National Aeronautics and Space Administration

# Large Array of Quantum Capacitance Detectors (QCDs) with Low Frequency Readout

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**Program: Strategic Initiative**

## Project Objective:

The objective of this effort is to develop a 500-pixel array of quantum capacitance detectors (QCDs) which have 1) per-pixel noise equivalent power (NEP) below $3\times10^{-20}$ W $Hz^{-1/2}$, 2) high absorption efficiency, 3) sufficient speed of response to count individual mid-IR through far-IR photons at rates up to 10 kHz, and 4) Low frequency readout for reduced power comsumption. The full array will be read out with a single microwave circuit using a suite of probe tones interacting with resonators. The sensitivity, speed, and multiplexing are the key enabling requirements for moderate-resolution (R~1000) zodi-limited spectroscopy on future cryogenic far-IR facilities such as the OST or a far-IR probe-class mission. The photon counting capability offers the potential for enhanced scientific performance for a) high-stability applications such as exoplanet spectroscopy and b) high-resolution direct-detection spectroscopy at the shot-noise Limit.

## Benefits to NASA and JPL

A large fraction of the total star formation and black hole growth throughout cosmic time has taken place in dust-obscured regions in which all of the optical / near-IR light is absorbed. The far-infrared through millimeter waveband provides access to this component of the Universe, and this waveband is undergoing rapid technical advances fueling major scientific breakthroughs. JPL has been at the forefront of this activity, leading the way in far-IR to mm-wave instrumentation (ground, sub-orbital, and spaceflight), enabled primarily by the world-leading detector technology such as the bolometer arrays flown in Herschel SPIRE and Planck HFI. The success of Spitzer and Herschel has given rise to future concepts for far-IR space astrophysics with cryogenic platforms, ranging from participation in SPICA to a US-led probe-class cryogenic telescope (a ~2-3 meter telescope) to the flagship-class Far-IR Surveyor (now called OST, potentially a ~5-10 m telescope) currently under NASA-funded study in preparation for the 2020 Decadal Survey. These facilities offer breakthrough scientific capability if suitable detector systems can be brought to bear. With this task, we are advancing the one far-IR detector technology which has demonstrated single-pixel sensitivities meeting the requirements of these future missions. Unlike for the other technologies, for the QCD the basic physics is clearly viable for sub-$10^{-19}$ W $Hz^{-1/2}$ sensitivities. Also, crucially, the QCD system is compatible with the emerging frequency-domain RF / microwave readout, which enables the high pixel counts desired. However, further fundamental work is required to demonstrate QCD yield and uniformity on large arrays, as well as a readout system. Our work will ready JPL and NASA for an OST-like mission and a potential far-IR probe-class mission. The ESA / JAXA SPICA mission is also a potential application in the slightly nearer term. These missions could begin implementation in the 2020 decade, with SPICA potentially launching in 2029, and the OST launching in ~2035. Finally, while the backgrounds are less demanding, the QCD approach can also be adapted to balloon-borne and SOFIA instrumentation if the large arrays can have a high yield.

## Introduction

QCD:
Infrared or sub-millimeter radiation couples to a superconducting absorber, providing energy to break Cooper pairs in the absorber. This generates phonons and non-equilibrium quasiparticles, which diffuse to the junctions of a Single Cooper-pair Box (SCB). When quasiparticles tunnel across the SCB junctions, they change its average quantum capacitance, resulting in a shift in the center frequency of the resonator. The frequency shift is measured using standard RF techniques.

