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

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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.
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

Orbit: 400-600 km circular
Inclination: ~98 deg

RF Ground Station
Location TBD

Optical Ground Station
Singapore / Other

Beacon Downlink
685 nm

QKD Signal
765 nm - 785 nm

Data Downlink
915 nm

Beacon Uplink
980 nm

GPS

TT&C
Nav (TLE)

Key Distribution
Possibly simultaneous

Lasercom Downlink

Data Downlink
915 nm

Possibly simultaneous

End of Life Operations

Key sifting RF Backup

4
OFE Baseline Architecture

- **Photon Source**: 765-785 nm
- **Data**: 915 nm, 200 mW
- **Telescope**: 765 to 785 nm entangled photons
- **WDM**: 915 nm downlink
- **Quadcell**: 980 nm uplink beacon
- **Calib**: MEMs FSM, sharp angle

**Quadcell view**:
- **Rx, 3 KHz**: PAT target
- **Tx, 2 KHz sub-mod**: (error: thermal drift)
- **PA angle**: 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

On-axis telescope divergence vs. obscuration

- Traditional
- With axicons
- Requirement

Graph showing Far-field FWHM (μrad) vs. Obscuration ratio, \( \gamma \).
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**: DC/DC, PLL, FPGA, RAM, Rx-ADC, Rx-TDC
- **Quadcell Board**: Quadcell, ADC
- **Optoelectronics Board**: Tx Laser, Beacon Driver
- **“Daughter” Board**: Heaters, RTCs, PT DAC, HV amp
- **Optical Train**: FSM, Dichroic, Collimator
- **Raceway**: WDM

- **QKD Source**: OFE control, High speed data
- **Bus**: Power, SPI or UART (ADCS control), Laser interlocks
- **Power**: SPI, Tx signal

Connections:
- **QKD Source** to **FPGA Board**
- **QKD Source** to **Optoelectronics Board**
- **Optoelectronics Board** to **Raceway**
- **Raceway** to **Optical Train**
FPGA Board

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

ADC 24 bits, 64 ksps, 4 ch

Charge pump + LDO from FPGA
SPI, Power

4 x TIA, 4 x filter

4 x TIA, 4 x filter

ADC 24 bits, 64 ksps, 4 ch
<table>
<thead>
<tr>
<th>Case</th>
<th>Beacon Uplink</th>
<th>Data Downlink</th>
<th>Key Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td></td>
<td>500 km</td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>978 nm</td>
<td>915 nm</td>
<td>760 nm to 790 nm</td>
</tr>
<tr>
<td>Transmitter divergence</td>
<td>500 μrad FWHM</td>
<td>20 μrad FWHM</td>
<td>12 μrad FWHM</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>2.5 W</td>
<td>100 mW</td>
<td>5.9×10^6 photon/s</td>
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<tr>
<td>Transmitter optical loss</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
</tr>
<tr>
<td>Pointing error</td>
<td></td>
<td>5 μrad</td>
<td></td>
</tr>
<tr>
<td>Receiver aperture</td>
<td>95 mm</td>
<td>600 mm</td>
<td>600 mm</td>
</tr>
<tr>
<td>Aperture obstruction ratio</td>
<td>10% to 40%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Receiver optical loss</td>
<td>3 dB</td>
<td>3 dB</td>
<td>1 dB</td>
</tr>
<tr>
<td>Minimum Elevation</td>
<td></td>
<td>20 degrees</td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td></td>
<td>Hufnagel-Valley 5/7</td>
<td></td>
</tr>
<tr>
<td>Atmospheric absorption</td>
<td></td>
<td>3 dB constant</td>
<td></td>
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</tbody>
</table>
QKD Downlink

- Raw received photon at OGS telescope aperture
- Assuming Micius source
With a 100 MHz detector, BER < $10^{-5}$ at 24 degrees
Higher data rate could be supported
The signal from each quadrants is used to find the spot position according to the quadcell.

\[
\begin{align*}
    x_{\text{quad}}(x, y) &= -\frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D} \\
    y_{\text{quad}}(x, y) &= -\frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D} \\
    \text{SNR}(x, y) &= \frac{V_A + V_B + V_C + V_D}{\sqrt{\sigma_A^2 + \sigma_B^2 + \sigma_C^2 + \sigma_D^2}}
\end{align*}
\]

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

\[
\begin{align*}
    s_x(x, y) &= \frac{\partial x_{\text{quad}}}{\partial \theta_x} \\
    s_y(x, y) &= \frac{\partial y_{\text{quad}}}{\partial \theta_y} \\
    \text{NEA}(x, y) &= \frac{1}{f_{PT} \text{SNR}} \sqrt{\frac{1}{s_x^2} + \frac{1}{s_y^2}}
\end{align*}
\]

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

NEA(x,y) for a 17 µm spot

- PA margin = -24.52 µrad
- NEA < 1 µrad
- Max PA = 53.9 urad

NEA(x,y) for a 108 µm spot

- PA margin = 36.79 µrad
- NEA < 1 µrad
- Max PA = 53.9 urad
Quadcell noise is adequate over the range of predicted point-ahead angles.

Currently investigating the accuracy and repeatability of the quadcell transfer function.
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.

This work is supported by the Singapore-MIT Alliance for Research and Technology
Backup Slides
Data Flow for Lasercom

QKD Source > 100 Mbps

FPGA SmartFusion 2

Laser Driver > 100 MHz
400 mA

Laser Diode
915 nm
200 mW
100 mW avg

WDM

QKD Source
765 nm - 785 nm

TBD Ground Recording Device

TIA and AC coupled Comparator

Si APD > 100 Mhz

Key sift.

RAM
4 Gb SECDED
9.6 Gbps peak

Optical Train
Collimator
Dichroic
FSM
Telescope

OGS
Telescope
Dichroic
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**

<table>
<thead>
<tr>
<th>FSM diameter (mm)</th>
<th>Beam waist (mm, T=0.99)</th>
<th>On-axis Telescope Magnification Needed (25% obscuration)</th>
<th>On-axis Telescope Magnification Needed (10% obscuration)</th>
<th>Off-axis Telescope Magnification needed (M^2=1.2)</th>
<th>Off-axis Telescope Primary diameter (mm, T=0.99)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>1.29</td>
<td>34.9</td>
<td>33.2</td>
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<td>91.83</td>
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