Superconducting Sensors for Microwave and Optical Photon-Starved Communications
(Plenary)

Dr. Bob Romanofsky
Senior Technologist
Communications and Intelligent Systems Division
NASA Glenn Research Center,
21000 Brookpark Rd., Cleveland, OH 44135

International Workshop for Superconducting Sensors and Detectors 2018
Sydney, Australia, 24th – 27th July 2018
Outline

• NASA Glenn Research Center
  • Communications Research and Technology

• Deep Space Communications
  • Optical versus Microwave

• Kinetic Inductance Detectors
  • Subtle Aspects of Transmission Line Resonators

• Superconducting Quantum Interference [Filter] Receivers
  • A “Noiseless” Receiver?

• An Optical Ground Array Concept
  • An Economically Viable Alternative to a Large Monolithic Reflector
National Aeronautics and Space Administration

Glenn Research Center

Plum Brook Station Test Site
(Sandusky)
• 6500 acres
• 11 civil servants and 102 contractors

Lewis Field
(Cleveland)
• 350 acres
• 1626 civil servants and 1511 contractors

as of 1/2013
Glenn Core Competencies

- Air-Breathing Propulsion
- In-Space Propulsion and Cryogenic Fluids Management
- Physical Sciences and Biomedical Technologies in Space
- Communications Technology and Development
- Power, Energy Storage and Conversion
- Materials and Structures for Extreme Environments
Communications Research and Technology

- Fundamental Research Materials and Devices
- High Power Amplifiers
- Simulation and Modeling
- Cryogenic Electronics & Superconductivity
- Laboratory Facilities
- Phased Array Antennas
- Deployable Antennas
- Aviation Safety and Security
- Architectures, Network Protocols
- Space Flight Experiments
- Emmy Award
  Depressed Collector Traveling Wave Tube Communications Technology Satellite
- Space Technology Hall of Fame
  Advanced Communication Technology Satellite Inflatable Antenna System
- Spaceflight Equipment Development
- Software Defined Radio
- Software Defined Radio
- Advanced Communication Technology Satellite
- Space Flight Experiments
- Emmy Award
  Depressed Collector Traveling Wave Tube Communications Technology Satellite

National Aeronautics and Space Administration
www.nasa.gov
Cryogenic Electronics & Superconductivity Heritage in the Advanced High Frequency Branch

- Space Qualified X-band Cryogenic Receiver Front end (NRL High Temperature Superconductivity Space Experiment) 1994
- Portable K-Band Cryogenically Cooled Low-Noise Receiver for the Direct Data Distribution Experiment 1999
- 40 GHz Cryogenic On-Wafer Probe Station 1994
- Ku-Band Ferroelectric/ YBaCuO Tunable Oscillator 2000
- Space Shuttle Return-to-Flight GPS Receiver Cryogenic Characterization 2004
- Chapter 7: Hybrid Superconductor/ Semiconductor Microwave Devices and Circuits 1996
- X-Band SQIF 2014
Increase of Date Rate as a Function of Time
The highest data rate from deep space was achieved by the Mars Reconnaissance Orbiter at 6 Mb/s (X-band) from Mars at perigee.

In October 2013 NASA’s Lunar Laser Communication Demonstration (LLCD) hosted by the Lunar Atmosphere and Dust Environment Explorer mission demonstrated a downlink rate of 622 Mb/s from lunar range.

Deep-Space optical communications differs from near earth communications because one-way link times can exceed 20 minutes (as opposed to a few seconds) and the great distances result in photon limited signals.

NASA JPL’s Deep Space Optical Communications project is developing technologies to enable an optical transceiver capable of 267 Mb/s at Mars perigee to a ≈12 m ground terminal.

Large aperture ground telescopes will be equipped with low noise, high detection efficiency, single photon counting detectors.
Let’s Compare Signals and Sensitivity

- Earth’s Magnetic Field
- Magnetic Field of the Human Heart
- Magnetic Field of the Human Brain
- Magnetic Field Received at Earth from Mars (apogee, 100 W Transmitter, 12 m aperture)
What is Channel Capacity?

