

Penn Array Receiver

Penn Array Receiver CDR Document 6: Detector Design Documents

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1. Introduction

The detector system for the Penn Array Receiver at the GBT is a superconducting transition edge sensor (TES) bolometer array and readout electronics. The array, manufactured at NASA/GSFC, consists of 64 pixels arranged in a close-packed 8x8 configuration, covering a 32''x32'' image on the sky. Its pixels Nyquist-sample the 8'' beam of the GBT at the operating wavelength of 3.3mm. Each detector is read out by a superconducting quantum interference device (SQUID) amplifier, produced at NIST/Boulder (Irwin 2001). The SQUID amplifier is chosen because of its ability to multiplex the inputs, resulting in a decrease in wire count and system complexity, and because of its large noise margin (Staguhn et al. 2001).

In the sections below, we provide a top-level detail of the design of the detector system components. This work benefits from related ongoing research at NASA/GSFC, such as the development of a 16x32 TES bolometer array for SOFIA/SAFIRE (Benford et al. 2002b).

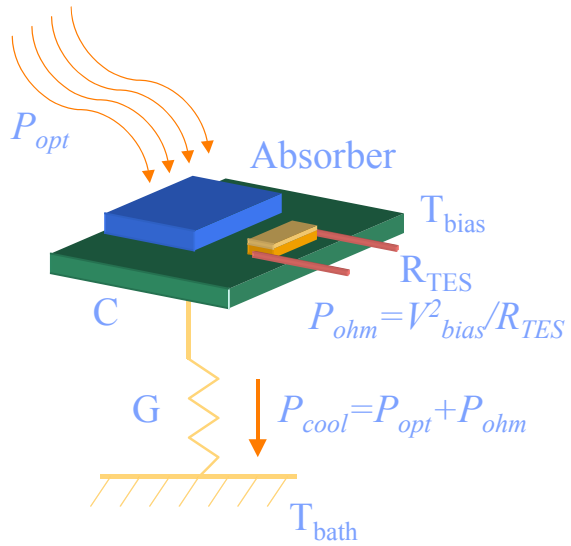
2. Detector Array Requirements

The requirements on the detector array are listed in tabular form below.

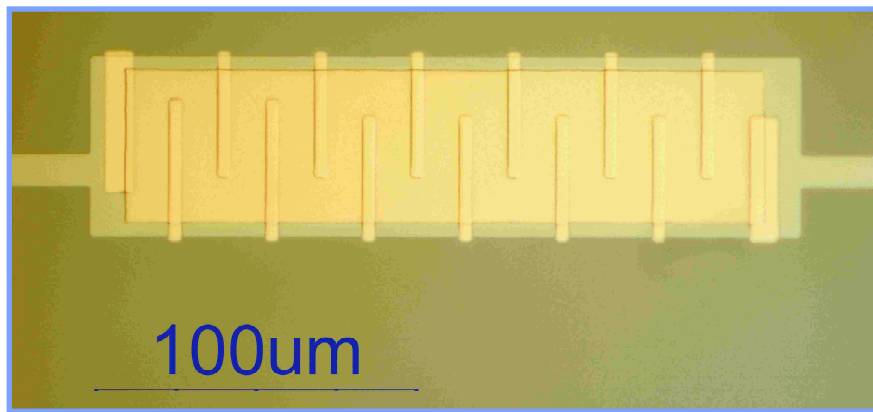
Required Parameter	Specification: Goal Minimum	Derivation
Array format	8x8 8x8	Field of view desired; convenience of multiplexer format
Pixel size	~3.3mm ~1.7mm	Coupling size scale of $\sim\lambda$
Filling factor	95% 80%	Focal plane utilization
Response time	20ms 5ms	Telescope slew speed modulating signal flux.
Saturation Power	12pW 8pW	Optical loading prediction of ~8pW max.
Noise Equivalent Power	$1 \cdot 10^{-17}$ W/ $\sqrt{\text{Hz}}$ $3 \cdot 10^{-17}$ W/ $\sqrt{\text{Hz}}$	Photon noise predicted to be $\sim 3 \cdot 10^{-17}$ W/ $\sqrt{\text{Hz}}$ at P_{sat}
Stability of base temperature	64nK/ $\sqrt{\text{Hz}}$ 191nK/ $\sqrt{\text{Hz}}$	Equivalent sky flux noise
Wavelength of response	3.3mm	Bandpass from 3.0-3.7mm
Optical Efficiency	80% 40%	Point source sensitivity
Adjacent pixel crosstalk	10%	Optical correlation
Power dynamic range	15 7.5	Min/Max optical loading
S/N dynamic range	$6 \cdot 10^5$ $2 \cdot 10^5$	Ratio of photon power to photon noise
Operating temperature	450mK 300mK	Capability of ^3He fridge

