Towards a global quantum internet, and what it will be useful for

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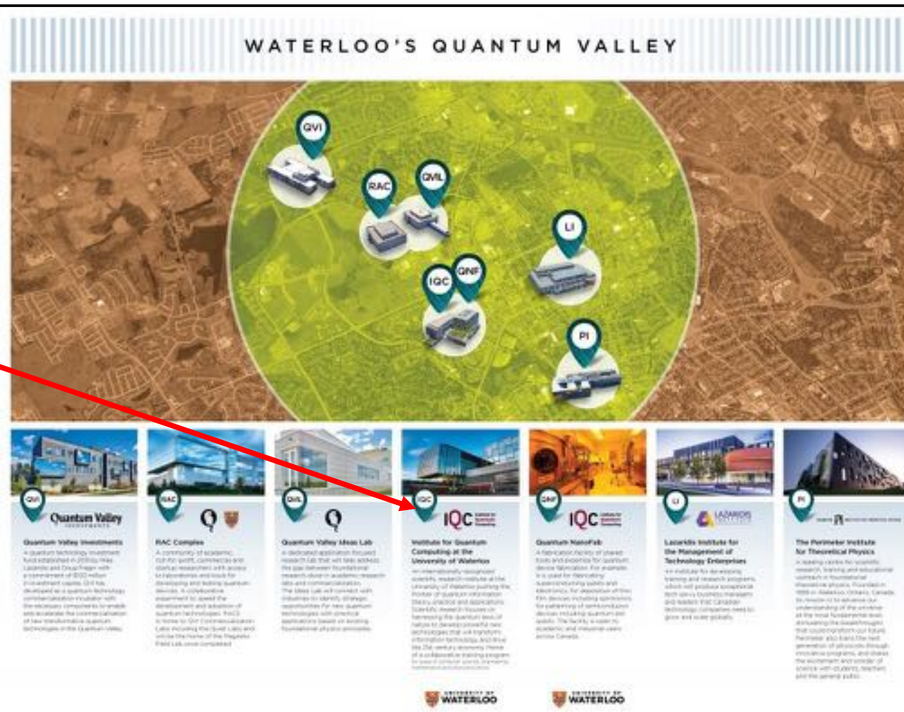


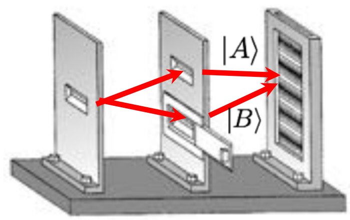
IQC @ 2019:
31 faculty
157 Grad students
57 Postdoc
1800+ publications
$600M+ funding
13 spin-offs

Superposition of quantum states

- Generalization of the wave-particle duality
- Consequence of the linearity of the Schrödinger equation.
- E.S: The essence of quantum mechanics (1927)

Erwin Schrödinger

$$\Psi = (\alpha|A\rangle + \beta|B\rangle)$$



- Leads to Quantum Entanglement:

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1\,|V\rangle_2 - |V\rangle_1\,|H\rangle_2\right)$$

Entanglement from Superposition of a single Photon

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1\,|V\rangle_2 - |V\rangle_1\,|H\rangle_2\right)$$

→the polarization of two photons are inherently correlated.
→Large superposition, no distance limits known
Einstein: „spooky action at a distance“ ?

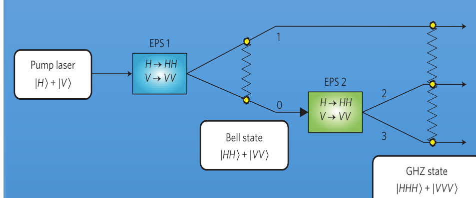
Clauser-Horne-Shimony-Holt Inequality: Bell's (1964). CHSH (1972)

$$|E(\alpha,\beta) - E(\alpha',\beta)| + |E(\alpha,\beta') + E(\alpha',\beta')| \leq 2$$

Q.M. predicts 2.828... violating the limit of 2!

2015 was THE big year for "Loop-hole free" Bell inequality tests:
Delft (2015), NIST/Boulder (2015), Vienna (2015)

Extension of superposition
3-photon GHZ entanglement
-> originates from initial superposition state of a pump photon



Shalm, Huebel, Miller, Marsili, Mirin, Nam, Resch, and TJ. NATURE PHOTONICS, 8(10):801–807, (2014).

Application of Superposition: Quantum Technologies

- Quantum information processing
- Extending the classical bit, to the **qubit**:

$|0\rangle; |1\rangle$

$\alpha|0\rangle + \beta|1\rangle$

The chip inside IBM's quantum computer.
https://www.technologyreview.com/s/610250/hello-quantum-world/

Quantum Internet

REVIEW SUMMARY

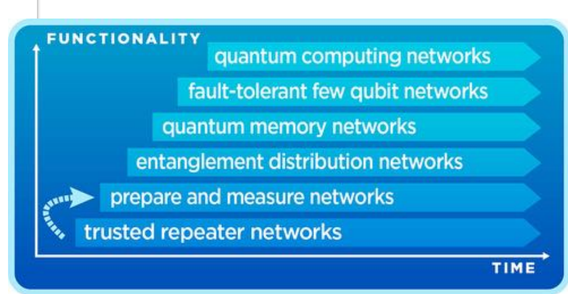
QUANTUM INFORMATION

Quantum internet: A vision for the road ahead

Stephanie Wehner*, David Elkouss, Ronald Hanson

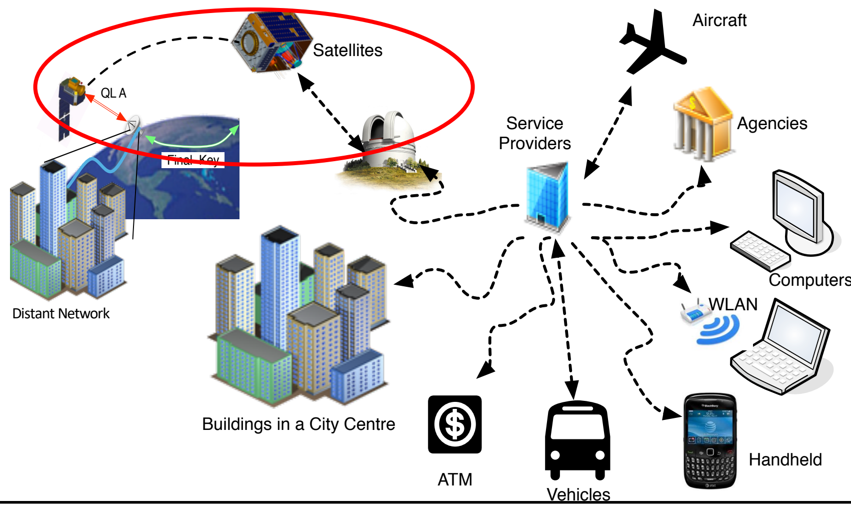
Science 362, 303 (2018)

Quantum computing in the cloud:



Quantum Internet Technologies

Qubit distribution through networks.
Multiple different physics systems and channels need to operate together.



Quantum Internet may be useful for …

- Secure communications (QKD)

  C. H. Bennett and G. Brassard. Quantum cryptography: Public key distribution and coin tossing. In Proceedings of the International Conference on Computer Systems and Signal Processing, Bangalore, page 175, Bangalore, 1984.

- Quantum Money

  Wiesner, 1983: long distance entanglement (stored spins)

- Quantum computing
  - Interfacing between quantum computers
  - Quantum computing “in the cloud”

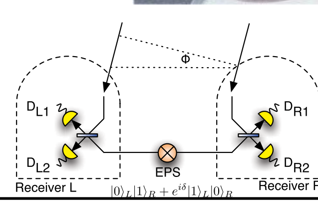
  Broadbent, Fitzsimons, Kashefi. Universal blind quantum computation. Foundations of Computer Science, IEEE Annual Symposium on, 0:517–526, 2009.

