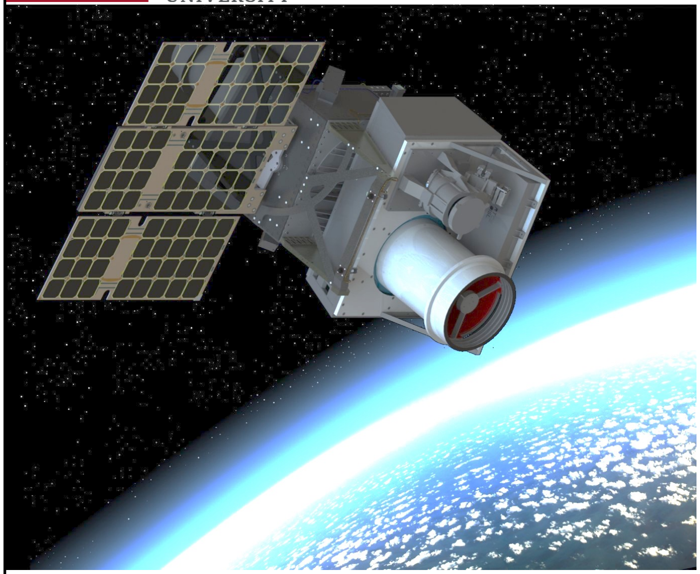


Implementation of Satellite Quantum Key Distribution (QKD)

Thomas Jennewein,
thomas_jennewein@sfu.ca

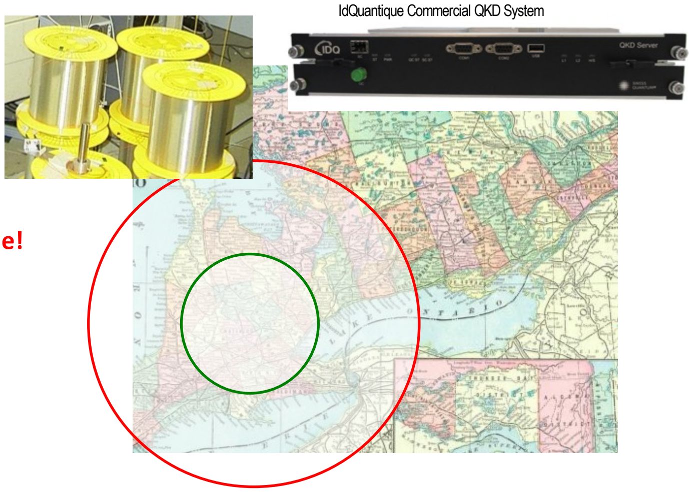
Simon Fraser University +
Institute for Quantum Computing, University of Waterloo

2026, August

SATELLITE BASED QKD

Why Satellites for Long Distance Q-Com?

- Ground-based
  - Practical systems typically 100 km
  - Demonstrations up to to 400 km
  - Optic fibre loss 0.15 dB/km at best
  - Free-space limited due to line-of-sight
  - Commercial Devices available:
  - **Note: Optical amplifiers not possible!**

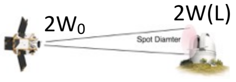


- Longer distances:
  - Trusted Repeaters
    (> 1000km networks under way)
  - Long lived Quantum Memories
  - Quantum Repeaters
  - **Satellites**

Takesue et al, Nature Photonics 1, 343 - 348 (2007)

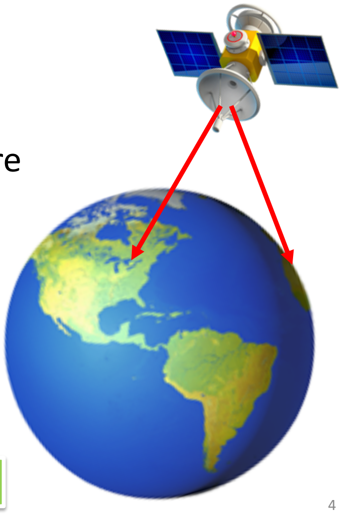
Ma, Fung, Lo, Phys. Rev. A 76, 012307 (2007)

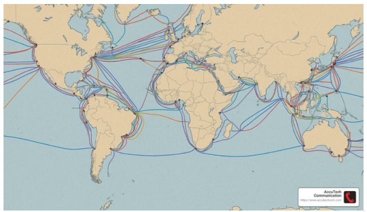
$$T_{geo} \approx \frac{D_R^2 D_T^2}{\lambda^2 L^2}$$



Why satellite Quantum Communications?

- Quantum repeaters are mostly in lab, and are expected to only cover shorter distances
- satellites already showed >1000 km entanglement distribution
- access ground sites with limited infrastructure
- cross oceans





Fibre channel link loss: ~ e^d

$$\eta_L \approx \eta_x \frac{D_{Tx}^2 D_{Rx}^2}{2Z^2\lambda^2}$$

Optical Antenna Gain (far field):

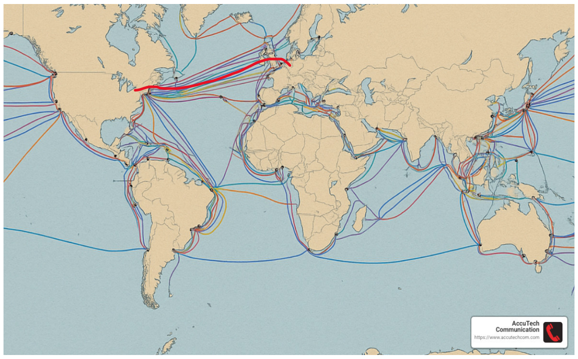
Klein & Degnan. 1 & 2 Appl. Opt., 1974.

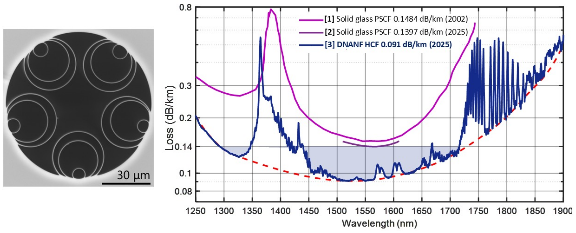
Satellite channel link loss: ~ d^2

In other words…

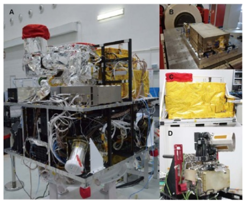
Consider transmitting photons between two cities separated by 6,500 km, using a 1 GHz photon source.

Even with an attenuation of only 0.1 dB/km (e.g. hollow core fiber), the expected time to successfully transmit a single photon would be approximately **3 ×10^48** years.





https://techcommunity.microsoft.com/blog/azurenetworkingblog/microsoft-azure-scales-hollow-core-fiber-hcf-production-through-outsourced-manuf/4455953

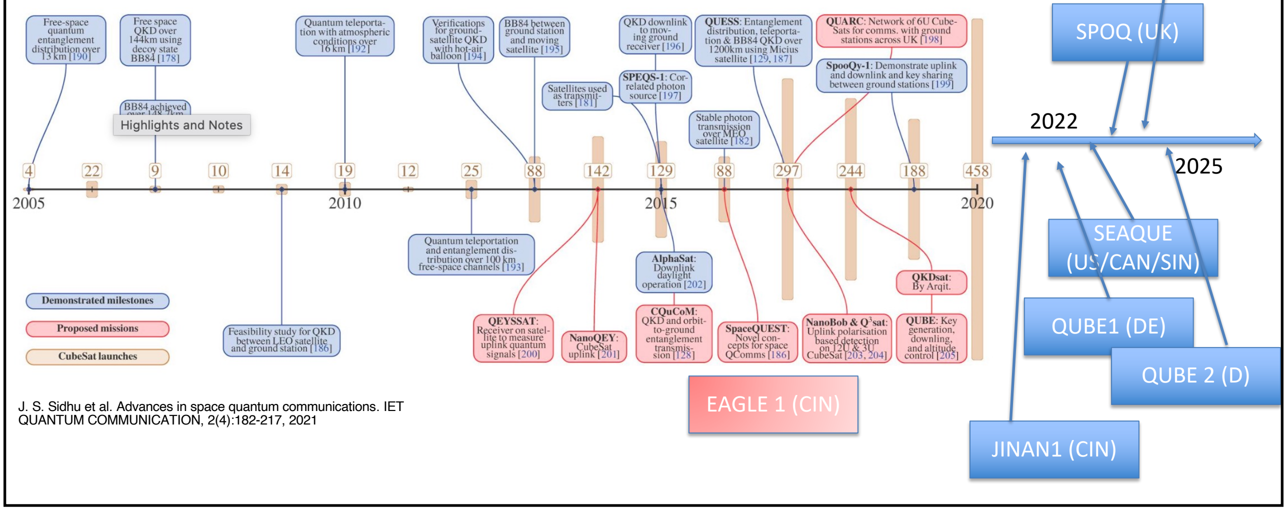


QKD Satellite Missions Overview

Entanglement Distribution over 1200 km ! (Science, 2017)

QKD, Teleportation (Nature 549, 43–47 and 70-73 (2017)

QKD between Bejing and Graz (PRL), QKD using Bell-pairs (CLEO 2019, Nature2020)



SpeQtre (UK-SIN)

SPOQ (UK)

SEAQUE (US/CAN/SIN)

QUBE1 (DE)

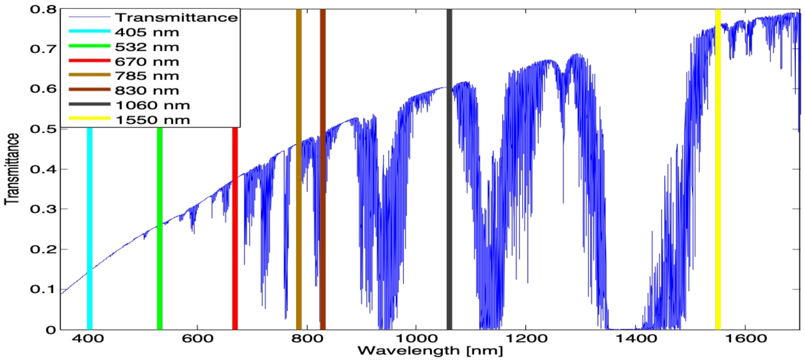
QUBE 2 (D)

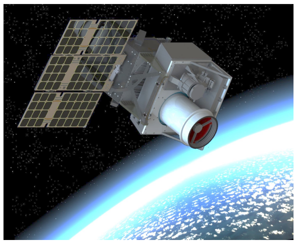
EAGLE 1 (CIN)