- **Capacity**
  - Is the *maximum information rate* that can be achieved across a channel with an arbitrarily small probability of error
  - Represents the *maximum mutual information* between the output (transmitter) and input (receiver) across a channel
  - Units of capacity are *bits per second*

- **Related performance metrics**
  - *Photon Information Efficiency*
    - PIE, bits per photon
  - *Dimensional Information Efficiency*
    - DIE, bits per mode
  - *Spectral Information Efficiency*
    - SIE, bits per second per Hertz

**Example:** Shannon capacity for Additive White Gaussian Noise (thermal) channel

\[
C = B \log_2 \left( 1 + \frac{S}{N} \right)
\]

- \(C = \text{capacity (bits / time)}\)
- \(B = \text{bandwidth (1 / time)}\)
- \(S = \text{signal power (energy / time)}\)
- \(N = \text{noise power (energy / time)}\)
Pulse Position Modulation (PPM)

- **Pulse Position Modulation (PPM, a form of generalized OOK) of a laser transmitter in combination with a photon counting receiver** is a near-optimal configuration for high PIE
  - “Poisson channel” model applies
  - Trades low DIE for high PIE
  - Uses high peak-to-average power lasers
  - **Photon Counting – Direct Detection (PC-DD) is easy to implement**
  - **Forward Error Correction codes are already known that approach within 1 dB of capacity**

- **In PPM, a single laser pulse in one of M symbol slots encodes \( \log_2 M \) information bits**
  - Additional non-signal slots may be appended to the PPM symbol to allow for slot clock recovery at the receiver and/or pulsed laser reset time

- With no minimum slot width constraint in place, the capacity of the Poisson channel may be bounded as:

  \[
  C \leq C_{\text{OOK}} = \frac{1}{\ln 2} \left( \left( \lambda_s + \lambda_b / M \right) \ln \left( 1 + \frac{\lambda_b}{M \lambda_s} \right) + \frac{(M - 1)}{M} \lambda_b \ln \left( \frac{\lambda_b}{M \lambda_s} \right) - \left( \lambda_s + \lambda_b \right) \ln \left( \frac{1 + \lambda_b / \lambda_s}{M} \right) \right) \text{ bits/sec}
  \]

  Where
  - \( \lambda_s \) = mean signal photons/second
  - \( \lambda_b \) = mean noise photons/second

William Farr, Space Optical Communications, Jet Propulsion Laboratory, December 2011
RF / Optical Capacity

- Although optical outperforms RF at high data rates, RF can outperform optical at large ranges and under high background conditions.

\[ C = \frac{4 \alpha \eta_r \eta_{r(op)}}{N_0 R^2} \left[ \frac{2 \ln M I_s \Omega_s \lambda_s R^2}{M \alpha_{op} \eta_{r(op)}} \right]^{\frac{\beta_{\alpha}}{\beta_{\alpha}}} \]

- For \( P_r > 2 \frac{P_b}{\ln M/M} \), the capacity goes as \( 1/R^2 \).

Equal-Mass Equal Capacity RF-Optical Performance

William Farr, Space Optical Communications, Jet Propulsion Laboratory, December 2011

**Approximate Formulas**

\[ C_{RF}(W) = W \log_2 \left( 1 + \frac{P_r}{N_0 W} \right) \text{ bps} \]

\[ C_{opt} = \left( (P_r + P_b/M) \log_2(1 + M P_r/P_b) \right) / E_\lambda \text{ bps} \]

For \( P_r > 2 \frac{P_b}{\ln M/M} \), the capacity goes as \( 1/R^2 \),

for \( P_r < 2 \frac{P_b}{\ln M/M} \) the capacity goes as \( 1/R^4 \).
Microwave Kinetic Inductance Detectors: Basic Principles

