Becker Thesis Outline

Title: A 350 GHz Passive Video Imaging System

Abstract:

Passive millimeter-wavelength video imaging systems hold promise for detection of security threats at a distance, such as including suicide bomb belts and maritime threats in fog. Achieving optimal noise and optical performance for these systems requires large numbers of cryogenic millimeter-wavelength radiation detectors. Large-format arrays of superconducting Transition Edge Sensor (TES) bolometers have been proven to meet requirement for both noise and number of detectors. We are developing a video- rate millimeter-wavelength imaging system using 1004 TES bolometers as detectors. This demonstration system detects is intended to have photon-noise-limited performance, and will be used to investigate phenomenology of passive millimeter-wavelength video images, with the goal of identifying what performance tradeoffs can be made when building a deployable system. It observes light in a 10\% band centered at 350 GHz, and is designed to take video images at distances ranging from 16 m to 28 m. When operating at 16 m, the resolution is 1 cm over a 1 m by 1 m field of view. The system is predicted to take video images with a noise equivalent temperature difference (NETD) of 100 mK at 20 frames per second. This thesis describes the design and implementation of this system, as well as imaging results from the first 251-detector subarray to be installed.

# Introduction

## Problem Statement & Our Solution

* + 1. Motivation for standoff imaging at millimeter wavelengths: detection of concealed weapons and/or bombs at a safe distance
    2. Much more challenging than IR wavelengths because much less available optical bandwidth and need for diffraction-limited througput
    3. Two approaches: passive and active/radar
    4. Required NETD for different atmospheric conditions
    5. Challenges for active imaging: specular reflections, image interpretation
    6. Challenges for passive: adequate NETD at video frame rates
    7. Uncooled bolometer can never achieve required sensitivity
    8. MMIC Amplifiers at these wavelengths do not yet have required performance
    9. Large-scale arrays of cryogenic TES bolometers can meet the requirements

## Prior Work on Cryogenic Passive Imaging (should this cover all mm wavelenghts? Or just 350 GHz?)

* + 1. Early Efforts - Grossman at NIST? Others?
    2. Artuu’s system
    3. Jena system

## What sets our system apart

* + 1. "gold standard" system with uncompromised noise performance: designed to hit photon noise limit
    2. Use this system to evaluate image phenomenology - something missing from the field
    3. Use this system to drive decisions about engineering tradeoffs in deploying real-world systems.

# System Specifications, Challenges and Solutions

## Specifications

* + 1. Uncompromised noise performance → photon-noise limited detectors.
    2. We chose our optical band as a tradeoff between attenuation in clothing/atmosphere and spatial resolution
    3. Our standoff distance allows detection of suicide bomb belts at safe distances\footnote{recall that William sent me a paper/report discussing required distances for this application}
    4. 1 cm resolution sufficient to identify objects such as guns knives (true?) $\rightarrow$ determines mirror size
    5. Video frame rates allow continuous monitoring
    6. In order to achieve these requirements in a cost-effective way, we compromised on other possible mission requirements (portability (size and weight), ability to steer system, power).

## Photon Noise Limit

* + 1. xxx calculation of this noise level for our system

## Challenges

* + 1. Need for cryogenics --> cryogenics adds engineering complexity and power requirements
    2. Need for large number of detectors leads to fab and readout complexity (many detectors $\rightarrow$ many wires $\rightarrow$ complex engineering, heat loads)

## Solutions

* + 1. The millimeter/submillimeter astronomy community has developed technology to address these problems: large-format arrays ofcryogenic bolometers.
    2. Cryogenic bolometers have required s/n
    3. voltage-biased TES bolometers can be manufactured lithographically in large quantities
    4. requires low-noise current amp $\rightarrow$ SQUIDs
    5. SQUIDS can also be manufactured in large amounts
    6. Multiplexing to reduce wire count. TMUX is our approach

# TES Bolometer Theory

## Introduction to TES Bolometers

* + 1. bolometer definition: thermally isolated heat capacity, thermometer, measures optical power
    2. Superconductor biased into transition is very sensitive thermometer --> “Transition Edge Sensor” bolometer
    3. Thermal and Electrical Circuits & relevant parameters
    4. Importance of voltage-bias and electrothermal feedback

## Theory of Behavior of Operating TES

* + 1. Thermal and Electrical Circuit equations
    2. Linearization (limit of small changes in power and current) leads to two coupled 1-st order ODEs
    3. Standard parameters for these equations: loop gain, tau, tau\_el, P\_opt, etc.

