# Hybrid Quantum and Optical Communications Terminal for Secure Communications and Time Transfer

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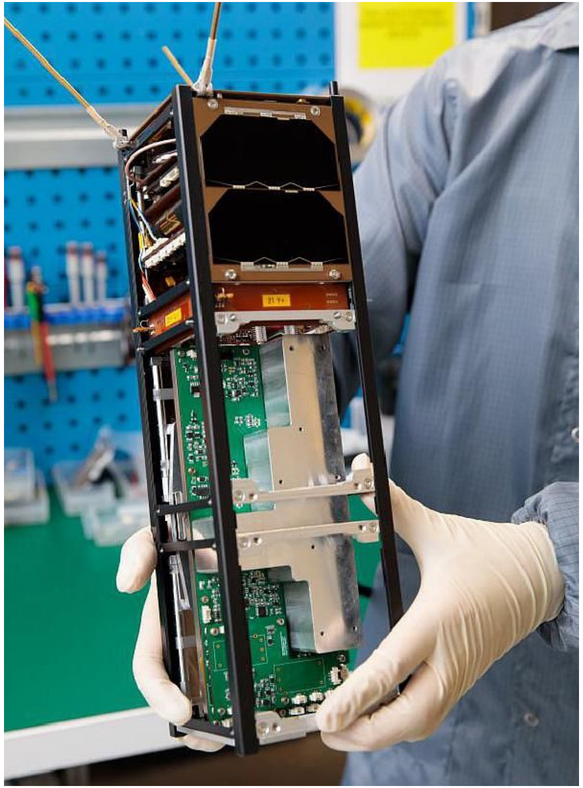
# Introduction

Quantum Key Distribution (QKD) provides a secure way of sharing a cryptographic key.

QKD puts unique requirements on optical channel because the brightness of entangled photon sources is inherently limited.

Advances in attitude control systems and fine steering methods enables 10 cm class telescopes on Cubesats, making QKD on a CubeSat possible.



SpooQy-1 and the SPEQS payload
Image: NUS, CQT

# Objectives

Objective: Develop an optical front-end capable of:

- Quantum key distribution, using SpeQtral's source, and
- Laser communication, reusing MIT's CLICK design

Key requirements

- Fit in a 12U CubeSat
- 12 µrad FWHM far field divergence for the QKD wavelength
- Pointing loss below 3 dB
  - 6 µrad half angle pointing error, 3-σ.