- Resonators gain kinetic inductance from Cooper pair motion when $T<T_c$.
- Photon absorption breaks pairs, perturbing the resonance.
- Usually $T<<T_c$ to maximize Cooper Pair population, minimize spontaneous pair breaking

B. Mazin, AIP Conference Proceedings, 1185, 135-142 (2009)
Superconducting Nanowire SPD

- Superconducting nanowire single photon detectors (SPDs) are used where precision timing and single photon sensitivity are required.
- Films (e.g. NbN) are generally about 10 nm thick and ≈ 200 nm wide.
- Devices are biased with a constant current near the critical current such that absorbed photons dissociate Cooper pairs and drive the nanowire normal.
- Generally formed into an array or meandering complex to improve detection efficiency.
- Generally cooled below 100 mK to minimize the quasiparticle population.
- Spontaneous pair breaking and recombination is biggest noise source above ~100mK.

Kinetic Inductance SPD

- Frequency of a transmission line resonator is inversely proportional to the square root of (geom + kinetic) inductance.
- Shift in the density of quasiparticles due to radiation results in a change of the kinetic inductance.
- Sensitivity proportional to Q.
- Noise equivalent power determined by quasiparticle generation–recognition can be as small as $10^{-19}$ W/√Hz using He$_3$ cryostats.
- Primary application of these devices has been astronomical observations.

GRC: Design and fabricate KIDs, investigate response near and at ~1/3 Tc.

---

SNSPD Operation and Assembly

$I < I_c$

$R = \text{small}, V = 0$

$R = \text{big}, V > 0$

Photon

Standard operating temp $\leq 2.5$ K

M2 Mounting hole

Zirconia fiber ferrule

Zirconia sleeve

SNSPD chip

Sapphire rod

Coax connector

Courtesy of www.QuantumOpus.com
SNSP Detectors

- Single-photon detectors at near-infrared wavelengths with high system detection efficiency (>80%), low dark count rate (<1 c.p.s.), low timing jitter (<100 ps) and short reset time (<100 ns) are required
- Commercially available turnkey superconducting nanowire single photon detector systems are available now that can support 8 channels (e.g. PhotonSpot, Quantum Opus)

http://www.quantumopus.com/
Subtle Aspects of Coupled Resonators

In a microstrip or coplanar transmission line resonator, the coupling is accomplished by using a narrow ($<<\lambda_g$) gap. This discontinuity can be modeled by a capacitive $\pi$ network, or equivalently, by an ideal transformer. The effect of loading is to increase the conductance of the resonator by an amount equal to the transmission-line characteristic admittance multiplied by the transformer turns ratio $n$. Hence, the modified $Q$ will be smaller and is given by

$$Q_L = \frac{\omega C_0}{G_0 + n^2 Y_0}$$

It is assumed that the coupled susceptance is negligible compared with the resonator susceptance. A comparison of $Q_L$ with $Q_O$ yields

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{n^2 Y_0 / G_0}{Q_0}$$

where $n^2 Y_0 / G_0$ is the ratio of coupled conductance to resonator conductance and is referred to as the coupling coefficient $\kappa$. The unloaded quality factor may therefore be expressed as:

$$Q_0 = (1 + \kappa) Q_L$$

When $\kappa < 1$, the resonator is under-coupled and is defined by:

$$\kappa = \frac{1 - |\Gamma_{io}|}{1 + |\Gamma_{io}|} \equiv \text{VSWR}^{-1}$$

When $\kappa > 1$, the resonator is over-coupled and is defined by:

$$\kappa = \frac{1 + |\Gamma_{io}|}{1 - |\Gamma_{io}|} = \text{VSWR}$$
Subtle Aspects of Coupled Resonators

The degree of coupling can therefore be determined from an inspection of the Smith chart impedance plot. The three possibilities correspond to $d = 1$ (critically coupled), $d < 1$ (under-coupled), and $d > 1$ (over-coupled).

Ideal impedance locus for under-coupled resonator (dashed line) and translated locus in presence of coupling loss and reactance. Point $D$, detuned resonator; point $R$, unloaded resonant frequency; point $M$, loaded resonant frequency; $\Gamma_i$, input reflection coefficient.