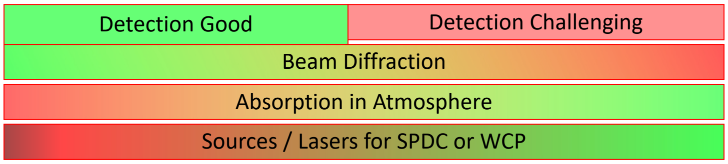
JINAN1 (CIN)

J. S. Sidhu et al. Advances in space quantum communications. IET QUANTUM COMMUNICATION, 2(4):182-217, 2021

Choosing the Optical Wavelength –Space to Ground







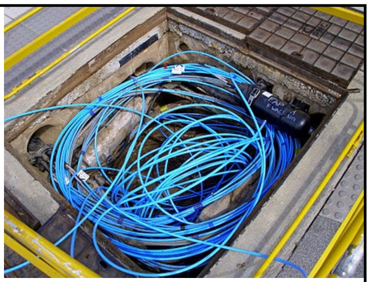
QEYSSAt: 785 nm
MICUS: 850nm; 810nm

Free-space or optical fiber

THE CHANNEL

Optical Fiber

- Optical field is confined due to wave guiding in a refractive index profile



By Bidgee - Own work, CC BY-SA 2.5 au, https://commons.wikimedia.org/w/index.php?curid=11970081

n_1 core, n_2 cladding

Guided ray from Snell's law:

$$\theta_c = cos^{-1}(n_1/n_2)$$

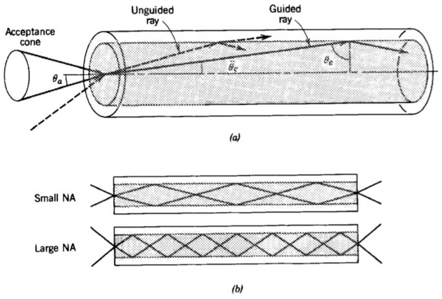
Numerical Aperture is the acceptance angle at front of fiber.

$$1 \cdot \sin(\theta_a) = n_1 \cdot \sin\bar{\theta_c}$$

$$NA = (n_1^2 - n_2^2)^{1/2} \approx n_1(2\Delta)^{1/2}$$

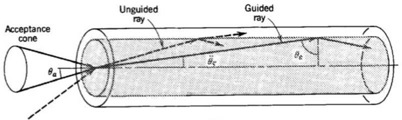
$$n_1 - n_2 = \Delta$$

$$n_1 \sim 1.45, \Delta \sim 0.001$$



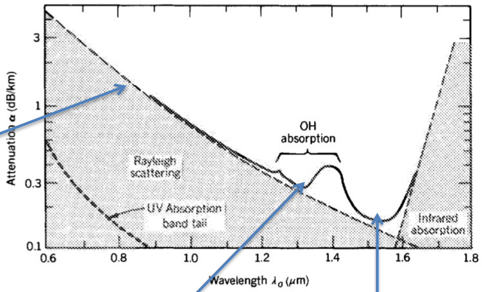
Fundamentals of Photonics, Saleh & Teich

Optical Fiber Absorption



Fundamentals of Photonics, Saleh & Teich

- SiO2 (Fused Silica) most common material



800 nm Fiber, ca. 1.5 dB/km
Corediamter ca. 5μm

$$\frac{P(z)}{P(0)} = 10^{-\alpha z/10} \approx e^{-0.23\alpha z}$$

Transmittance for 100km:
1550 nm: 0.031623
1310 nm: 0.001000
800 nm: 1.0000e-15 **(!)**

Dispersion minimum
@ 1310nm, 0.3 dB/km
SMF-28 for telecom

Absorption minimum
@ 1550nm, 0.16 dB/km
SMF-28 for telecom
Core diameter ca. 9μm

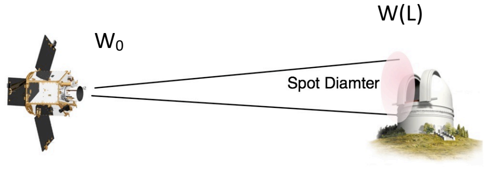
Transmittance of the free space link

Optical Antenna Gain: coupling Gaussian beam to circular aperture:

Klein & Degnan. Optical antenna gain 1 & 2 Appl. Opt., 1974.

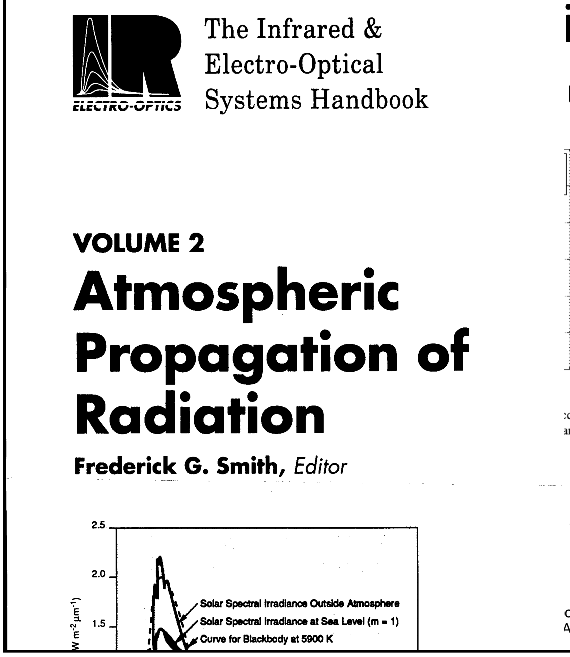
$$\eta_L(\vec{Z}) = \eta_x(\vec{Z}) \left(1 - exp(\frac{-2\pi^2 D_{Tx}^2 D_{Rx}^2}{\pi^2 D_{Tx}^4 + (M^2)^2 \, |\vec{Z}|^2 \lambda^2}\right)$$

- M^2: beam quality, (perfect M^2 =1)
- η_x: other losses (optics, atmo)
- Transmitter aperture: D_{Tx}
- Receiver aperture: D_{Rx}
- Wavelength: λ
- Distance: L



Simplistic approximation: Transmittance In the far field:

$$\eta_L \approx \eta_x \frac{D_{Tx}^2 D_{Rx}^2}{2Z^2\lambda^2}$$



The Infrared & Electro-Optical Systems Handbook

ELECTRO-OPTICS

VOLUME 2

Atmospheric Propagation of Radiation

Frederick G. Smith, *Editor*

ing due to turbulence

uctuations in air

Beam waist is widened after travelling through atmosphere:

$$w = \frac{2\sqrt{2}\,d\lambda}{\pi r_0}$$

For comparison, Gaussian beam: $\theta_0 = \frac{2}{\pi}\frac{\lambda}{2W_0}.$

:cord-
arison

With r_0 transverse coherence length:

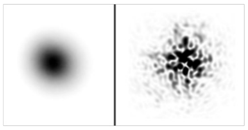
$$r_0 = \left[1.46 \sec\left(\frac{\pi}{2} - \zeta\right)\left(\frac{2\pi}{\lambda}\right)^2 \int_0^h C_n^2(z)\left(1 - \frac{z}{h}\right)^{\frac{5}{3}} dz\right]^{-\frac{3}{5}}$$

on

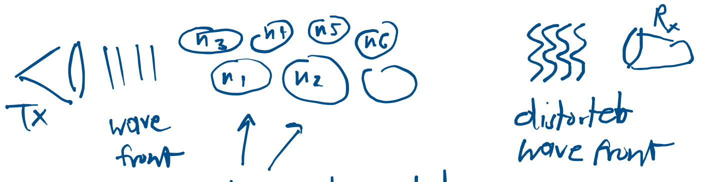
....

ook. Frederick. G. Smith, 1993.
ATIONS, RADIOENGINEERING, VOL. 19, NO. 2, JUNE 2010

Atmospheric turbulence



Atmosphere is not static, due to temperature induced fluctuations



different pockets of refractive index due to Temperature, and wind

- Beam Wander
- Intensity fluctuations
- Wavefront distortions

index fluctuations:

$$C_N^2 \propto \left(\frac{\partial n}{\delta T} C_T\right)^2$$

structur

Hufnagel – Valley Model (H–V)

$$C_n^2(h) = 0.00594\left(\frac{W}{27}\right)^2\left(10^{-5}h\right)^{10} e^{-\frac{h}{1000}} + 2.7\cdot 10^{-16} e^{-\frac{h}{1500}} + A e^{-\frac{h}{100}}$$

$A = 1.7\ 10^{-14}\ m^{-2/3}$

elevation (m), W...wind speed $[m/s]$, A is nominal value of C_n^2.

Impact of Turbulence on quantum channel

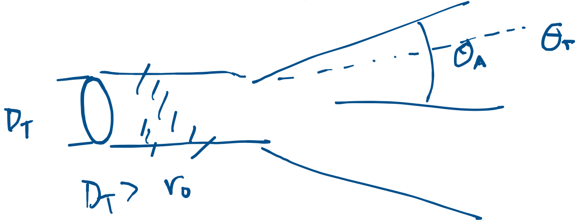
Coherence width (Fried parameter):

$$r_0 = \left[0.42 \sec(\xi) k^2 \int_{h_0}^{H} C_n^2(h)\, dh\right]^{-3/5}$$

r_0 ... <1cm to 10's cm ↑ good site

k... k-vector

ξ ... zenith angle



$D_T > r_0$

$$\theta_A \simeq \frac{\lambda}{r_0}$$

$$\theta_{eff}^2 = \theta_A^2 + \theta_T^2$$

beam diverges effectively, as if it had a waist of r_0

Geometric: $T = 0.62 \frac{D_R^2 \cdot D_T^2}{\lambda^2 z^2} \Rightarrow 0.62 \frac{D_R^2}{z^2} \frac{1.27^2}{\theta_T^2} \Rightarrow \quad T \simeq \frac{D_{Rx}^2}{z^2} \frac{1}{(\theta_A^2 + \theta_T^2)}$

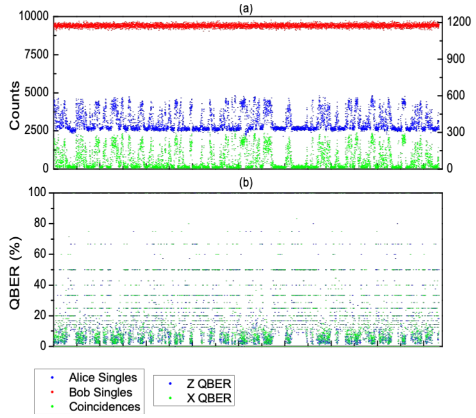
$\theta_T \approx 1.27 \frac{\lambda}{D}$

avg long term! T is variable in time.