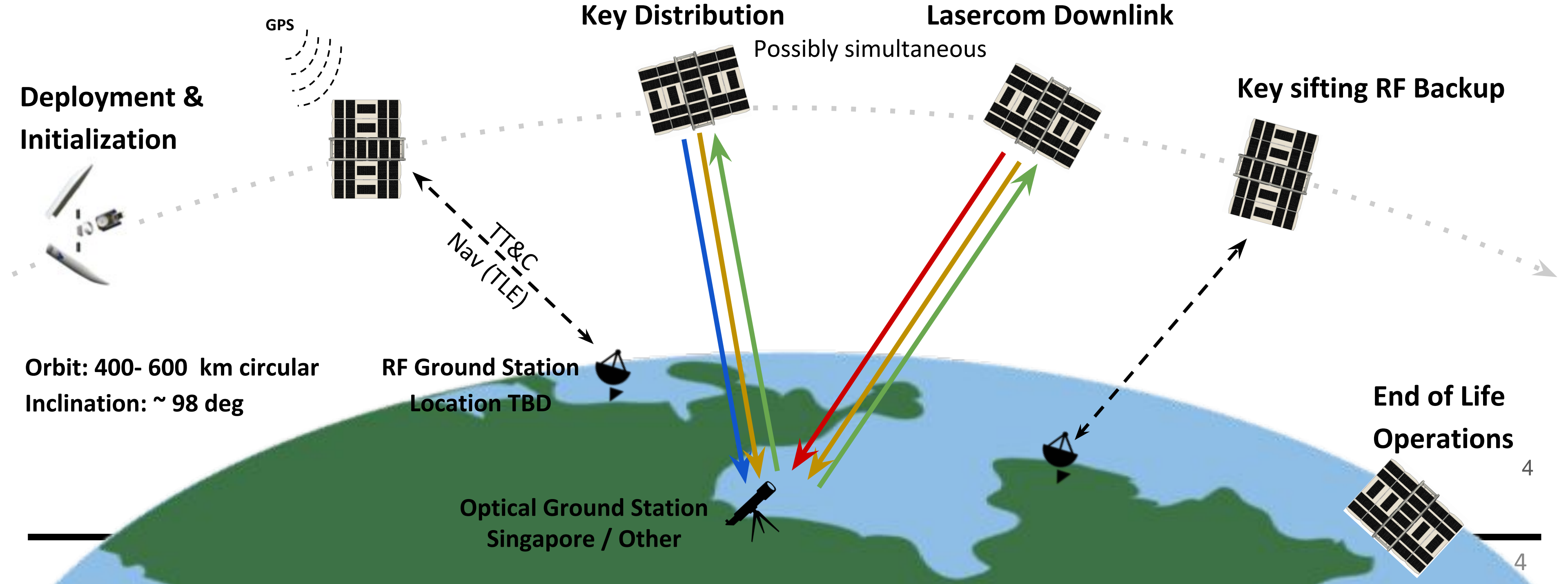
# Mission CONOPS

Beacon Downlink
685 nm

QKD Signal
765 nm -785 nm

Data Downlink
915 nm

Beacon Uplink
980 nm





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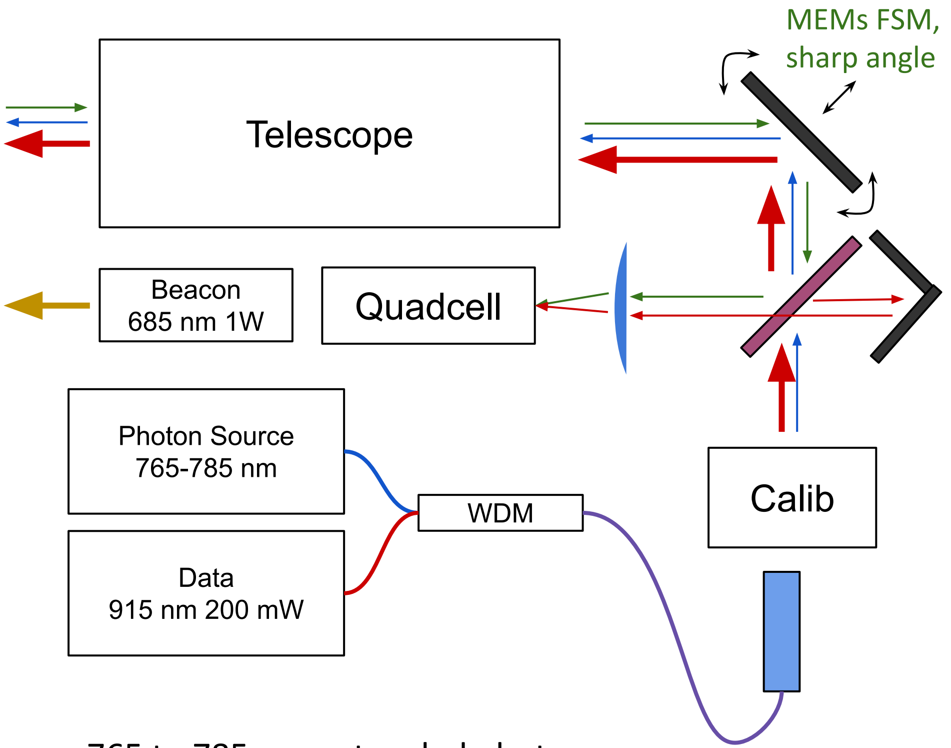
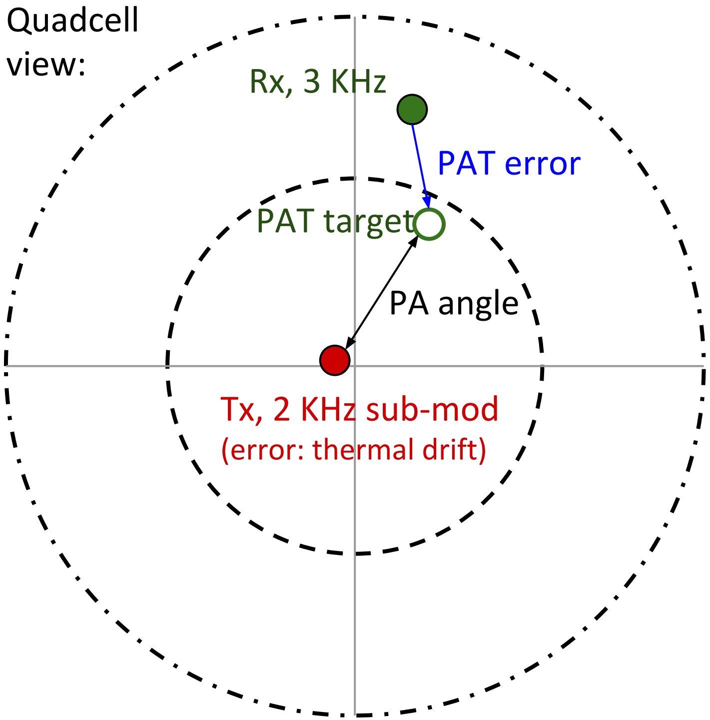
# OFE Baseline Architecture



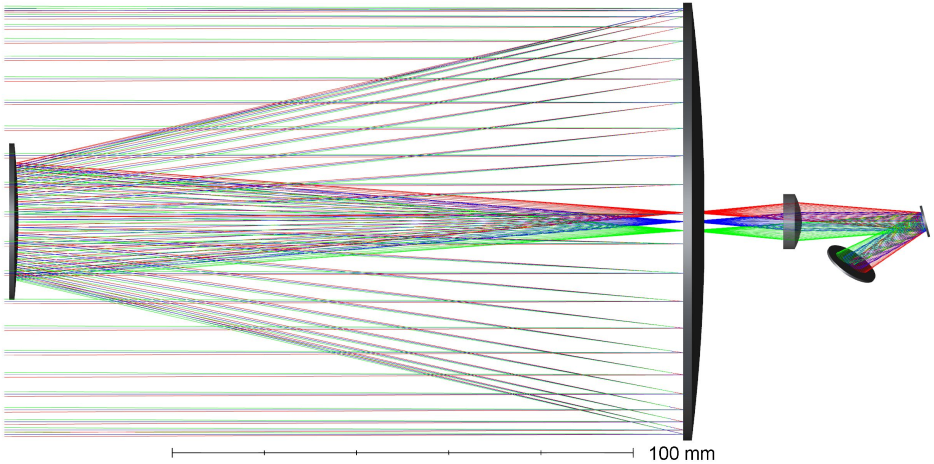

- 765 to 785 nm entangled photons
- 915 nm downlink
- 980 nm uplink beacon



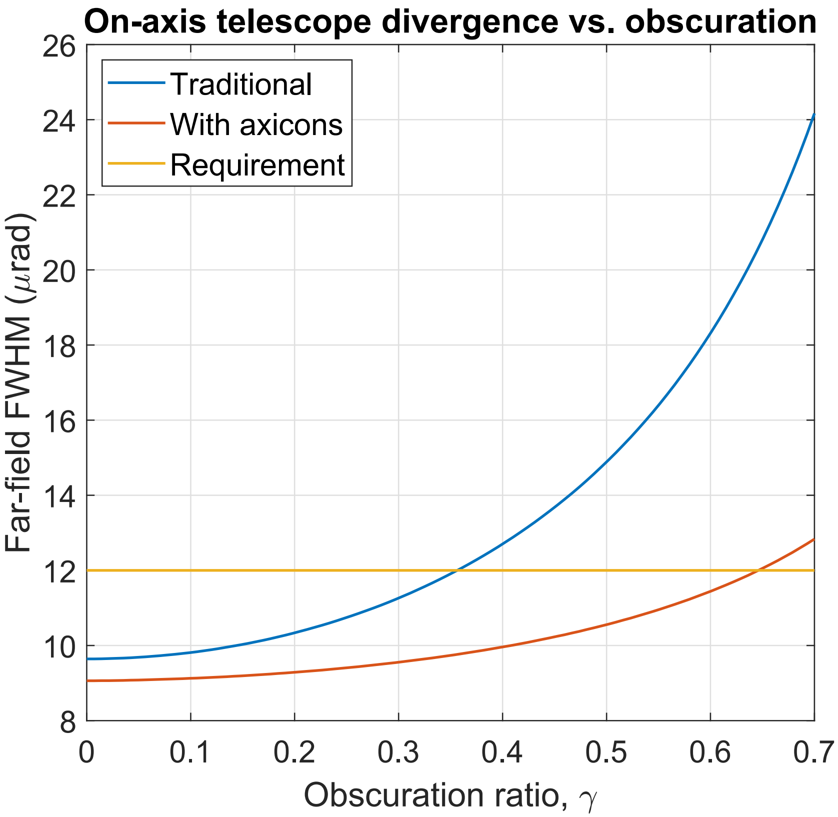

- - - 1 urad noise equivalent angle limit (Max point ahead + margin, 55 to 60 urad)

- · - Field of view (Acquisition limit, 5 mrad)