Typical resonator reflection coefficient magnitude with various degrees of coupling for $Q_o = 100$ in absence of series loss.
The apparent resonant frequency of an inductively or capacitively coupled resonator is pulled from the natural resonant frequency of the isolated circuit because of the reactance or susceptance associated with the coupling mechanism.

Subtle Aspects of Coupled Resonators

![Diagram of coupled resonators]

![Graph showing normalized resonant frequency vs. reduced temperature]
Semiconductor Receiver versus
SQIF Receiver ($E$ vs. $B$)

**Conventional Receiver**
Mars link at 64 MBPS

- EIRP = 84 dBW ($\approx 2.5 \times 10^8$ W)
  - Assumes 100 W TWT, 12 m aperture
  - Range = $3.7 \times 10^8$ km
- Power density at receiver $\approx 2.8 \times 10^{-16}$ W/m$^2$
  - Electric Field $\approx 4.6 \times 10^{-7}$ V/m
  - Displacement flux density $\approx 10^{-18}$ C/m$^2$
- Receive Antenna Aperture
  - QPSK, Block Turbo Code, 3 dB margin
  - Required $E_b/N_0 = 4.6$ dB

Aperture size 34 meters

**SQIF Superconducting Receiver**
Mars link at 64 MBPS

- EIRP = 84 dBW ($\approx 2.5 \times 10^8$ W)
  - Assumes 100 W TWT, 12 m aperture
  - Range = $3.7 \times 10^8$ km
- Power density at receiver $\approx 2.8 \times 10^{-16}$ W/m$^2$
  - Electric Field $\approx 4.6 \times 10^{-7}$ V/m
  - Displacement flux density $\approx 10^{-18}$ C/m$^2$
  - Magnetic Field $\approx 10^{-9}$ A/m
  - Magnetic flux density $\approx 10^{-15}$ Wb/m$^2$
- Receive Antenna Aperture
  - Flux Concentrator
  - Mechanical refrigerator at 4K

Aperture Size ???

SQUIDs can detect magnetic fields lower than one flux quantum
$h/(2e) \approx 10^{-15}$ Wb, $10^{-18}$ Wb reported in the literature (DC)
Can We Make a “Noiseless” Receiver

The fundamental argument against a noiseless receiver goes something like this. From the uncertainty principle $\Delta E \Delta t = \hbar / (4\pi)$ where energy $E = hf$, $h$ is Planck’s constant, $f$ is frequency and $t$ is time. (The more localized energy is in frequency, the less it is localized in time.) Since $\Delta \theta = 2\pi f \Delta t$ and substituting $\Delta E = hf \Delta n$ where $\Delta n$ is photon number uncertainty we conclude:

$$\Delta n \Delta \theta \geq 1/2$$  \hspace{1cm} (1)

Hence a large number of photons must be received if the phase is to be known accurately. A noiseless amplifier would produce $G$ output photons for every input photon where $G$ is the amplifier gain (i.e. $n_i$ input photons produce $n_o = G n_i$ output photons). For a linear amplifier, the output phase $\theta_o$ is equal to the input phase $\theta_i$ plus some constant. A perfect detector would permit the measurement of $n_o$ and $\theta_o$ with an uncertainty $\Delta n_o \Delta \theta_o = \frac{1}{2}$. But uncertainty $\Delta n_o$ corresponds to an input uncertainty $\Delta n_i = \Delta n_o / G$ and output uncertainty $\Delta \theta_o$ corresponds to input uncertainty $\Delta \theta_i = \Delta \theta_o$. Therefore the apparent measurement uncertainty is $\Delta n_i \Delta \theta_i = 1/(2G)$ in violation of equation (1) leading to the conclusion that a noiseless amplifier is impossible.

Nevertheless, with a sufficient number of SQIF loops, $T_e$ will approach and possibly reach the quantum limit hf/k, where k is Boltzmann’s constant.