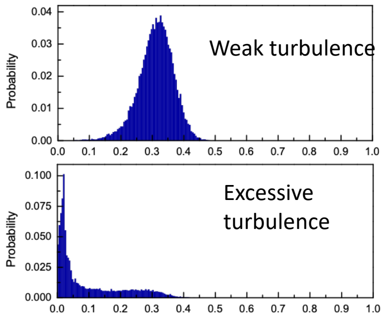
Scintillation - Beam intensity fluctuation

- (twinkling of stars!) Intensity fluctuations ~ 50%

$$\sigma_\chi^2(L) = 0.56k^{7/6}[\sec(\varphi)]^{11/6}\int_0^L C_n^2(\eta)(L-\eta)^{5/6}\,d\eta \qquad \sigma_I \approx 4\sigma_\chi \qquad \mathcal{P}(\eta_{atm}) = \frac{1}{\sqrt{2\pi}\sigma\eta_{atm}}\exp\left[-\frac{1}{2}\left(\frac{\ln\eta_{atm}+\bar{\theta}}{\sigma}\right)^2\right]$$



Log-normal distribution

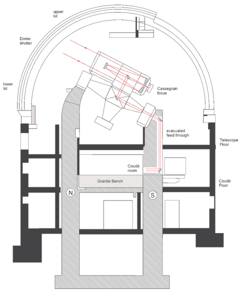


C. Erven et al, NJP 2013

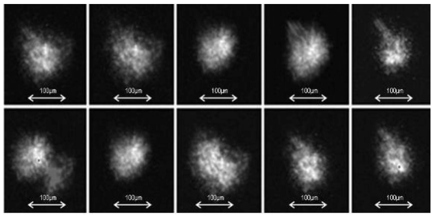
Beam distortion at receiver

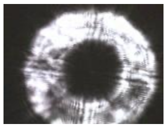
- Atmospheric effects
- Pointing errors
- Optical quality of transmitter and receiver telescopes

- It will be difficult to confine the received light mode into a single-mode fiber or detector smaller than 10µm.



Measured laser spots at OGS / Tenerife, inter-island link 144km: [R. Ursin et al, Nat. Physics, 2007]





Atmospheric absorption

Rayleigh due to atmospheric molecules

A. Bucholtz. Rayleigh-scattering calculations for the terrestrial atmosphere. Appl. Opt., 34(15):2765– 2773, May 1995.

$$\sigma(\lambda) = \frac{24\pi^3}{\lambda^4 N_s^2}\left(\frac{n_s^2-1}{n_s^2+2}\right)\left(\frac{6+3\rho_n}{6-7\rho_n}\right)$$

Cross-section per molecule

$d \ll \lambda$

N_s … molecular density, $2.54 \cdot 10^{19}\ \mathrm{cm}^{-3}$

n_s … refractive index at λ

ρ_n … depolarization factor

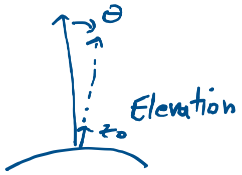
} standard air 15 C, 1013 mbar 0.03% CO2

With altitude z: $\sigma(\lambda, z)$

Volume scattering $\beta(\lambda,z) = \sigma(\lambda,z) \cdot N(z)$

Optical depth for vertical passage: $\tau_R(\lambda, z_0) = \int_{z_0}^{\infty} \beta(\lambda, z)\, dz$

Intensity: $\frac{I(\lambda)}{I_0(\lambda)} = \exp\left(-\frac{\tau_R(\lambda,z_0)}{\cos\theta}\right)$



Other scattering phenomena

Scattering at aerosols $d_A \gtrsim \lambda$ diffraction, leads to "white" scattering, clouds e.g.

depends on purity of air, industry, city, …

Atomic / molecular resonances certain spectral regions have many resonances.

Models contain data of known atmospheric constituents.

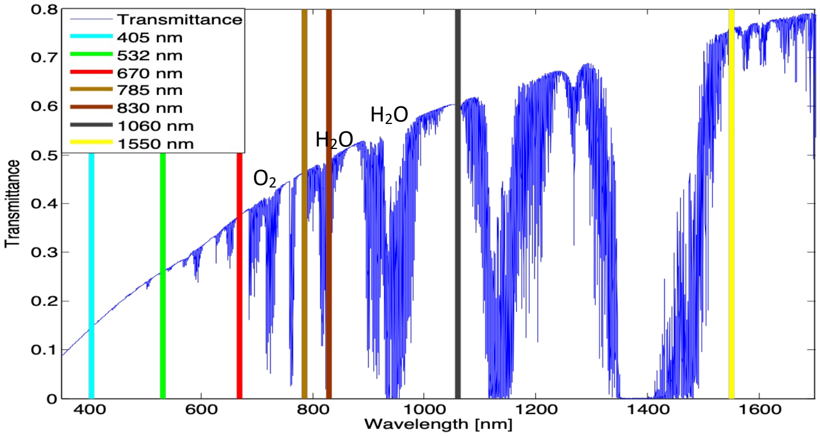
e.g. HITRAN https://hitran.org

(high-resolution transmission molecular database)

Total optical depth: $\tau(\lambda) = \underbrace{\tau_R(\lambda)}_{\text{Rayleigh}} + \underbrace{\tau_a(\lambda)}_{\text{Aerosols}} + \underbrace{\tau_g(\lambda)}_{\text{Gases}}$

Atmospheric transmission

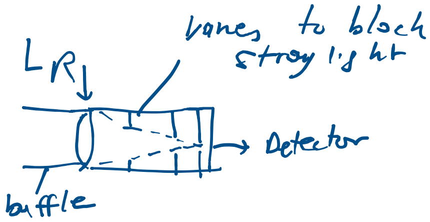
- Vertical passage from sea level to space



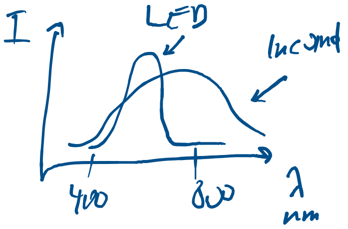
Modeled by MODTRAN 5, J. Bourgoin et al, NJP 2013

Back-ground light rejection - filtering

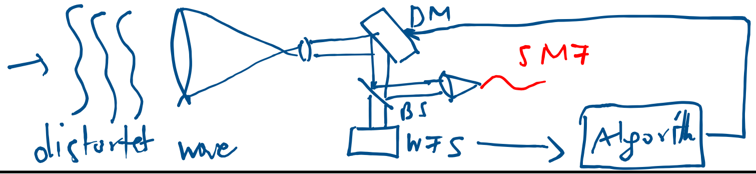
Employ all these several filtering techniques to manage high-background links.



Wavelength selection important, the background light can have spectral structure, e.g. lamps



Adaptive Optics allows to use spatial filter, such as SMF, reject stray light



Algorithm actively computes the required correction to the wave front.

M. Gruneisen et al., arXiv:2006.07745 [physics.optics]

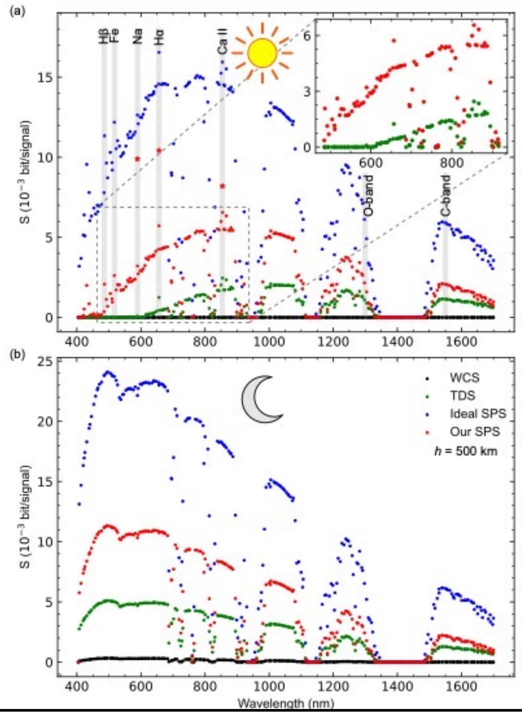
Optimal Wavelength?

Study conducted by colleagues at Jena, Strathclyde, Wiener Neustadt

- Assume multiple types of photon sources
- Single photon emitters (SPS)
- Weak coherent pulses

Optimum ~ 840 nm

Abasifard et al. arXiv:2303.02106v1 [quant-ph]
APL Quantum 1, 016113 (2024)



Qubit encoding

D. Höhn. Appl. Opt., 8(2):367, 1969.

Polarization

works very well, not impacted by atmosphere
issues are optics, and reference frame alignment.

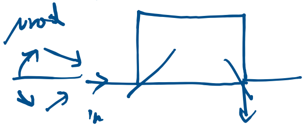
telescopes, mirrors
etc can cause pol. rotation

most used for
free space QKD.

Time Bin

not easily useful, because angle-of-arrival fluctuations
will cause interferometer to be unstable.

due to turbulence
few mod



fix: - Adaptive optics

M. Gruneisen et al., arXiv:2006.07745 [physics.optics]

- imaging interferometers

J. Jin, et al. Phys. Rev. A, 97:043847, 2018.

Qubit Encoding

Orbital-angular momentum

Laguerre - Gauss Modes LG_{nl}

→ wave front distortion issu

→ shorter links

A. Sit et al., Optica, 4(9):1006–1010, 2017.

Continuous Variables

Intensity fluctuations cause issues.

High losses in free space channel.

Local oscillator distribution?

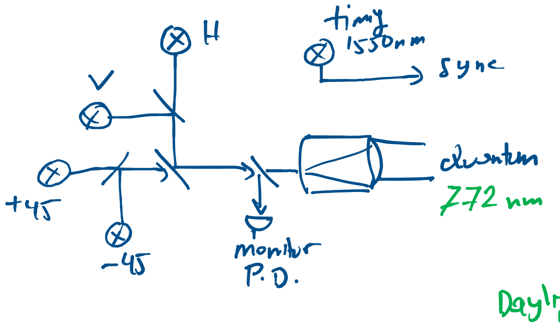
Benefit: background spression better

B. Heim, et al. New Journal of Physics, 16(11):113018, 2014.

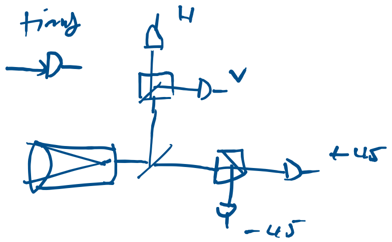
Free Space QKD

R. J. Hughes, J. E. Nordholt, D. Derkacs, and C. G. Peterson. Practical free-space quantum key distribution over 10 km in daylight and at night. New Journal of Physics, 4:43–43, 2002.