# On-axis Telescope

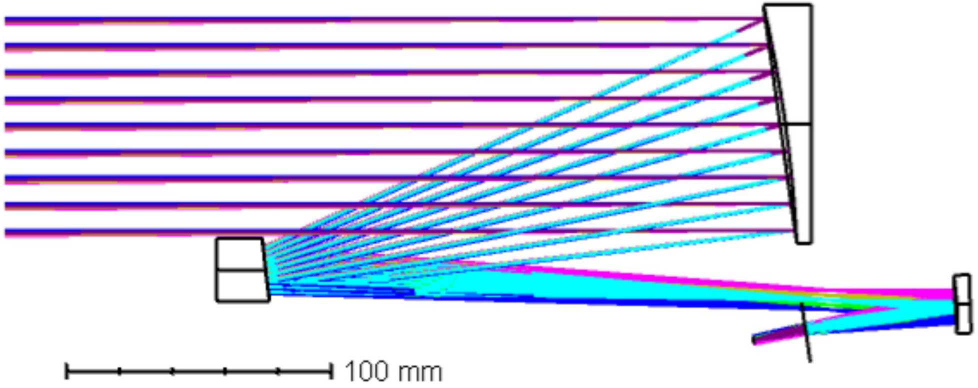


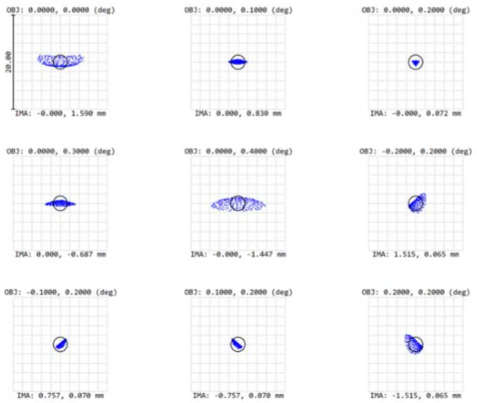

- Similar to NASA LLCD
- Tertiary lens to create exit pupil at FSM
- Pros
  - Easier alignment
  - Equal impact on polarizations
- Cons
  - Obscuration has to be minimized
  - Tertiary lens needed to get clearance for FSM → extra chromatic aberration



# Off-axis Telescope

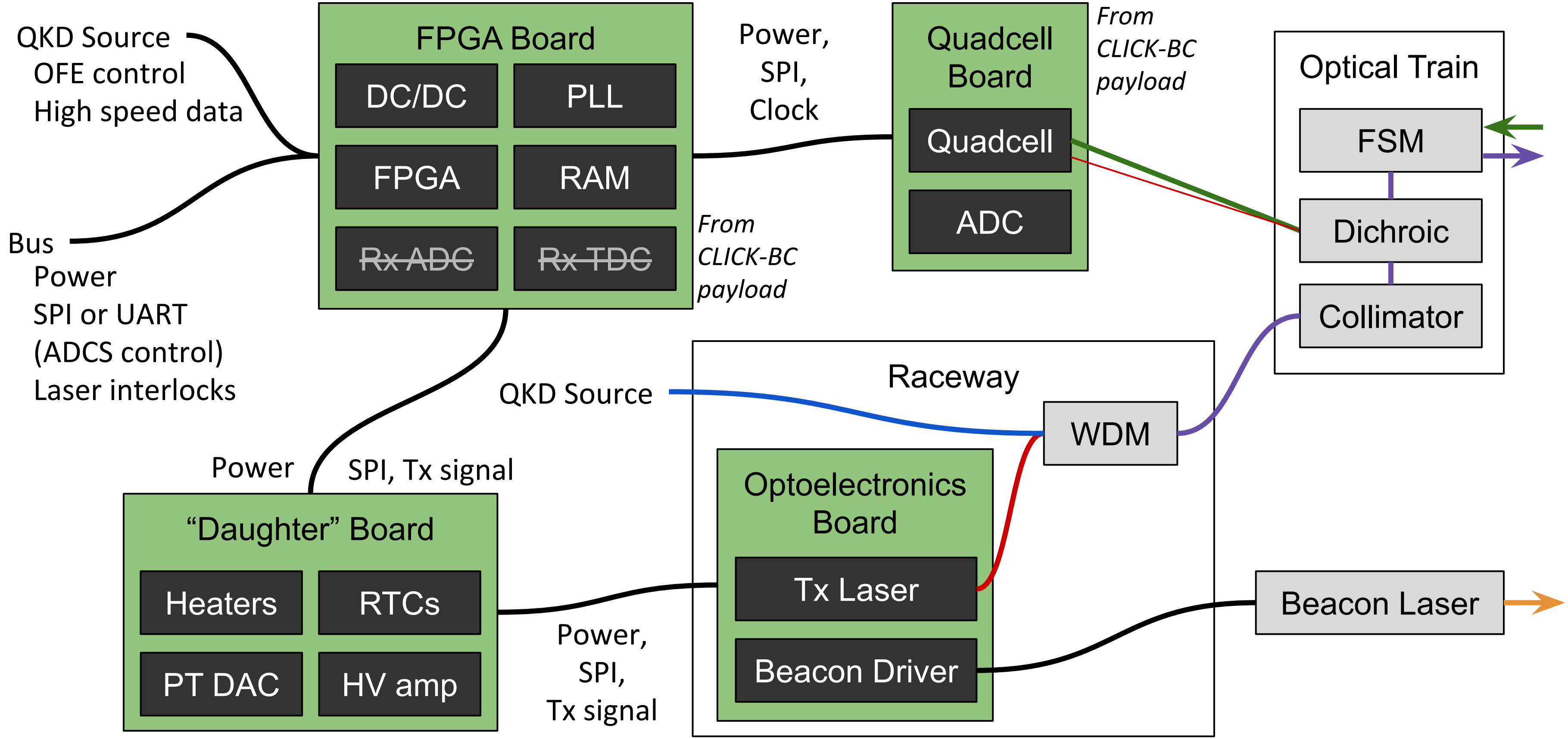
- Conceptual design from University of Arizona
  - Dae Wook Kim, Ewan Douglas
- Uses a freeform optic (M3) to create clearance for FSM exit pupil