- Metrology
  - Clock Synchronization
  - Telescopes

  Gottesman, Jennewein, and Croke. Longer-baseline telescopes using quantum repeaters. Physical review letters, 109(7):070503–070503, -Aug- 2012.

Image NIST

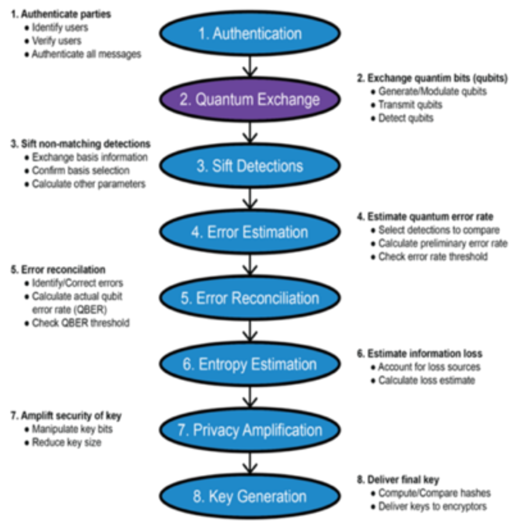
Austrian National Bank



Quantum Key Distribution

Fixes the loophole of key distribution, where classical keys could be copied or compromised during transport.
Only transmit single quanta of light per bit.

Alice prepares single photons			Bob measures single photons	
Random encoding basis	Random bit value	Prepared photon state	Random decoding basis	Measurement result
⊕	0	|↔⟩	⊕	0 or 1
⊕	1	|↕⟩	⊗	Random
⊗	0	|⤢⟩	⊕	Random
⊗	1	|⤡⟩	⊗	0 or 1



L. O. Mailloux et. al. Journal of Cyber Security and Information Systems, 4, 2 – Basic Complexity

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Historical note on QKD

VOLUME 84, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 2000

Quantum Cryptography with Entangled Photons

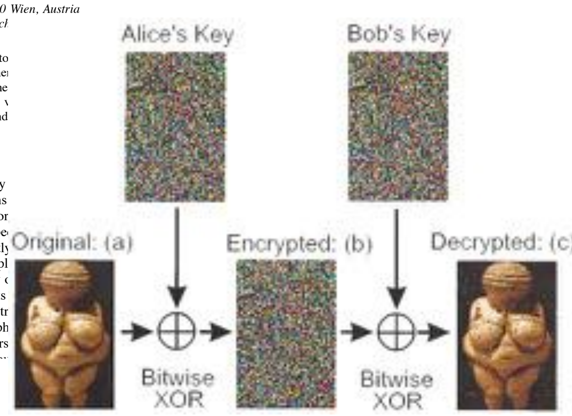
Thomas Jennewein,[1] Christoph Simon,[1] Gregor Weihs,[1] Harald Weinfurter,[2] and Anton Zeilinger[1]
[1]*Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria*
[2]*Sektion Physik, Universität München, Schellingstrasse 4/III, D-80799 Münch*
(Received 24 September 1999)

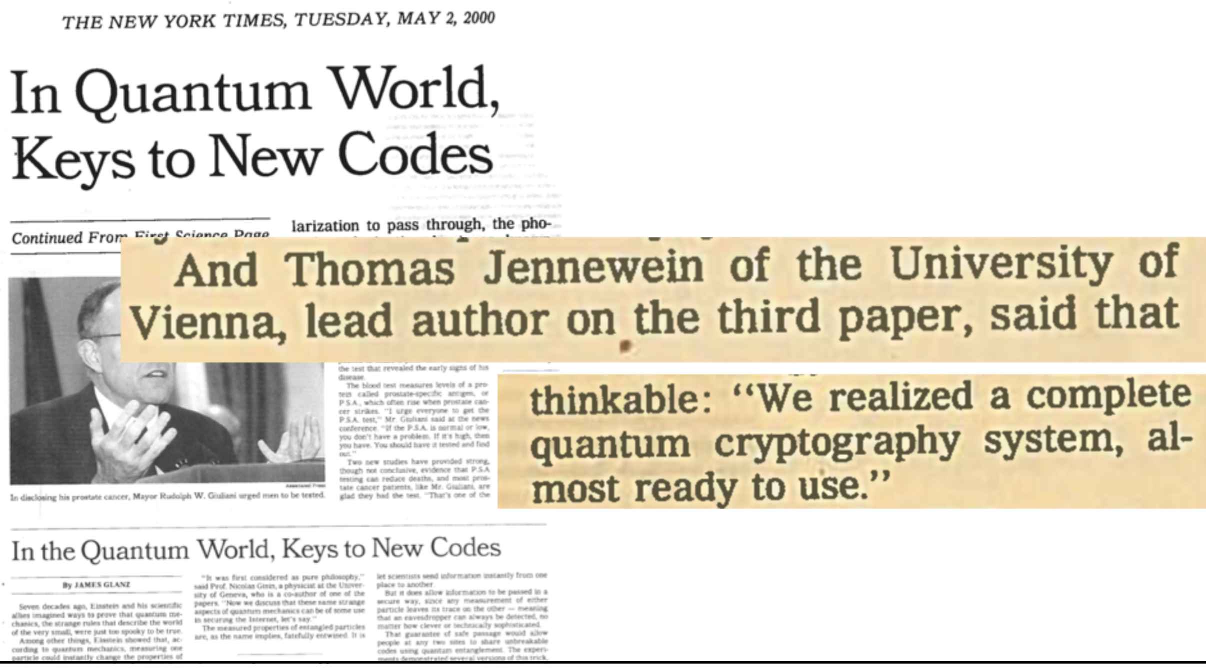
By realizing a quantum cryptography system based on polarization entangled photo
highly secure keys, because a single photon source is approximated and the inhe
quantum measurements is exploited. We implement a novel key distribution sche
inequality to test the security of the quantum channel, and, alternatively, realize a v
protocol. Our system has two completely independent users separated by 360 m, and
at rates of 400–800 bits/s with bit error rates around 3%.

PACS numbers: 03.67.Dd, 42.79.Sz, 89.80.+h

The primary task of cryptography is to enable two parties (commonly called Alice and Bob) to mask confidential messages, such that the transmitted data are illegible to any unauthorized third party (called Eve). Usually this is done using shared secret keys. However, in principle it is always possible to intercept classical key distribution unnoticedly. The recent development of quantum key distribution [1] can cover this major loophole of classical cryptography. It allows Alice and Bob to establish two completely secure keys by transmitting single quanta (qubits) along a quantum channel. The underlying principle of quantum key dis-

In any real cryptography
by Alice and Bob contains
rected by classical error cor
nel. Furthermore, it has be
and Bob share a sufficiently
its security by privacy ampl
allow them to distill a key
A range of experiments
bility of quantum key distr
using the polarization of ph
tons in long interferometers





THE NEW YORK TIMES, TUESDAY, MAY 2, 2000

In Quantum World, Keys to New Codes

Continued From First Science Page

larization to pass through, the pho-

And Thomas Jennewein of the University of Vienna, lead author on the third paper, said that

thinkable: "We realized a complete quantum cryptography system, almost ready to use."

In disclosing his prostate cancer, Mayor Rudolph W. Giuliani urged men to be tested.

