An Update on MUSIC: A Kinetic Inductance Detector Camera for Sub/Millimeter Astrophysics at the Caltech Submillimeter Observatory

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Abstract—**MUSIC (Multiwavelength Sub/millimeter kinetic Inductance Camera, formerly the MKID Camera) is a new facility-class instrument for submillimeter- and millimeter-wave astrophsics at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. The instrument utilizes microwave kinetic inductance detectors (MKIDs), coupled to slot-line antennae through lithographic bandpass filters, offering simultaneous imaging in four bands between 2 mm and 850 μm with 576 spatial pixels. The MKID technology naturally leads to implementation of a frequency-division multiplexing scheme, with several hundred detectors read out through a pair of coaxial connections and a single cryogenic HEMT amplifier. Room-temperature readout is handled with commercial software-defined radio techniques. MUSIC is a collaborative project between the California Institute of Technology, the Jet Propulsion Laboratory, the University of Colorado at Boulder and the University of California, Santa Barbara, and is due for commissioning in late 2010. This paper presents an overview of the project, and an update on the current status and latest results.**

I. INTRODUCTION

The development of large-format instruments with arrays of incoherent detectors for astronomy at millimeter and submillimeter wavelengths has proved to be extremely challenging. However, in the last few years considerable success has been realized through the use of transition-edge sensor (TES) bolometers [1] multiplexed with SQUID arrays [2], with instruments such as SCUBA-2 on the James Clerk Maxwell Telescope [3] producing first results. However, such focal planes present considerable technical challenges in implementation.

We report on the progress towards deployment of a new instrument for millimeter wave astronomy from the Caltech Submillimeter Observatory (CSO), Mauna Kea, Hawaii. MUSIC, the Multicolor Submillimeter kinetic Inductance Camera (formerly the MKID Camera), use microwave kinetic inductance detectors, or MKIDs, a novel superconducting detector that overcomes many of the complexities associated with SQUID multiplexing systems for TES detectors. This paper discusses a number of the key design features of the MUSIC instrument, in addition to a summary of the current status of the project.

II. MICROWAVE KINETIC INDUCTANCE DETECTORS

MKIDs are a type of superconducting detector in which the energy absorbed from an incoming photon breaks Cooper pairs. The physics of MKIDs have been extensively discussed elsewhere [4], and only an overview will presented in this work.

For alternating currents, superconductors have a non-zero impedance since the Cooper pairs can be accelerated by an electric field, allowing energy to be stored in or extracted from the kinetic energy of the paired electrons. The inertia of the Cooper pairs contributes to what is known as the kinetic inductance.

At finite temperatures below the transition temperature, T_c, a small fraction of electrons are thermally excited out of paired states to produce a surface impedance, Z_s. The surface impedance of a pure superconductor is imaginary since the inductive response of the Cooper pairs is lossless. The free electrons, or "quasiparticles", produce a real component in Z_s, analogous to the skin effect in a normal metal. Cooper pairs are bound by electron-phonon interaction with a binding energy $\approx 3.5kT_c$, where k is the Boltzmann constant. Photons with energy greater than this binding energy can break Cooper pairs, causing an increase in the quasiparticle density and a change in Z_s.

To use this effect as a photon detector, thin films of aluminium and niobium are used to construct LC resonant circuits. When a photon is absorbed, the change in $\Re(Z_s)$ due to quasiparticle production increases the attentuation of the feedline, while the change in $\Im(Z_s)$ reduces the phase velocity (Fig. 1). These changes are measured as a change in Q and in the resonant frequency.