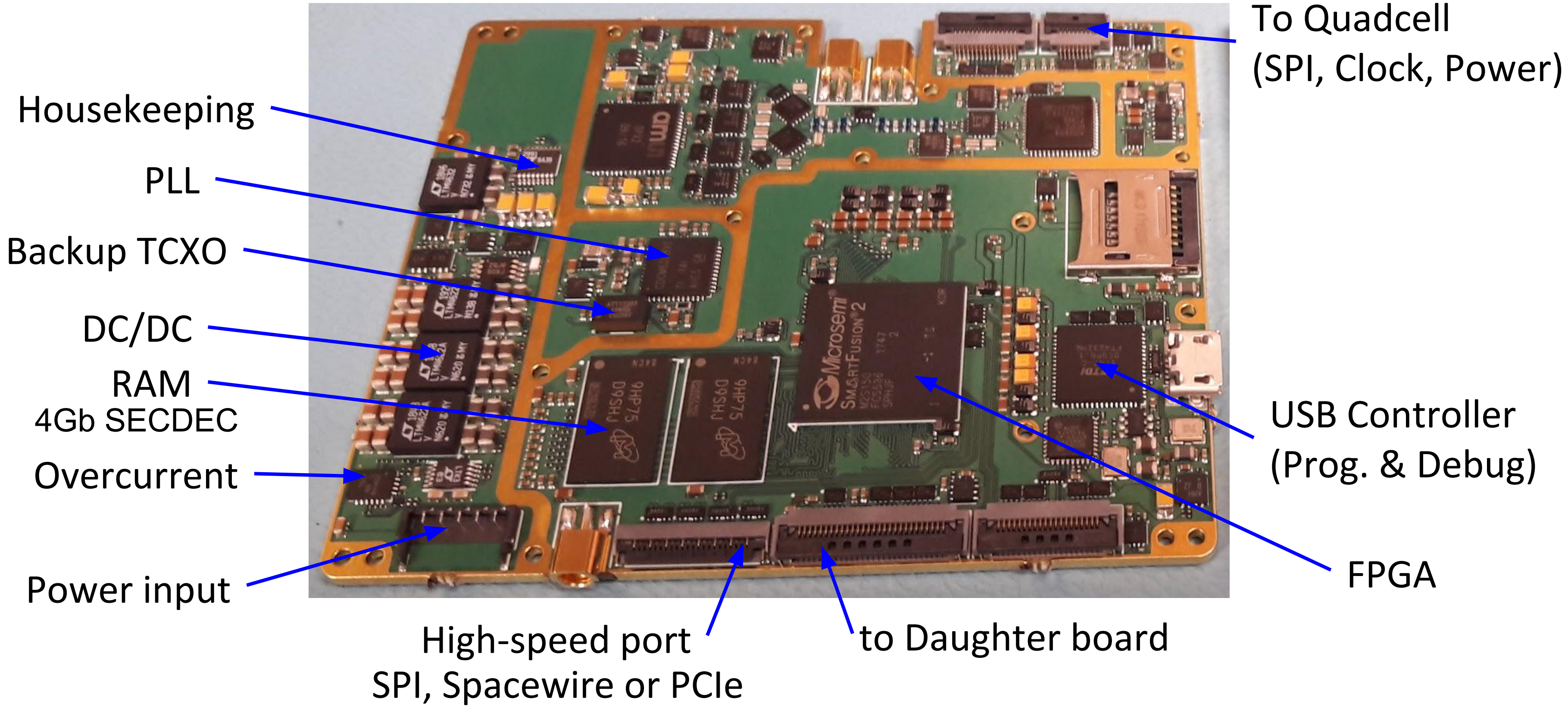




- Pros
  - No obscuration, higher gain
  - Smaller magnification
  - No chromatic aberration
- Cons
  - Asymmetric impact on polarization
  - More difficult alignment

# Proposed Configuration

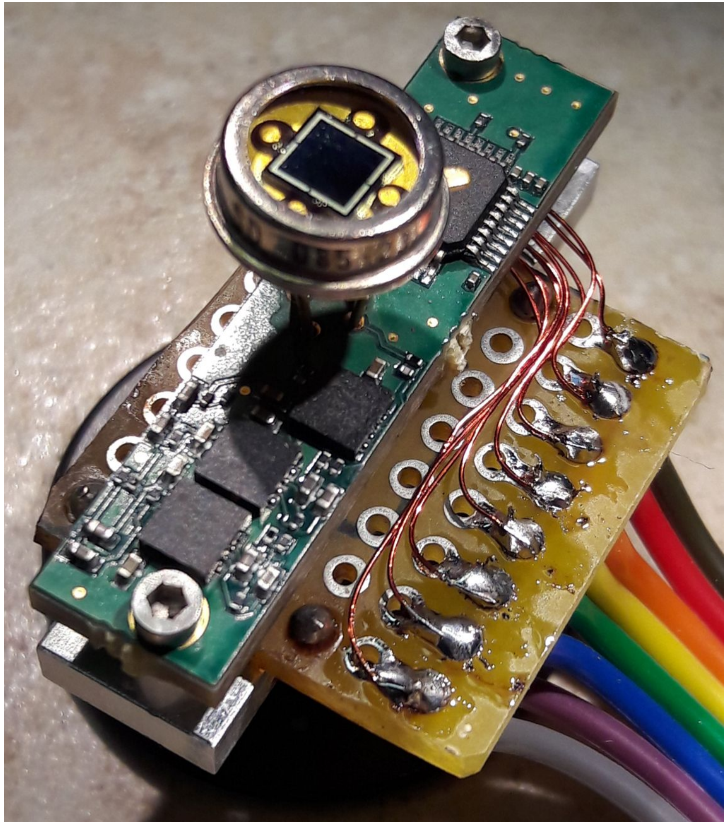


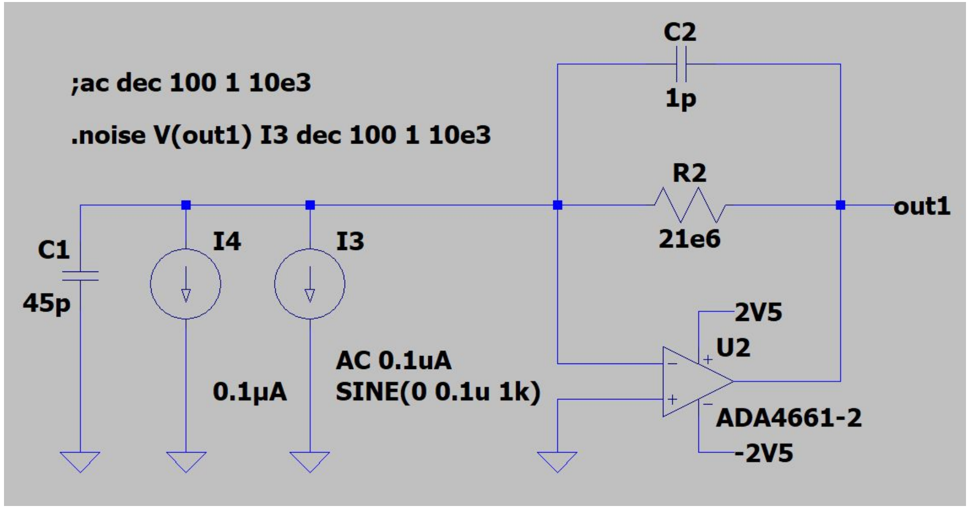
# FPGA Board



Housekeeping
PLL
Backup TCXO
DC/DC
RAM
4Gb SECDEC
Overcurrent
Power input
High-speed port
SPI, Spacewire or PCIe
to Daughter board
FPGA
USB Controller
(Prog. & Debug)
To Quadcell
(SPI, Clock, Power)