Alice



Bob (Bob module, passive Basis choice)



Daylight, 10 km

$\epsilon \sim 4\%$

1 MHz clock, $\mu < 1$

Filter: 0.1 nm $\Delta\lambda$ (very narrow)

Dark counts ~ 1.6 KHz

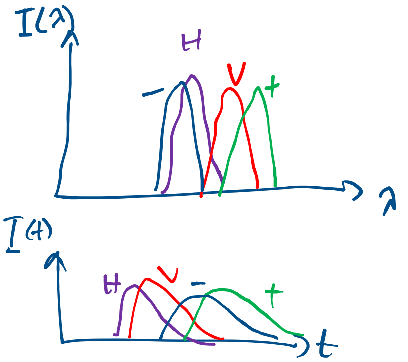
4-Laser source

The four lasers are polarized in the different BB84 states, as required by BB84.

While this approach is elegant, it does raise the question of distinguishability.

of spectrally

temporally:



Mutual Info between Alice & Eve:

e.g. $I_\beta(A:B) = 1 + \sum_\lambda \sum_b \frac{p_\beta(\lambda|b)}{2} \log_2\left(\frac{p_\beta(\lambda|b)}{2p_\beta(\lambda)}\right)$

where $p_\beta(\lambda)$... spectrum for $\beta \in \{H, V, +, -\}$ states

$b = 0, 1$ bit value

S. Nauerth, et al. New Journal of Physics, 11(6):065001, 2009.

26

Free-space Experiment

R. J. Hughes et al. New Journal of Physics, 4:43–43, 2002.

Multiple runs:

ca. 2005, 200 k – 400 k bits

QBER 2 – 5 %

daytime!

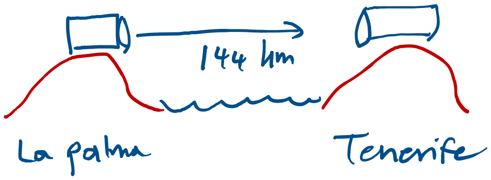
Not yet decoy states (2005), they assumed Eve cannot do elaborate PNS attack.

Detailed finite-size considerations also later.

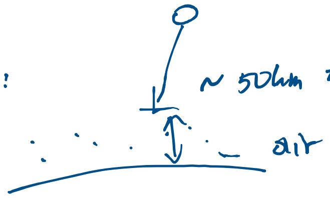
28

Long-range Horizontal Quantum Link

R. Ursin et al. Entanglement-based quantum communication over 144 km. Nat Phys, 3(7):481–486, 2007.



Satellite:



~ 50km Amosphere, vertically ⟺ few km horizontally

turbulence ~ 1.1 km

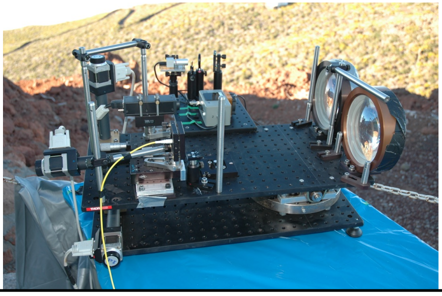
absorption ~ 5 km

144km >> air passed by a ground to space link.

Free space quantum communication over 144 km

Transmitter on La Palma

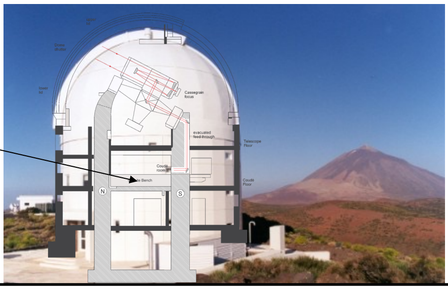
- Next to Nordic Optical Telescope (NOT) at 2400 m elevation
- Source equipment in a container on LaPalma



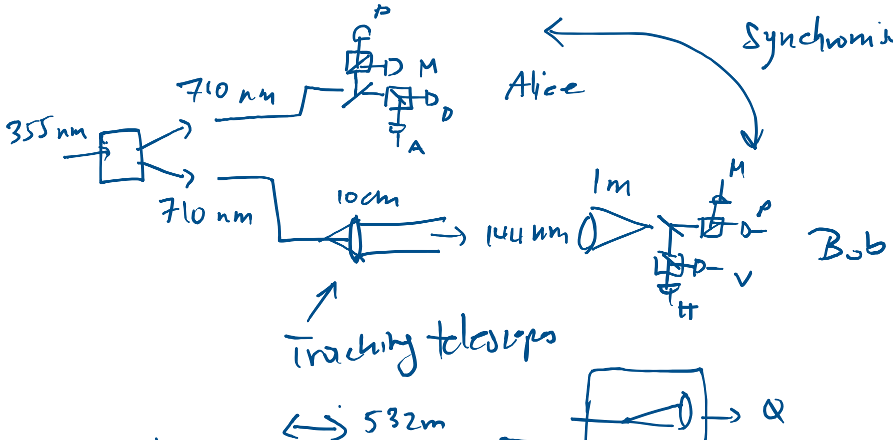
Receiver on Tenerife

- Optical Ground Station of ESA, 1 m aperture
- polarization analyzer and 4 Si APDs in the focus

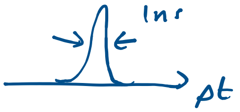
Pol Analyzer+ Detectors

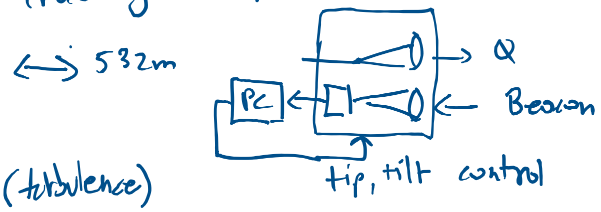


144 km entanglement distribution



Synchronisation: use GPS signals
ca. 50 – 100 ns accura
then use photons
themselves for
final synchronisatio





beam wander
col. ± 100 μrad
Fast: ± 10 μrad (turbulence)

Results

R. Ursin et al. Entanglement-based quantum communication over 144 km. Nat Phys, 3(7):481–486, 2007.

Alice: ca 900 Kcps
Bob: 300 cps signal (+ 1500 cps dark)

Coincidence rate: ca. 5 — 10 cps.

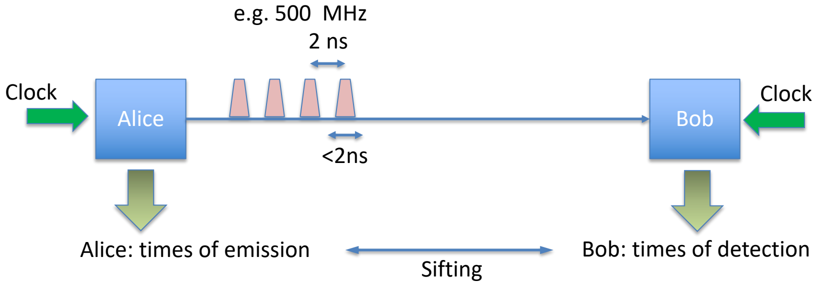
→ Bell inequality: CHSH

recall: $|E(\alpha_1,\beta_1) + E(\alpha_1,\beta_2)| + |E(\alpha_2,\beta_1) - E(\alpha_2,\beta_2)| \leq 2$

-0.435 $\quad -0.812$ $\quad -0.775$ $\quad 0.486$

$\Rightarrow 2.508 \pm 0.037 \leq 2$ violation by 13 standard deviations.

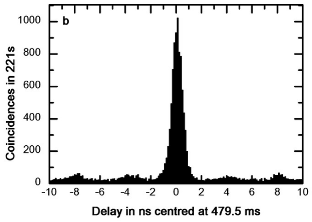
Timing Synchronization and Coincidences



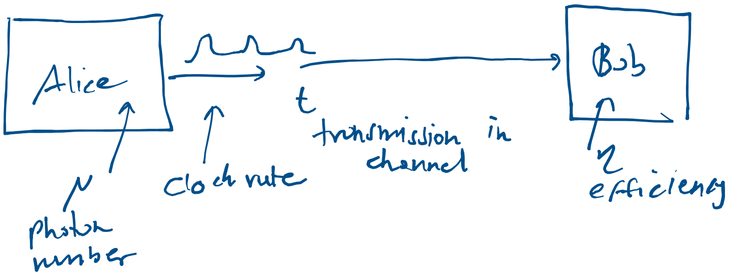
Alice: times of emission ← Sifting → Bob: times of detection

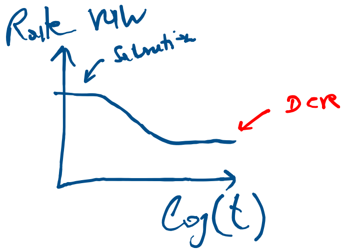
Synchronization aided by various methods:
- Stable clocks (stabilized crystal or atomic)
- Position (GPS position and time)
- Pulsed/modulated laser signals
- Quantum signal itself (clock recovery)

Nature Physics, 10.1038/nphys629 (2007)