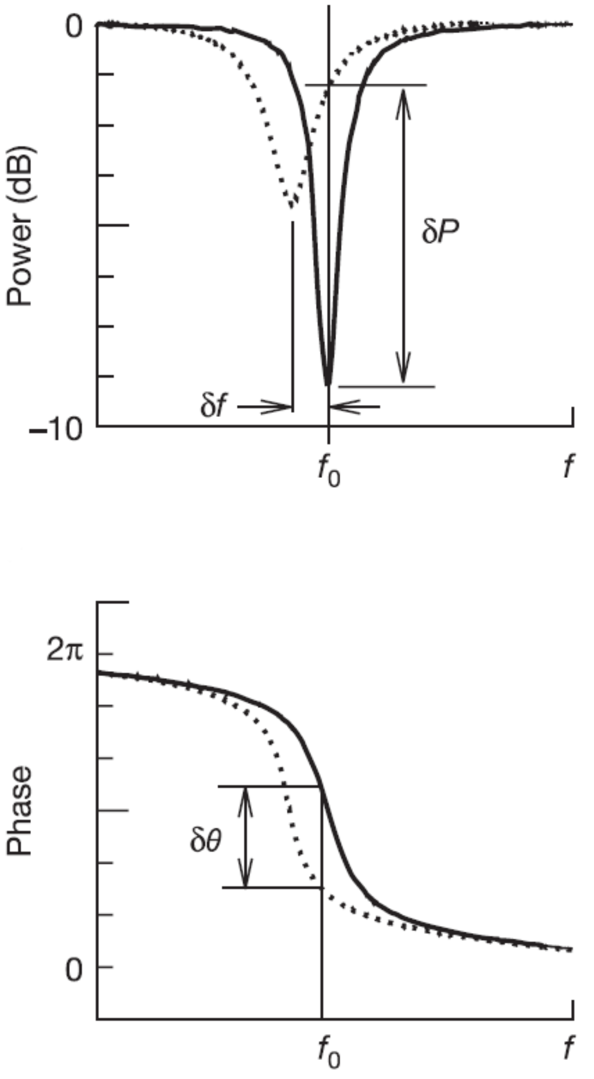

Fig. 1. Illustration of the MKID detection principle. On resonance, the *LC* circuit loads the feedline, producing a dip in transmission. Absorbtion of a photon produces quasiparticles, increasing the surface impedance, resulting in a frequency shift of the resonance and a broader, shallower dip. Both effects contribute to a change in amplitude and phase of the microwave transmission. Figure adapted from Ref. [4].

The readout scheme for MKIDs uses homodyne mixing to measure the complex transmission of a microwave probe signal. An MKID is excited at its resonance frequency, while the output of the detector is amplified with a cryogenic HEMT and room-temperature electronics. The output signal is demodulated using a copy of the input signal with an IQ mixer, producing a recovered signal that has in-phase and quadrature components.

Away from resonance, the transmission of the *LC* circuit is close to unity, so multiple resonators with slightly different frequencies may be coupled to a single transmission line. The quality factors of these resonators is high ($> 10^4$), allowing resonant frequencies to be closely spaced. Sufficient control over resonant frequency for submillimeter detectors has been demonstrated to allow resonance spacing of as little as a few MHz.

TABLE I
MUSIC OBSERVING BANDS.

Band	Band center / GHz	Band width / GHz
0	150	36
1	226	48
2	293	35
3	349	19

The MKID design currently under development for submillimeter radiation is a hybrid design using niobium and aluminium. A schematic of the design is shown in Fig. 3a. Radiation is coupled into an aluminium strip where the pair-breaking occurs. The aluminium section forms part of an inductive meander. The capacitive section of the resonator is a niobium interdigitated design that displays advantageous noise properties over previous designs [5]. The resonator is capacitively coupled to a coplanar waveguide transmission line that carries the microwave probe signal. Current MKID designs have resonant frequencies between 3 and 4 GHz.

III. INSTRUMENT DESCRIPTION

MUSIC implements a focal plane of antenna-coupled MKID resonators, filling a field-of-view of 14 arcminutes at the Cassegrain focus of the 10.4 m Leighton telescope of the Caltech Submillimeter Observatory. The key features of the instrument design are discussed in more detail in the following sections.