# Quadcell Board



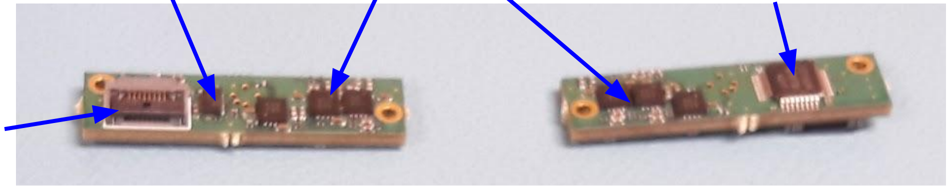



Charge pump + LDO

4 x TIA, 4 x filter

ADC 24 bits, 64 ksps, 4 ch

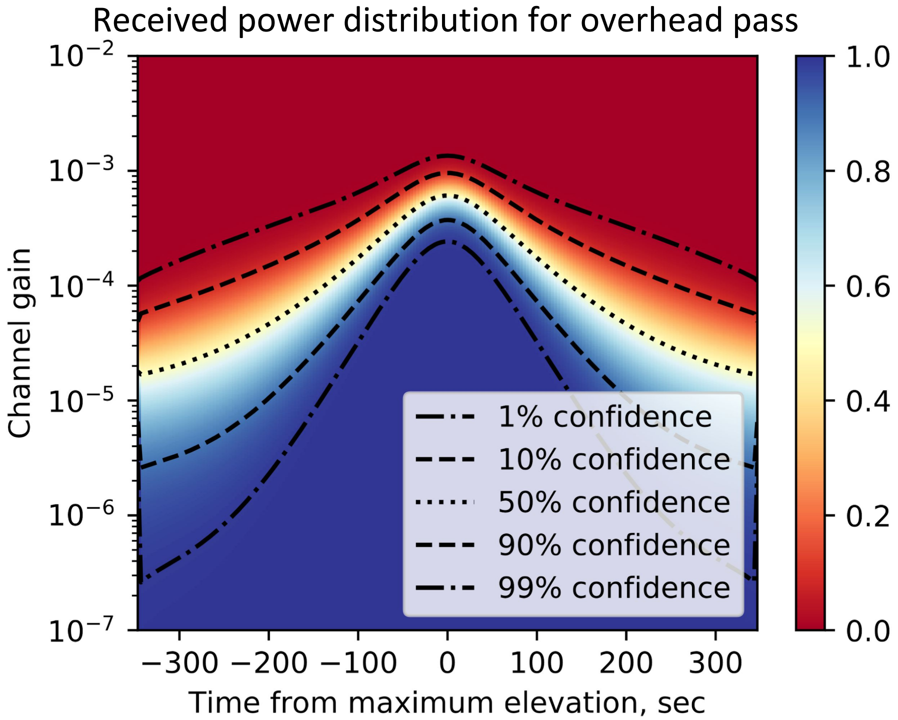
from FPGA SPI, Power

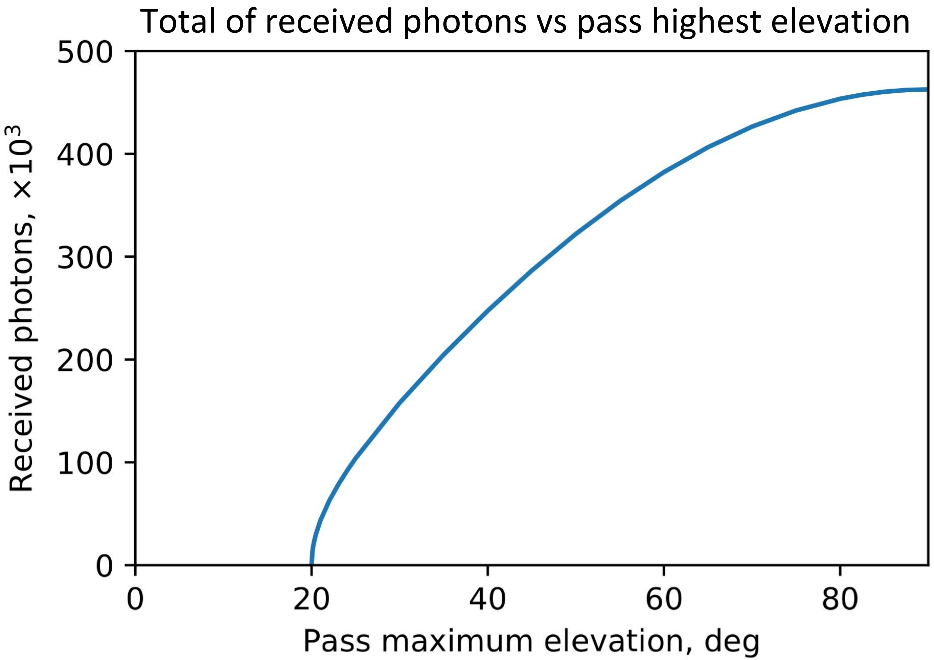


# Assumptions

| Case | Beacon Uplink | Data Downlink | Key Downlink |
|---|---|---|---|
| Altitude | 500 km | | |
| Wavelength | 978 nm | 915 nm | 760 nm to 790 nm |
| Transmitter divergence | 500 µrad FWHM | 20 µrad FWHM | 12 µrad FWHM |
| Transmitter power | 2.5 W | 100 mW | $5.9{\times}10^6$ photon/s |
| Transmitter optical loss | 3 dB | 3 dB | 3 dB |
| Pointing error | 5 µrad | | |
| Receiver aperture | 95 mm | 600 mm | 600 mm |
| Aperture obstruction ratio | 10% to 40% | 40% | 40% |
| Receiver optical loss | 3 dB | 3 dB | 1 dB |
| Minimum Elevation | 20 degrees | | |
| Turbulence | Hufnagel-Valley 5/7 | | |
| Atmospheric absorption | 3 dB constant | | |