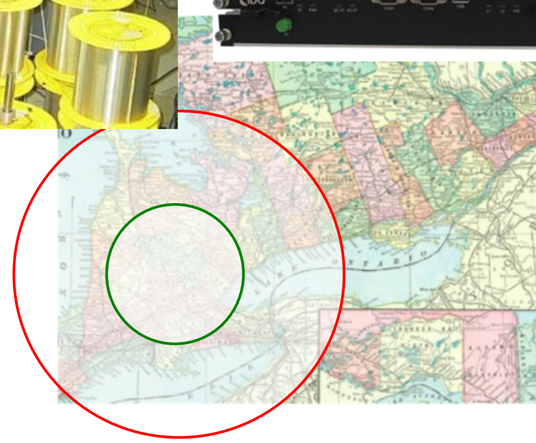
In the Quantum World, Keys to New Codes

By JAMES GLANZ

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!**

IdQuantique Commercial QKD System

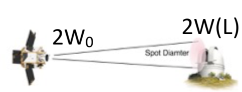


- Longer distances:
  - Trusted Repeaters (> 2000km network China)
  - Long lifetime Quantum Memories
  - Quantum Repeaters
  - **Satellites**

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

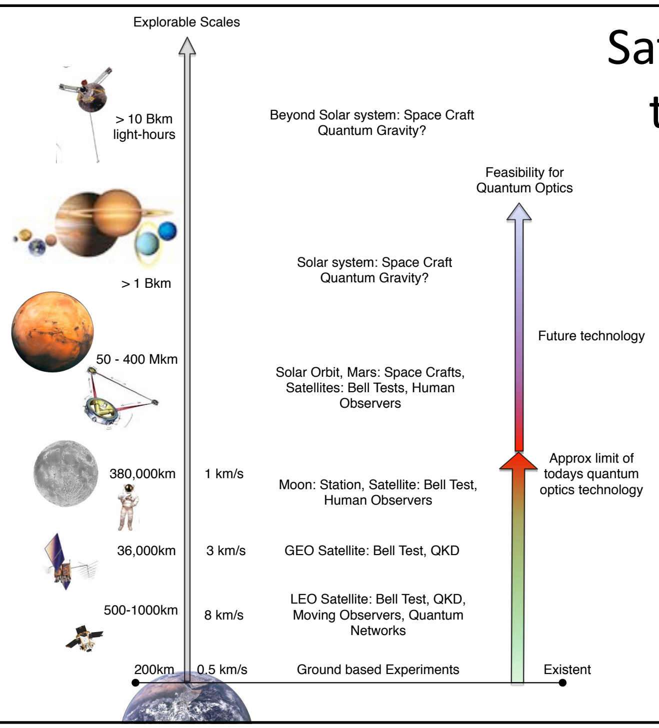
Ma, Fung, Lo, Phys. Rev. A 76, 012307 (2007)

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



Quantum Entanglement Science in Space

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.

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Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities

David Rideout[1,2,3], Thomas Jennewein[2,4], Giovanni Amelino-Camelia[5], Tommaso F Demarie[6], Brendon L Higgins[2,4], Achim Kempf[2,3,4], Adrian Kent[3,7], Raymond Laflamme[2,3,4], Xian Ma[2,4], Robert B Mann[2,4], Eduardo Martín-Martínez[2,4], Nicolas C Menicucci[3,8], John Moffat[3], Christoph Simon[9], Rafael Sorkin[3], Lee Smolin[3] and Daniel R Terno[6]

Abstract

Physical theories are developed to describe phenomena in particular regimes, and generally are valid only within a limited range of scales. For example, general relativity provides an effective description of the Universe at large length scales, and has been tested from the cosmic scale down to distances as small as 10 m (Dimopoulos 2007 *Phys. Rev. Lett.* **98** 111102; 2008 *Phys. Rev.* D **78** 042003). In contrast, quantum theory provides an effective description of physics at small length scales. Direct tests of quantum theory have been performed at the smallest probeable scales at the Large Hadron Collider, $\sim 10^{-20}$ m, up to that of hundreds of kilometres (Ursin *et al* 2007 *Nature Phys.* **3** 481–6). Yet, such tests fall short of the scales required to investigate

D. Rideout, T.J, et al. Class. Quant. Grav., 29(22):224011 , 2012.

Contents

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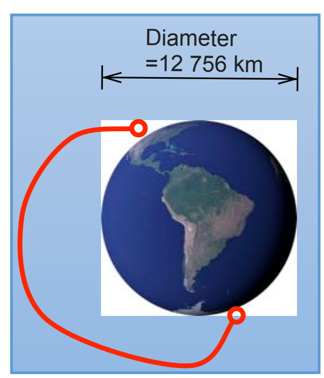
The Case for Entanglement Science in Space?

- Certain effects may never show up in the parameter space available on ground
- Global Quantum Networks & QKD & Quantum Computing rely on the validity of QM
- Human-operated Bell-tests
  - Earth – Moon or
  - Earth – "Space Ship" on its way to Mars
- International collaborations will allow community to strengthen Scientific case and output

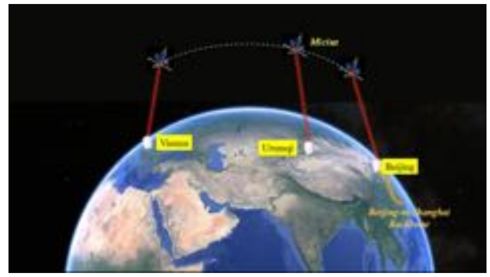


Rideout, T.J, et al. Class. Quant. Grav., 29(22):224011 , 2012.

Quantum Communication in Space

Dedicated quantum hardware in Space:

- China (J.W. Pan)
  - **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)**
- Japan (NICT)
  - 50 kg satellite: Nature Photonics 11, 502–508 (2017)
- Singapore (A. Ling)
  - Correlated Photon Source onboard CubeSat (Phys. Rev. Applied 5, 054022, 2016)
  - SpooQey-1: July 2019: Entanglement in space



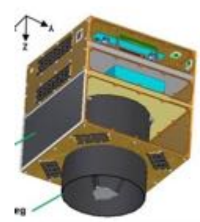
Beijing and Vienna have a quantum conversation
September 2017, www.physicsworld.com
http://english.cas.cn/newsroom/news/201709/t20170928_183577.shtml

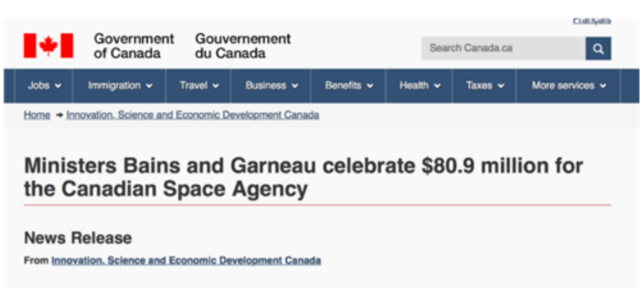
Proof of concept demonstrations

- Germany (G. Leuchs): Demonstration of quantum limited states sent from GEO satellite to ground (Vol. 4, No. 6 Optica, 2017)
- Italy (P. Villoresi): Demonstrating a quantum channel from space to ground, (Phys. Rev. Lett. 115, 040502 (2015))
- Canada (T.J.): Airborne demonstration of a quantum communication satelltie payload (QST, 2017)

Canadian Quantum Satellite

http://www.asc-csa.gc.ca/eng/sciences/qeyssat.asp





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Ministers Bains and Garneau celebrate $80.9 million for the Canadian Space Agency

News Release

From Innovation, Science and Economic Development Canada

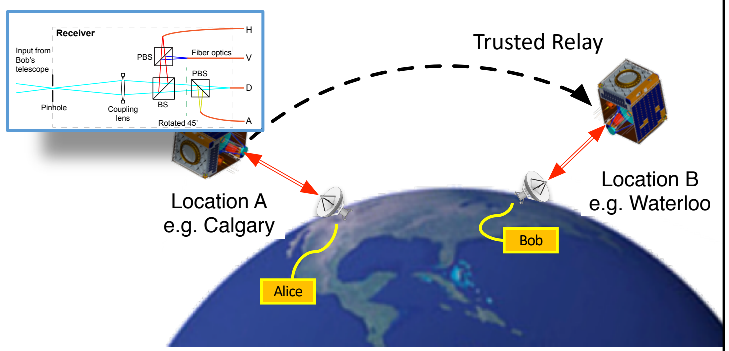
Funding will support new projects that will use Canadian innovations in space