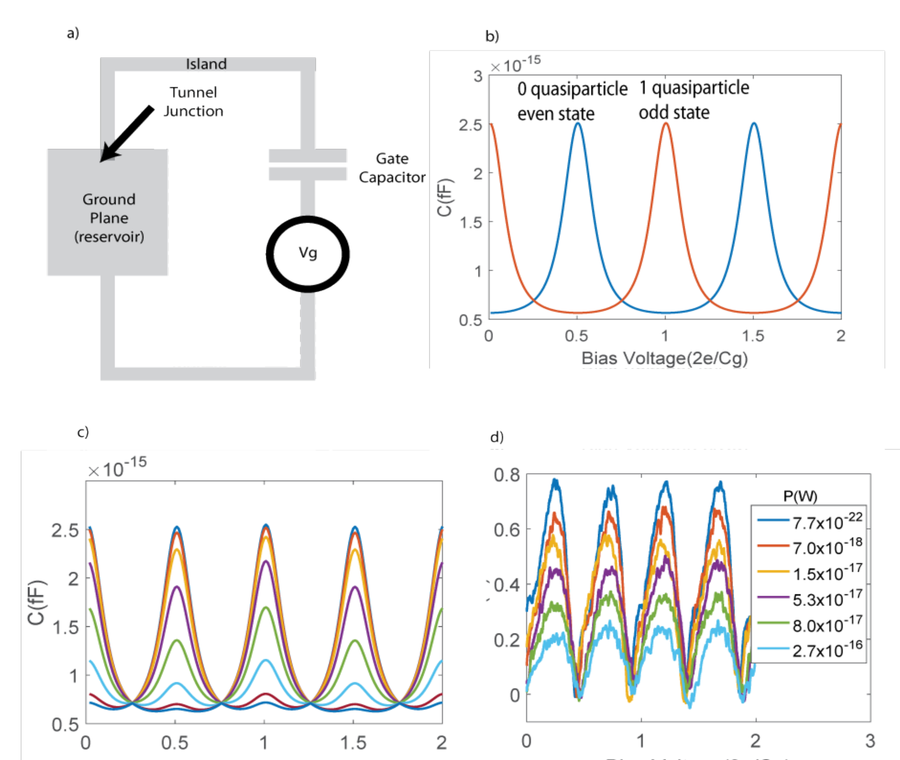


Figure 1. QCD concept

**a)** Schematic representation a single Cooper-pair box (SCB) for which single electrons influence the charging Hamiltonian and thus the capacitance. **b)** Simulated quantum capacitance trace (the SCB quantum capacitance as a function of bias voltage in units of $2e/C_g$). The system has a periodic capacitance as a function of bias voltage, and electron tunneling shifts the system between the even and odd states. **c)** Simulated quantum capacitance traces for various levels of optical illumination. Increased quasi-particle density in the absorber (due to increased photon flux) suppresses the quantum capacitance effect by increasing the rate of tunneling into the SCB, spoiling the pure even state. Note that the traces are e-periodic. **d)** Measured response of the devices studied here for a few illumination levels.

**Single Photon Detection demonstration:**

Sweeping the gate voltage at a fast rate allowed us to demonstrate single photon detection and counting. A photon absorption event generates 20 quasiparticles which trigger a burst of tunneling into the island. This burst of tunneling destroys a quantum capacitance peak.