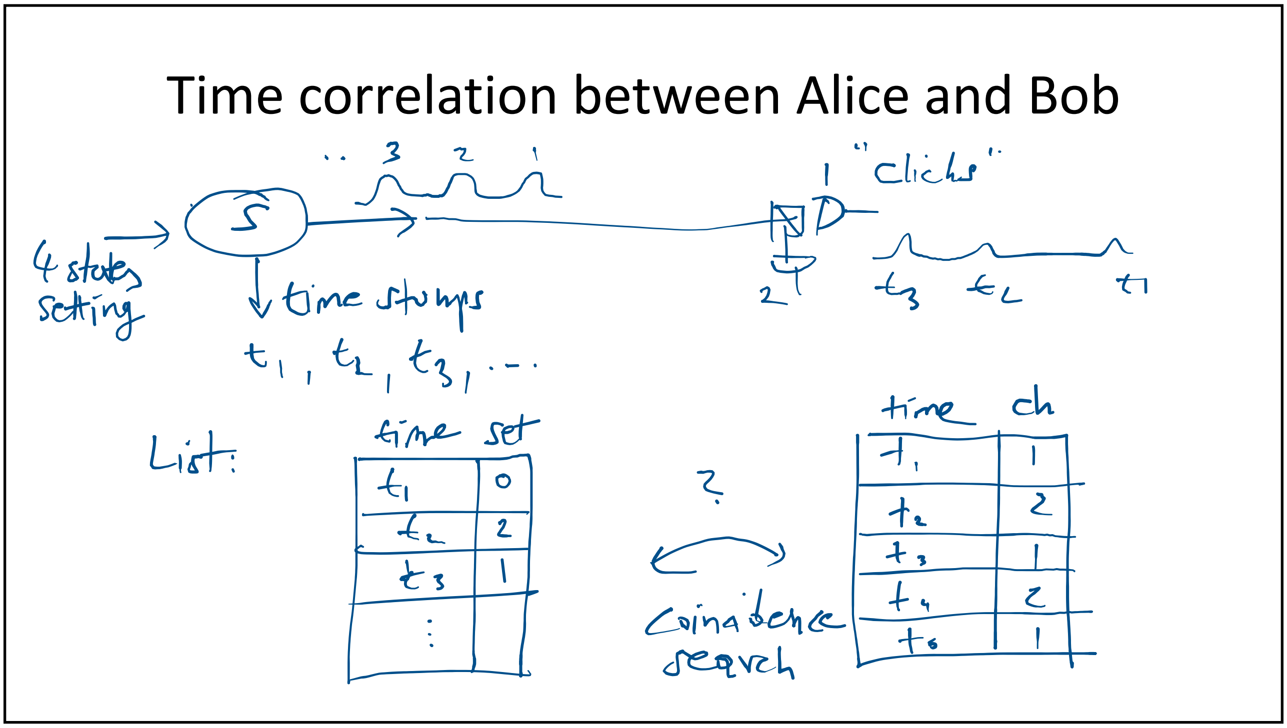
QKD Key Rates estimations





For a given detector: Raw photon rate: (very simplistic) $\text{Rate} \simeq C \cdot \mu \cdot t \cdot \eta + \text{DCR}$

limited by detector saturation/dead time



Time correlation between Alice and Bob

4 states setting

time stamps

$t_1, t_2, t_3, \ldots$

List:

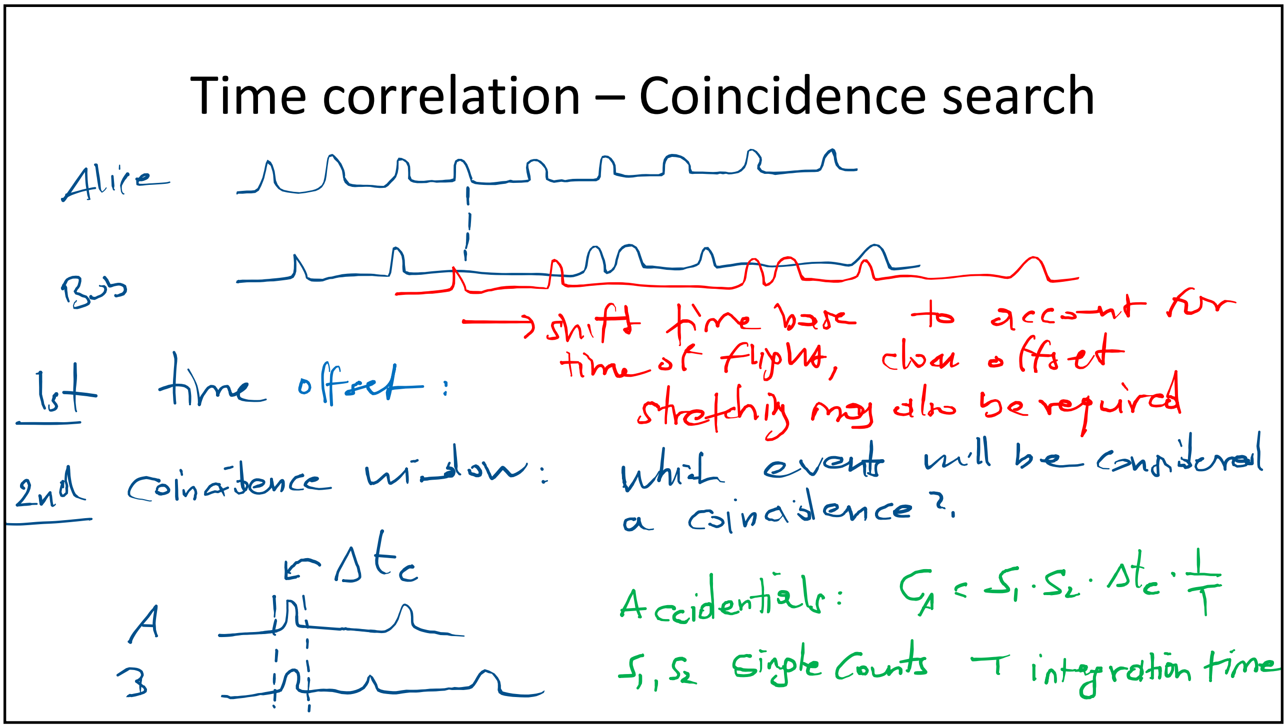
time	set
t_1	0
t_2	2
t_3	1
⋮	

?

coincidence search

time	ch
t_1	1
t_2	2
t_3	1
t_4	2
t_5	1

35



Time correlation – Coincidence search

→ shift time base to account for time of flight, clock offset
stretching may also be required

1st time offset:

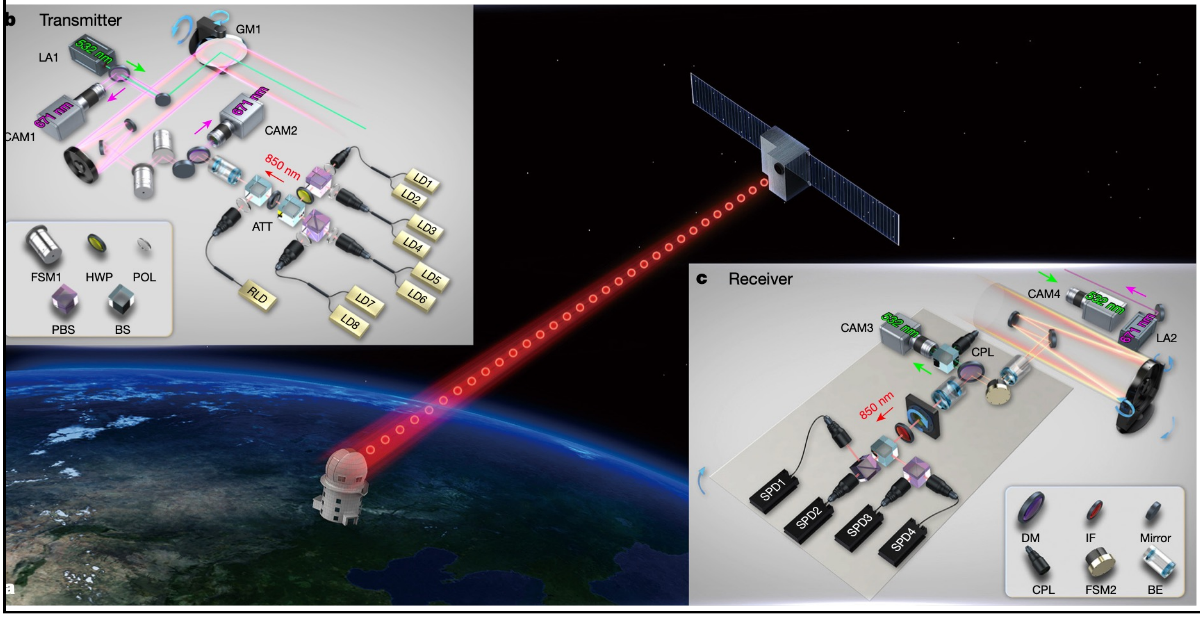
2nd coincidence window: which events will be considered a coincidence?

Accidentials: $C_A < S_1 \cdot S_2 \cdot \Delta t_c \cdot \frac{1}{T}$

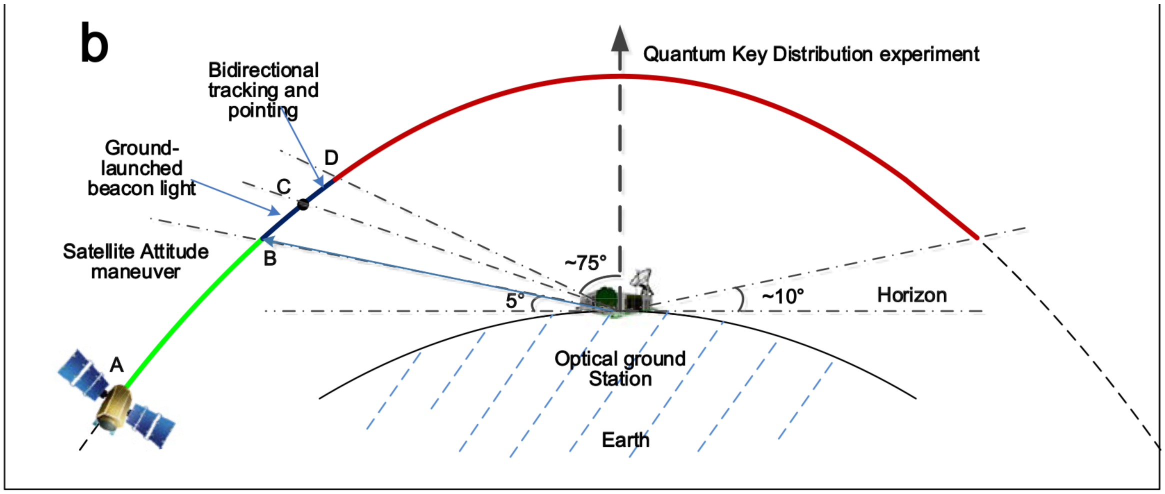
S_1, S_2 single counts T integration time

36

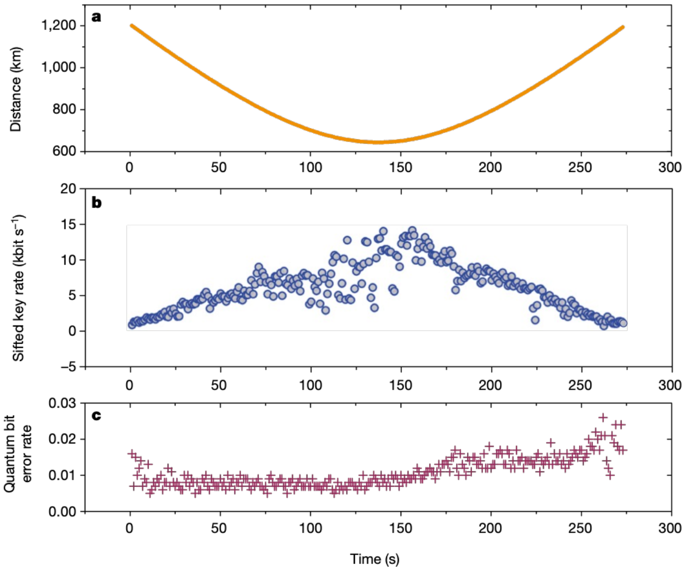
S.-K. Liao et al, J.-W. Pan. Satellite-to-ground quantum key distribution. Nature, 549:43 (2017).