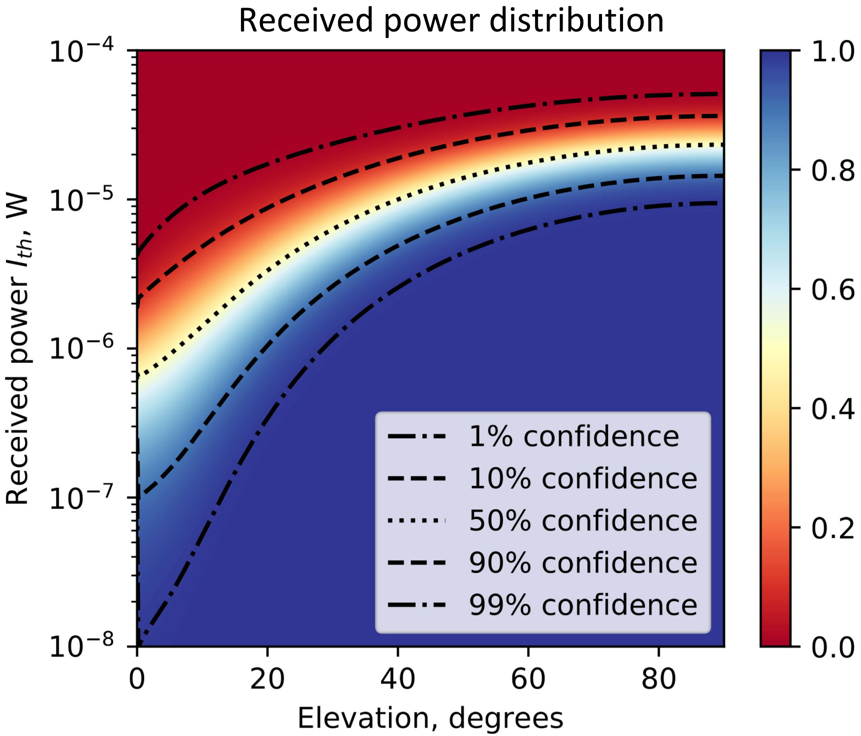
# QKD Downlink

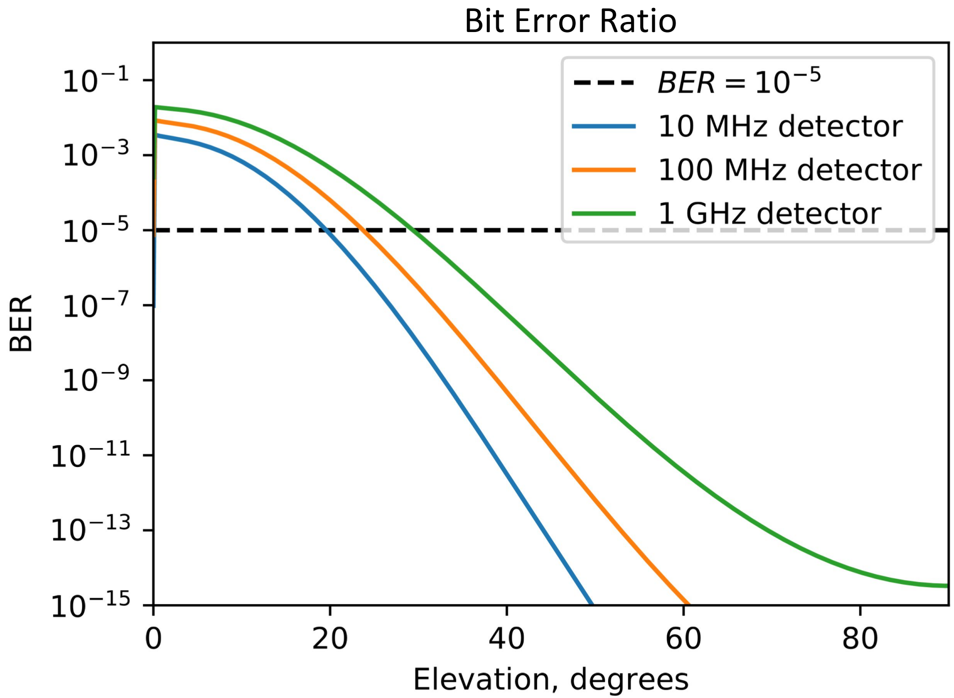



- Raw received photon at OGS telescope aperture
- Assuming Micius source

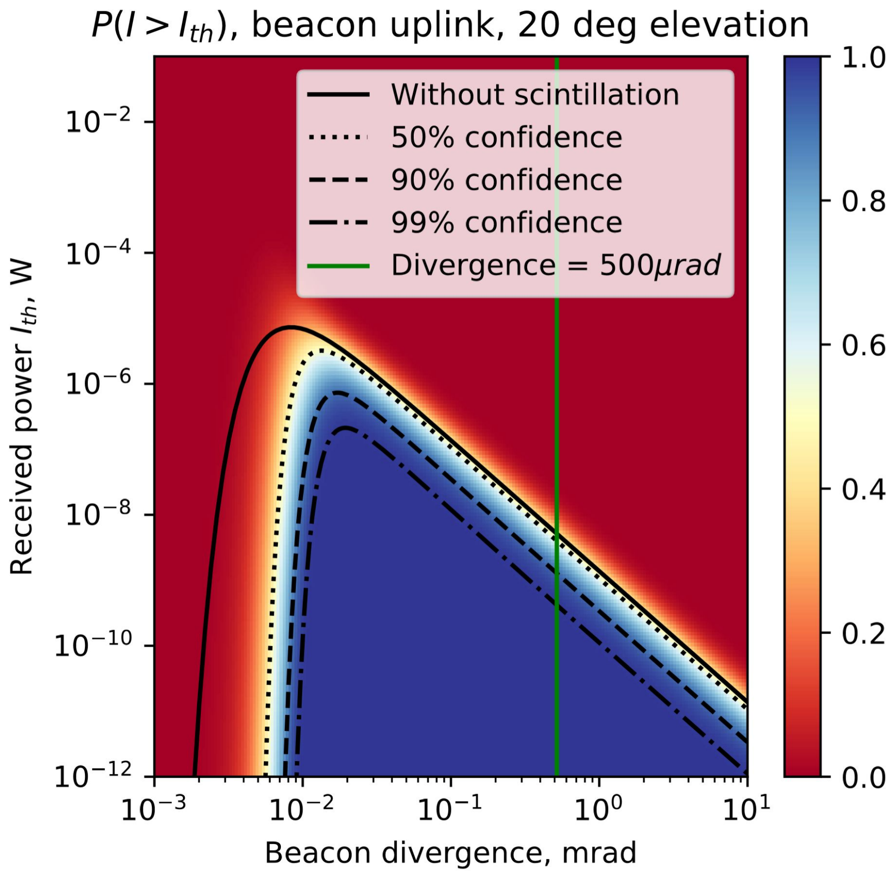
# Data Downlink




- With a 100 MHz detector, BER < $10^{-5}$ at 24 degrees
- Higher data rate could be supported

# Beacon Uplink Power




The signal from each quadrants is used to find the spot position according to the quadcell.

$$x_{quad}(x,y) = -\frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D}$$

$$y_{quad}(x,y) = -\frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D}$$

$$SNR(x,y) = \frac{V_A + V_B + V_C + V_D}{\sqrt{\sigma_A^2 + \sigma_B^2 + \sigma_C^2 + \sigma_D^2}}$$