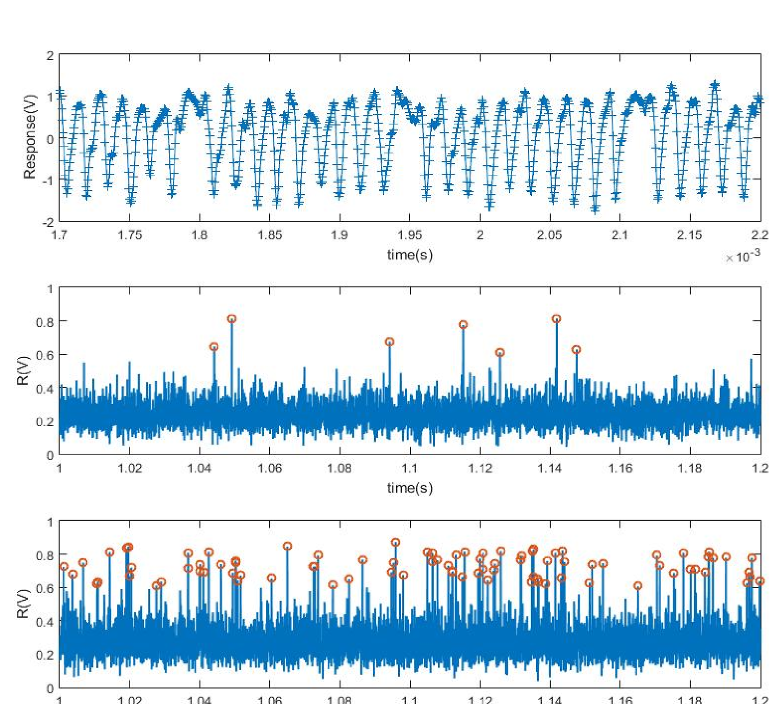


Figure2. Top: Quantum Capacitance displaying gaps corresponding to single photon detection. Single photons highlighted for photon rate 1Hz (center) and 408Hz (bottom).

The measured photon rate agrees very well with the expected rate based on the coupled optical power. The statistics of photon detection also agrees with a Poisson distribution

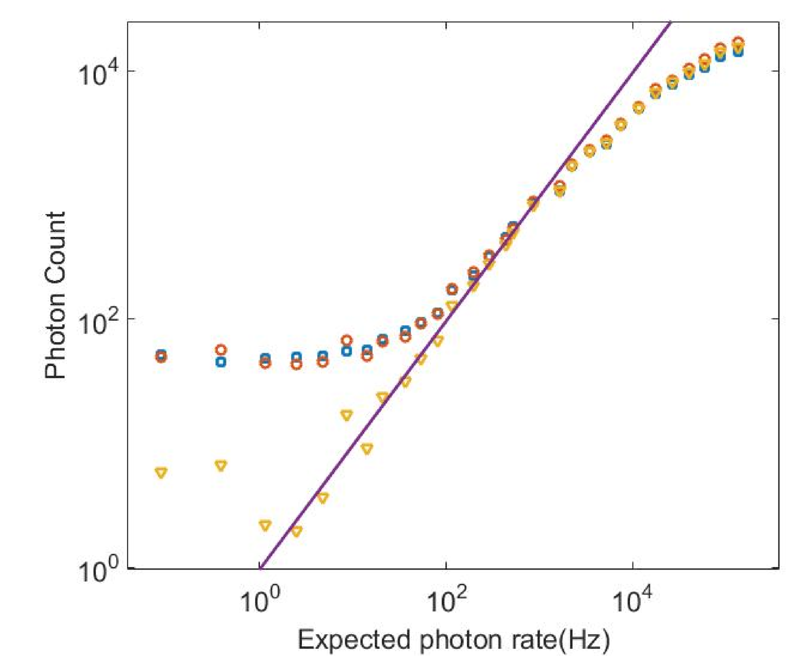


Figure 3. Measured versus expected photon rates (blue squares and red circles, orange triangles with background removed). Purple line displays 96% efficiency.

## FY18/19 Results:

In FY 19 we fabricated and characterized 5x5 arrays and 21x21 arrays of Quantum Capacitance Detectors with low frequency readout