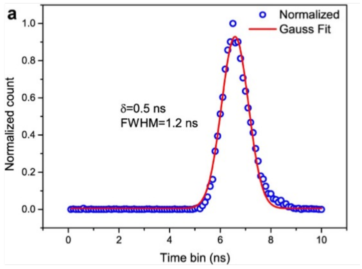


Concept of operation



Measured link performance



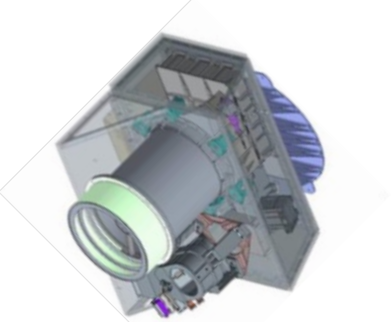


Key stats:
- 273 s duration of link
- 3,551,136 detection events
- 1,671,072 bits of sifted keys
- 1.1% average QBER
- 300,939 secure bits

Nature, 549:43 (2017).

QEYSSat – a Canadian Technology Demonstrator

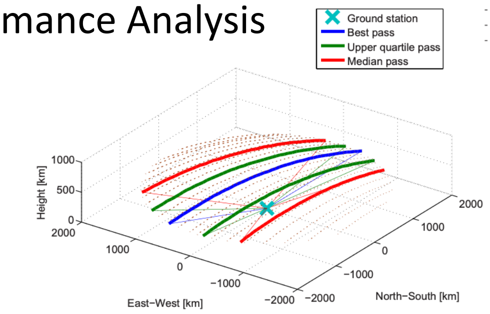
- Launch anticipated in End 2026
- Microsat, ca. 120 Kg
- Quantum Receiver
- Quantum Transmitter - WCP source
- Science Tests
  - Quantum networks on ground
  - Ground station technology AO
  - Ddifferent quantum emitters
  - Qquantum memories
- Funding:
  - Canadian Space Agency (30 M$)
  - NSERC Alliance 5 M$

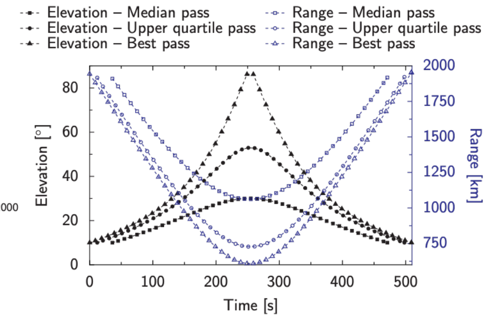


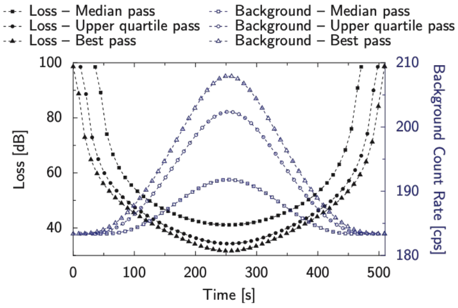
QEYSSat, Scott et al., SPIE 2020

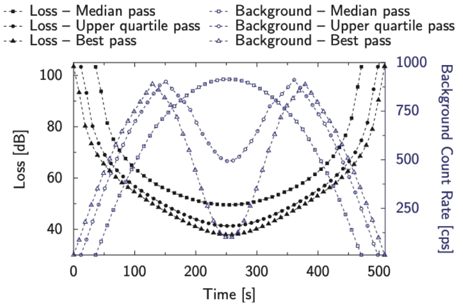
T. Jennewein et al., volume 8997 of Proceedings of SPIE, 2014.

Link Performance Analysis





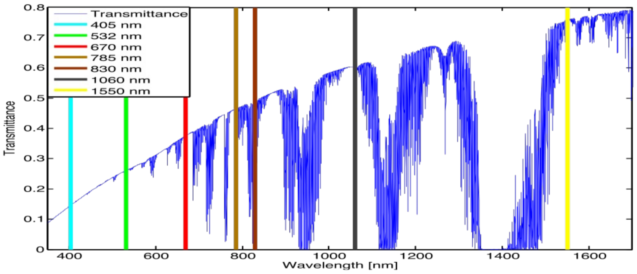




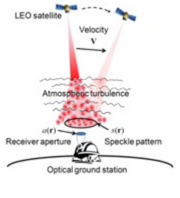
J.P. Bourgoin, et al, NJP, 15:023006, 2013

Modeling the performance of satellite to ground quantum link

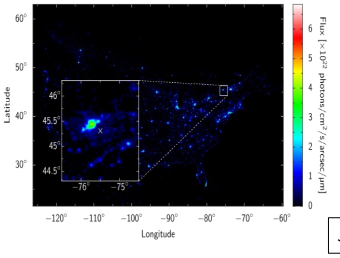
- Analysis of wavelengths with windows of ‘good’ atmospheric transmission
- Link modelled using turbulence; diffraction to account for beam obstruction; background signals



North America – the cutout is centred around Ottawa



M. Toyoshima, op.Ex. 2011



Wavelength (nm)	Secure key length obtained for the upper quartile satellite pass (kbit)			
	Downlink, WCP source	Uplink, WCP source	Downlink, entangled photon source	Uplink, entangled photon source
405	68.5	3.5	6.2	0
532	264.5	33.1	119.3	12.1
670	465.6	87.7	324.7	67.4
785	458.3	111.3	272.9	75.7
830	317.3	82.1	136.1	39.7
1060	175.4	67.6	21.8	8.1
1550	123.9	94.8	12.8	14.4

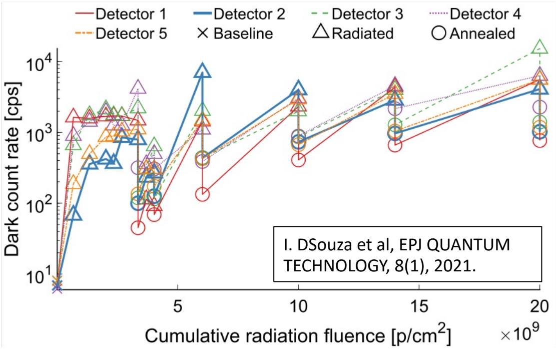
J.P. Bourgoin, et al, NJP, 15:023006, 2013

Related analysis:
J. Rarity et al, NJP, 2002
P. Villoresi group, NJP, 2009
R. Ursin group, NJP, 2013

Space environment?

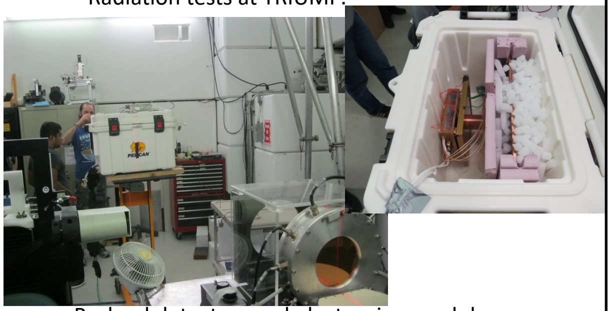
Representative quantum receiver – payload prototype

- Tests: Radiation, TVAC, outdoor and aircraft links

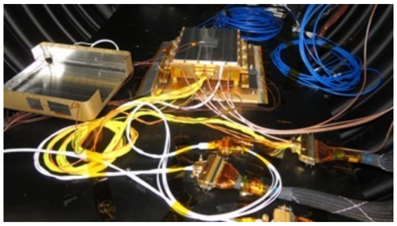


I. DSouza et al, EPJ QUANTUM TECHNOLOGY, 8(1), 2021.

Radiation tests at TRIUMF:



Payload detectors and electronics, module in thermal-vacuum chamber:



J.P. Bourgoin, et al, NJP, 15:023006, 2013
C. Pugh et al., Quantum Science and Technology, 2017; 2 (2): 024009
J.-P. Bourgoin et al. PRA, 92(5), 2015.
E. Anisimova et al. EPJ QUANTUM TECHNOLOGY, 2017.

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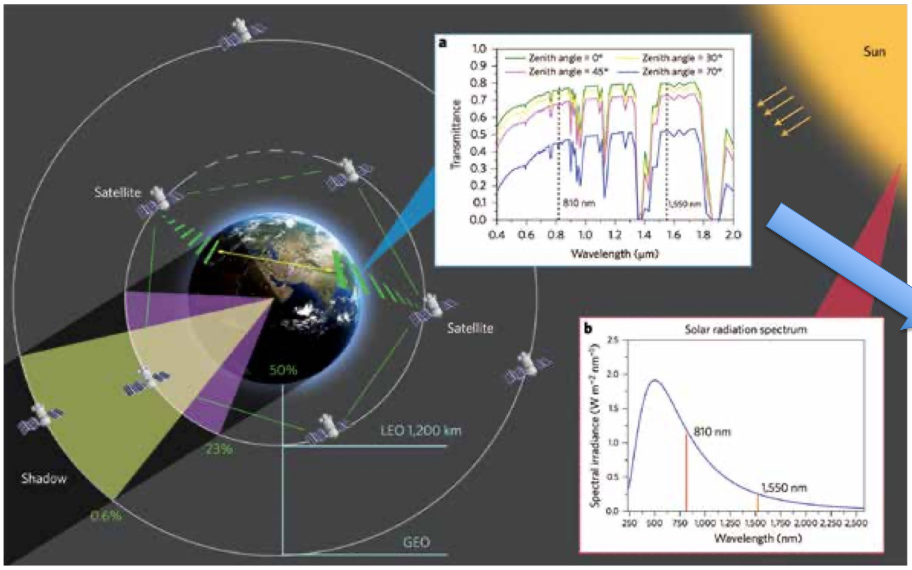
Future scenarios for satellite QKD



Need for daylight operation

BCAS Vol.31 No.3 2017

Schematic illustration of a global quantum network based on a constellation of satellites. (Picture by PAN's team)

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Challenges and Outlook for Space Quantum Networks

- Efficient and robust q-channels
- Dimensions – power – mass
  - chip scale systems ?
- Interfaces / transducers
  - connect channels with stationary qubits
- Long term q-memories
- Routing technology
- Cost
- …..