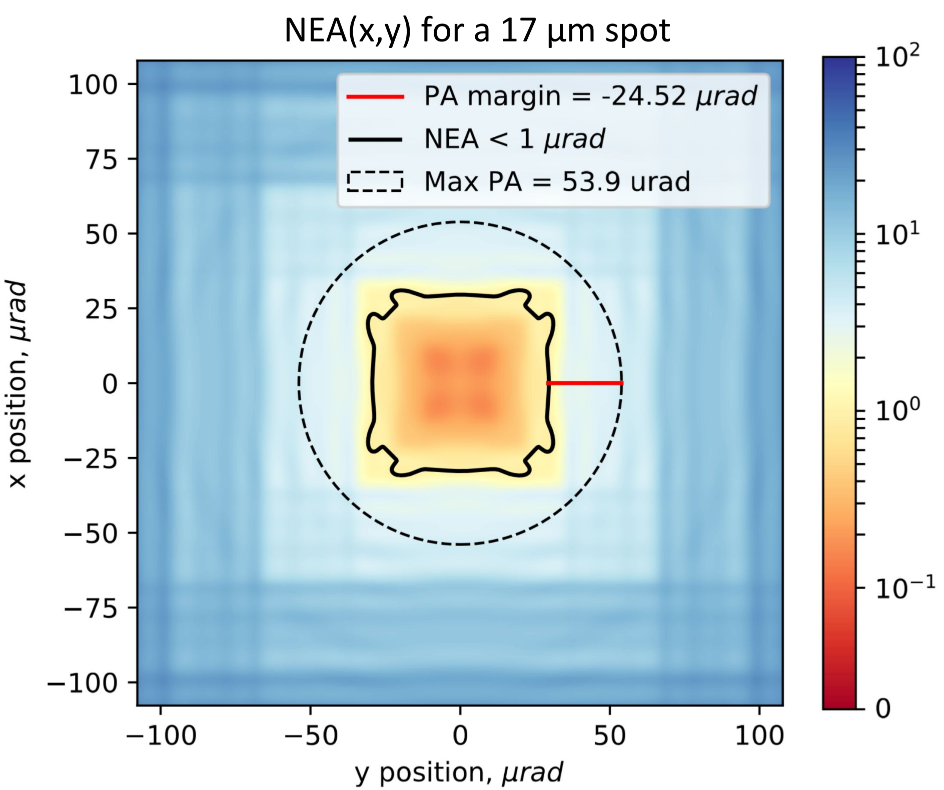
The SNR can then be converted back to an angle, called the Noise Equivalent Angle (NEA):

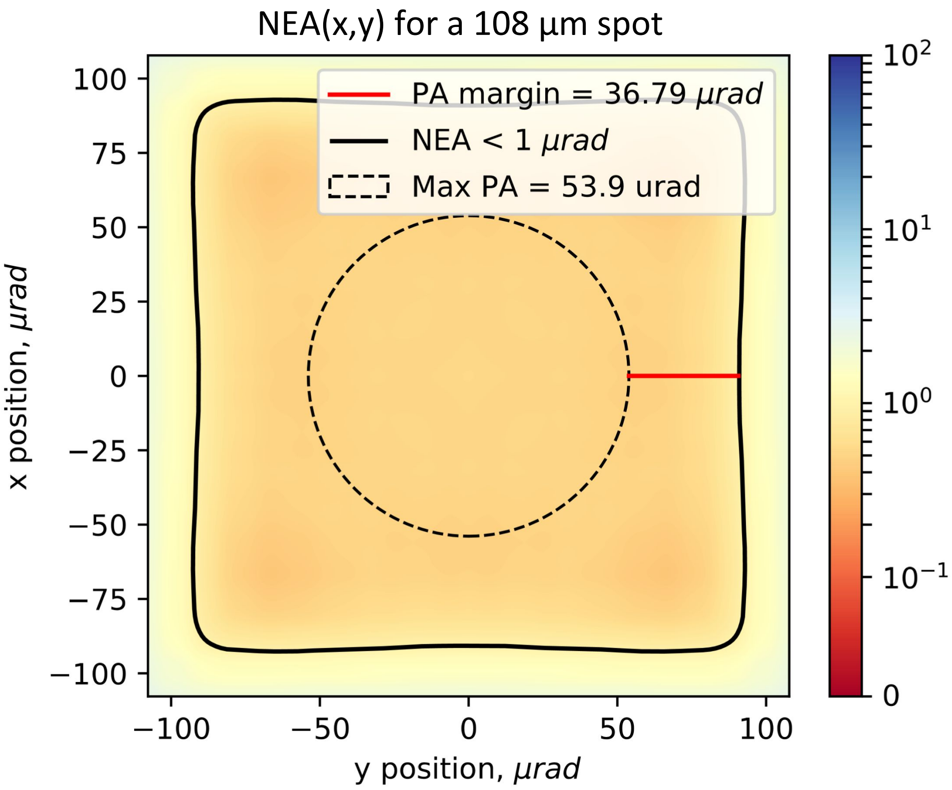
$$s_x(x,y) = \frac{\partial x_{quad}}{\partial \theta_x} \qquad s_y(x,y) = \frac{\partial y_{quad}}{\partial \theta_y}$$

$$NEA(x,y) = \frac{1}{f_{PT} SNR}\sqrt{\frac{1}{s_x^2} + \frac{1}{s_y^2}}$$

The targeted quadcell NEA is 1 μrad for 1-σ.