<table>
<thead>
<tr>
<th>Receiver Technology @ 32 GHz</th>
<th>Sky Noise Temperature (K)</th>
<th>Receiver Noise Temperature (K)</th>
<th>System Noise Temperature (K)</th>
<th>Sensitivity Improvement over MASER (dB)</th>
<th>Sensitivity Improvement over 20 K HEMT (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASER</td>
<td>10</td>
<td>9.0</td>
<td>19.3</td>
<td>-----</td>
<td>+1.5</td>
</tr>
<tr>
<td>HEMT</td>
<td>10</td>
<td>16.1</td>
<td>27.0</td>
<td>-1.4</td>
<td>-----</td>
</tr>
<tr>
<td>SQIF</td>
<td>10</td>
<td>1.5</td>
<td>11.6</td>
<td>+2.3</td>
<td>+3.6</td>
</tr>
</tbody>
</table>
Superconducting Quantum Interference Filter (SQIF) – 
potentially the world’s most sensitive microwave receiver  
(in fact, a “noiseless” receiver!)

When a SQUID\(^1\) (the building block of a (SQIF) is biased with a constant current, 
the voltage across it oscillates with increasing \(\phi\) and period \(\phi_0 (h/2e)\). 
SQUIDs can detect magnetic fields lower 
than one flux quantum, with \(10^{-18}\) Wb 
reported in the literature. \(\Phi\) is the 
magnetic flux from the communications 
signal that pierces the superconducting loop

\(^1\) J. Clarke, Scientific American, August, 1994
Calculated SQUID and SQIF sensitivity (noise temperature) as a function of frequency with loop inductance as a parameter.

- The calculation assumes flux noise spectral density ($\phi_0/\sqrt{\text{Hz}}$) stays white to the frequency range of interest which should be valid as long as we stay well below the Josephson frequency.
- A noise spectral density of $5 \times 10^{-6}$ is typical for a Nb SQUID.
- A SQIF with $N=20,000$ loops (solid blue curve) comes very close to the quantum limit.
- The analysis additionally assumes the noise indeed continues to scale inversely as $N^{1/2}$. In practice the magnetic field must be efficiently directed through the array plane.
Superconducting Quantum Interference Filter (SQIF)

Operating Principles

- SQUID voltage response is periodic in the applied magnetic field
- SQIF is an array of SQUIDs of incommensurate area with a unique magnetic flux-to-voltage response
- Sensitivity improves with arraying more SQUID cells ($S/N \sim \sqrt{N}$)

Integrated circuit of 2-D SQIF arrays

Comparative Technologies

- Energy sensitivity of about $10^{-31}$ J/Hz, compared to semiconductor $10^{-22}$ J
- Sensitivity approaches quantum limit, while increasing dynamic range and linearity
- Attractive for wideband-sensitive receivers
- Robust to variation in fabrication spread (e.g. junction critical current, inductance, etc.)

SQIF receiver conceptual block diagram

- Receiver will consist of a flux concentrator (antenna), SQIF sensor, and digital signal processor
SQIF Testing

Typical Measured Voltage Flux Response

Measurements start by verifying Flux-Voltage transfer Characteristic. Operating point is selected mid-point of anti-peak slope ($I_c$ and $I_b$) 50 μV/div, 2 mA/div
Results

First reported high gain results at X-band, September 2014

Voltage response of the SQIF array in the ON and OFF states
April, 2017: Four representatives from CSIRO visit GRC to conduct tests on unique high temperature superconductor SQIF devices fabricated by CSIRO.

The unique voltage response of SQIF-sensors is intrinsically robust against scatter of junction parameters in the array (self averaging)
An Optical Ground Array: Introduction

• The purpose of this study is to outline the design of an optimal array of optical telescopes to emulate performance of a monolithic 12 m telescope in support of deep-space communications. In this case, optimal means minimizing the initial capital investment and operational cost while maintaining performance requirements of the deep-space link. The design is approached from a practical, engineering perspective. Pulse position modulation (PPM) signal formatting and photon counting detectors are assumed at each telescope in the array. That is, the telescopes function as so-called light buckets, so direct detection (as opposed to coherent reception) of the received signals is assumed, and there is no intention to consider active compensation for atmospheric turbulence-induced phase fluctuations.