A. *Focal plane*

Development of MKIDs for submillimeter astronomy at Caltech has adopted an antenna-coupled scheme. Radiation is coupled from the telescope to broadband planar slot antennae. [6] A binary summing network combines the received power from the antenna slots, and then feeds this power to the MKID resonators. In the case of the MUSIC implementation, lithographic filters define the final bandpass of the resonators, allowing multiple MKIDs to be connected to a single antenna to form a multicolor spatial pixel. The final focal plane design will have four observing bands between 850 μm and 2 mm well-matched to the atmospheric transmission windows from the summit of Mauna Kea. Details of the bands are summarized in Table I, while Fig. 2 shows the 4 MUSIC bands overlaid on an atmospheric transmission plot for the summit of Mauna Kea with 1.68 mm of water vapor (the historical median at CSO). As may be seen, the bandpasses are well-matched to the atmospheric windows between 100 and 380 GHz.

Current prototype arrays have 36 spatial pixels in a 6×6 layout, each with three resonators operating in bands 1–3. A fourth, dark resonator is also included. This resonator is coupled to the transmission feedline, but not to the antenna. Four of these spatial pixels on an early prototype 36-pixel array are shown in Fig. 3b. Also shown here is the transition from the CPW feedline on the array to a microstrip line. The resonant frequencies on these arrays have a target spacing of 5 MHz, such that the 144 resonators fit within two $\sim$400 MHz

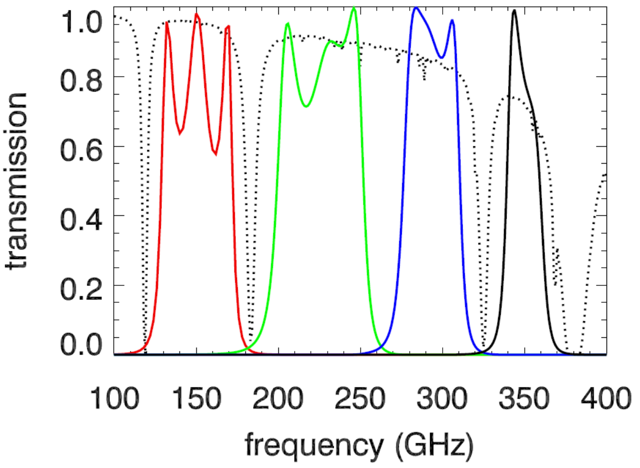

Fig. 2. Simulated bandpasses of the four MUSIC observing bands (solid lines) overlaid on an atmospheric transmission plot (broken line) for the summit of Mauna Kea at 1.68 mm water vapor. Figure adapted from Ref. [7].

blocks of readout bandwidth, a limit set by the readout electronics discussed later in this section. The arrays are back illuminated, with an antireflection coating provided by a fused silica tile tuned to $\lambda/4$ at 1 mm. Concerns over heating in the AR tiles from absorbed optical power have prompted a move to Z-cut single crystal quartz as a substitute.

The MUSIC focal plane will be formed from a mosaic of octant tiles, each approximately 66 × 34 mm, with 72 spatial pixels and 288 resonators per tile. Each octant is essentially two arrays of 36 pixels fabricated on a single wafer. The frequency spacing of the resonators will be reduced over the prototype arrays such that each block of 36 pixels is placed within the bandwidth of one readout module. The full focal plane therefore has a total of 576 spatial pixels, and 2304 illuminated resonators. Additional dark resonators may also be included.

B. *Cryomechanical design*

The MUSIC cryostat is based on a modified system built by High Precision Devices,[1] cooled by a Cryomech[2] PT-415 pulse tube cooler, providing stages at 50 K and 4 K for radiation shielding, infrared filtering and heat sinking. A Chase Cryogenics[3] two-stage ^{3}He sorption refrigerator provides sub-Kelvin stages: an intermediate heat sinking stage at ~0.36 K and the focal plane heat sink at ~0.25 K. An overview of the cryostat is shown in the CAD solid model in Fig. 4a.