# Quadcell Performance

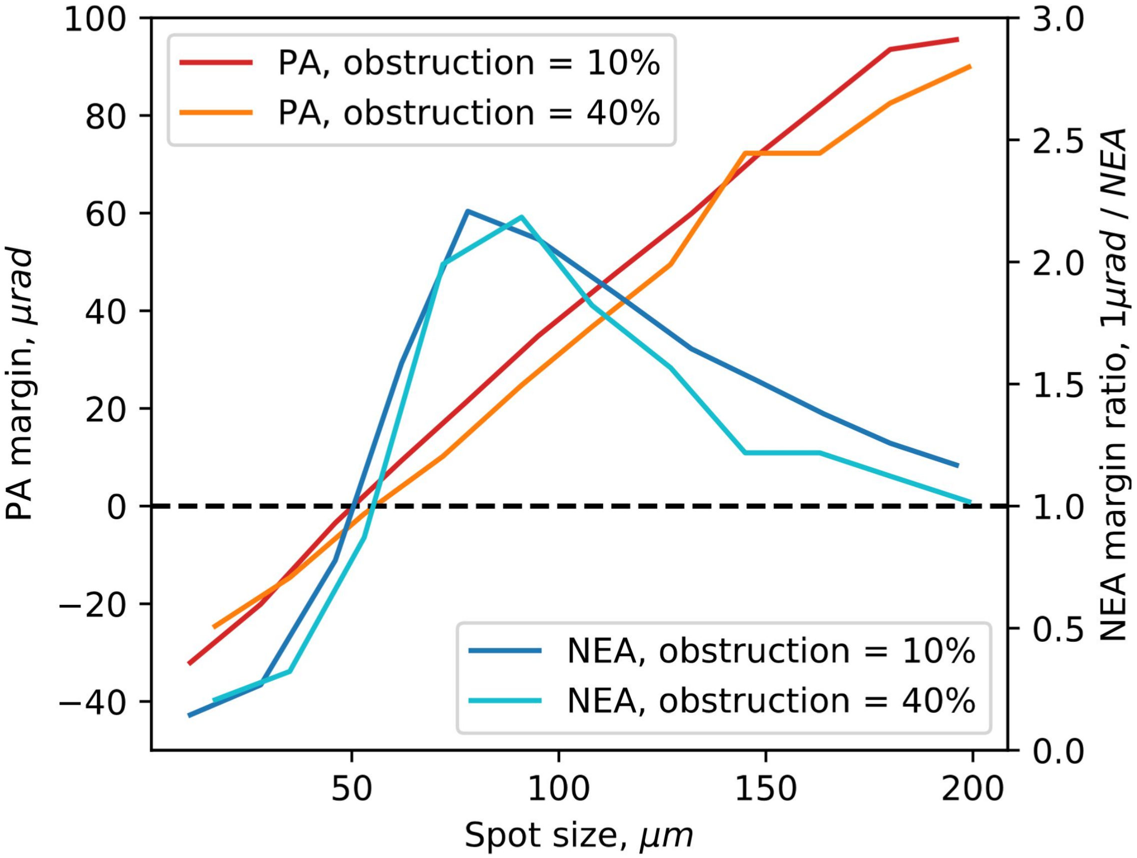


# Quadcell Spot Size

Quadcell noise is adequate over the range of predicted point-ahead angles

Currently investigating the accuracy and repeatability of the quadcell transfer function



# Conclusion

Quantum Key distribution on a CubeSat platform seems feasible, thanks to low-SWAP fine pointing systems.

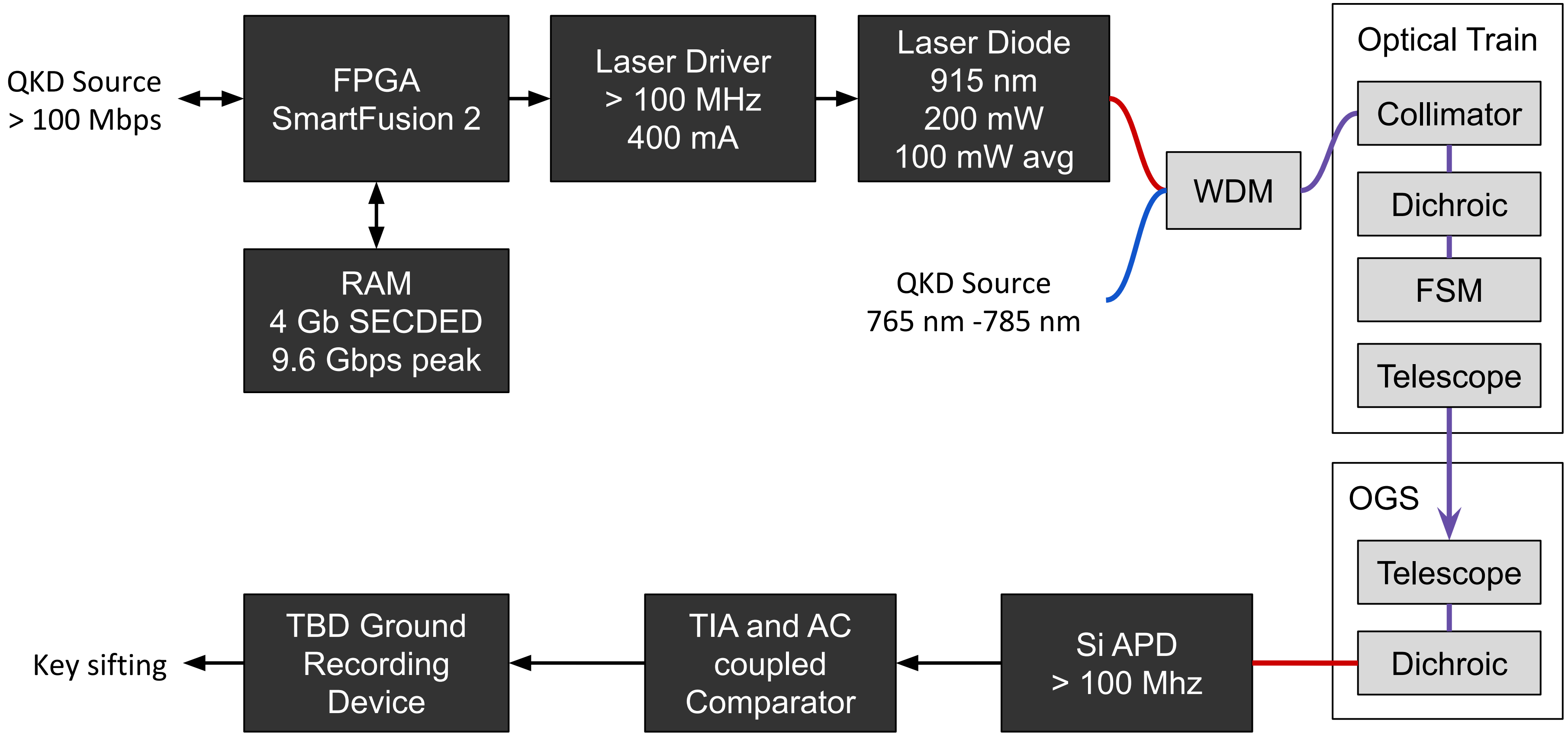
MIT and the University of Arizona are working toward a 2 year effort to help SpeQtral fly a CubeSat QKD demonstrator.

Singapore-MIT Alliance for Research and Technology

This work is supported by the Singapore-MIT Alliance for Research and Technology

# Backup Slides

# Data Flow for Lasercom



# Telescope Selection

- Requirements:
  - **12 µrad** far-field FWHM at 756 - 785 nm
  - Maintain polarization within **1 deg**
  - GDD within **5 deg/nm** (phase)
- Constraints:
  - Target <1U primary diameter, assume **95 mm** max diameter
  - Magnification depending on FSM
- Open trades:
  - On-axis vs. off-axis telescope

- FSM diameter determines the telescope magnification needed

- On-axis "prefers" wider gaussians to mitigate obscuration loss → higher magnification

| FSM diameter (mm) | Beam waist (mm, T=0.99) | On-axis Telescope Magnification Needed (25% obscuration) | On-axis Telescope Magnification Needed (10% obscuration) | Off-axis Telescope Magnification needed (M^2=1.2) | Off-axis Telescope Primary diameter (mm, T=0.99) |
|---|---|---|---|---|---|
| 4.2 | 1.29 | 34.9 | 33.2 | 22.64 | 91.83 |
| 4.6 | 1.41 | 31.9 | 30.3 | 20.67 | |
| 5 | 1.54 | 29.4 | 27.88 | 19.02 | |
| 6.4 | 1.97 | 22.9 | 21.78 | 14.86 | |
| 7.5 | 2.31 | 19.58 | 18.57 | 12.68 | |