Global Quantum Internet

Entanglement distribution over long distance and many nodes.

- Secure communications – including QKD
  - quantum key distribution
- Distributed quantum computing
  - blind quantum computing
- Enhanced metrology
  - large-baseline telescopes

Next steps:

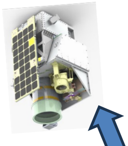
- **High-altitude feeder links (HAP to ground, HAP to sat)**
- **Quantum repeater** interfacing quantum memories with
  - short range networks (fibre optic) &
  - long haul links (satellites)
- **Interconnects** between different quantum computers
  - Entanglement between separated logical qubits

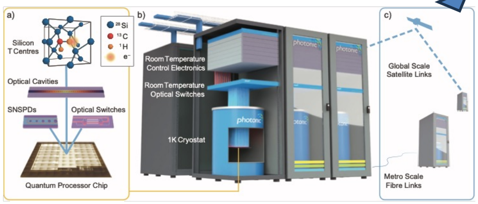
Hyperspace:
Entanglement between
Canada and Europe

Hyper Space

QEYSSAT 2.0: Design & build **Teleportation across Canada**

Jennewein et al.
arXiv:2306.02481 **[quant-ph]**



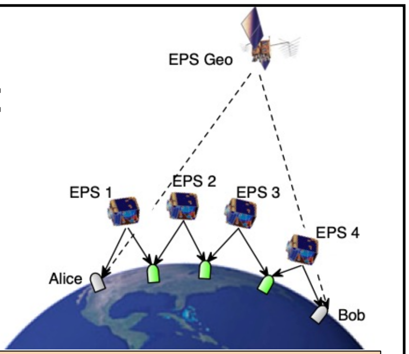


photonic

Quantum processor system

Simmons, arXiv:2311.04858v1 [quant-ph]

Quantum repeaters in sp



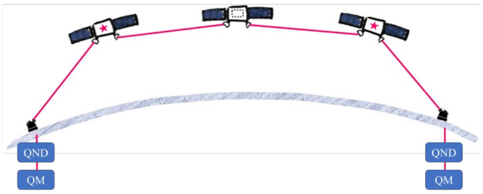
Intercontinental distances will suffer from low transfer rates
Multiple approaches for quantum memory assisted schemes proposed.

Ground based repeater nodes, space based EPS

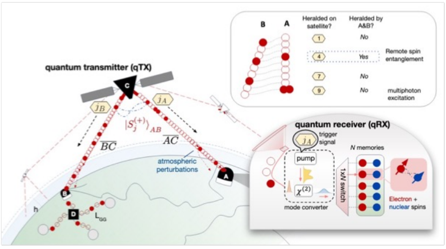
K. Boone, Bourgoin, Meyer-Scott, Heshami, Jennewein, Simon. PRA 91, 052325 (2015)

Space based quantum memories

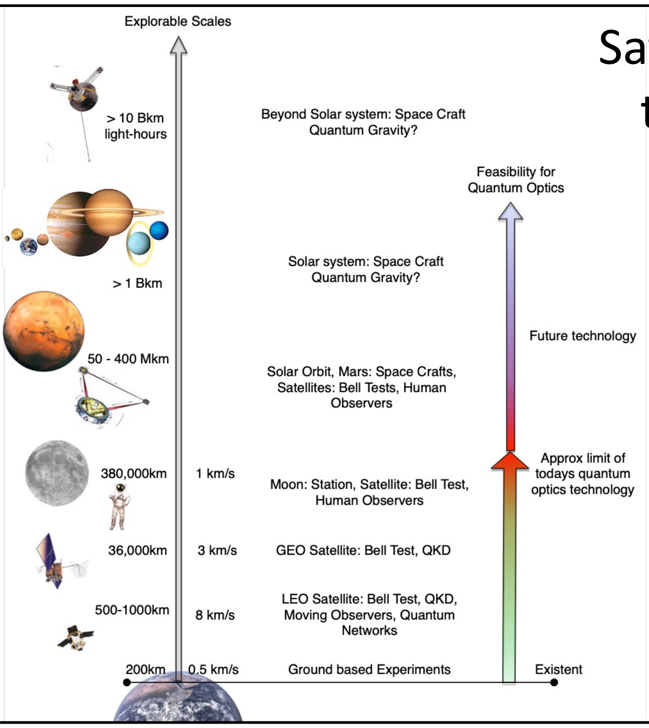
J.-M. Mol et al. Quantum Science and Technology, 8(2):024006, 2023.



M. Gundogan, et al. npj Quantum Information, 7(1):128, 2021.



K. C. Chen, P. Dhara, M. Heuck, Y. Lee, W. Dai, S. Guha, and D. Englund. Phys. Rev. Appl., 19:054029, 2023.



Satellites will enable unique tests of q-entanglement

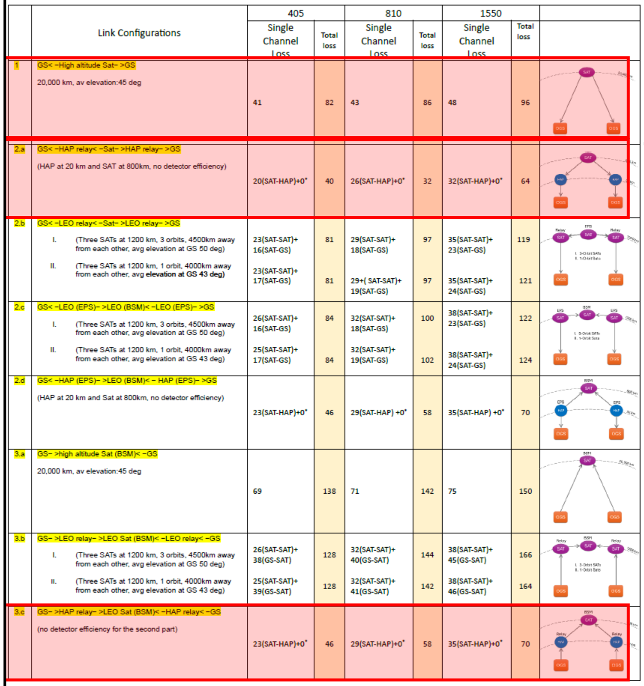
Probe the validity of QM
Explore the Interplay of QM + GR

Explore distances, speeds, gravity gradients,… that cannot be achieved on the ground.

Review of possible science test for quantum entanglement in space:
Fundamental quantum optics experiments conceivable with satellites-reaching relativistic distances and velocities
D. Rideout, T.J, et al. Class. Quant. Grav., 29(22):224011 , 2012.

Future / Open Questions

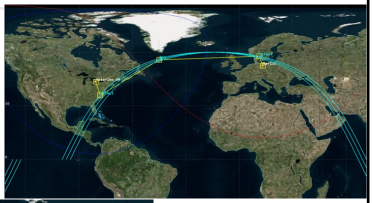
How to reach ‘truly useful’ QKD rates of global distances

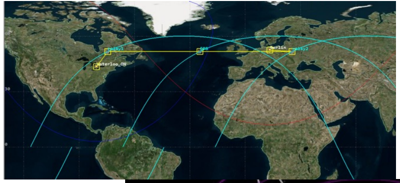


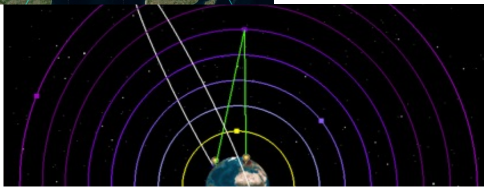
	Link Configurations	405		810		1550		
		Single Channel Loss	Total loss	Single Channel Loss	Total loss	Single Channel Loss	Total loss	
1	GS< –High altitude Sat– >GS 20,000 km, av elevation:45 deg	41	82	43	86	48	96	
2.a	GS< –HAP relay< –Sat– >HAP relay– >GS (HAP at 20 km and SAT at 800km, no detector efficiency)	20(SAT-HAP)+0*	40	26(SAT-HAP)+0*	32	32(SAT-HAP)+0*	64	
2.b	GS< –LEO relay< –Sat– >LEO relay– >GS I. (Three SATs at 1200 km, 3 orbits, 4500km away from each other, avg elevation at GS 50 deg) II. (Three SATs at 1200 km, 1 orbit, 4000km away from each other, avg **elevation at GS 43 deg)**	23(SAT-SAT)+ 16(SAT-GS) 23(SAT-SAT)+ 17(SAT-GS)	81 81	29(SAT-SAT)+ 18(SAT-GS) 29+(SAT-SAT)+ 19(SAT-GS)	97 97	35(SAT-SAT)+ 23(SAT-GS) 35(SAT-SAT)+ 24(SAT-GS)	119 121	
2.c	GS< –LEO (EPS)– >LEO (BSM)< –LEO (EPS)– >GS I. (Three SATs at 1200 km, 3 orbits, 4500km away from each other, avg elevation at GS 50 deg) II. (Three SATs at 1200 km, 1 orbit, 4000km away from each other, avg elevation at GS 43 deg)	26(SAT-SAT)+ 16(SAT-GS) 25(SAT-SAT)+ 17(SAT-GS)	84 84	32(SAT-SAT)+ 18(SAT-GS) 32(SAT-SAT)+ 19(SAT-GS)	100 102	38(SAT-SAT)+ 23(SAT-GS) 38(SAT-SAT)+ 24(SAT-GS)	122 124	
2.d	GS< –HAP (EPS)– >LEO (BSM)< – HAP (EPS)– >GS (HAP at 20 km and Sat at 800km, no detector efficiency)	23(SAT-HAP)+0*	46	29(SAT-HAP) +0*	58	35(SAT-HAP) +0*	70	
3.a	GS– >high altitude Sat (BSM)< –GS 20,000 km, av elevation:45 deg	69	138	71	142	75	150	
3.b	GS– >LEO relay– >LEO Sat (BSM)< –LEO relay< –GS I. (Three SATs at 1200 km, 3 orbits, 4500km away from each other, avg elevation at GS 50 deg) II. (Three SATs at 1200 km, 1 orbit, 4000km away from each other, avg elevation at GS 43 deg)	26(SAT-SAT)+ 38(GS-SAT) 25(SAT-SAT)+ 39(GS-SAT)	128 128	32(SAT-SAT)+ 40(GS-SAT) 32(SAT-SAT)+ 41(GS-SAT)	144 142	38(SAT-SAT)+ 45(GS-SAT) 38(SAT-SAT)+ 46(GS-SAT)	166 164	
3.c	GS– >HAP relay– >LEO Sat (BSM)< –HAP relay< –GS (no detector efficiency for the second part)	23(SAT-HAP)+0*	46	29(SAT-HAP)+0*	58	35(SAT-HAP)+0*	70	