The 4-K space is a cylindrical volume of ~450 mm diameter and 850 mm in height. Due to the sensitivity of the MKIDs to changes in the magnetic field environment (for example, as the the cryostat moves through the Earth's field as the telescope scans in azimuth), the focal plane hardware is enclosed by a cylindrical shield of high-magnetic permeability material. In the past, the material most commonly used for such cryogenic shields was Cryoperm-10, a mu-metal annealed to maximize its magnetic permeability at ~4 K produced by Vacuumschmelze GmbH. in Germany and primarily distributed through Amuneal Manufacturing Corp.[4] The shield in MUSIC is fabricated from a new material, Amumetal 4K, produced exclusively for Amuneal and displaying improved shielding properties over Cryoperm-10 at considerably reduced cost. The high-permeability shield for MUSIC comprises a double-walled cylinder of 1 mm-thick material with an outside diameter of 358 mm and length 625 mm. Further shielding is provided by a niobium superconducting can, heat sunk at the intermediate sub-K stage inside the high-permeability shield. A CAD cross-section of the magnetic shield and enclosed hardware is shown in Fig. 4b.

The cold hardware structure is supported from the 4-K cold plate by a truss composed of carbon fiber-epoxy composite rods. Although this truss is not intended to be thermally isolating, the carbon fiber supports have a higher Young's modulus and much lower density that materials such as aluminium alloys and copper, and are considerably less expensive. Carbon fiber trusses with cooling provided by copper straps therefore offer an inexpensive and extremely stiff structural support for instrument cold hardware. The total mass supported from this truss is ~40 kg, while the deflection of the support structure under gravity, as predicted using finite-element analysis, is ~50 μm. The mass of the cold structures has been minimized through the extensive use of aluminium alloys with copper thermal straps for critical cooling paths, rather than bulk fabrication using copper.

The sub-K stages are also supported by trusses of reinforced carbon fiber. Although the thermal conductivity of carbon fiber-epoxy composites are higher than traditional low temperature structural materials such as Vespel (see, for example, Ref. [8]), the higher Young's modulus allows smaller cross-sectional areas to be used. Furthermore, carbon fiber composites may be obtained at a fraction of the price of Vespel.

C. *Optomechanical design*

MUSIC is intended to be mounted at the Cassegrain focus of the CSO, the position currently utilized by the Bolocam instrument. However, in order to maximize the instrument field of view, the tertiary mirror assembly (a system of movable mirrors designed to allow instruments at the Nasmyth foci to be selected) and relay optics were redesigned, increasing the field of view from 8 arcminutes as in the current configuration to at least 14 arcminutes. The field of view is then limited by the aperture in the telescope primary reflector. The new relay optics from the secondary focus are essentially a scaled-up version of the existing Bolocam relay optics, with two flat mirrors to fold the optical path, and an elliptical mirror to form an image of the primary. All mirrors are of order 1 m in size and machined from aluminium alloy.

Within the cryostat, a cold stop is positioned at the image formed by the elliptical mirror to define the illumination of the primary. The lyot stop is sized such that ~9 m of the 10.4 m telescope primary is illuminated. This illumination is chosen such that point-source sensitivity is maximized while limiting the primary spillover power to <1% in all four bands. Rays are