3. Bolometer Design

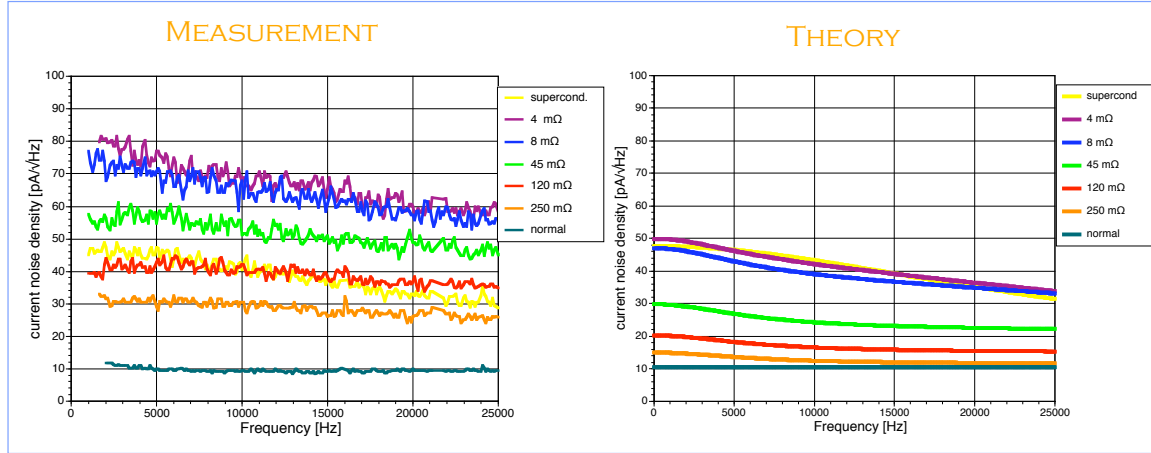
A schematic of the function of a bolometer, illustrating its key components, is shown at right. Our present bolometer design uses a single $\sim 3\text{mm}$ square SiNx membrane of $0.5\mu\text{m}$ thickness, isolated by means of low thermal conductance micromachined structures. Incident power is absorbed by means of a full-sheet resistive coating of Bismuth, designed to be impedance-matched to free space ($377\Omega/\square$). The TES element is a bilayer of Mo and Au, where the relative thickness is adjusted to select the transition temperature and the total thickness is adjusted to select the resistance per square. The normal resistance of the TES is adjusted by geometry.



The figure below illustrates the most successfully recent TES devices manufactured by our group. The vertical stripes are normal metal (Au) bards, providing a constraint on the superconducting region when the device is operated on its transition. Devices with uniform superconducting regions – both those made by our group and others – have been shown to feature excess white noise over the thermodynamically-limited performance predictions. This white noise, while of uncertain origin, has been ascribed to fluctuations in the current flow in the TES. It is thought that reducing the number of degrees of freedom of fluctuations through engineering the geometry or boundary conditions of the superconductor may reduce or eliminate this noise mechanism. Recent results (Staguhn et al. 2003; Benford et al. 2003) have shown this to be the case. The TES shown below has very little ($<50\%$) excess noise when biased near the middle of its transition.



A noise spectrum from the above TES bolometer is compared with the theoretical predictions in the figure below.

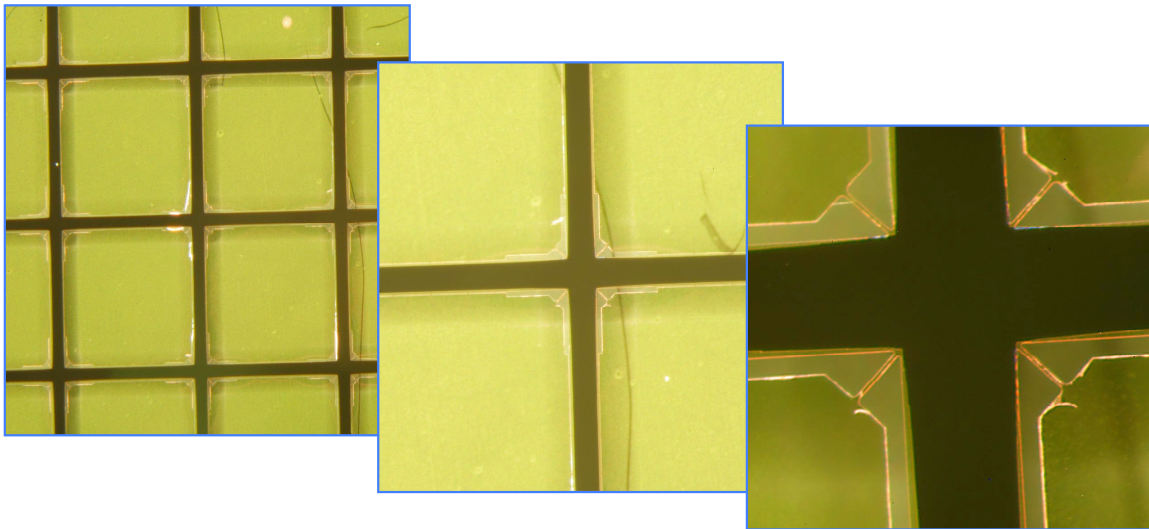


The bolometer design for the GBT is still under refinement. When electromechanical test devices are made with a TES in place, a measurement of the thermal conductance $G(T)$ will be made. This will define the phonon noise limit of the bolometer at any temperature. When the design is such that this is acceptable at an achievable transition temperature, the detector array will use the most advanced TES approaches available at that time. It is expected that the NEP will be around $3 \cdot 10^{-17} \text{ W}/\sqrt{\text{Hz}}$, near the minimum performance specification. The response time can be estimated at $\tau < 1 \text{ ms}$, but with large uncertainty.

4. Array Design

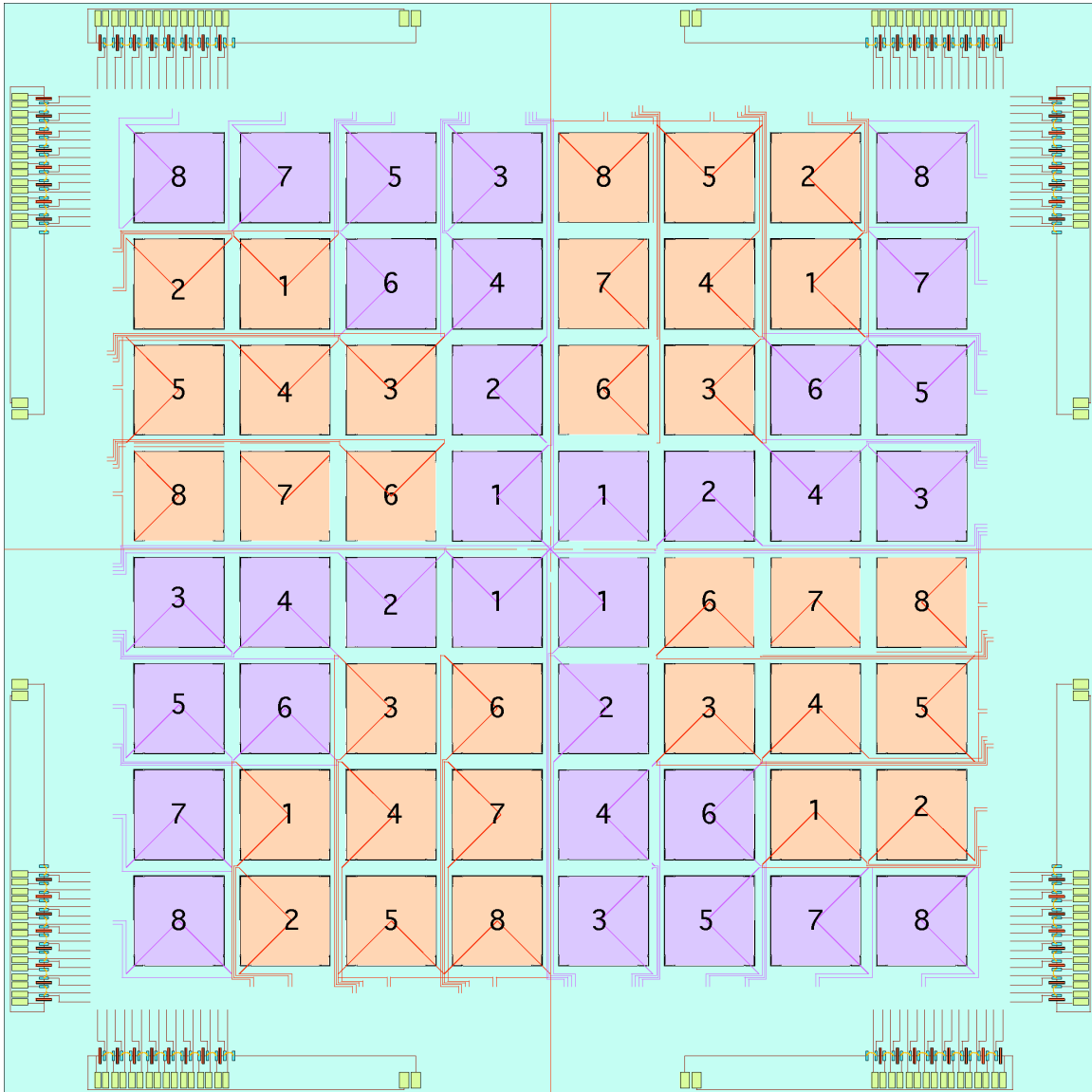
The mechanical design of a compact, close-packed, planar detector array is challenging. Two of the difficulties relate to the difficulty of compact pixels (i.e., producing a low thermal conductance feature in a small space) and close-packing (i.e., having little dead space between pixels) in a single membrane layer. We have produced several mechanical prototypes to test ideas of detector fabrication in thin ($0.5\mu\text{m}$) SiN_x membranes on silicon wafers. These membranes feature very low thermal conductivity but have high internal stresses, and therefore can disintegrate during processing. Once manufactured, the high strength of the material makes them robust to handling.

The present design uses 2.9mm-wide membranes suspended by a variety of small stubby attachment points. The filling factor is 80%, and could probably be brought to 90% without compromising the structural integrity of the streets between the pixels. Photos of one design of these membranes are shown below, at various magnifications.

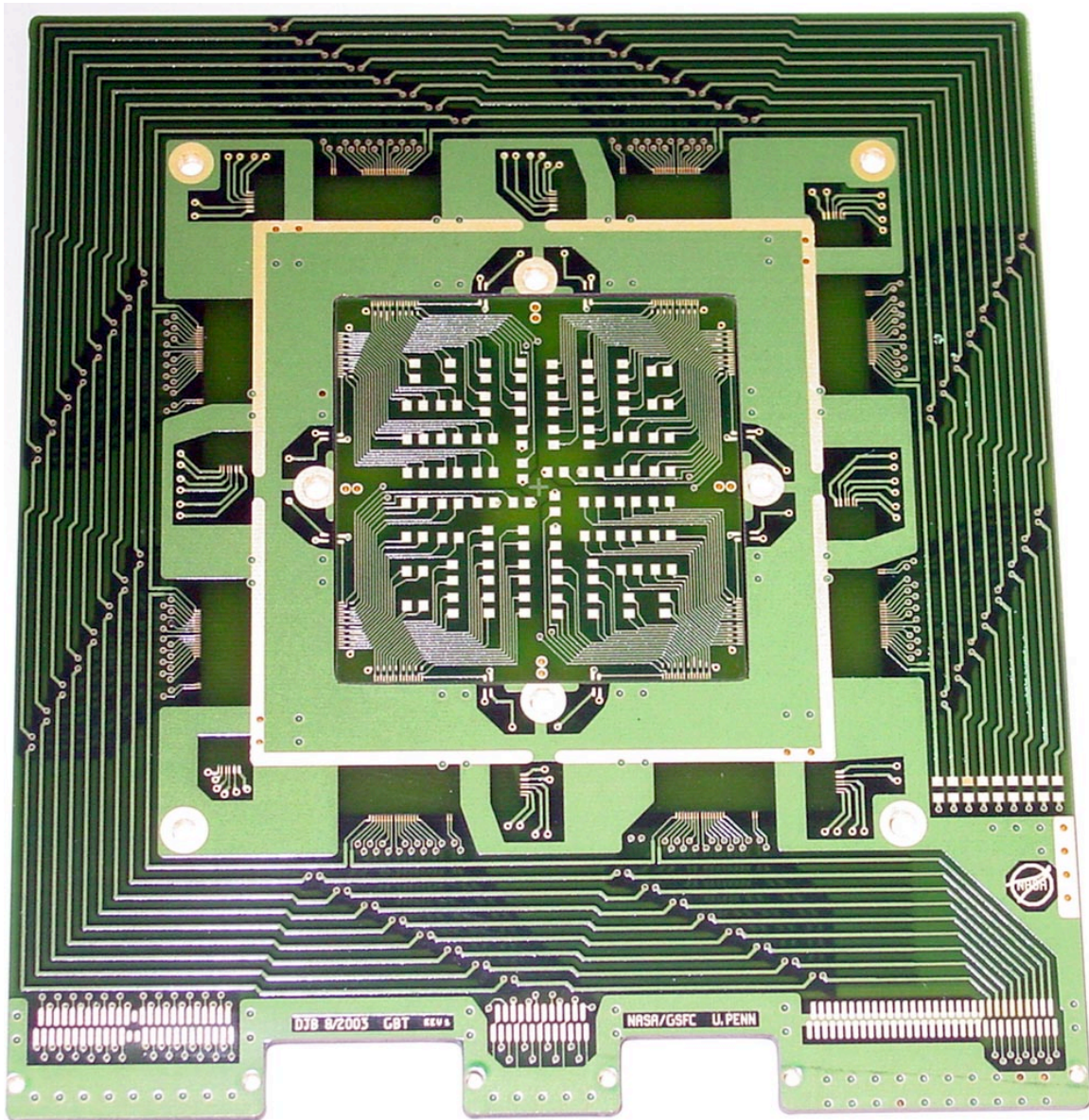


A second challenge in the detector array is to produce a single layer for wiring all TES electrical connections to the outside, where wirebond pads permit the SQUID multiplexer attachment.

We have designed a wiring layout to bring all electrical leads along the 300 μ m-wide streets between bolometers. No more than two pixels' wires are brought along any street. The pixels are adjacent, and so will have a high degree of optical correlation, which should dominate over any electrical crosstalk. At the edge of the wafer, eight sets of bond pads (each for 8 bolometers) are arrayed around all four sides of the square array frame. These bond pads include a shunt resistor for providing a voltage bias to each TES when a constant current is passed through them in series. The array layout is shown in the figure below. The eight regions are highlighted in different colors, and numbered in the order in which they are read by the multiplexers.

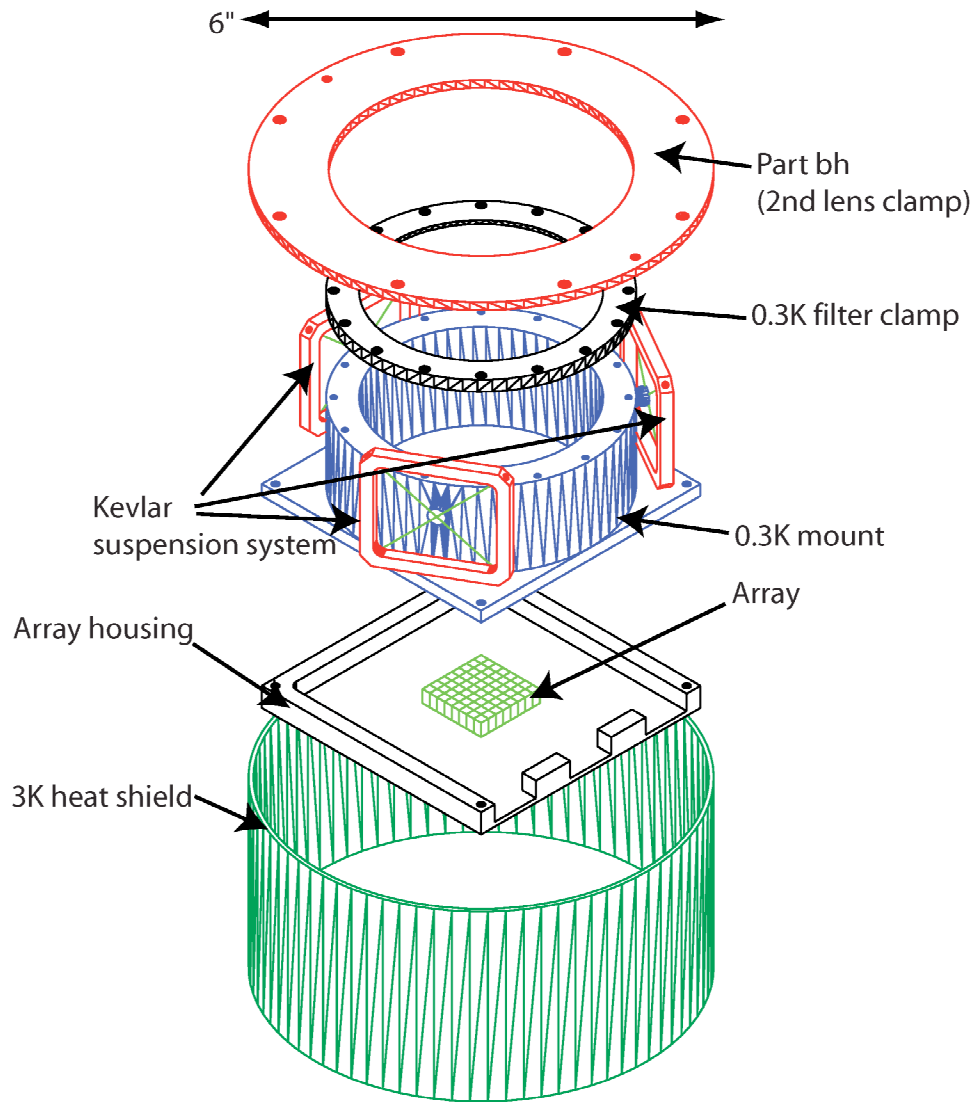


The detector array is read out by a circuit board which surrounds the array chip itself. This geometry allows all the wiring for control and readout of the multiplexer to be routed around the outside in a “bus” configuration. The lines are made in microstrip to have controlled impedance of $\sim 50\Omega$ to provide good signal quality. Each SQUID multiplexer is attached into the bus by a set of coplanar stripline taps. The circuit board consists of 8 metallization layers on a fiberglass board. Much of each layer is filled with copper to provide good heat sinking. A dummy circuit board to mimic the detector array, but with constant resistance devices of $\sim 10\text{m}\Omega$, has been produced to permit the testing of the SQUID multiplexers on the main circuit board. These boards are shown below, in their operational configuration.



For simplicity of handling, the circuit board with the SQUID chips and the array chip are mounted by screw/spring holddowns into a copper box about 10cm on a side and ~1cm thick. This box has a light-light filter holder bolted onto its top, constraining the light entering the box to be at $\lambda=3.3\text{mm}$ and in the direction of the optical elements. This package is then suspended by means of a kinematic Kevlar suspension system. A drawing of the assembly is shown below.

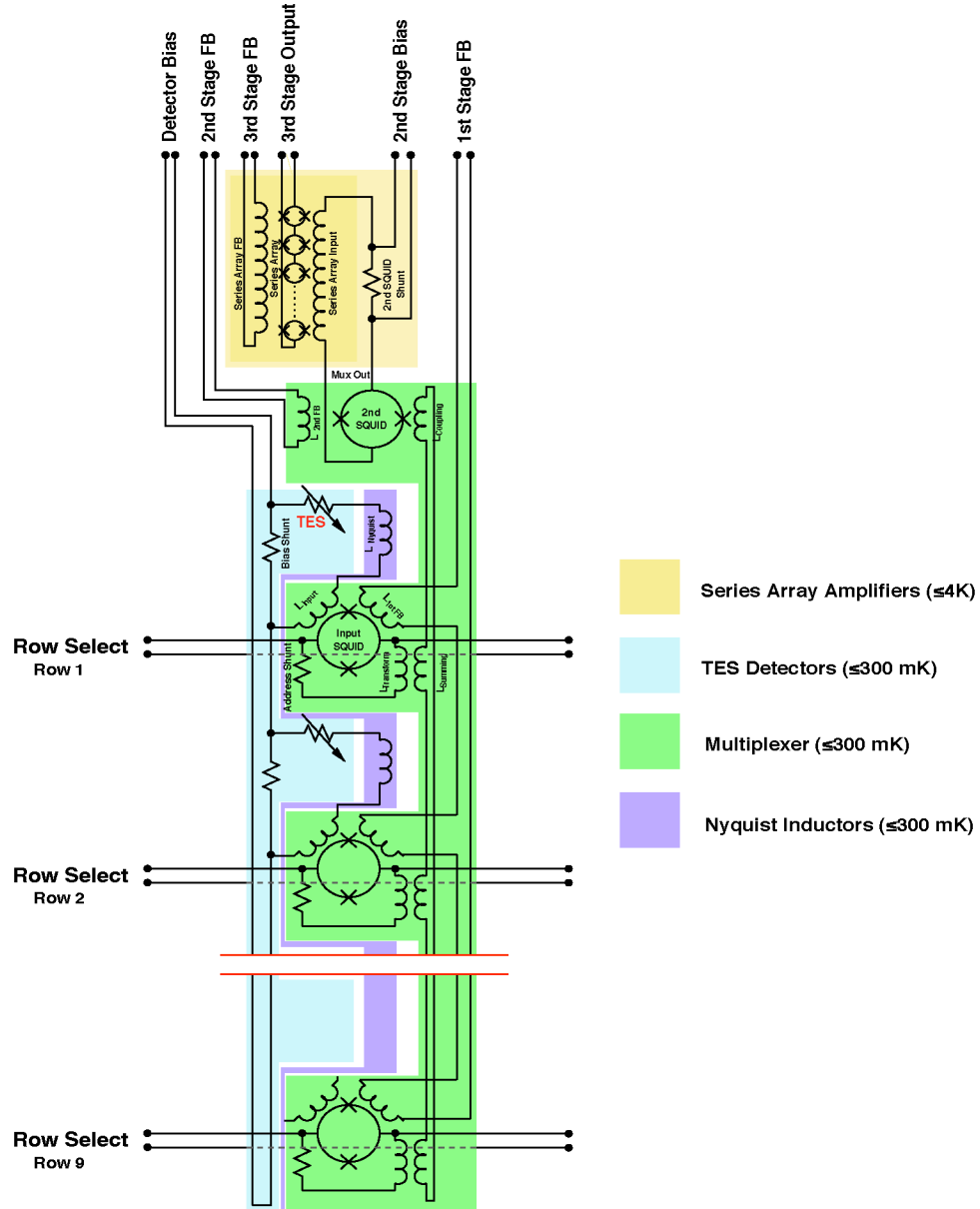
An exploded view of the array mount



This suspension system has been used in several similar instruments produced at NASA/GSFC (Benford et al. 2001), and is found to have a typical loading on a ^3He system of around $3\mu\text{W}$, well within the performance specification of the refrigerator. Electrical dissipation within the detector array itself is quite small; it is predicted to be $\sim 700\text{nW}$, dominated by the dissipation in the address bus termination resistors.

5. Data Acquisition System

A detailed explanation of the data acquisition process is given elsewhere. In this document, we highlight the overall system design for the detector data acquisition. Before beginning a discussion of the system, we start with a description of the multiplexing approach. The figure below shows the schematic of a single SQUID multiplexed channel, which reads out 8 bolometers (Benford et al. 2002a).

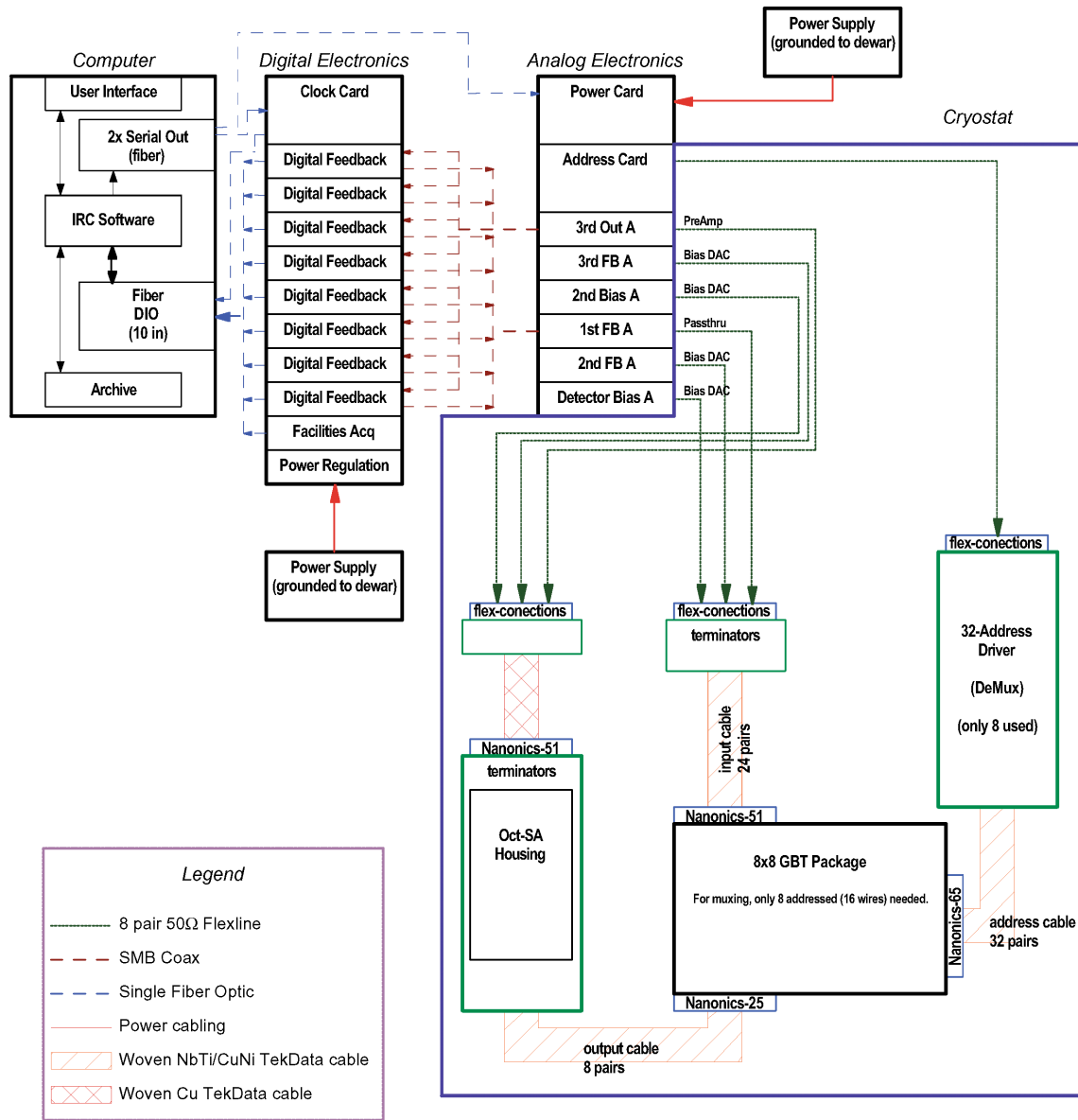


A single SQUID multiplexed channel is actually a three-stage amplifier. The first stage is a 9-input multiplexer, reading 8 bolometers and one dark channel. The dark channel is used for the removal of drifts in the readout system, which are expected to be dominated by correlated first and second stage drifts. The second stage, which is the uppermost of the multiplexer SQUIDs indicated in the figure above, is used for impedance transformation. This SQUID drives the long leads to the Series Array SQUID, which has a $\times 100$ voltage gain of a single SQUID. The signal from the Series Array is strong enough to be read out by conventional room temperature OpAmps.

The data acquisition electronics must control all stages of this amplification; these connections are illustrated above. The “Row Select” signals are the control for the first stage inputs. The “Second Stage Bias”, “Third Stage Feedback”, “Second Stage Feedback”, and “Detector Bias” are static bias supplies. The “First Stage Feedback” is an input which is used to provide a nulling flux to the first stage SQUIDs. When properly operated, this feedback produces a zero output on the “Third Stage Output”. In this case, the current in the “First Stage Feedback” loop is proportional to the current in the TES detector, and therefore is a linearized response to the incident photon rate.

What is not shown above is the warm electronics. This includes the sources that provide the static bias supplies and the digitally-controlled feedback loop. Because the multiplexer operates in the time domain, at any given point in time the “First Stage Feedback” must be set appropriate to the TES being read out. This synchronous feedback requires that the present value of the feedback be stored such that it can be used again at the next time that the multiplexer reads out that TES. A brief description of the multiplexer feedback is given by Benford et al. (2000).

The block diagram of this system is given below.



The components are discussed in order from coldest to warmest.

Detector Package

This consists of the 8x8 bolometer array, the 8x9 SQUID multiplexer array, and the second stage SQUID amplifier. The package interface is in the form of three Nanonics Duallobe connectors, with 25 pins, 51 pins, and 65 pins.

DeMux Address Driver

This is a cryogenic circuit board with components to drive the “Row Select” addresses from a binary input. Up to 32 pixels can be driven, using a 5-bit address carried (along with power and synch signals) on a FlexLine circuit board / harness.

Series Array Housing

A single Series Array Housing consists of a set of eight Series Array Amplifier Chips on eight Series Array Chip Boards, contained in a well-magnetically-shielded enclosure and attached to a Series Array Box Board, which features a 51-pin Nanonics connector for interface with warmer components.

Terminator Boards

The terminator boards are located at ~4K and serve to terminate or rescale signal levels from the FlexLine harness on their way to colder components.

Analog Electronics Tower

The sensitive analog electronics are housed in an EMI-tight enclosure mounted to the cryostat. This electronics box contains four DAC boards for the static voltages, a PreAmp card (for the “Third Stage Out”), a passthrough card for the feedback, an Address Interface card to command the Address Driver, and a Power/Control card.

Digital Electronics

The digital electronics consist primarily of the Digital Feedback card, which takes a multiplexed output and produces the appropriate time-synchronous feedback signal. One of these cards is needed for each of the 8 SQUID multiplexers. They reside in a 3U rack attached to the cryostat. There is also a Clock Card for timing signals and a “Facilities Acquisition” card to permit digital and analog inputs to be accepted synchronously with the detector data.

Computer

A data acquisition computer is used to command the digital and analog electronics and to receive, via fiber optic to a custom PCI circuit board, the detector data. The computer runs custom software (low level drivers and the Instrument Remote Control interface software) to facilitate data acquisition.

6. Summary of Expected Performance

The best estimate performance of the detector array parameters as related to the requirements is listed in tabular form below.

Required Parameter	Specification: Goal Minimum	Expectation
Array format	8x8 8x8	8x8
Pixel size	~3.3mm ~1.7mm	2.95mm on 3.3mm pitch
Filling factor	95% 80%	80%
Response time	20ms 5ms	≤1ms
Saturation Power	12pW 8pW	10±2pW
Noise Equivalent Power	$1 \cdot 10^{-17}$ W/√Hz $3 \cdot 10^{-17}$ W/√Hz	$3 \cdot 10^{-17}$ W/√Hz
Stability of base temperature	64nK/√Hz 191nK/√Hz	TBD
Wavelength of response	3.3mm	3.3mm
Optical Efficiency	80% 40%	75%
Adjacent pixel crosstalk	10%	≤1%
Power dynamic range	15 7.5	10
S/N dynamic range	$6 \cdot 10^5$ $2 \cdot 10^5$	$3 \cdot 10^5$
Operating temperature	450mK 300mK	380±30mK

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