Minister Bains, April 2017

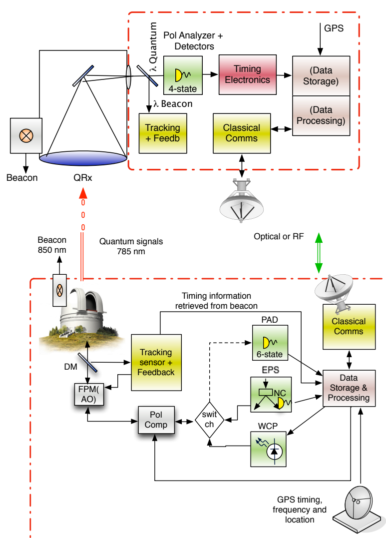
QEYSSat will be a Technology Demonstration Platform

- Optimized Quantum Receiver
- Multiple partners across Canada
  - Transmitter telescopes are 'compact'
  - Networking with fiber optics
  - Test link with various quantum sources
- Study of quantum link and entanglement science
- Multiple ground stations in Canada, and around the globe
- Research on ground station capabilities such as AO or different quantum emitters, etc.

http://www.spaceq.ca/honeywell-aerospace-wins-30-million-contract-to-build-qeyssat-satellite/

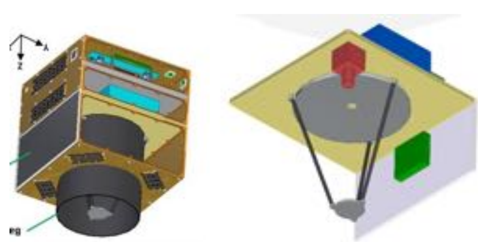


QEYSSat (Quantum Encryption and Science Satellite)



Anticipated Timeline:

- 2017 - 2022: Scientific PI Contract, Dr. Thomas Jennewein
- Industrial Implementation Contract **July 2019**
- Launch 2021/22

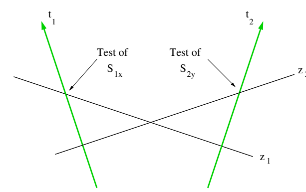


Micro-QEYS study, SFL + IQC, 2016
Quantum Sci. Technol. 2 (2017) 024009

T. Jennewein et al., volume 8997 of Proceedings of SPIE, 2014.
https://spaceq.ca/canadian-qeyssat-quantum-satellite-program-gets-next-round-of-funding/

Quantum links between ground and space

- Quantum source on ground:
  - QKD interfaces to fiber optics
  - Entanglement tests at varying distances and height
  - Gravitational decorrelation
  - Special relativity and QM
  - Variable-delay quantum memory
  - Quantum Teleportation, Quantum repeater interfaces



Timing ambiguity scenario,
Class. Quant. Grav., 29(22):224011 , 2012.

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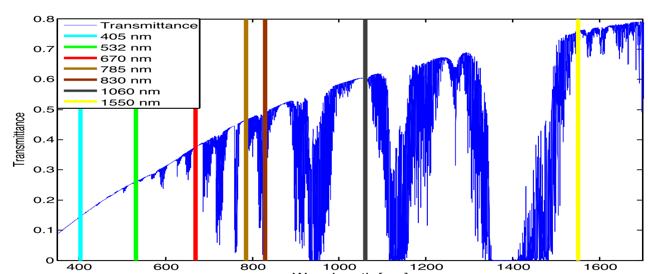
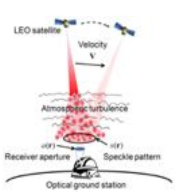
Modeling the performance of satellite to ground quantum link

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

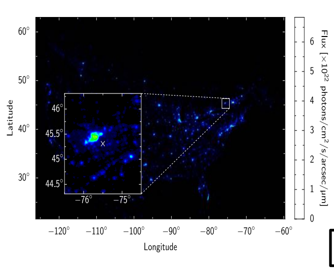


Wavelength (nm)	Downlink, WCP source	Uplink, WCP source	Downlink, entangled photon source	Uplink, entangled photon source
	Secure key length obtained for the upper quartile satellite pass (kbit)			
405	68.5	3.5	6.2	0
532	264.5	33.1	119.3	12.1
670	465.6	87.7	324.7	67.4
785	458.3	111.3	272.9	75.7
830	317.3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

North America – the cutout is centred around Ottawa



M. Toyoshima, op.Ex. 2011



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

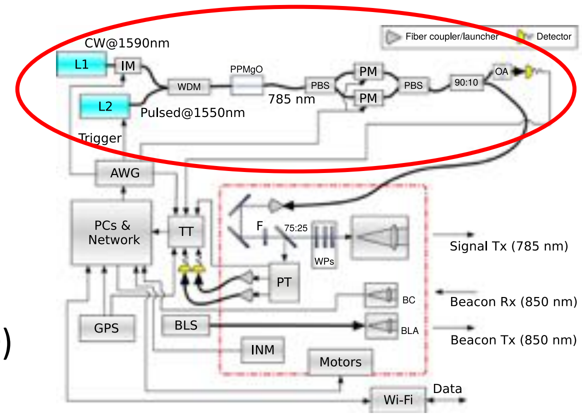
Related analysis:
J. Rarity et al, NJP, 2002
P. Villoresi group, NJP, 2009
R. Ursin group, NJP, 2013

QKD Source

Zhizhong Yan et al, Thomas Jennewein. JOURNAL OF LIGHTWAVE TECHNOLOGY, 31(9)1 2013.

C. Pugh et al., Quantum Science and Technology, 2017; 2 (2): 024009

- Weak coherent pulses
- Source rate up to 500 MHz
- Pulse duration <150 ps
- SFG two laser: pulsed 1550nm + CW 1590nm
- Signal at 785nm
- Polarization modulation with polarization MZI
- 3 Decoy state levels (μ = 0.5, 0.1, 0.0)

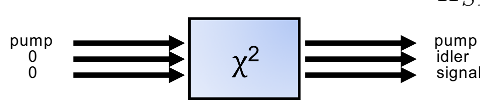


SPDC Entanglement Source – Optimal Rate?

$$\omega_p = \omega_s + \omega_i \quad \vec{k_p} = \vec{k_s} + \vec{k_i},$$

$$H_{SPDC} = \epsilon(a^\dagger b^\dagger + ba)$$

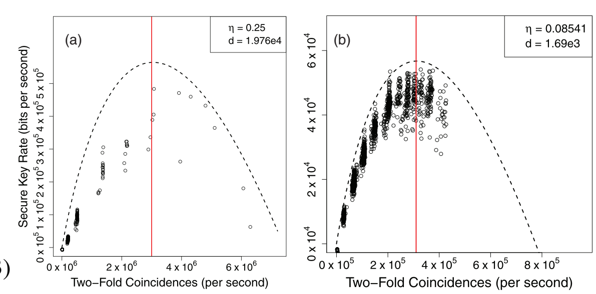
- Phase matching:



$$|\psi(\omega_i, \omega_s)\rangle = \int d\omega_i d\omega_s\, \delta(\omega_p - \omega_i - \omega_s)\mathrm{sinc}\left(\frac{L\Delta\mathbf{k}}{2}\right) a^\dagger_{i,H}(\omega_i) a^\dagger_{s,V}(\omega_s)\, |0\rangle\, .$$

- Pair production rate limited to around 100 MHz.
- SPDC suffers from multi-pair emission
- Optimization of source rate…

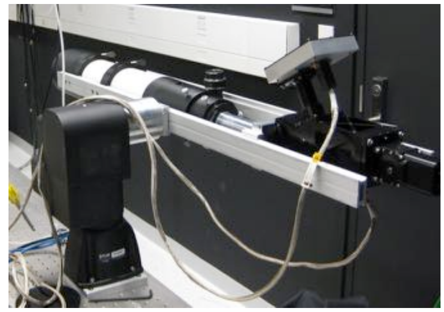
C. Holloway, et al. TJ, PHYSICAL REVIEW A **87**, 022342 (2013)