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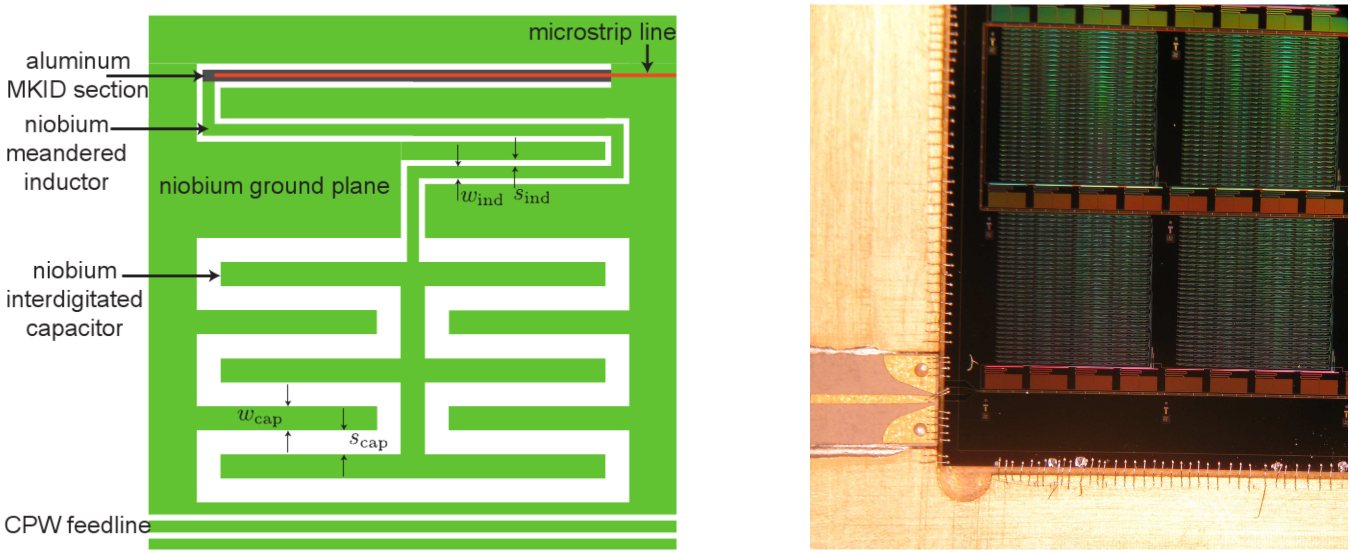
[1] http://www.hpd-online.com

