEX, SPTpol, PolarBear
- Space optimized hardware shown on the left. Key components brought to TRL5.

Microwave SQUID multiplexer: concept

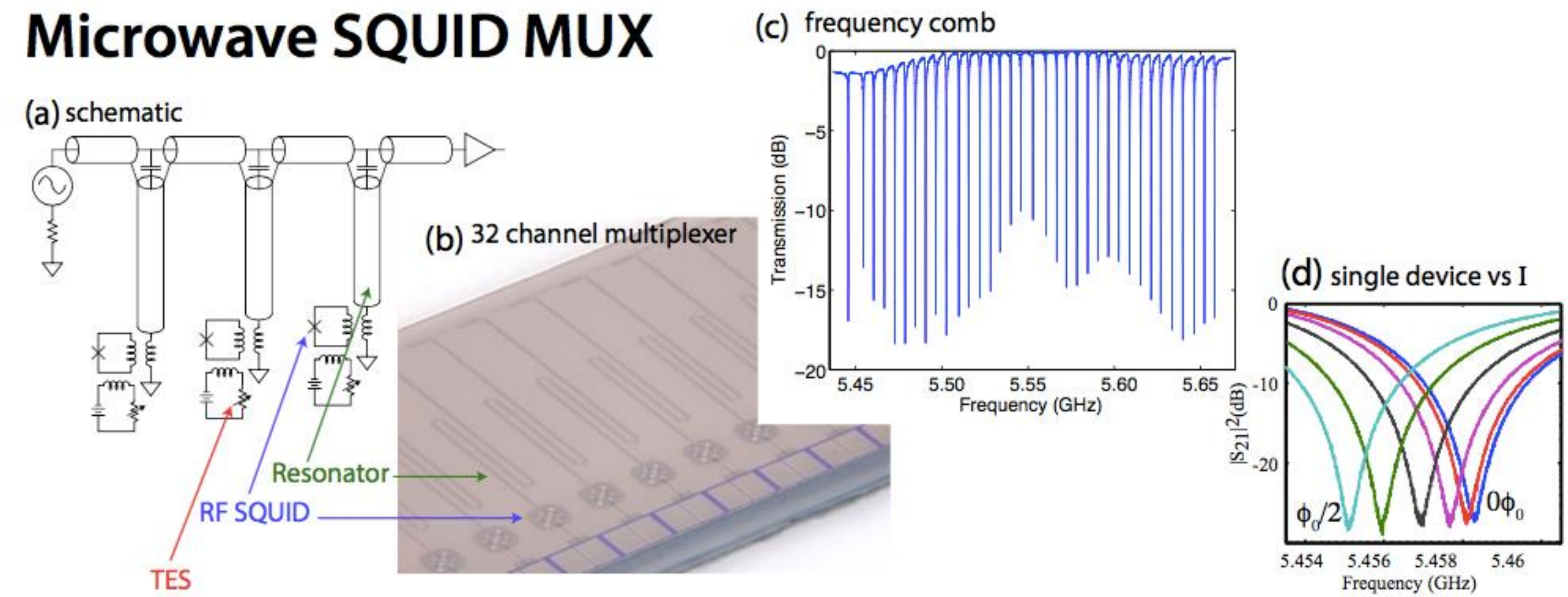
Dissipationless rf-SQUIDs modulate non-overlapping resonators



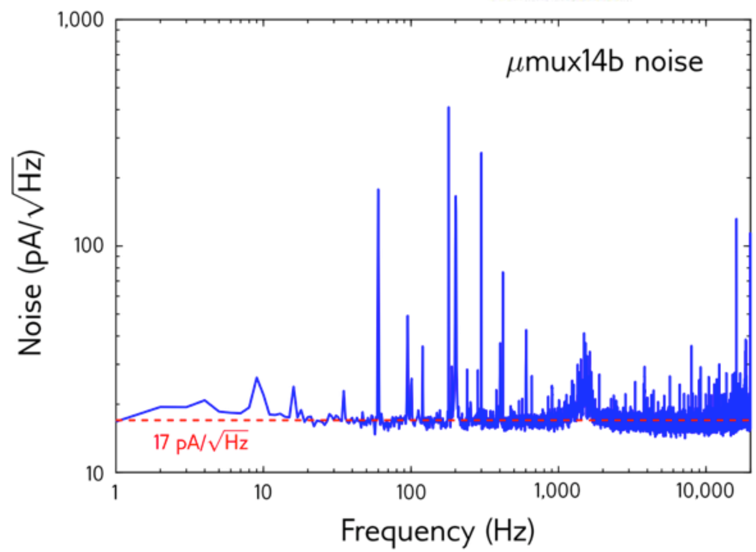
Read out large array with two coax + a handful of DC lines

Mates ASC 2014

Microwave SQUID multiplexing



- Frequency scalability of MKIDs + proven sensitivity of TES
- 32 channels demonstrated in season 1 of MUSTANG2
- 64 channel demonstration on MUSTANG2 this season
- scales to ~1000 channels



Electronics for GHz readout

- MKID and microwave SQUID extremely similar but not identical
- Useful bandwidth typically set by ADCs and DACs with high effective number of bits: 500 MHz – 1 GHz typical. Can obtain more bandwidth per HEMT with additional ADCs and DACs
- Several implementations:
  - ROACH, ROACH2. Used in MUSTANG, ARCONS (ground) & BLAST-TNG (balloon)

  - SPACEKIDs
  - Others? SLAC, 4DSP, …
- 100 & 500 mW/channel for Bonn/SRON & Grenoble electronics [Weds]

TDM vs MHz FDM for TESs

- We are pursuing both at NIST; this provides a clear-eyed perspective on strengths and weaknesses
- Both are candidates
- Both have been used in challenging environments including balloons (SPIDER, EBEX)
- Multiplexing factors are similar
  - TDM 64:1 for Advanced ACTPol
  - FDM 64:1 for SPT3G
- Power/channel in readout electronics similar
- Progress has been made on space-qualified electronics for both (SPACECUBE, McGill & SAFARI).
- DC-biased TES operation can be easier than AC-biased
- TDM is >10x more compact: L/R filters vs LC
- FDM usually requires fewer wires to the focal plane
- FDM usually requires less power dissipation at the focal plane but the dissipation from TDM is seldom significant

MHz vs GHz Readout

- We are pursuing both MHz and GHz readout at NIST; this provides a clear-eyed perspective on strengths and weaknesses
- Both are candidates
- TRL of GHz readout is lower but there is time for it to mature
- GHz readout will provide higher multiplexing factors, but CORE isn't an extreme consumer of readout bandwidth
  - Intermediate sensor count
  - Low bandwidth per sensor
- In implementations so far, GHz control electronics dissipate more power per channel: 100 mW/channel (GHz) vs 37- 49 mW/channel (TDM, FDM). <u>This is not a universal law: a more detailed analysis of the power limits is needed.</u>