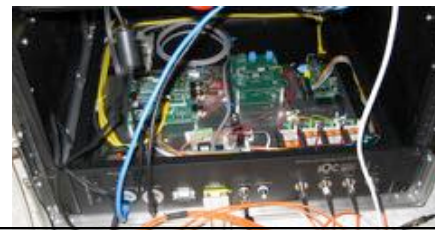
QEYSSat Payload Prototype

- Fully functional form-representative quantum-payload
- Components have ‘path to flight’
- Projected mass: ~ 23 kg, Power <30W, envelope ~ 60cm^3
- Tests: Radiation, TVAC, aircraft link

Full quantum receiver optics



Payload detectors and electronics



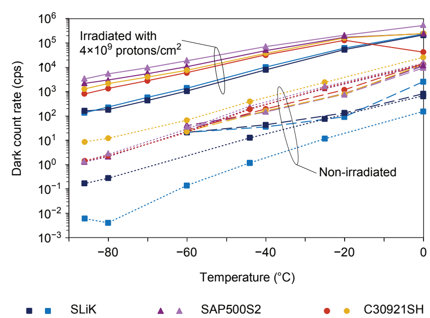
C. Pugh et al., Quantum Science and Technology, 2017; 2 (2): 024009

Press release: https://uwaterloo.ca/institute-for-quantum-computing/news/iqc-advances-quantum-satellite-mission

Radiation test of single-photon detectors

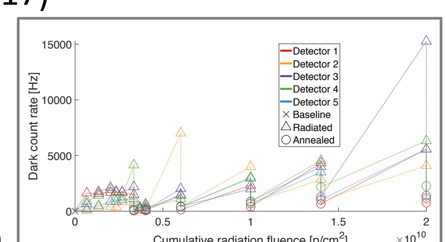
- Tests of equivalent-radiation-dose for LEO satellite (2015)
  - up to 2 years of mission life time: 100 MeV, $4*10^9$ p/cm^2
  - Several groups with SLIK, SAP500, CS30902, PMT

E. Anisimova et al, EPJ Quantum Technol. 4, 10 (2017)



- Detector Assembly (2017)
  - Cooling lower than -80 C
  - Annealing (up to +100 C)
  - Within requirements for mission.
  - SLIK (Excelitas)

In preparation.



Payload Prototype Installed in Aircraft

Payload on aircraft represents the full satellite prototype!

NRC Twin Otter aircraft, air speed: 90 kn to 120 kn
Lateral distance from ground station:
3 km to 10 km

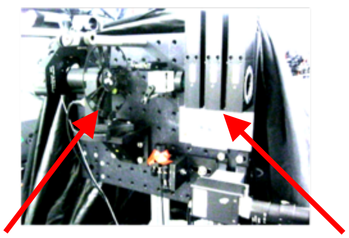
C. Pugh et al., Quantum Science and Technology, 2017; 2 (2): 024009

Ai

C. Pugh et al, Quantum Science and Technology, 2, 2, 024009 (2017)

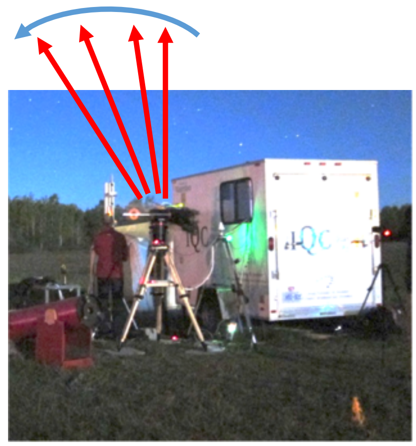
Example for Benefit of Source on Ground: Reference-Frame Independent Protocol

- Challenge for QKD implementations
  - How to align the reference frames (e.g. polarization states at Alice have to match Bob's)?
  - Particular problem in our case is the motion of the telescope
  - Realtime Compensation:



arxiv.org 1810.04112

Tomography Compensation



Airborne Transmitter, Smith Falls, 2016

C. Pugh et al, Quantum Science and Technology, 2, 2, 024009 (2017)

Our satellite receiver has limited resource of 4 states

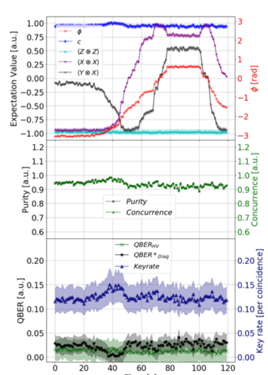
- New variant of the protocol: 6 – 4 state protocol

Channel Verification:

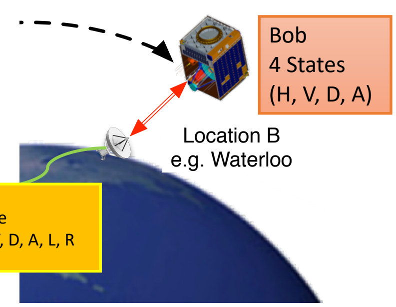
$$C = \sqrt{\langle X_A X_B \rangle^2 + \langle Y_A X_B \rangle^2},$$

$$\langle \sigma_Z \otimes \sigma_Z \rangle = (1 - 2Q)$$
$$\langle \sigma_X \otimes \sigma_X \rangle = (1 - 2Q) \cdot \cos\theta$$
$$\langle \sigma_Y \otimes \sigma_X \rangle = -(1 - 2Q) \cdot \sin\theta$$

$$\langle \sigma_V \otimes \sigma_X \rangle = (1 - 2Q)$$
$$\sigma_V = (\cos\theta)\sigma_X - (\sin\theta)\sigma_Y$$



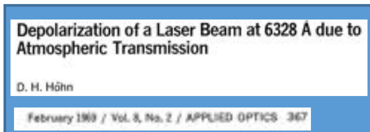
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A |1\rangle_B + e^{-i\phi} |1\rangle_A |0\rangle_B\right)$$



C will be constant even under varying phase theta, and if C drops <1, would reveal Eve!

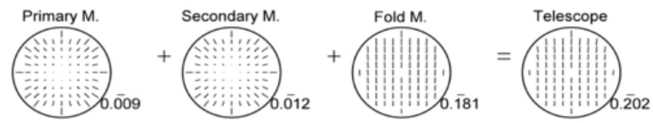
R. Tannous, et al. APL in press
Arxiv 1905.09197

Myth: You can only use polarization encoding in free-space quantum communications



Dpolarization measured ca. 10^{-7} to 10^{-5} rad.
Limited by apparatus and background light.

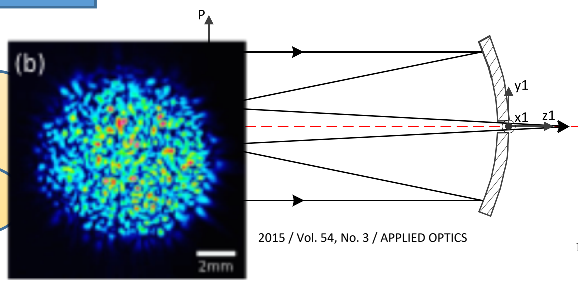
Polarization effect of mirrors due to **Fresnel-coefficients**



Retardance maps for each mirror element (*first three panels*) and the cumulative retardance for the entire telescope (*last panel*).

Breckinridge, Lam, Chipman, Publications of the Astronomical Society of the Pacific, Vol. 127, No. 951 (2015), pp. 445

What about Time-bin encoding in Free-Space?