## Important solutions to TES equations

* + 1. Current response to change in applied power (freqeuncy domain)
    2. current response to change in applied power (time domain)
    3. current response to chang in applied bias voltage (time domain)

## Noise In TES Bolometers

* + 1. G Noise
    2. Other noise sources sub-dominant thanks to electrothermal feedback

# System Design Overview

## Cryostat Design

* + 1. Design goals: simple, turn-key operation, proven/commercial designs
    2. Three temperature stages: 50 K, 4K, 1K.
    3. Commercial PTC for cooling to 3-4 K. Few-sentence explanation of PTC operation
    4. T\_c = 1.2 K means that liquid He4 is sufficient for T\_bath. A sorption fridge is a good solution because closed system, easy to operate
    5. How does our sorption fridge work? Exact steps to operate. It is automated.
    6. Performance summary of our sorption fridge
    7. Predicted heat load on 1K stage: readout wiring, SA, mux, shunts, TiN, optical power, etc.

## Optical Design

* + 1. choice of cassegrain optical system
    2. design of primary, secondary, lens
    3. band-defining filters
    4. thermal blocking & lowpass filters
    5. predicted optical loading
    6. predicted optical efficiency

## Feedhorn Design

* + 1. Q: Why smoothwalled feedhorn coupling? A: easy to manufacture, acceptable beam quality for polarization-insensitive detectors, proven in field.
    2. Factors affecting choice of feedhorn size (coupling efficiency vs number of feedhorns)
    3. Summary of code/algorithm used to choose optimal size
    4. Summary of results
    5. Predicted beam size at object

## Optical Coupling to Detectors

* + 1. choice of waveguide size
    2. choice of waveguide length (kill higher order modes)
    3. Rules of thumb for designing absorbing mesh
    4. Simulation approach for absorbing mesh
    5. Summary of simulation results
    6. Choice of backshort distance

## Scanning Strategy

* + 1. Need for dithering (Nyquist sample focal plane)
    2. Summary of scanning strategy simulations

## Detector Readout - Q: how little can i get away with here?

* + 1. A SQUID is a highly non-linear current amplifier
    2. 1-paragraph summary of NIST TMUX and components
    3. We use MCE for warm readout electronics - simple operation and software suite honed over years of use on demanding astophysics experiments
    4. choice of mux chip version - mux11c
    5. choice of series array version -
    6. bandwidth issues on readout wiring? Data that Mike & I took relevant / useful here?
    7. MCE Faraday Cage Design: vacuum tubing to serve as cage for wires from cryostat to MCE. Tricky part was putting MCE in right location, given limited flexibility of vacuum tubing.

## Cryostat mount on Mirror

* + 1. 6 degrees of freedom provided by rods
    2. Extremely difficult to align “perfectly”, but pretty easy to get close, as demonstrated by by quality of beam maps and video images
    3. However, we don’t have any quantitative measurement how close our alignment is.

# Detector Design

## Parameter Choices for our Bolometers

* + 1. Interrelated nature of choice of G, P\_sat, T\_bath.
    2. T\_Bath (G-noise based on our noise / video frame rate requirements)
    3. T\_c (something convenient that is higher than T\_bath)
    4. P\_sat (based on predicted optical loading)
    5. G
    6. tau (need to avoid blurring at video rates) --> additional heat capacity

## Detector Detailed Design

* + 1. membrane material & thickness
    2. leg length & why metal on all legs
    3. TES dimensions/thickness
    4. Heat Capacity ring
    5. Thermal relaxation time for ring of metal

### Gold vs PdAu: gold much less heat capacity, but PdAu relaxation time uncomfortably close to relevant time constants

### Reference most recent RRR measurements here

### heater resistor

# Focal Plane Design (xxx this chapter needs better structure / organization)

## design constraints

* + 1. location in cryostat
    2. cryogenic isolation
    3. differential contraction
    4. detector/feedhorn alignment
    5. wiring & mux chips & series arrays for 1004 detectors
    6. backshort

## Focal Plane Hardware Design

* + 1. Why Al instead of Cu
    2. T-box and Ti struts

## Detector wafer layout

* + 1. Choice of square array instead of hex array
    2. much of layout (wiring, bondpads) via python autogen
    3. estimated crosstalk
    4. heaters

## Detector Package Assembly

* + 1. Glue (2850 FT LV23) detector wafer to backshort wafer. Process for glueing. Machines used. Glug Jig.
    2. Invar & apiezon solve Si/metal differential contraction issues. Reference to other projects using this approach.
    3. Process for applying apiezon. Use of alignment jig.

## Approach to wiring layout

* + 1. challenge comes from large number of detectors on single wafer, and limited space for wiring on focal plane.
    2. Design of breakout chip required to get signals to mux/interface chips.
    3. Estimated wiring chip crosstalk.

## Interface chips

* + 1. choice of interface chip versions (reasonable R & L values, already available)

# Detector Characterization

## Overview

* + 1. Review of TES circuit & parameters to be measurement
    2. where each circuit element lives (i.e. on what chip)
    3. overview of measurement process (we take zero-bias superconducting johnson noise measurements (at different bath temperatures) to measure RL and Ltot in the circuit. We then take superconducting bias steps to measure Rpar/Rsh and L/RL. Now we have enough to interpret IV curves. Etc)

## Superconducting Johnson Noise

* + 1. Johnson noise measurements at different bath temperatures
    2. white noise level gives Rsh
    3. 3 dB rolloff gives Ltot

## Superconducting bias steps

* + 1. change in current gives Rpar/Rsh
    2. time constant gives Ltot / RL

## IV Curves

* + 1. Description of expected features of an IV curve
    2. Parameters that need to be known
    3. Parameters extracted from individual IV curves: Rn, Psat vs % Rn
    4. Parameters extracted from Psat vs T\_bath: G, T\_c
    5. difficulty in direct measurement of T\_c (al wire bonds)

## Estimation of R\_htr (flesh out)

* + 1. Psat at const Tbath vs heater bias current

## Measurement of tau via Heater Steps

* + 1. Apply steps to heater bias lline, measure change in current \Delta I\_{TES}, \tau\_{eff}. Very high in the transition, \tau\_{eff} -> \tau, but responsivity becomes very small.
    2. We can derive a relationship between \Delta I\_{TES}, \tau\_{eff}, I\_b, \tau that holds independent of \alpha & \beta. High in transition there is a linear model we can fit too
    3. Take bias steps at various bias points above Loop=1, and can extrapolate to Loop = 0

## Transition bias steps

* + 1. An alternative to complex impedance for extracting alpha and beta.
    2. Derivation of governing equations
    3. Curve-fitting approach
    4. presentation of measurements

# Imaging

## Readout of mirror position

* + 1. Carl’s crazy idea
    2. Do we see pickup on detectors?
    3. Constant of proportionality b/w DAC value and actuator offset (easy, but not quite as trivial as you would think)

## Focus Distance

* + 1. Determine far-field focal plane by taking beams maps of BB source at different distances.
    2. What is the depth of field?

## Beam Maps

* + 1. beam maps tell you size of beam, any ellipticity, where detectors are pointed.
    2. Raster scans over stationary blackbody source
    3. Mapping as described later in this chapter
    4. Data analysis approach: fit 2-D gaussian near peak in map
    5. summary of results
    6. comparison to predicted results

## Optical Efficiency

* + 1. Manual chop between eccosorb and LN2 source
    2. summary of results
    3. comparison to predicted results

## Image processing algorithm

* + 1. Removal of detector offsets
    2. Handling relative detector gains
    3. Binning data to create a map
    4. deconvolution (?)
    5. other ideas (?)

## Development of $\Delta T$ scale

* + 1. optical efficiency + detector responsivity give you an absolute measurement of $\Delta T$.
    2. Comparison of this approach with still frame from videos: is the contrast between skin & background correct?

## Quantitative analysis of noise performance

* + 1. Take video of stationary target
    2. stdev and mean of each pixel across several seconds
    3. Summary of results