• The projected cost of a 12 m diameter monolithic optical receiver system is ≈$120 M. It will be shown that given certain assumptions the optical array cost is close to 2/3 this estimate.

• A parametric analysis among aperture size, detector size, and primary mirror surface quality, in the context of field-of-view expansion, is presented to minimize the cost function.

• Besides potentially very substantial cost savings, other advantages of a telescope array include: minimal gravitational effects (i.e. primary mirror/sub-reflector structural sag), reliability through redundancy, and scalability. A possible drawback of a large telescope array is the complexity associated with synchronization of the individual telescope PPM signals.

• From empirical data

\[
C = q \left( \alpha \left( \frac{D}{\sqrt{q}} \right)^x + 0.47 q^{-0.33} \right)
\]

(1)

where C is the cost in millions of dollars, D is the telescope diameter in meters, q is quantity, and x is ≈ 2.6. The value of \( \alpha \) is a function of “blur circle diameter” which is essentially corresponds to resolution in arcseconds. Each telescope has an independent focal plane detector, and that detector is cooled with a closed cycled helium refrigerator. The term on the right represents refrigerator cost.
Array Cost Minimization (Aperture vs. Quantity)

Estimated telescope array cost as a function of the number of telescopes to emulate a single monolithic 15 m (red), 12 m (blue) and 10 m (black) monolithic telescope. In all cases an alpha=0.2 is assumed (this corresponds to a 0.5 arcsecond spot size).

Corresponding array telescope diameter (m) to emulate equivalent monolithic reflector as a function of telescope quantity for the three different monolithic telescope cases.
Estimated cost of telescope enclosure based on commercial grade domes

Including telescope housing cost equation (1) is modified as:

$$C \approx q (\alpha (D/Vq)^x + 0.47q^{-0.33} + 0.02D(D-1) + 0.01)$$  \hspace{1cm} (2)
Atmospheric Turbulence and Detector Size Considerations

- Atmospheric turbulence can cause the actual FoV (i.e. telescope beam solid angle) to be many times the theoretical diffraction limit – essentially increasing background stray light (e.g. scattered sun light). The actual spot size or blur circle diameter is greater than the diffraction limited focus because the turbulence induces angle-of-arrival fluctuations causing spot displacement.

  Geometry of basic telescope system illustrating effect of turbulence on point spread function. Turbulence is regarded as distributing the signal into \((D/r_o)^2\) random spatial modes at the detector plane.

- The focused spot size becomes \(d_s \approx 2f \lambda/r_o\). A larger detector is necessary to encircle the signal energy, which increases the FoV. Since \(d_s\) must be smaller than the detector diameter \(d_A\), this implies

  \[
  f \leq d_A r_o/(2\lambda) \tag{3}
  \]

- From a manufacturing point of view, an f# >1 is desirable. This leads to the conclusion

  \[
  D \leq f \leq d_A r_o/(2\lambda) \tag{4}
  \]

- This is on the cusp for a 1.3 m telescope assuming a typical 20 cm Fried parameter.
Mirror Surface Quality Effects and Encircled Energy

- For photometric measurements, the encircled energy is used to represent the integrated flux contained within the detector radius.
- A “real” optical surface has random surface errors which result in scattering and modification of the point spread function.
- The mirror is assumed to contain normally distributed surface errors having zero mean and standard deviation $\sigma$ (i.e. $\sigma$ is the RMS roughness in terms of $\lambda$).
- The scattered field also depends on the surface autocorrelation function and the characteristic correlation length $\tau$ – also assumed to be normally distributed.

![Graph showing two different rough surfaces with zero mean and the same RMS value (\(\sigma=1\)) but different correlation lengths.](image_url)

- The fraction of optical energy, $P_E$, focused onto the detector is determined by integrating the modified point spread function over the detector area. It is assumed that point spread function is centered on the detector array.

\[
P_E = 1 - e^{-\left(\frac{4\pi \cdot \sigma}{\lambda}\right)^2} \cdot \sum_{m=1}^{\infty} \frac{(4\pi \cdot \sigma)^{2m}}{m!} \cdot e^{-\left(\frac{1}{m}\right)} \cdot \left(\frac{\pi \cdot \tau}{2}\right)^2
\]

(5)
Scaling Aperture Size to Compensate for Surface Defects

• tradeoff between scaled primary mirror size and RMS surface roughness with correlation length as a parameter

![Graph showing the relationship between aperture size scaling and RMS surface roughness for different correlation lengths.](image)

Manufacturable telescope scale factor relative to a perfect mirror as a function of RMS surface roughness, with correlation length expressed in terms of $\lambda/FoV$ (i.e. $\lambda f/d_\lambda$) as a parameter, and RMS surface roughness ranging up to $\frac{1}{4} \lambda$.

• According to the formulation, for long correlation length ($\tau>1$) there is virtually no mirror diameter increase necessary for surfaces with up to a $\lambda/10$ RMS error. For relatively smooth surfaces (say $\sigma/\lambda<0.1$), the diameter scaling is essentially independent of correlation length for $\tau<0.1 \lambda/FoV$
Hypothetical Mirror Manufacturing Costs

- As a sanity check to estimate relatively small SiC mirror cost versus aperture size and quality, the cost of modest size glass mirrors is used along with the 5% scaling factor (i.e. 20X lower removal rate during polishing) for SiC

  Mirror cost based on equation (1) (solid line) compared to data extrapolated from small glass mirrors and scaled to reflect the added complexity of SiC processing (dashed line) in $K.

- The small mirror power law curve indicates a roughly 25% higher cost in the region of interest.
Conclusions

• Based on the initial conclusion that an array of 141, 1.01 m diameter mirrors is nearly optimal, the cost of the array should be bounded by:

\[
C_H = q \left[ (0.397) \cdot \left( \frac{D}{\sqrt{q}} \right)^{2.03} + 0.47 \cdot q^{-0.33} + \left[ \frac{D}{\sqrt{q}} \cdot \left( \frac{D}{\sqrt{q}} \cdot 0.035 - 0.026 \right) + 0.012 \right] \right] \tag{18}
\]

on the high side. Using this equation, the projected total array cost is $73 M, with $57 M, $13 M and $3 M attributed to the telescopes, refrigerators and domes, respectively.

• Equation [5] or Figure 11 can be used to trade cost of the highly polished SiC mirror with a less perfect but somewhat larger mirror. For example, instead of polishing to a micro-roughness of \( \lambda/100 \), a 1.92 m mirror with a \( \lambda/10 \) micro-roughness could be used (assuming a correlation of 0.25 is feasible), enabling a \( \approx 3 \)X reduction in post-polishing costs. This implies an initial investment of about $55 M for the optical ground array, and a 25 year life-cycle cost of about $85 M.

• Finally, consider an optimal mirror scaled from a nominal 1.3 m SiC mirror (assuming feasibility from a manufacturing perspective and turbulence issues). The scaled mirror would be \( \approx 2.5 \) m in diameter and the upper cost is slightly lower – about $51 M. In this case, $38.4 M, $9.2 M and $3.2 M are attributed to the telescopes, refrigerators and domes, respectively. And, only 85 telescopes are required. 2.5 m is considered to be an upper limited on SiC mirror manufacturing technology.

• These costs can be further reduced by dedicating one refrigerator to multiple channels (detectors). There is precedent to suggest that at least 8 single photon detector channels can be accommodated by a single refrigerator.
Next steps...

Insert an X-band SQIF into the 34 m DSS_13 antenna at Goldstone!
References

4. Ibid.