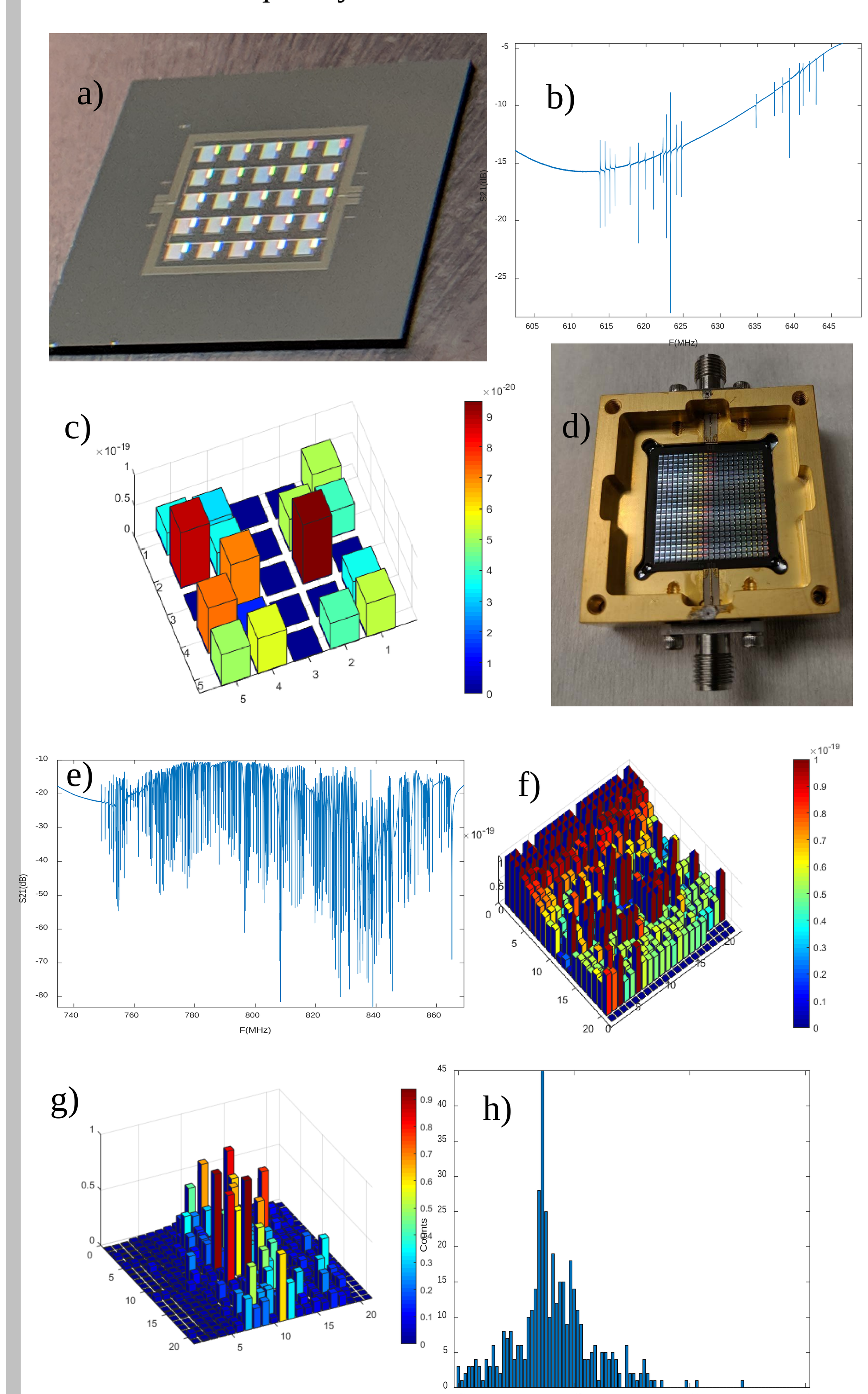


Figure 3. a) 5x5 array of low frequency readout QCD.b) Transmission through 5x5 array.c)NEP map of 5x5 array – NEP> $10^{-19}$W/$Hz^{1/2}$ were plotted as zero. Center column has pixels with no mesh absorbers. d 21x21 QCD array. e) Transmission through 21x21 array. f) NEP map of 21x21 array. g) Efficiency map of 21x21 array. h) NEP histogram of 21x21 array

## Publications:

P.M. Echternach, B.J. Pepper, T. Reck & C.M. Bradford, Single Photon Detection of 1.5THz radiation with the Quantum Capacitance Detector, Nature Astronomy, Volume: (2018).

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