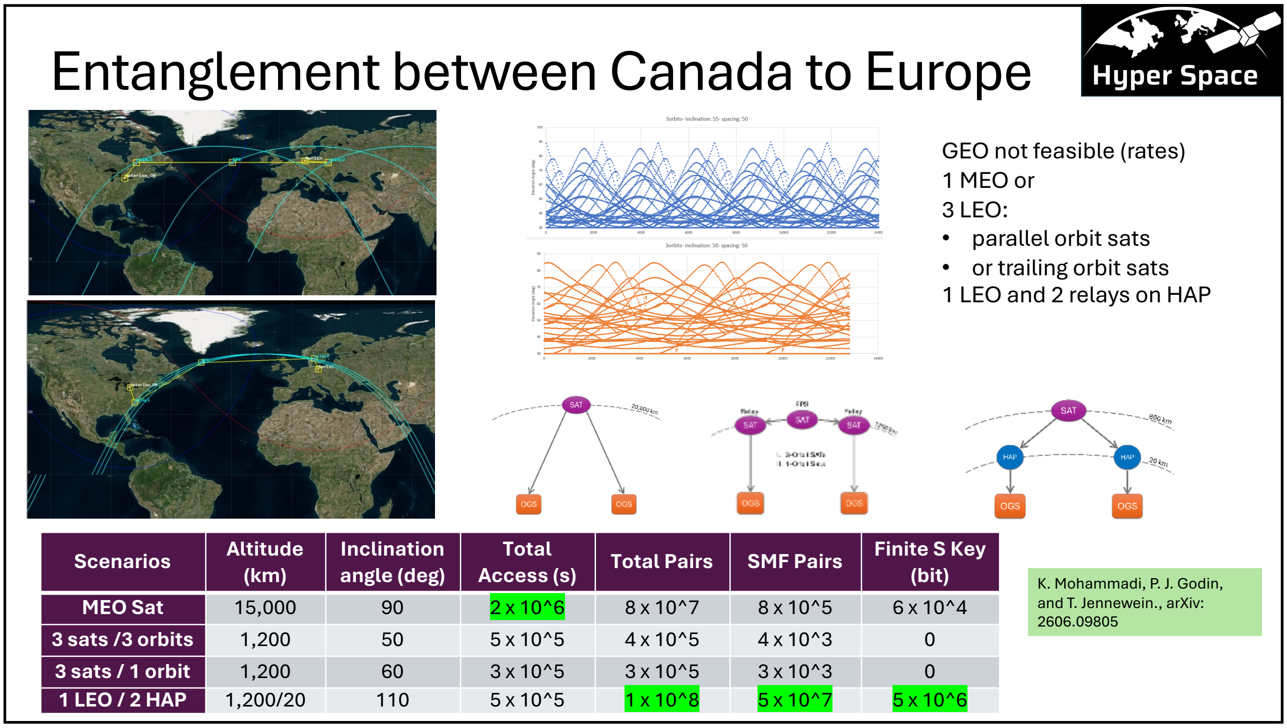
Hyper Space

- Analyzed 10+ scenarios
- Multi-node and relay









Entanglement between Canada to Europe

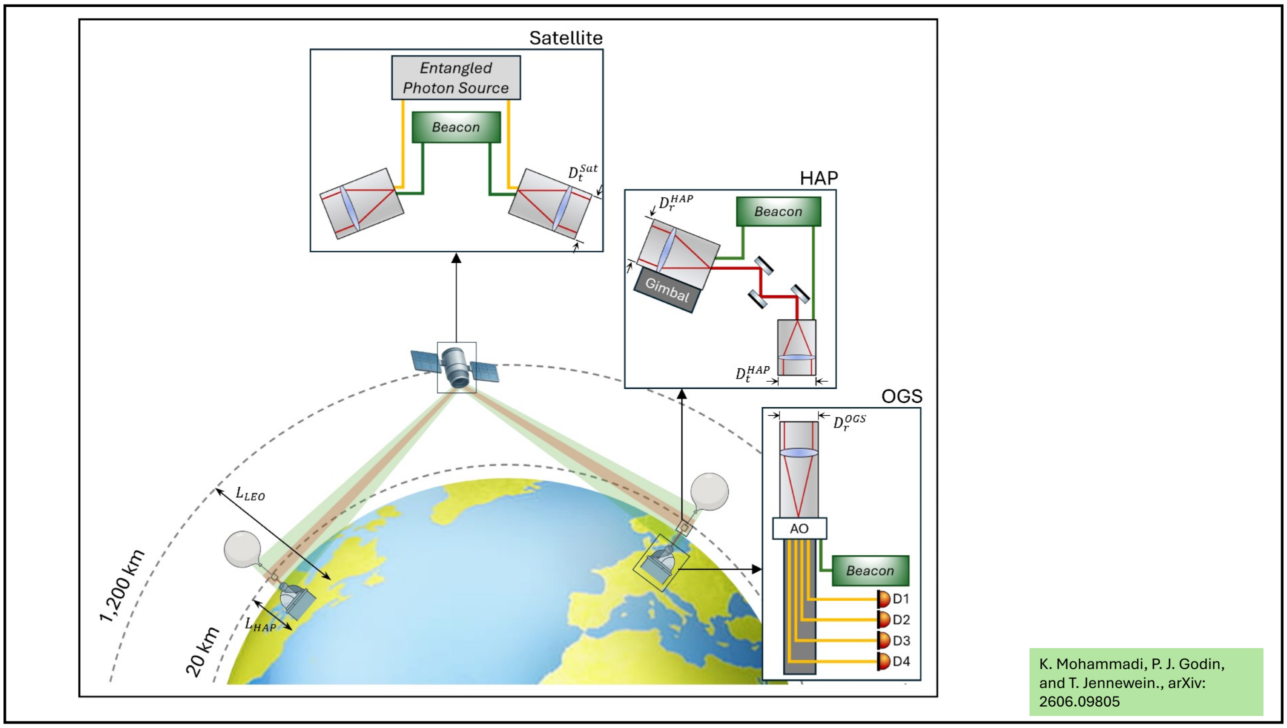
GEO not feasible (rates)
1 MEO or
3 LEO:

- parallel orbit sats
- or trailing orbit sats

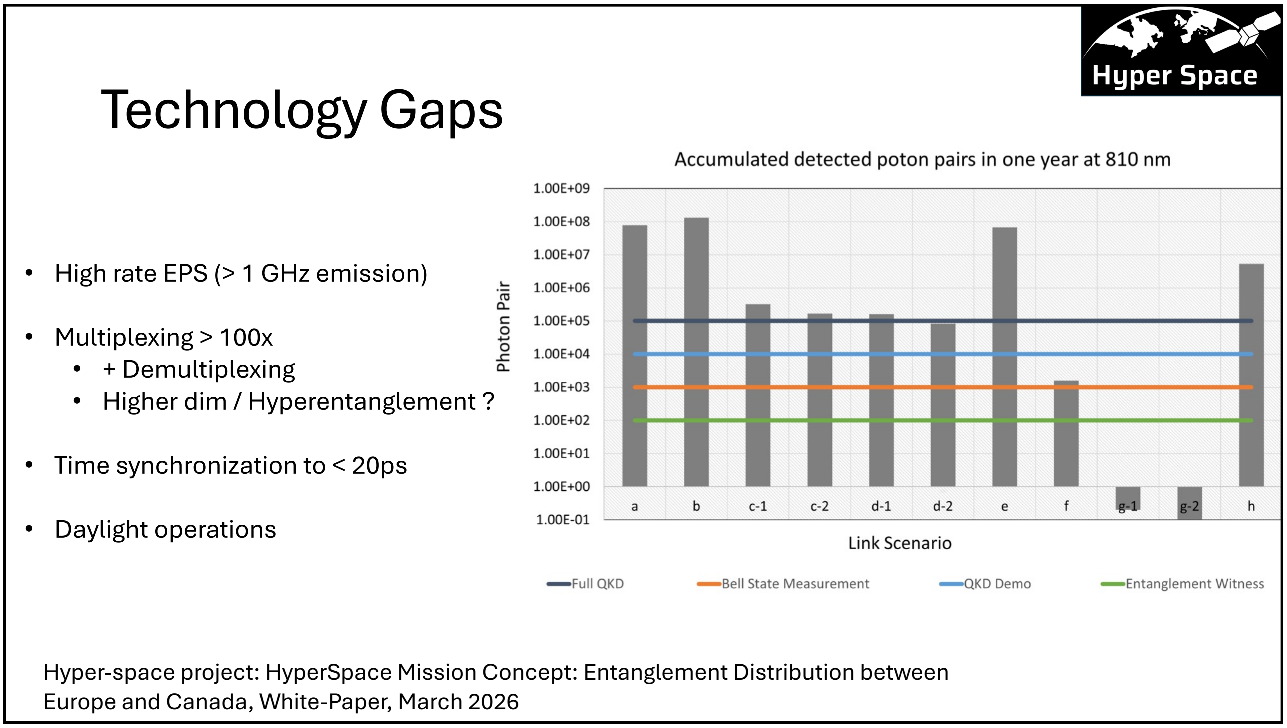
1 LEO and 2 relays on HAP

Scenarios	Altitude (km)	Inclination angle (deg)	Total Access (s)	Total Pairs	SMF Pairs	Finite S Key (bit)
MEO Sat	15,000	90	2 x 10^6	8 x 10^7	8 x 10^5	6 x 10^4
3 sats /3 orbits	1,200	50	5 x 10^5	4 x 10^5	4 x 10^3	0
3 sats / 1 orbit	1,200	60	3 x 10^5	3 x 10^5	3 x 10^3	0
1 LEO / 2 HAP	1,200/20	110	5 x 10^5	1 x 10^8	5 x 10^7	5 x 10^6

K. Mohammadi, P. J. Godin, and T. Jennewein., arXiv: 2606.09805



K. Mohammadi, P. J. Godin, and T. Jennewein., arXiv: 2606.09805



Technology Gaps

- High rate EPS (> 1 GHz emission)
- Multiplexing > 100x
  - + Demultiplexing
  - Higher dim / Hyperentanglement ?
- Time synchronization to < 20ps
- Daylight operations

Hyper-space project: HyperSpace Mission Concept: Entanglement Distribution between Europe and Canada, White-Paper, March 2026