2015 / Vol. 54, No. 3 / APPLIED OPTICS

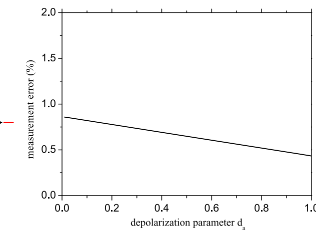
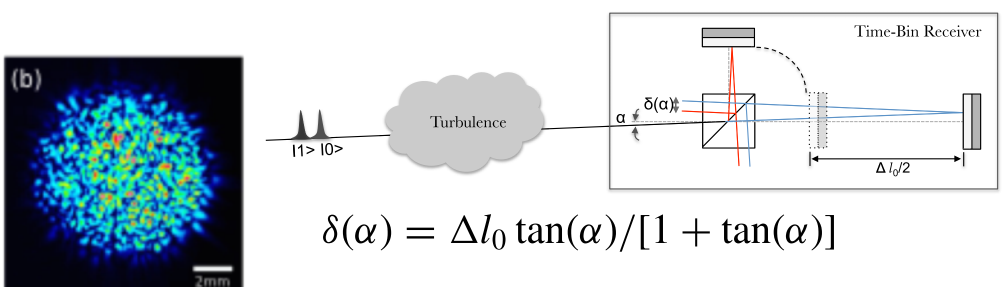


Fig. 4. Measurement error, induced by a Cassegrain telescope

The issue with asymmetric MZI and distorted modes

- Different incident angles and modal distortions experience different Phase
- Tim—bin analyzer interferometer with ‘flat’ optics not suitable

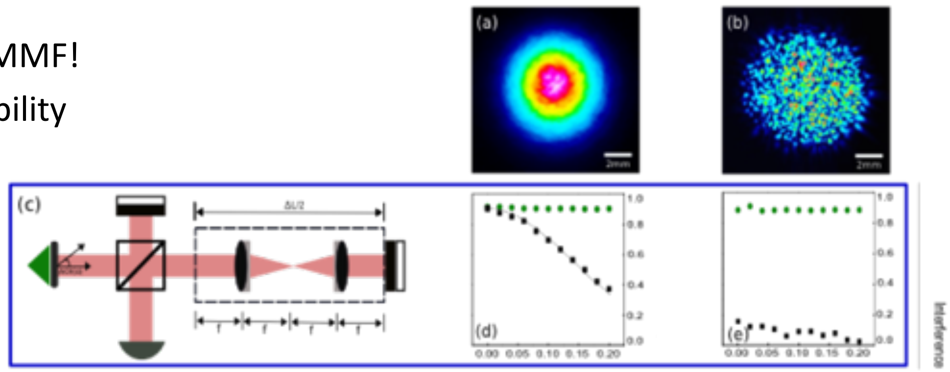


$$\delta(\alpha) = \Delta l_0 \tan(\alpha)/[1 + \tan(\alpha)]$$

- [J. Jin, S. Agne, J.P. Bourgoin, Y. Zhang, N. Lutkenhaus, T. Jennewein, arXiv:1509.07490,
- Phys. Rev. A 97, 043847 (2018)]

Unbalanced Interferometer Suitable for Multi-mode Quantum States

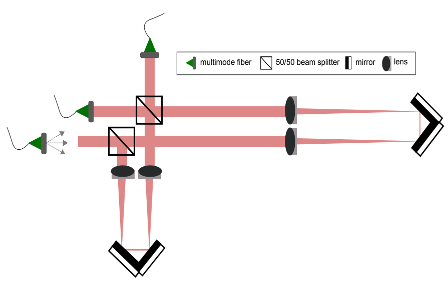
- Compatibility with Multi-mode Photonic Qubits
- QKD over MMF!
- > 93 % visibility

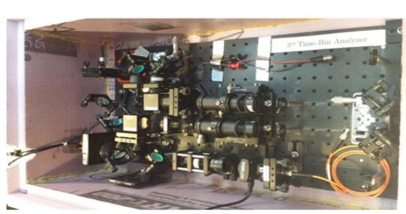


- [J. Jin, S. Agne, J.P. Bourgoin, Y. Zhang, N. Lutkenhaus, T. Jennewein, arXiv:1509.07490,
- Phys. Rev. A 97, 043847 (2018)]

2018: New Configuration with Symmetric Imaging Paths

- Observed interference visibilities of >97 % for both outputs,
- average visibility of 98.5 % for the 4 QKD states.
- Photon collection into a multimode fiber of 80 %, from input to output!





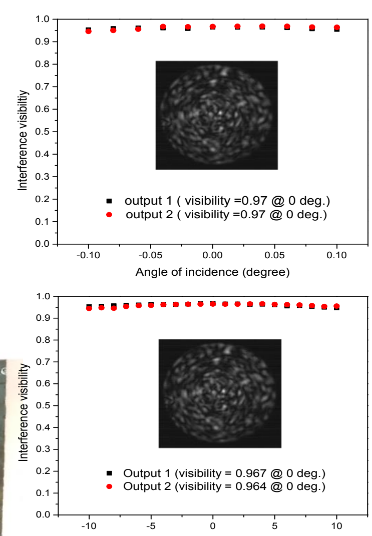
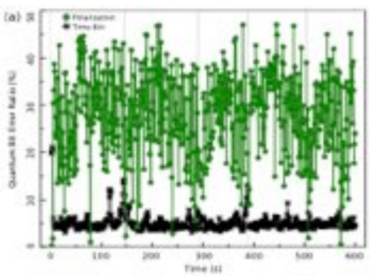


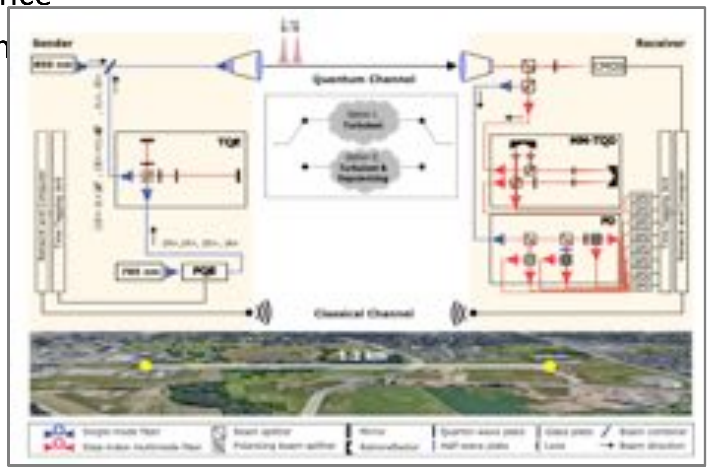
Figure 2. Measured interference visibilities with multimode beam (inset) while varying incidence (a) and rotation (b) angles.

Outdoor Time-Bin QKD Channel

- 1.2 km outdoor link
- Introduced additional turbulence
- also introduced depolarization
- Full BB84 protocol

	Turbulent	Turbulent & Depolarzing
Signal photons/ pulse	0.488	0.520
Decoy photons/ pulse	0.082	0.094
Background/ pulse	3.65×10^{-7}	3.45×10^{-7}
Channel loss (dB)	38.4	38.8
$QBER_{time}^{mean}$ (%)	5.32	5.08
Key rate (bits/s)	154.2	138.8



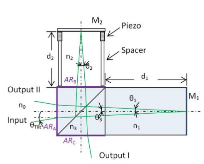


Jeongwan Jin et al., arxiv. arXiv:1903.06954 [quant-ph], To appear in Optics Express.