[2] http://www.cryomech.com

[3] http://www.chasecryogenics.com

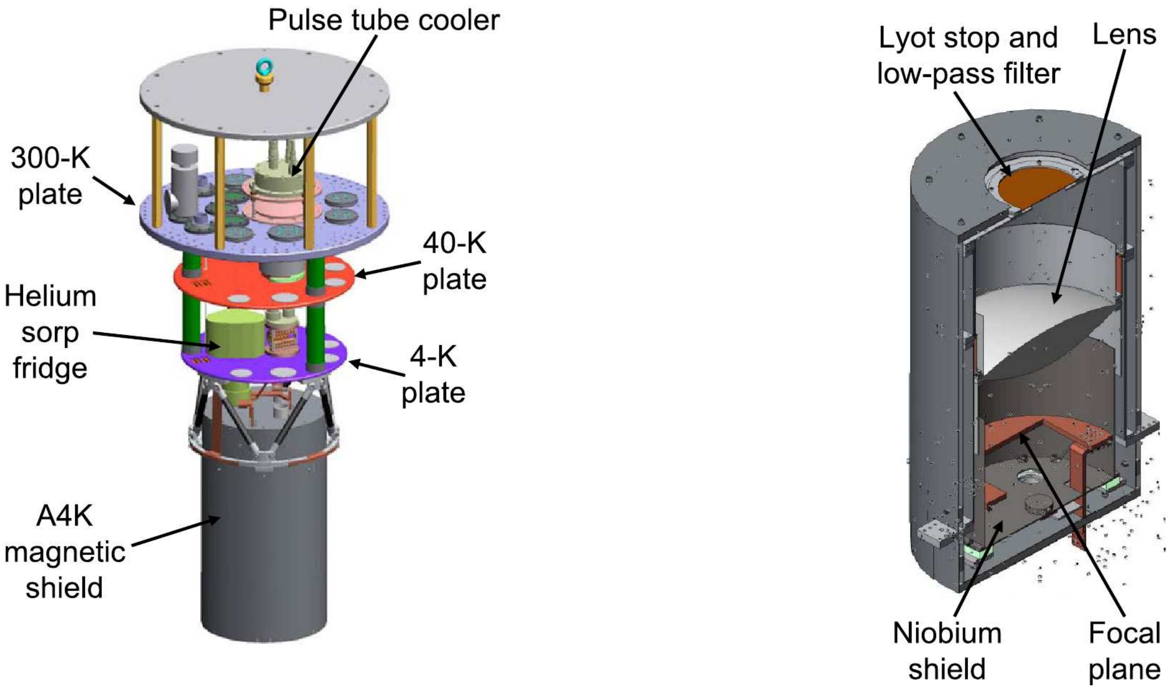
[4] http://www.amuneal.com



(a) Schematic of an MKID resontator with an interdigitated capacitor architecture. See text for further details. Figure adapted from Ref. [5]

(b) Image of a prototype array. Four spatial antenna pixels may be seen, each coupled to 4 MKID resonators. Also seen here is the transition from on-chip CPW feedline to microstrip (lower left corner of image).

Fig. 3. Microwave kinetic inductance detectors for submillimeter wavelengths.



(a) Overview model of the MUSIC cryostat cold hardware.

(b) Cross-section of the MUSIC magnetic shield showing the sub-K stages and the cold optics.

Fig. 4. CAD solid models of the MUSIC instrument.

focused to the focal plane by a cold lens 275 mm in diameter and $\sim$65 mm-thick at its center. This lens is machined from ultra high-molecular weight polyethylene (UHMWPE), with an antireflection coating of Porex[5] porous teflon attached by melting thin intermediate layers of low-density polyethylene. The coating is tuned to a wavelength of 1 mm. The path length from the lyot stop to the focal plane is over 450 mm, while the final image at focal plane has a diameter of $\sim$130 mm. The overall optical efficiency of the system ranges from $\sim$8 to $\sim$13% in the four observing bands. This low efficiency is dominated by spillover at the cold stop, and the fact that the antennae only couple to a single polarization.

Infrared filtering in MUSIC is achieved with a combination of capacitive metal-mesh and dielectric filters. The cryostat has a UHMWPE vacuum window. The relatively high thermal conductivity of polyethylene compared to Zotefoam, a cross-linked block foam commonly used as a window in millimeter-wave instruments, means that the window does not passively cool to any great extent. Combined with the large surface area (the window aperture is $\sim$300 mm), the result is a large radiative load on the first infrared blocking filters. In order to reduce this loading, the outermost filter on the 50-K radiation shield is a polypropylene IR shader produced by QMC Instruments Ltd.[6] [9]. Further filtering is provided by a pair of 16 mm-thick PTFE discs, with Porex AR coating as described previously.

At the 4-K shield, further infrared rejection is provided by a pair of 6 mm-thick AR-coated PTFE discs sandwiching a 3 mm-thick Fluorogold (glass loaded teflon) filter with 250 mm clear apertures. Finally, a 125 mm diameter QMC metal-mesh low pass filter at the lyot stop defines the high-frequency edge of the passband at 405 GHz (13.5 cm^{-1}).

D. Readout

As described previously, the MUSIC focal plane is composed of a mosaic of octant tiles Each of the 8 tiles requires an input and output coaxial cable. Semirigid coaxial cables are used throughout the cryostat. From the room temperature flange to the 4-K cold plate, the coaxs are single lengths of 0.086” stainless steel, approximately 500 mm long, with a copper clamp approximately half way along the cable for heat sinking at the 50-K cold plate. The stainless steel coaxs are terminated with SMA connectors, fabricated by welding rather than soldering in order to increase cryogenic reliability. The stainless steel coaxs connect to a bulkhead at the 4-K cold plate, which includes fixed attenuators (typically 30dB on the input coaxs and 1dB on the output).

On the cold side of the 4-K plate, the input coaxial lines transition to 0.064” NbTi semirigid cables, providing thermal isolation between the 4-K plate and the intermediate heat sinking stage at $\leq$0.4 K, where the coax is again heat sunk using an attenuator (typically 10dB). NbTi coax is used between the intermediate heat sink and the focal plane, terminating is adaptors from SMA to GPO blindmate connectors[7] for the final connections to the focal plane.

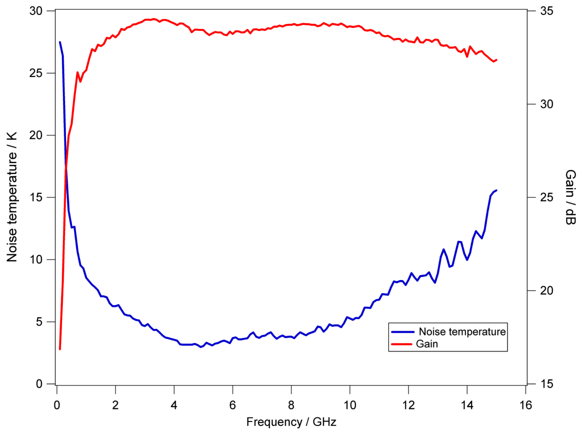


Fig. 5. Typical noise and gain performance of a broadband cryogenic HEMT LNA of the type used for MUSIC, measured at 15 K. Data courtesy of H. Mandi and S. Smith (California Institute of Technology).

The output coaxs from the focal plane are again NbTi. After the intermediate heat sink stage, the coaxs connect to cryogenic HEMT amplifiers mounted on the 4-K cold plate (one amplifier per output cable). The final connection from the HEMTs to the 4-K bulkhead is made with 0.086” copper coax. The HEMTs are provided by S. Weinreb’s group at Caltech, and at the MUSIC resonator frequencies typically provide a gain of 30–40dB and a 5 K noise temperature, with $\sim$30 μW power dissipation. Typical performance data at 15 K for one of the MUSIC HEMTs is shown in Fig. 5.

E. Room-temperature electronics

The analog homodyne readout scheme described in § II for a single resonator is clearly not practical for the implementation of an MKID array. Readout of multiple resonators can be achieved using a system to generate a comb of probe signals simultaneously [10]. Large-bandwidth, high-speed digital-to-analog converters are used to play back a predefined waveform at audio frequencies. The I and Q components of the probe signal are generated independently, and are mixed and upconverted to the resonator band at GHz frequencies. The frequency comb is passed through the cryostat to excite the resonators, then mixed back down to audio frequencies. The individual resonator responses recovered using an FPGA as a channelizer, demodulating the signal at each comb frequency to determine the response of each resonator. A simplified block diagram of this system is shown in Fig. 6. The electronics are designed in modules, since current limitations on fast ADCs limit the bandwidth of a single unit to approximately 500 MHz, so multiple copies of the electronics are required to read out large focal planes.

Two different systems have been developed for resonator readout. The first is a commercial system from Omnisys Instruments AB in Sweden. In parallel, a project led by UC-Santa Barbara is developing an open source FPGA readout system based on the ROACH platform developed by the CASPER group at UC-Berkeley. This open source readout uses largely commercial software-defined radio techniques from the telecommunications industry to produce a generic

[5] http://www.porex.com/

[6] http://www.terahertz.co.uk/

[7] Corning Gilbert, http://www.corning.com/gilbert

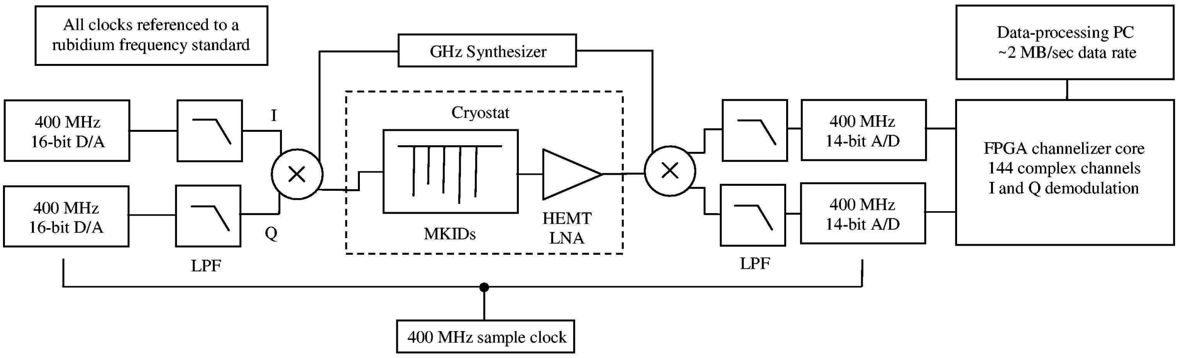


Fig. 6. Simplified block diagram for a multiple resonator MKID readout system. A frequency comb at audio frequencies is played back from memory using fast DACs. The I and Q components are combined with an upconverting mixer and based through the cryostat. The signal is then mixed back to audio frequencies and the individual resonator responses are recovered by Fourier transforms of the I and Q components.

readout system for superconducting resonators. The system is modular, so is easily upgradable, and the open source nature of the firmware programming allows extensive customization. At present, prototype modules of each system are under evaluation.

IV. CURRENT STATUS AND TIMELINE

Development of arrays and the integration of camera hardware has been separated in order to allow parallel development tracks. At present, the cold hardware for the MUSIC cryostat has been fully fabricated, and the process of assembly and integration is due to commence shortly. Although the base cryostat has been operational for over a year, the dewar has so far been used for unrelated testing and for cryogenic testing of HEMT amplifiers.

Array testing and development has primarily been conducted using a smaller cryostat, that has also served as a prototype instrument for testing arrays on-sky at the CSO. This cryostat, known as DemoCam, has been used for extensive lab testing, and in 2007 was used for the first astronomical demonstration of MKIDs using a 16 pixel, 2 color array [11]. Based on lessons learned during that engineering run, a number of modifications were implemented in the cryostat, in addition to an upgrade to a 36-pixel, 3 color focal plane in preparation for a second engineering run. One of the key changes in advance of this second run was the installation of a high-permeability magnetic shield to counteract the observed response of the MKID resonators to changes in the magnetic field environment during telescope scans. Measurements made during the 2007 engineering run showed resonator frequency responses to magnetic fields of order 100 kHz/Gauss. Lab measurements of the resonator response with the new shielding installed has indicated a reduction of response of 4 orders of magnitude. More extensive shielding integrated with the MUSIC cryostat and focal plane is expected to reduce this effect by a further 2 orders of magnitude.

Preparations are currently underway for a second engineering run at CSO with the improved demonstration camera and a 36 pixel, 3 color focal plane. This run will also be an on-sky test of the CASPER/ROACH-based readout electronics. Based on lab measurements carried out with the current array, it is expected that sensitivities at or very close to the background limit will be demonstrated during this run.

With the successful conclusion of this second run, array development will continue with the first fabrication of 72 pixel, 4 color arrays for the MUSIC focal plane. It is not anticipated that this development will be a technically challenging process, since the new arrays will simply be a scaled version of the current generation of 36-pixel arrays. However, there will likely be issues with fabrication yield that will be overcome through process iteration. Modifications at the CSO in preparation for the new instrument will be carried out during the annual maintenance shutdown in July, with MUSIC anticipated for deployment for initial commissioning towards the end of 2010.

V. SUMMARY

This paper has discussed details of the MUSIC project - a new sub/millimeter array camera intended for use at the Caltech Submillimeter Observatory as a replacement for the current Bolocam instrument. In parallel with the assembly and integration of the camera, array development has been ongoing in a prototype instrument known as DemoCam. It is expected that commissioning of MUSIC will begin in late 2010, pending in part the successful conclusion of a telescope engineering run with DemoCam.

ACKNOWLEDGMENT

The MUSIC project is supported by NSF grant AST-0705157 to the University of Colorado, NASA grant NNGC06C71G to the California Institute of Technology, the Gordon and Betty Moore Foundation, and the JPL Research and Technology Development Fund.

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