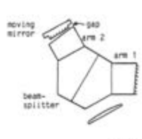
Asymmetric Interferometer Using Refraction

- We tested a different approach: using refraction to compensate field
- Refractive index cancels walk-off!

$$\boxed{d_1 / n_1 - d_2 / n_2 = 0.}$$



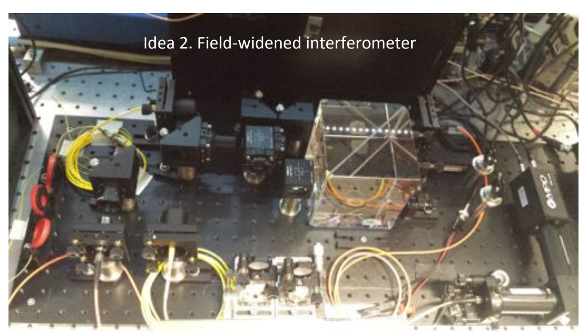
Dong Liu ,
2012 / Vol. 20, No. 2 / OPTICS EXPRESS



DOPPLER IMAGING WITH FIELD-WIDENED MICHELSON INTERFEROMETERS

G.G. Shepherd, W.A. Gault, R.H. Wiens, W. Ward
Centre for Research in Experimental Space Science
York University, Downsview, Ontario, M3J 1P3, Canada

sponsorship of the Space Division of the National

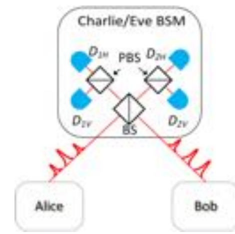


Measured Interference Visibilities, 118 mm glass cube:
Time delay: 0.57 ns
Multimode Fiber input beam:
V= 0.95 (comp basis), V=0.90 (superposition basis)

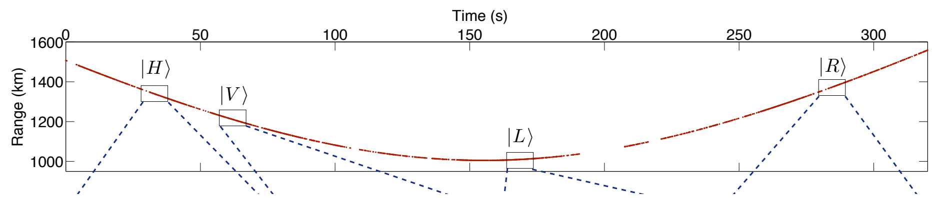
- [J. Jin, S. Agne, J.P. Bourgoin, Y. Zhang, N. Lutkenhaus, T. Jennewein, arXiv:1509.07490,
- Phys. Rev. A 97, 043847 (2018)]

Towards free-space MDI-QKD

- No trust on the central Bell-state measurement
- Ideally, the BSM would be located on the moving Systems, such as airplanes or satellites.
    - Challenge: The time-of-flight for each channel will be variable



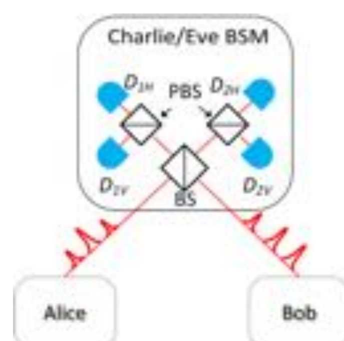
Hoi-Kwong Lo group, Physical Review Letters 112(19), 2013



Vallone et al. PRL, 2014

Challenge

- How to synchronize the wave packets emitted by Alice, Bob, such that they interfere on Charlie's beam splitter?
- With a moving systems, a real-time compensation is challenging.
    - Alice-Charlie, and Bob-Charlie, must independently measure the exact round trip time for their channels, and actively compensate for any changes.
    - This measurement requires two-way propagation of synchronization information (a-la Einstein)



Hoi-Kwong Lo group, Physical Review Letters 112(19), 2013

Generalized HOM Interference

- HOM with CW beams

$$G^{(2x)}(t_3,t_4) := \left\langle \hat{E}_3^-(t_3)\hat{E}_4^-(t_4)\hat{E}_4^+(t_4)\hat{E}_3^+(t_3)\right\rangle$$

CW lasers:

$$G^{(2x)}(\tau) = 1 - \frac{1}{2}\exp\left[-\frac{2|\tau|}{\tau_{\mathrm{coh}}} - \frac{2\tau^2}{\tau_{\mathrm{coh}}^2}\right]$$

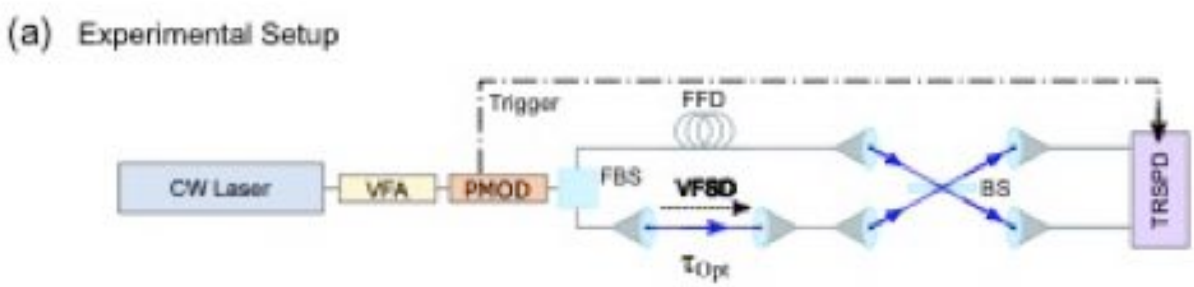
Square Modulated Lasers:

$$G^{(2x)}(t_0,\tau_{\mathrm{Opt}}) = \frac{1}{4}\left(3 - \mathrm{SW}_{-1}^{1}\left[\frac{t_0}{T_{\mathrm{Mod}}}\right]\mathrm{SW}_{-1}^{1}\left[\frac{t_0-\tau_{\mathrm{Opt}}}{T_{\mathrm{Mod}}}\right]\right).$$

$$\begin{aligned}G^{(2x)}(t_3,t_4) = {} & \frac{1}{4}|\zeta_1(t_3)\zeta_1(t_4)|^2\left\langle|\alpha_1(t_3)|^2|\alpha_1(t_4)|^2\right\rangle_{\alpha_1} \\ & + \frac{1}{4}|\zeta_2(t_3)\zeta_2(t_4)|^2\left\langle|\alpha_2(t_3)|^2|\alpha_2(t_4)|^2\right\rangle_{\alpha_2} \\ & + \frac{1}{4}|\zeta_1(t_3)|^2|\zeta_2(t_4)|^2\left\langle|\alpha_1(t_3)|^2\right\rangle_{\alpha_1}\left\langle|\alpha_2(t_4)|^2\right\rangle_{\alpha_2} \\ & + \frac{1}{4}|\zeta_1(t_4)|^2|\zeta_2(t_3)|^2\left\langle|\alpha_1(t_4)|^2\right\rangle_{\alpha_1}\left\langle|\alpha_2(t_3)|^2\right\rangle_{\alpha_2} \\ & - \frac{1}{2}\Re\left\{\zeta_1^*(t_3)\zeta_1(t_4)\zeta_2(t_3)\zeta_2^*(t_4)G_1^{(1)}(\tau)G_2^{*(1)}(\tau)\right\},\end{aligned}$$

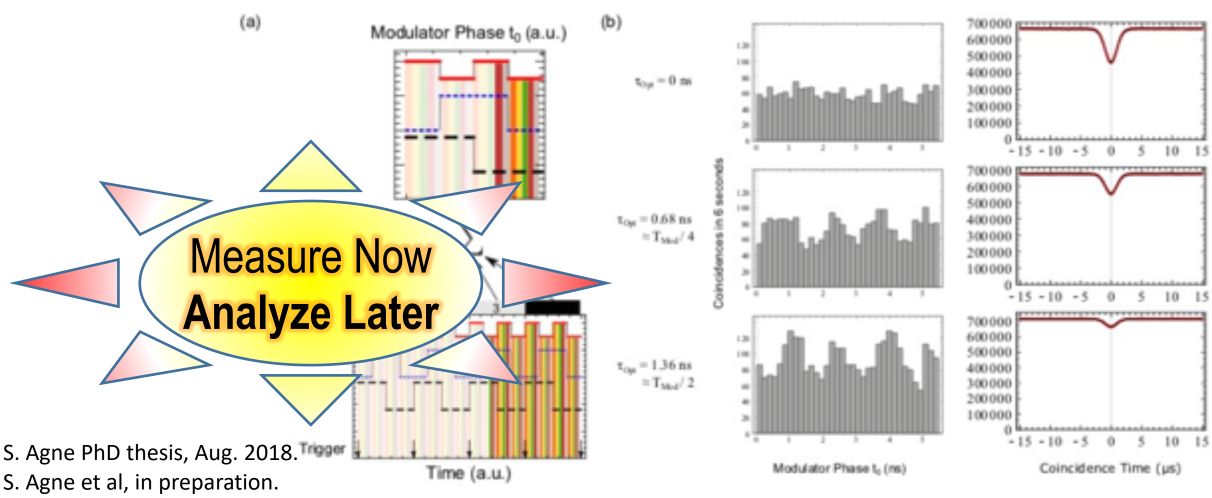
Experiment

Utilized narrow-band CW laser
Delay larger than coherence time (> 1 µs)



Time-resolved HOM

HOM coincidences sorted
based on modulation timing.



S. Agne PhD thesis, Aug. 2018.
S. Agne et al, in preparation.

Quantum Network enhanced telescopes

PRL **109,** 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

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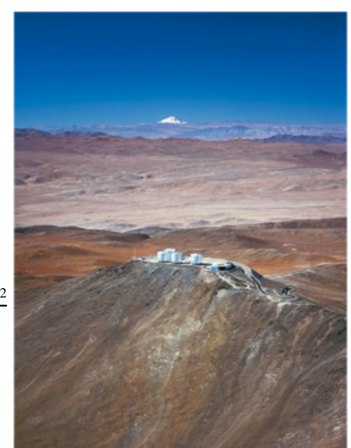
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)



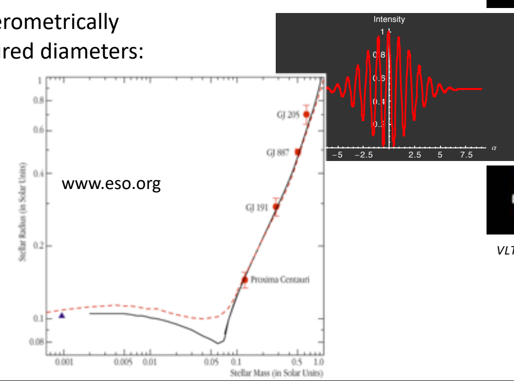
VLTI, ESO.org
ESO/G.Hüdepohl (atacamaphoto.com)

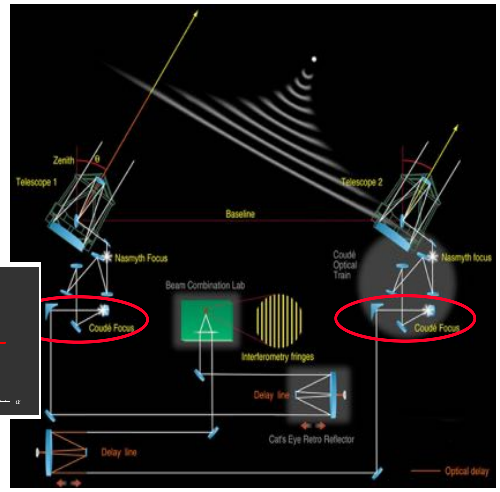
66

VLBI Scheme

- Two telescopes
  - Baseline B
- The beams are interfered
- Visibility(B) gives the highly detailed image (after processing)

Interferometrically measured diameters:

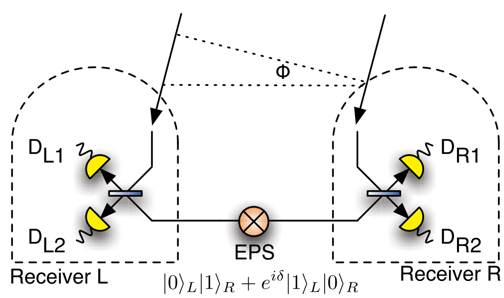




VLTI Concept & technical aspects, B. Koehler, 20 November 2001, Garching

We can do the same using entanglement

$$\rho = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & \mathcal{V}^* & 0 \\ 0 & \mathcal{V} & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \rightarrow |0\rangle_L|1\rangle_R + e^{i\phi}|1\rangle_L|0\rangle_R$$

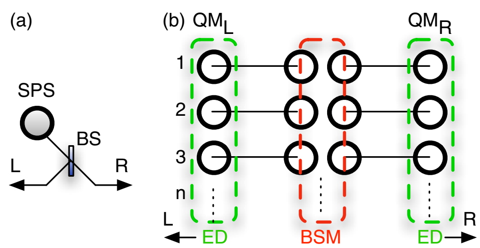


- Double detection (L,R) post-selects entangled states, and fringes with the Visibility (B)
  - Click probability (L1,R1 or L2,R2):

$$\boxed{[1 + \mathrm{Re}(\mathcal{V}e^{-i\delta})]/2}$$

Establish the entangled state

- Simplest case is just one single photon and a BS.
- Source on a satellite
- Ideal: quantum repeaters



Experimental Estimates

- Detector timing jitter ca. 35 ps
- BW of the photons narrow filtered, so that coherence times match the (0.025nm@532nm), jitter (see 2019 on interference between single photon and star light)
- Short exposure due to atmosphere (10 ms)
  - **Sensitivity: apparent Mag 7.5**

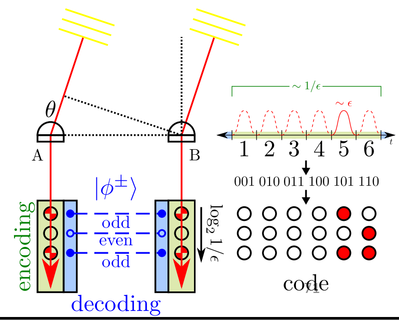
Quantum repeaters for astronomy

Eventhorizontelescope.org

- For much larger baselines, the direct optical connections might be very hard to achieve.
  - Quantum repeaters can help, because they ideally overcome losses and fidelity
- Connecting multiple telescopes: W-state
- Optimize repeater protocols for this regime
- Recent work by Lukin Group (Haravard)

$$e^{i\delta_1}|100\ldots0\rangle + e^{i\delta_2}|010\ldots0\rangle + e^{i\delta_3}|001\ldots0\rangle + \cdots + e^{i\delta_n}|000\ldots1\rangle$$

e.g. Sanguard et al, Phys. Rev. A 78, 050301 (2008)



E. T. Khabiboulline, J. Borregaard, K. De Greve, and M. D. Lukin. Optical interferometry with quantum networks. Phys. Rev. Lett., 123:070504, 2019.

E. T. Khabiboulline, J. Borregaard, K. De Greve, and M. D. Lukin. Quantum-assisted telescope arrays. Phys. Rev. A, 100:022316, Aug 2019.

Summary

- Quantum Internet
- Quantum Communication in Space
- QEYSSat mission
- Exploring new directions for Free-Space Quantum Communications:
  - Time-bin
  - MDI-QKD
  - RFI-QKD

Research on 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 technologies
- Cost

Thank You

UNIVERSITY OF WATERLOO
IQC Institute for Quantum Computing
Honeywell
CSA ASC
UTIAS SFL
neptec
Xiphos Technologies
INO
QEYnet As Secure as Physics Itself
EXCELITAS TECHNOLOGIES
UQDevices
DEFENCE DÉFENSE
NSERC CRSNG
Industry Canada
Industrie Canada
TQT Transformative Quantum Technologies
CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH
Ontario MINISTRY OF RESEARCH & INNOVATION
MINISTRY OF ECONOMIC DEVELOPMENT AND INNOVATION
INNOVATION.CA CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION