DEPARTMENT OF NETWORKED SYSTEMS AND SERVICES

Technological challenges of free-space and satellite-based quantum communication systems

May 12, 2025

Quantum Computing and its Applications

BMEVIHIMA16, Spring 2025

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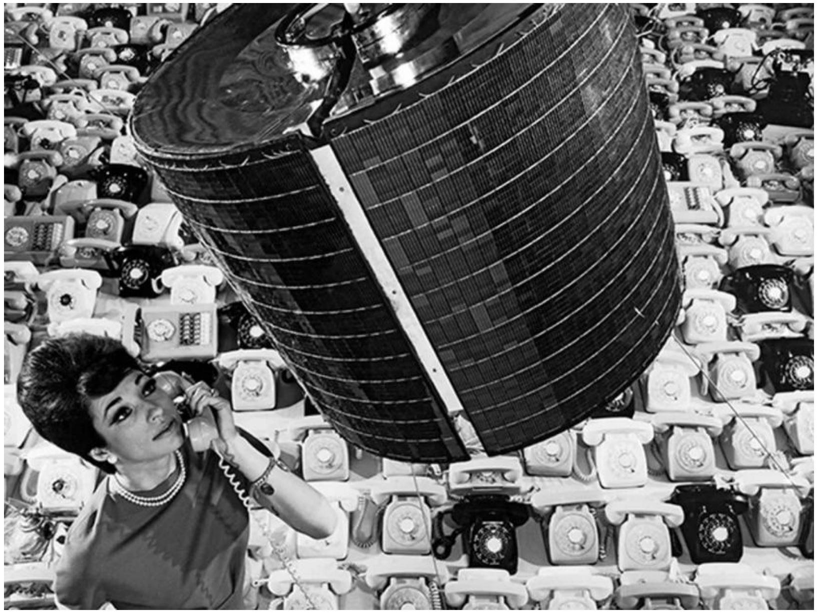
MŰEGYETEM 1782

SATELLITE COMMUNICATION

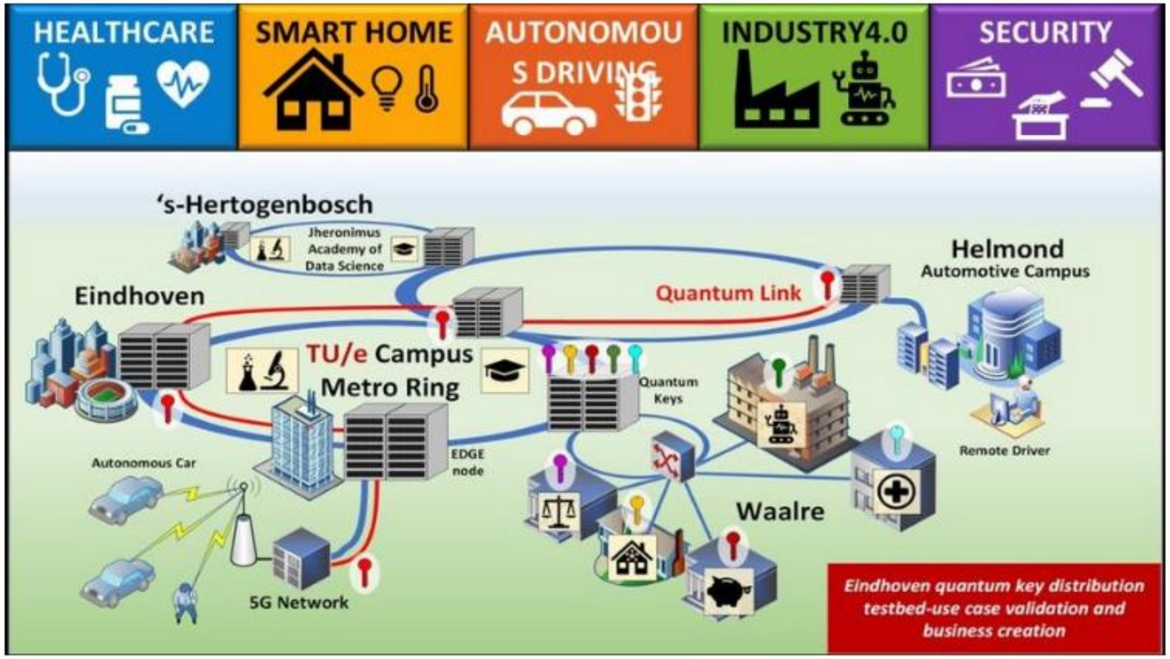
- 1965. Intelsat 1F-1 (Early Bird)
- Passive or active space segment
- Point to point, zone, global network



Quantum Connections

QSN: Quantum Security Network

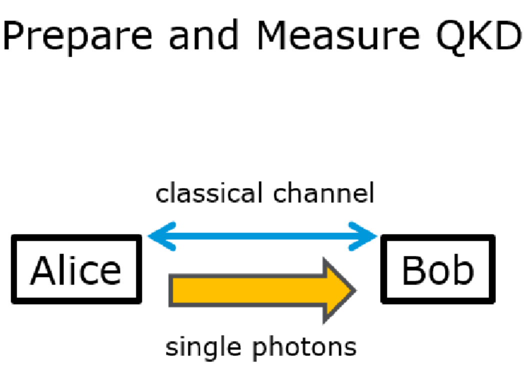
QIN: Quantum Information Network

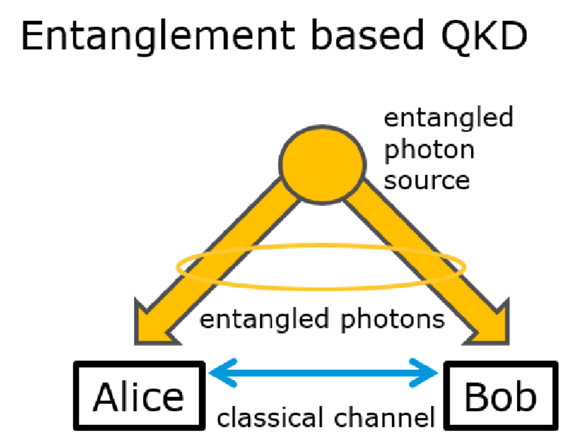


TYPES OF QKD

Two types

① Prepare-and-measure ② Entanglement based

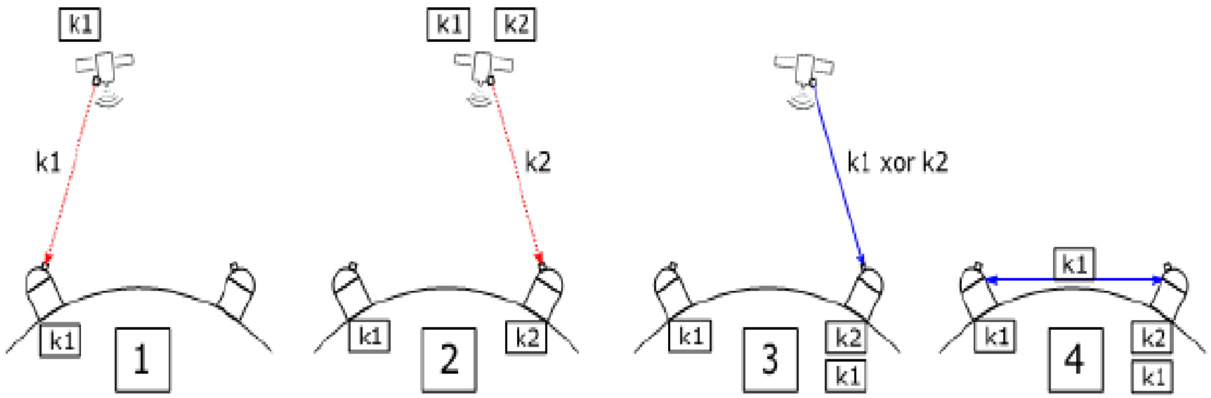




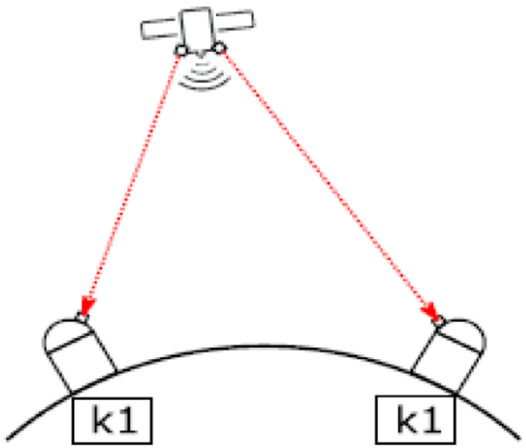
Two generations

First generation: Discrete Variable, DV QKD)
Second generation: Continues Variable, CV QKD)

ARCHITECHTURES OF QKD-BASED SATELLITE

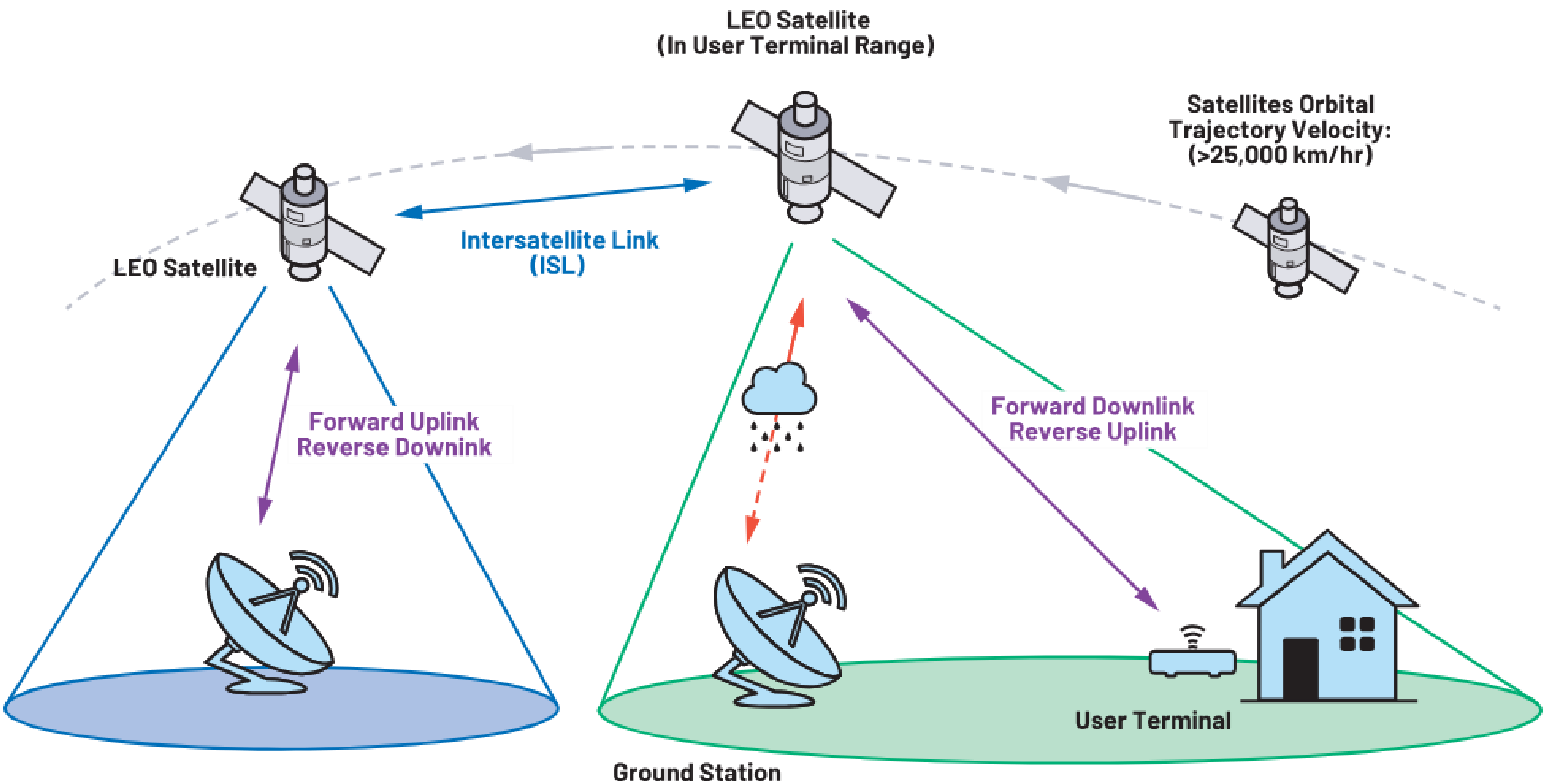


Prepare & Measure



Entanglement-based

GROUND-SPACE SCENARIO FOR LEO SATELLITE COMMUNICATION



CHALLENGES

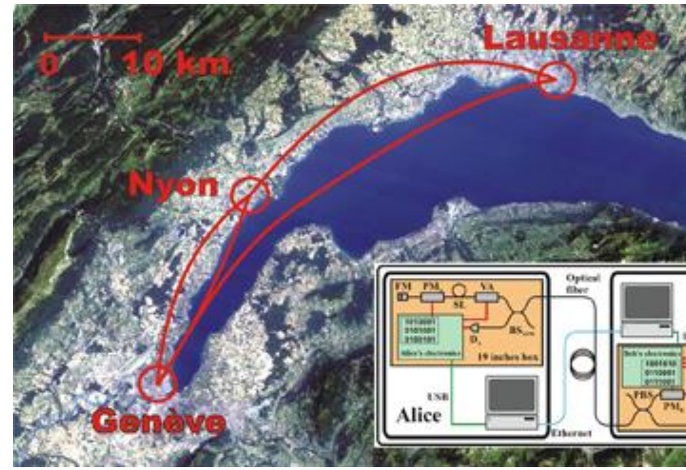
CHALLENGES

- How to create 1 photon only?
- How to make the right measurement?
- Speed / bandwidth / capacity
- Scalability
- Errors on channel
- Syncronization

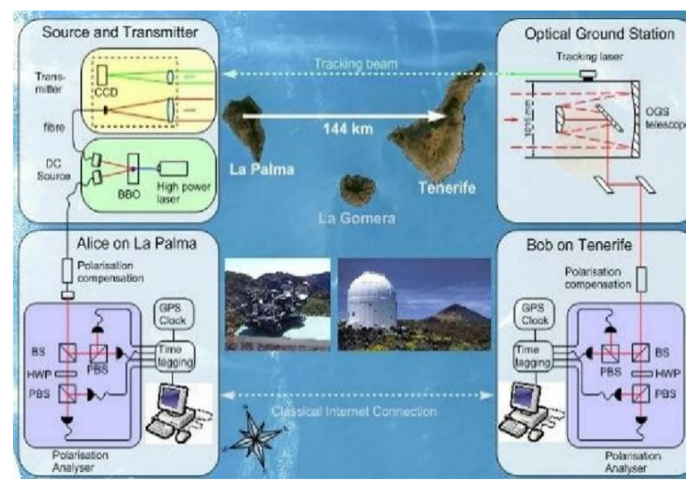
Free-space quantum communications

DISTANCES

1989/91	0.3 m
1993	1100 m
1995	23 km
2007	67 km
2016	404 km
2020	509 km

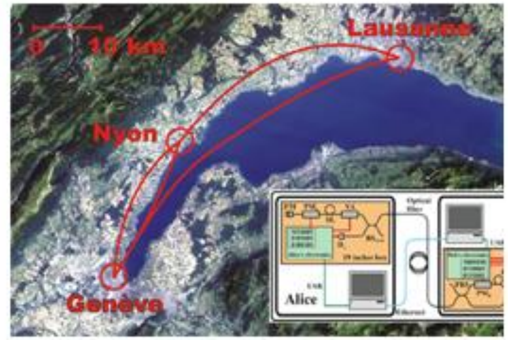


1991	0.3m
1996	75 m
1998	1 km
2002	10 km
2006/2007	144 km
2016	space



DIFFERENT IMPLEMENTATIONS

1989/91	0.3 m
1993	1100 m
1995	23 km
2007	67 km
2016	404 km
2020	509 km



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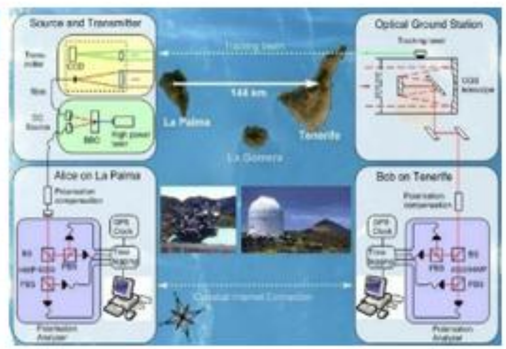


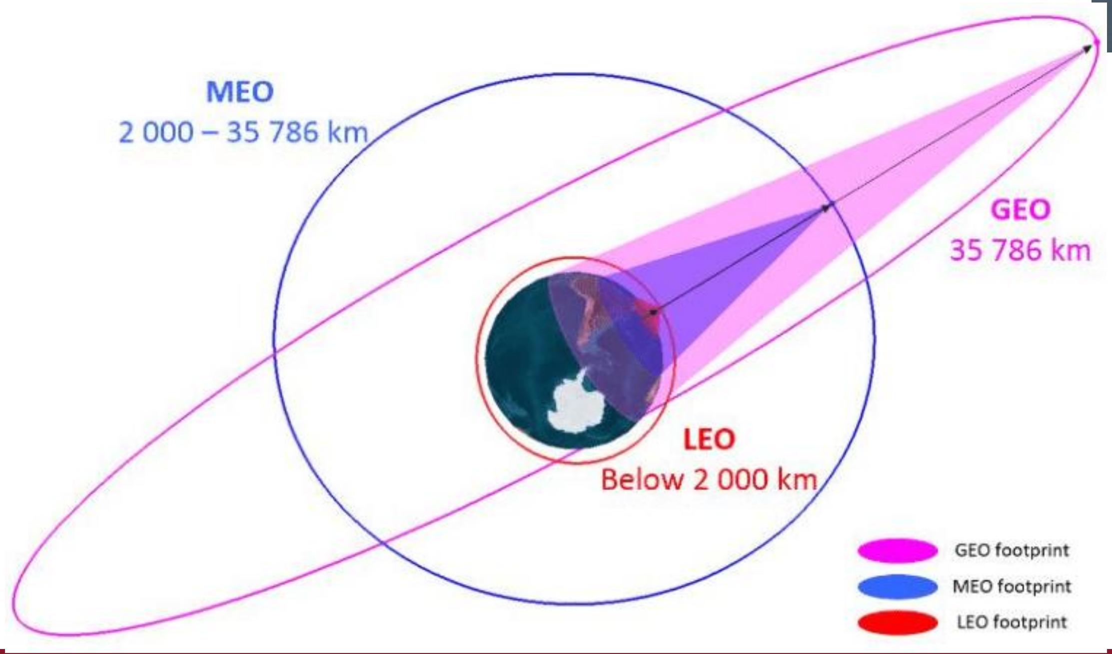
1991: First introduced over optical path of about 30 cm
1998: The research group at Los Alamos National Laboratory, reached 950 m under nighttime conditions
2002: The same laboratory demonstrated that free-space QKD is possible by daylight or at night, at 9.81 km
2006/2007: Distance of 144 km was reached by an international research group (TU Wien, Austria) (QKD)
2016: China- Micius
2019: Singapore –SpooQy-1
2023: The work continues

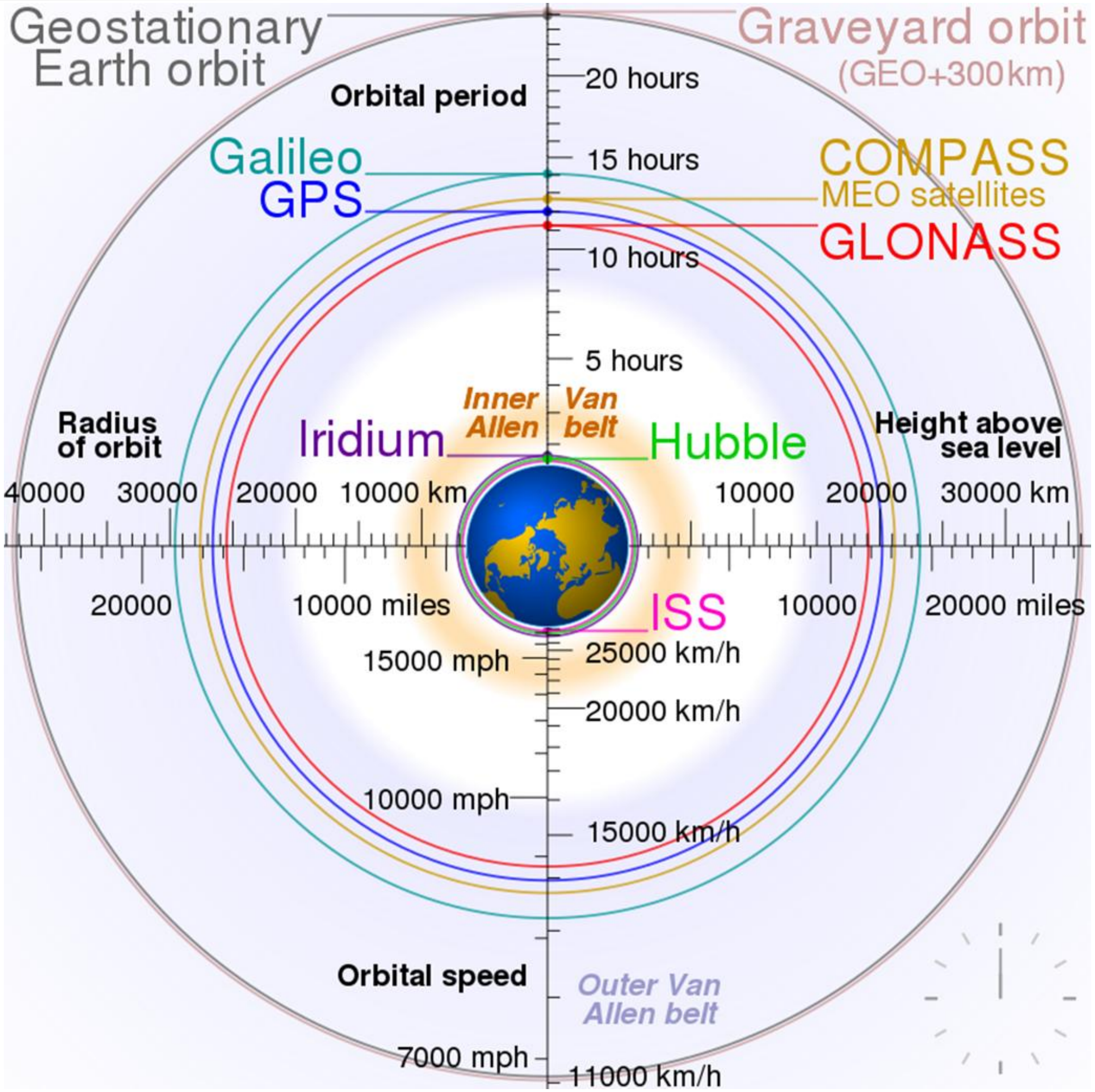
SATELLITE ORBITS

LEO (Low Earth Orbit)

MEO (Middle Earth Orbit)

GEO (Geostationary Orbit)




Geostationary Earth orbit
Graveyard orbit
(GEO+300km)
Orbital period
20 hours
15 hours
10 hours
5 hours
Galileo
GPS
COMPASS
MEO satellites
GLONASS
Inner Van Allen belt
Iridium
Hubble
Radius of orbit
Height above sea level
40000
30000
20000
10000 km
10000
20000
30000 km
20000
10000 miles
10000
20000 miles
ISS
15000 mph
25000 km/h
20000 km/h
10000 mph
15000 km/h
Orbital speed
Outer Van Allen belt
7000 mph
11000 km/h

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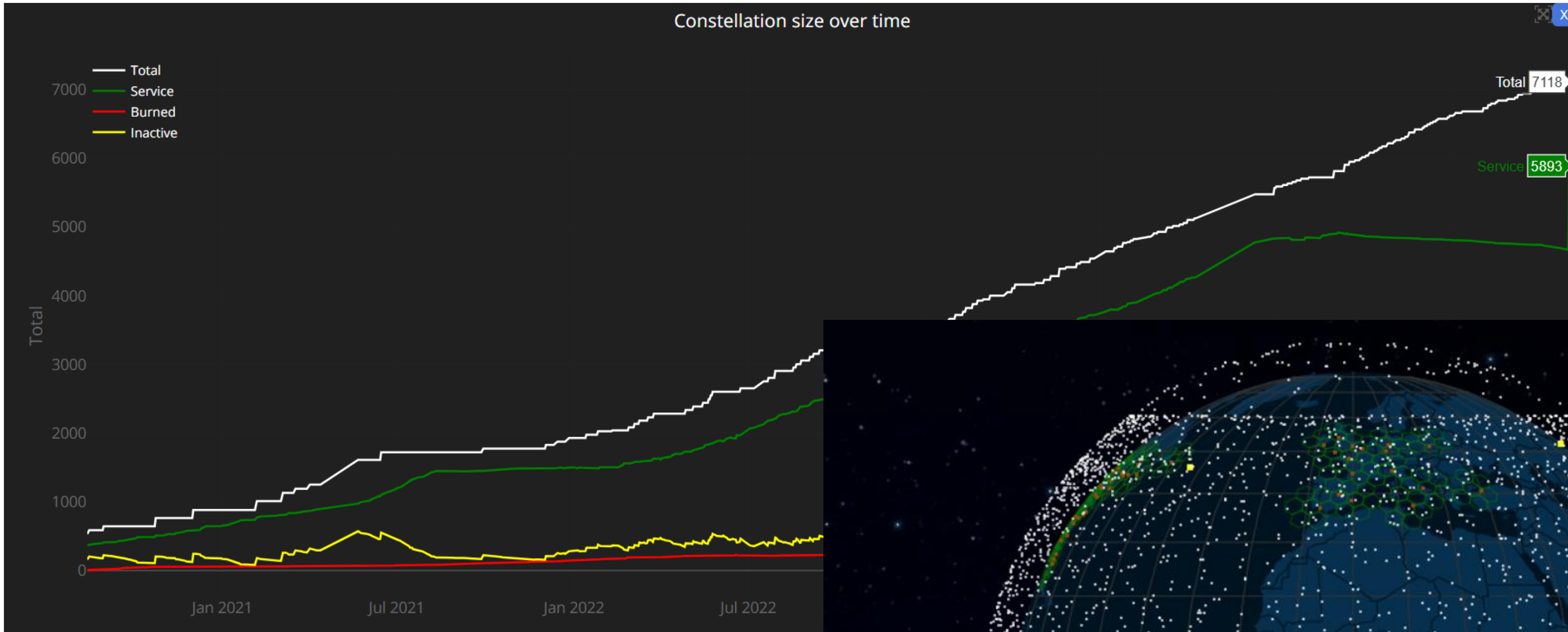
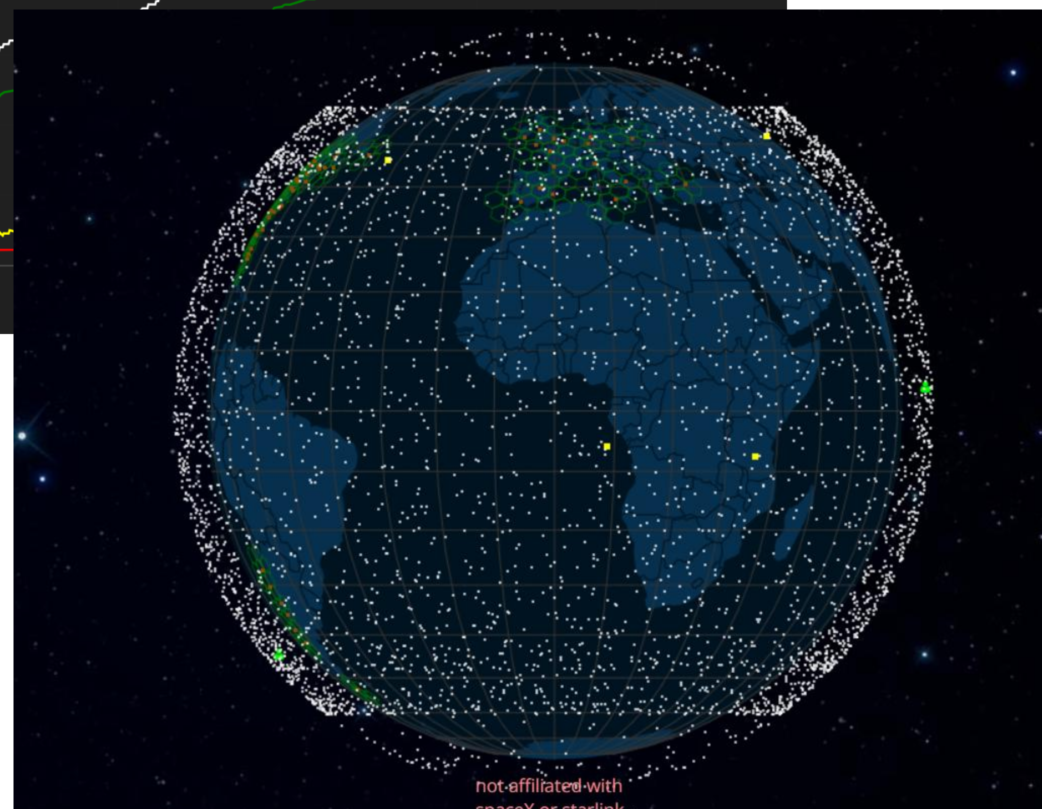
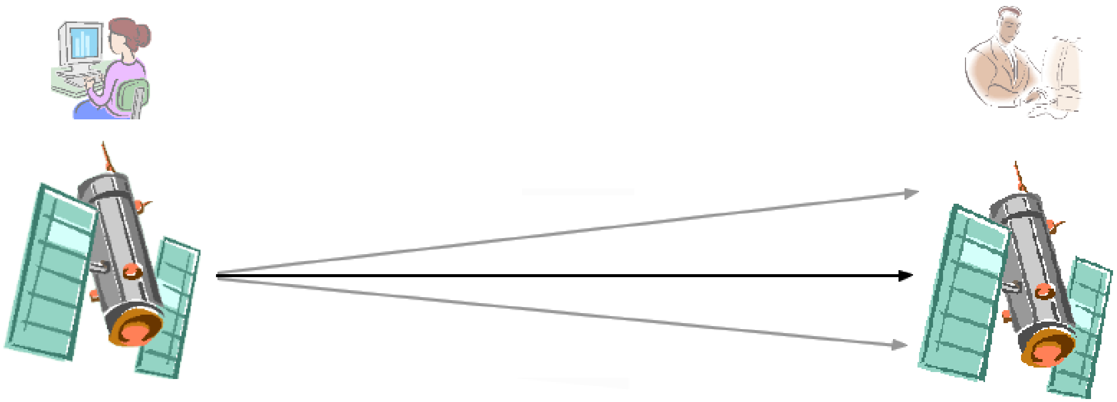
STARLINK

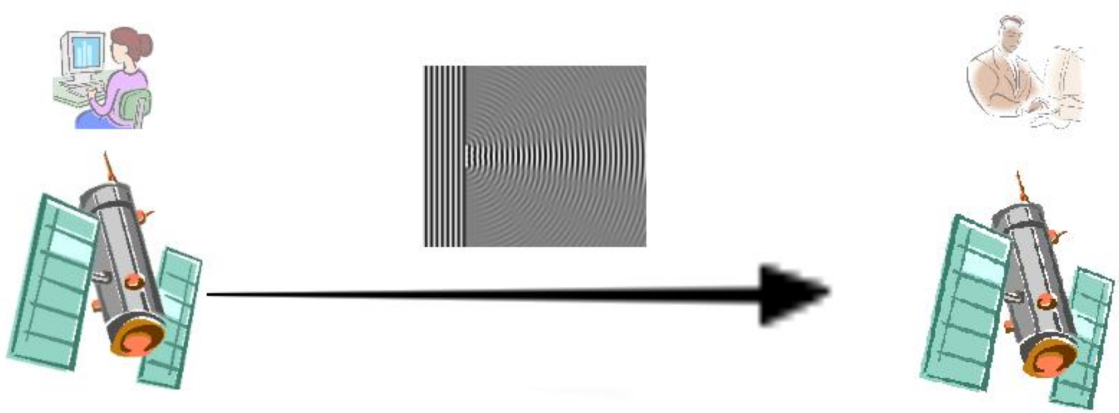




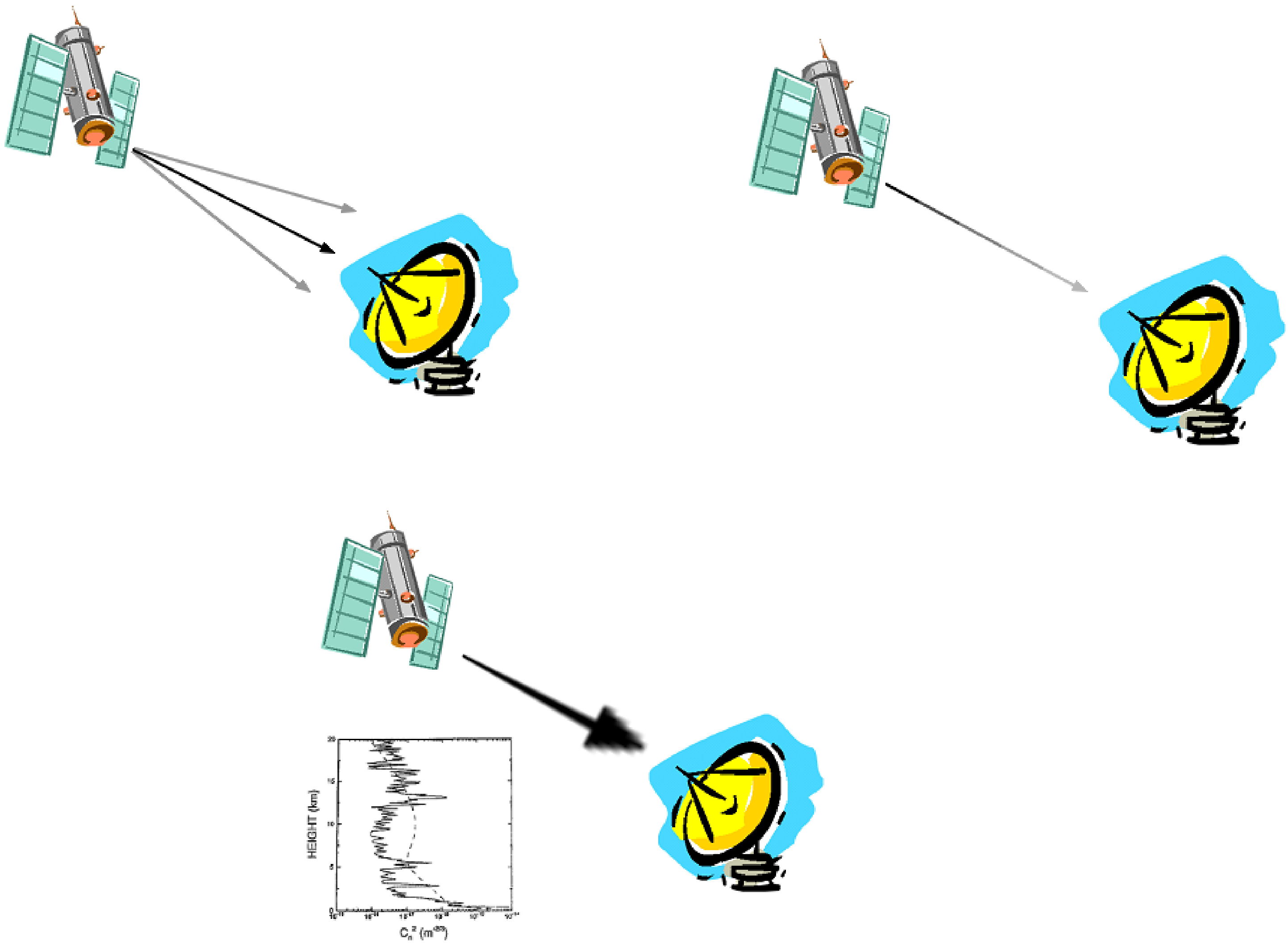
https://satellitemap.space/?constellation=starlink#

MODELING SATELLITE-SATELLITE QUANTUM CHANNEL





MODELING SATELLITE-GROUND QUANTUM CHANNEL



CHANNEL MODEL

- The model is based on
  - the properties of recently used single-photon sources
  - the loss caused by the gases of the atmosphere
  - the aerosols and optical turbulence of the atmosphere.
- In space–space links
  - photons can miss Bob’s detector because of diffraction induced beam spreading and the pointing error of Alice’s apparatus.
- In ground–space or ground–ground links
  - optical turbulences further spread the beam, and even cause long term beam wonder.

CHANNEL MODEL

- Beam spreading in space-space communication

$$\rho = \sqrt{\frac{4L^2}{k^2 {D_A}^2} + \frac{{D_A}^2}{4}}$$

D_A : aperture size of Alice's telescope
L: link distance
k: wavenumber of laser

- In atmosphere

$$\rho = \sqrt{\frac{4L^2}{k^2 {D_A}^2} + \frac{{D_A}^2}{4} + \frac{4L^2}{(k \cdot \rho_0)^2}\left(1 - 0.62\left(\frac{\rho_0}{D_A}\right)^{1/3}\right)^{6/5}}$$

where

$$\rho_0 = \left[1.46 k^2 \int_{L_1}^{L_2} C_n^2(z)\left(1 - \frac{z}{L}\right)^{5/3} dz\right]^{-3/5}$$

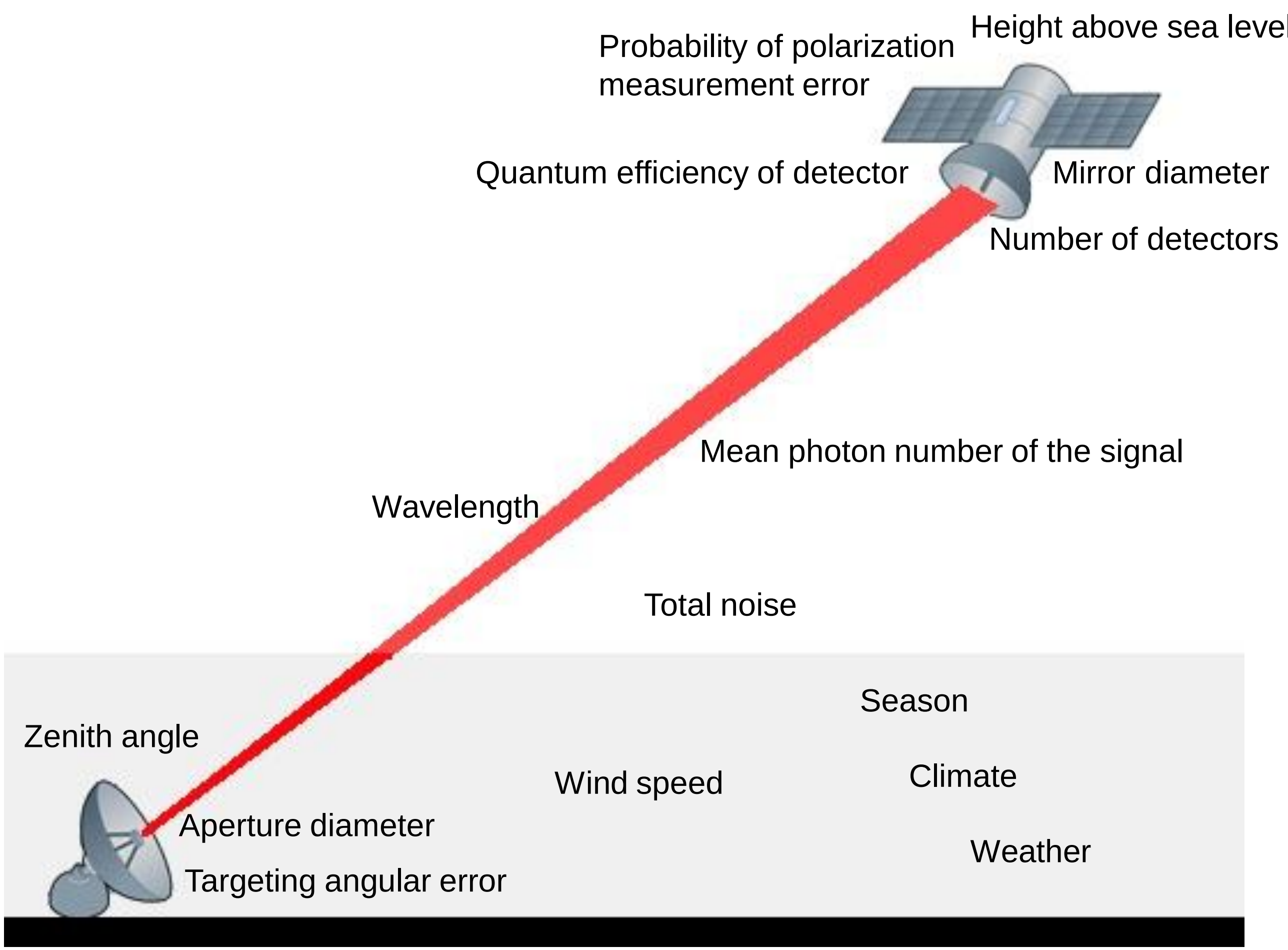
C_n^2 : turbulence strength

from the Hufnagel-Valley 5/7 model

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

h : com.channel in kilometers
W: high altitude wind speed (typical 21 m/s)
A: strength of turbulence near the ground (typical: $1.7 \cdot 10^{-14}$ $m^{-2/3}$)

CHANNEL MODEL



L. Bacsardi and S. Imre, “Supporting Space Communications with Quantum Communications Links”, Global Space Exploration Conference. Washington D.C., USA, 2012, Paper 12300.

CHANNEL MODEL

Total transmittance

$$\tau = \tau_{\mathrm{AIR}} \cdot \tau_{\mathrm{DET}}$$

τ_{DET}

percentage of photons arriving to a circular detector with R_B radius

where

τ_{AIR}

losses in the atmosphere

$$\tau_{\mathrm{AIR}} = \exp\left(-\sum_{\mathrm{i}} (s_{\mathrm{i}} + a_{\mathrm{i}}) \cdot \Delta L_{\mathrm{i}} \right)$$

ΔL_{i} given layer
s: scattering coefficient
a: absorption coefficient

s and *a*: depends on weather and location

ANALYZING BB84

- Quantum Bit Error Rate (QBER)

$$QBER = p_{pol} + \frac{p_{dark} \cdot n}{\tau \cdot \eta \cdot 2 \cdot \mu}$$

p_{pol} probability of a photon arriving at the wrong detector
p_{dark} probability of dark count
n number of detectors
η mean photon number
μ efficiency of detector

If QBER is higher than 0.11, the communication is not safe.

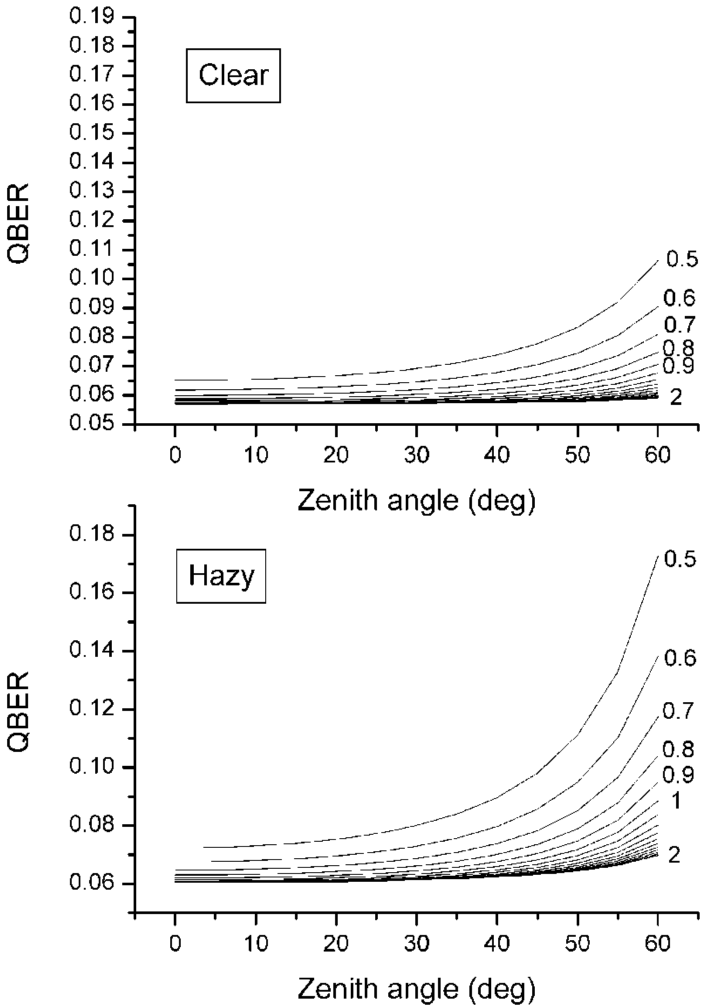
Errors are caused by the channel or by an eavesdropper?

- bitrate

$$R = \frac{1}{2} \cdot f_{\text{Laser}} \cdot \mu \cdot \tau \cdot \eta$$

f_{Laser} frequency of generated laser pulses

ANALYZING BB84

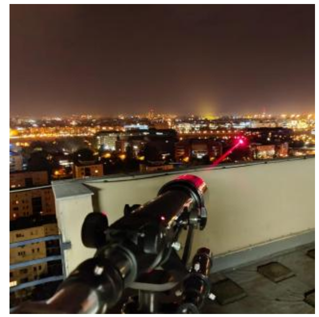


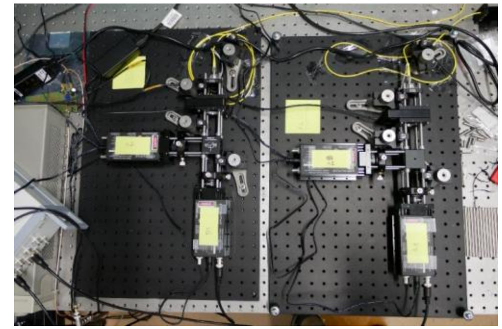
$$QBER = p_{pol} + \frac{p_{dark} \cdot n}{\tau \cdot \eta \cdot 2 \cdot \mu}$$

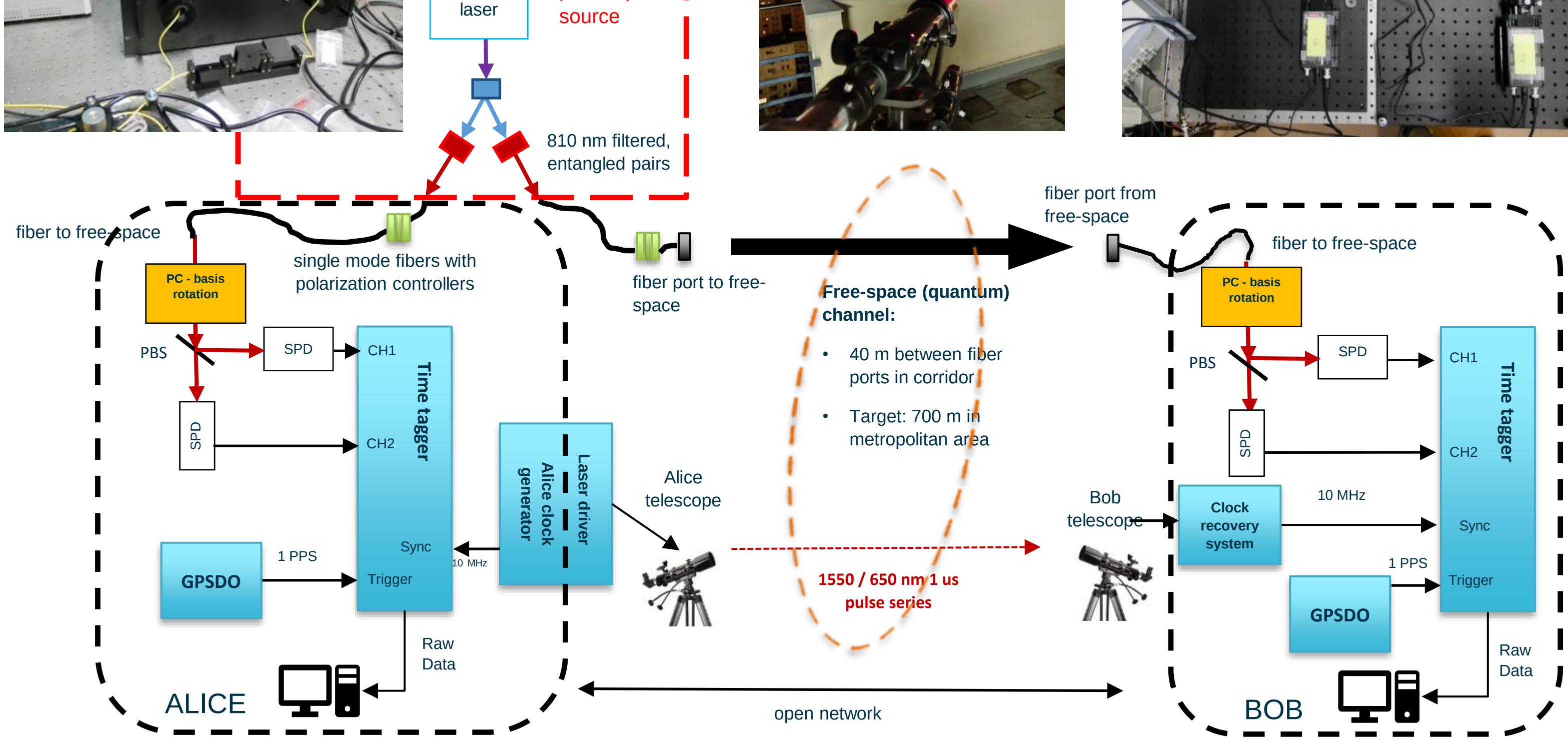
Summer, normal climate
Orbit: 300 km
Clear weather: 23 km
Hazy weather: 5 km
Size of Alice's aperture: 0.2 m
P_{pol}=0.05;
$P_{dark}=2\cdot 10^{-4}$;n=4; μ=0.1; η= 0.7

Experiments at BME

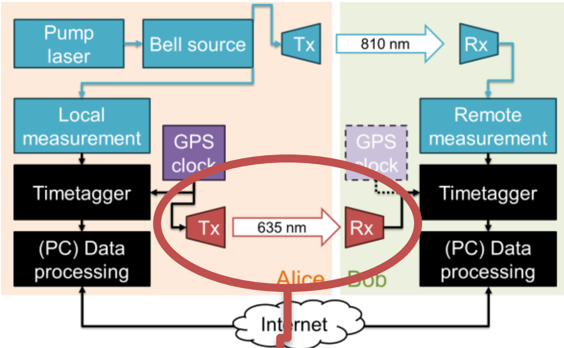
OUR FREE-SPACE QKD SETUP







CLOCK SYNCHRONIZATION



- Alice’s and Bob’s time tagging clocks slightly differ
- Master clock is required
  - Can be two GPS disciplined oscillators
  - Or a GPSDO and an optical transmitter
- Time is measured from master clock
- Delay is found either by Fourier transform or start stop histogram

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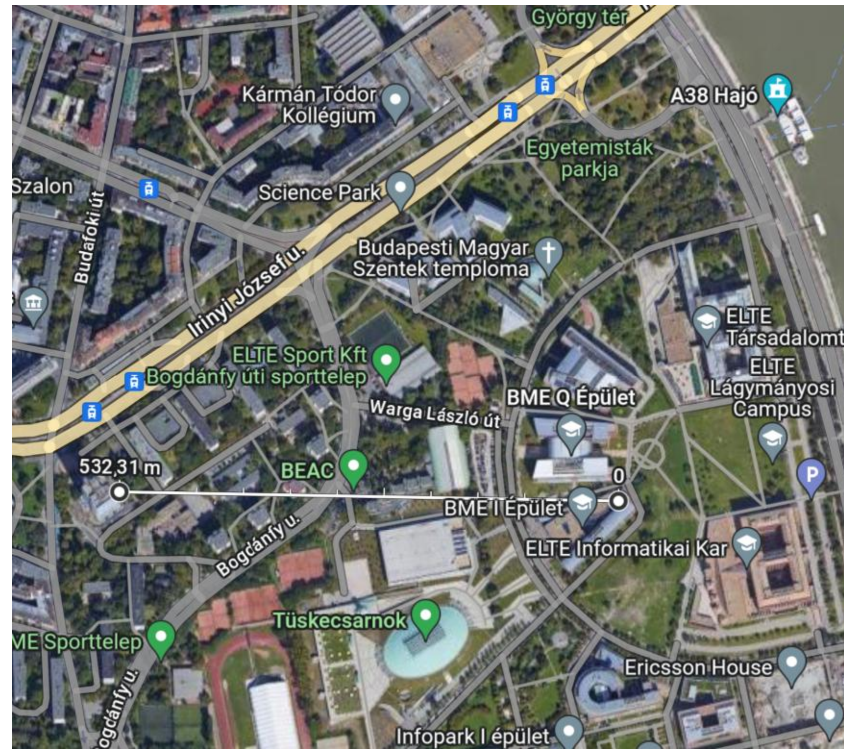
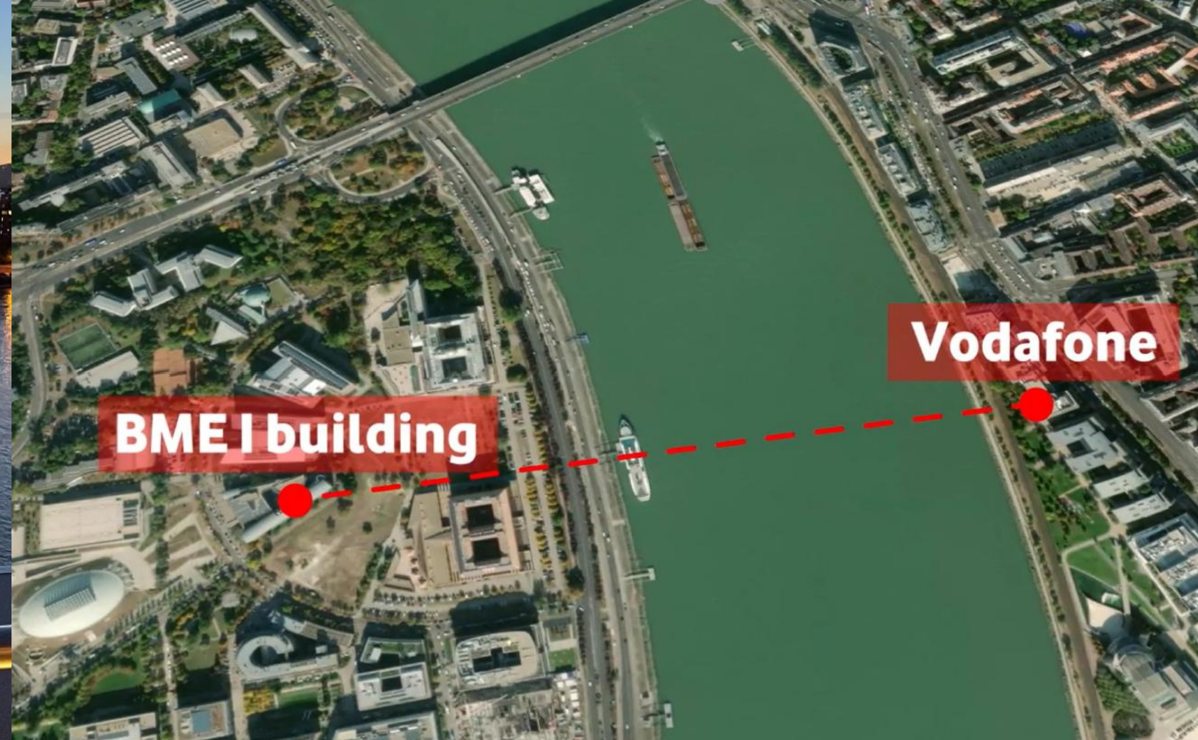
FIELD EXPERIMENT ON OCTOBER 12, 2023




Vodafone
BME I building

TOWARDS SPACE

Quantum Communications Capable Optical Ground Stations in Hungary (QuStation)

ADVANCED TECHNOLOGY OF LASER

MŰEGYETEM 1782

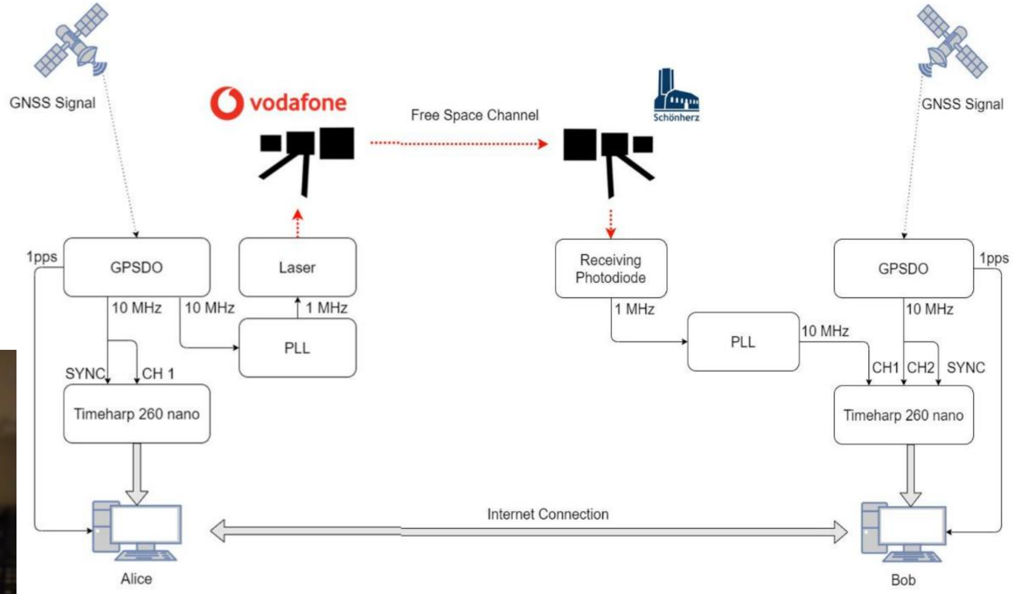
Complex electronic hardware for free-space entanglement-based quantum key distribution system (Certain)

Relcom

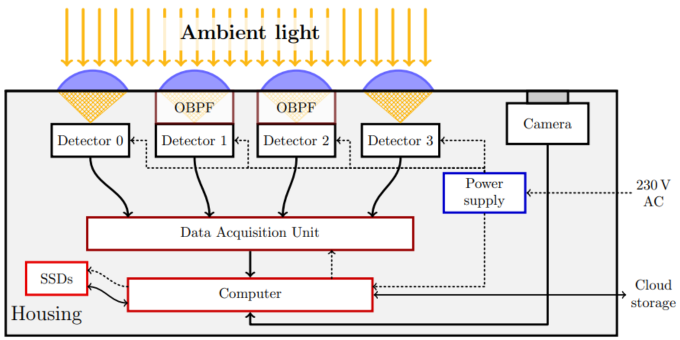
MŰEGYETEM 1782

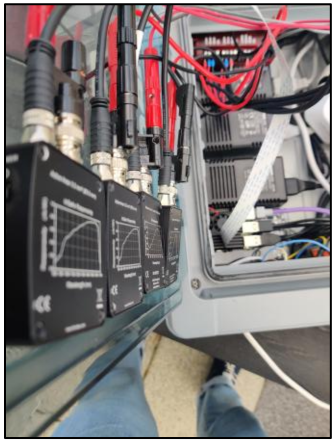
CLOCK TRANSMISSION VIA FREE SPACE OPTICAL CHANNEL

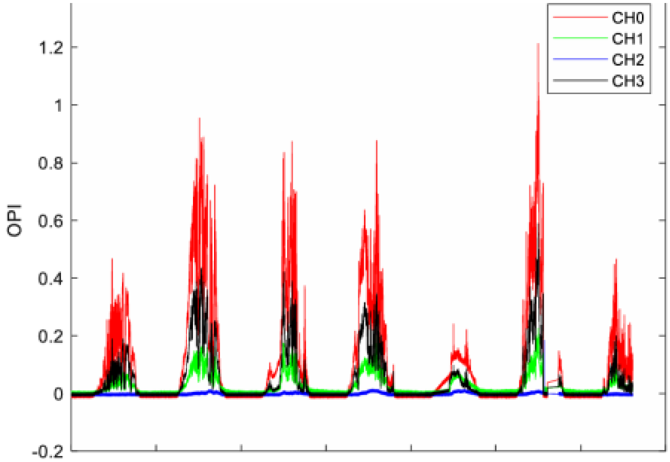
1550 / 650 nm experimental laser sync by Relcom Ltd. and BME



OPTICAL BACKGROUND MEASUREMENT

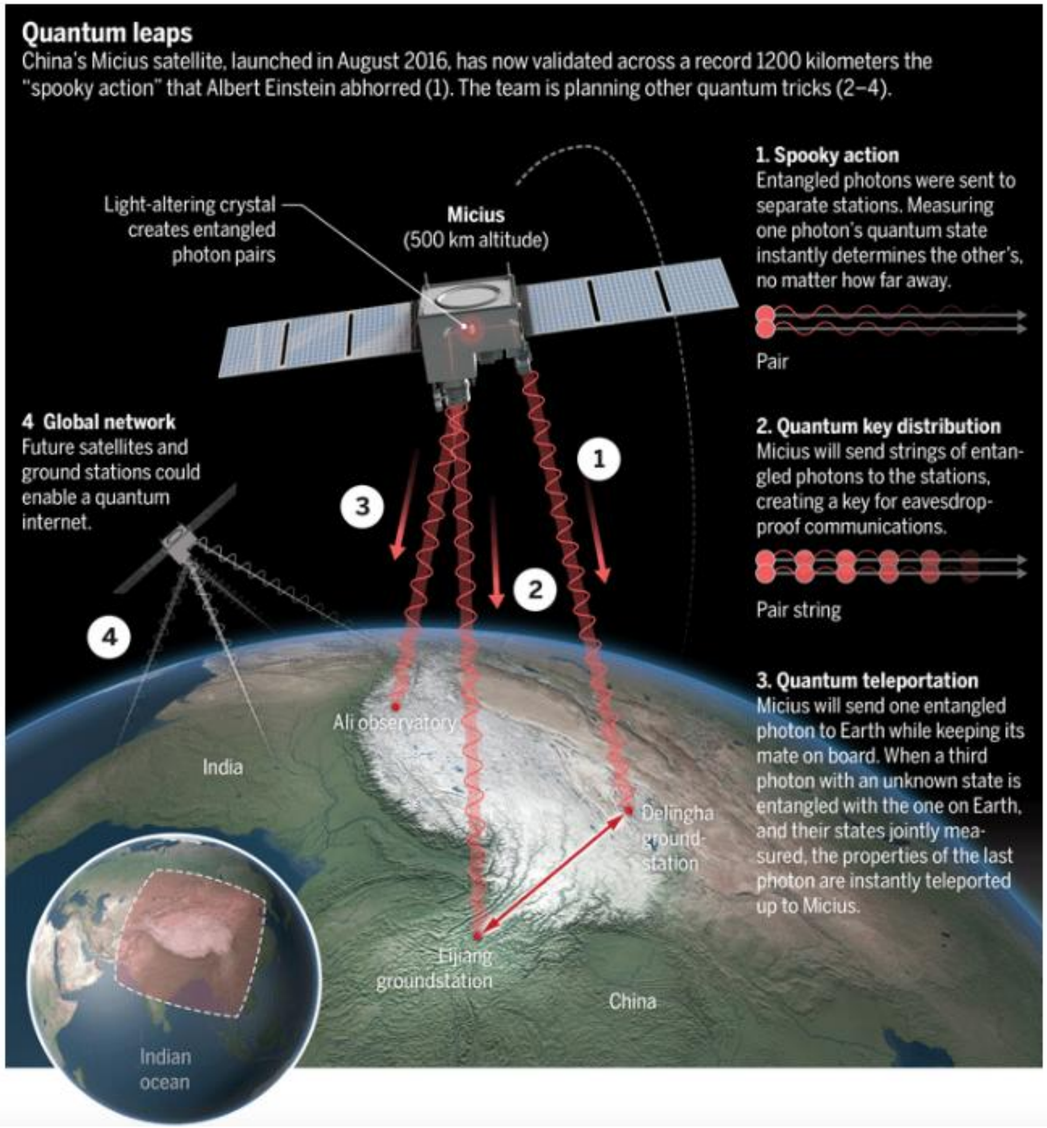




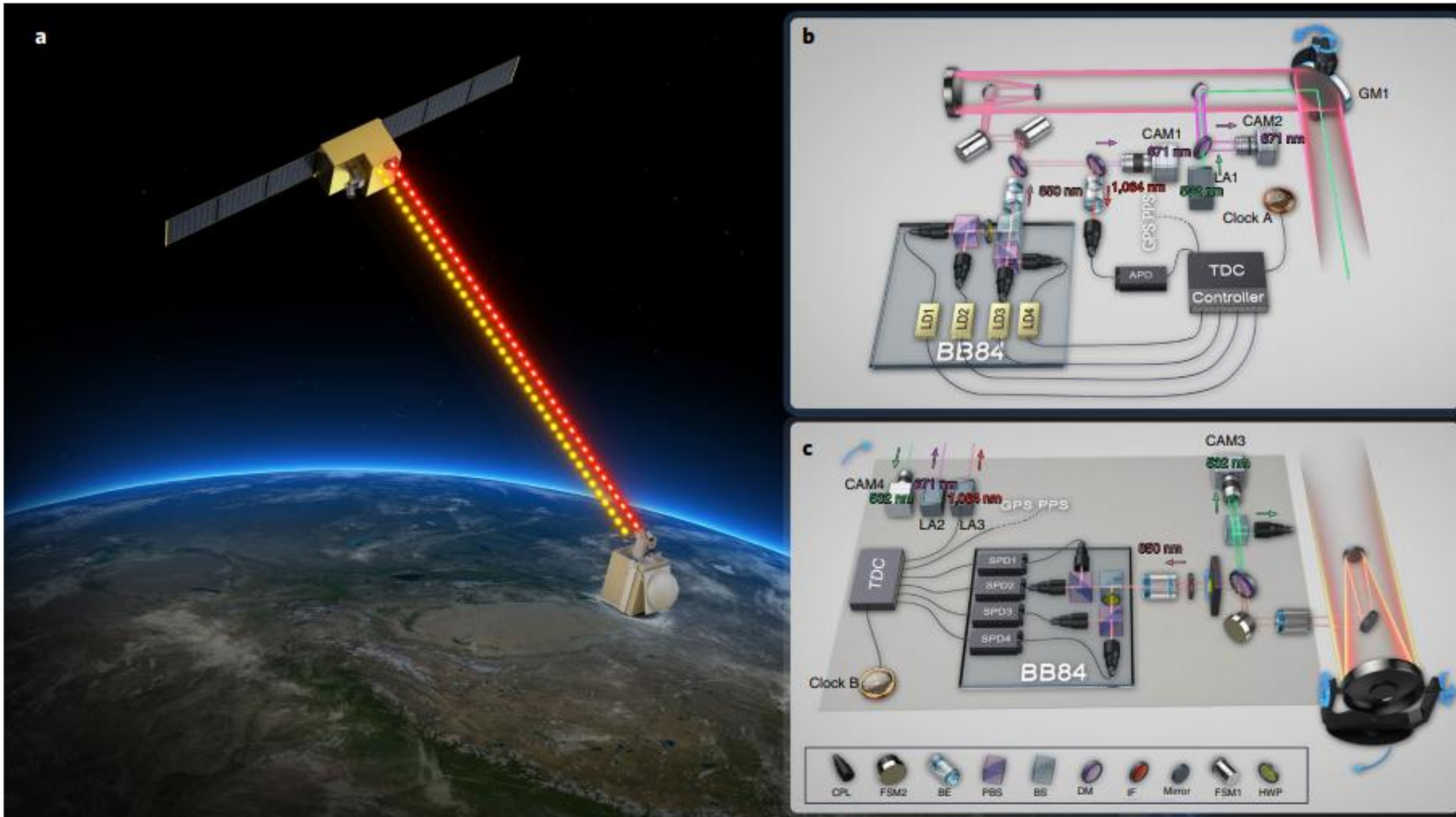


Experiments all over the world

2016.


Quantum leaps
China's Micius satellite, launched in August 2016, has now validated across a record 1200 kilometers the "spooky action" that Albert Einstein abhorred (1). The team is planning other quantum tricks (2–4).
Light-altering crystal creates entangled photon pairs
Micius
(500 km altitude)
1. Spooky action
Entangled photons were sent to separate stations. Measuring one photon's quantum state instantly determines the other's, no matter how far away.
Pair
2. Quantum key distribution
Micius will send strings of entangled photons to the stations, creating a key for eavesdrop-proof communications.
Pair string
3. Quantum teleportation
Micius will send one entangled photon to Earth while keeping its mate on board. When a third photon with an unknown state is entangled with the one on Earth, and their states jointly measured, the properties of the last photon are instantly teleported up to Micius.
4 Global network
Future satellites and ground stations could enable a quantum internet.
1
2
3
4
Ali observatory
India
Delingha ground-station
Lijiang groundstation
China
Indian ocean

QUANTUM EXPERIMENTS AT SPACE SCALE QUESS - MICIUS



SINGAPORE

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MENU

SCIENTIFIC REPORTS

Article | Open Access | Published: 10 May 2016

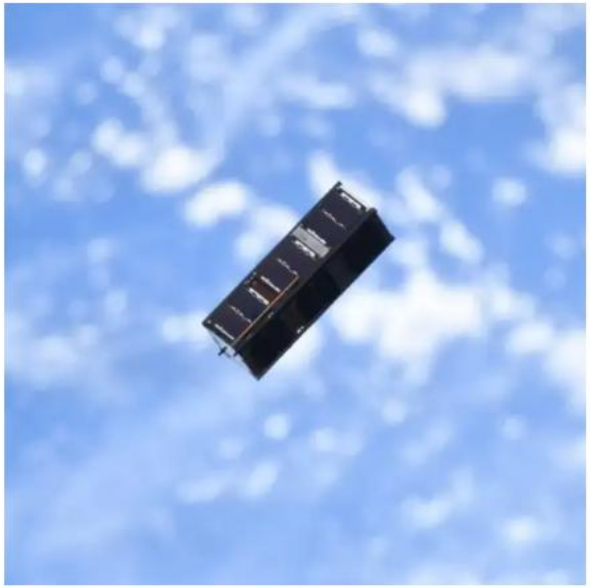
The photon pair source that survived a rocket explosion

Zhongkan Tang, Rakhitha Chandrasekara, Yue Chuan Tan, Cliff Cheng, Kadir Durak & Alexander Ling

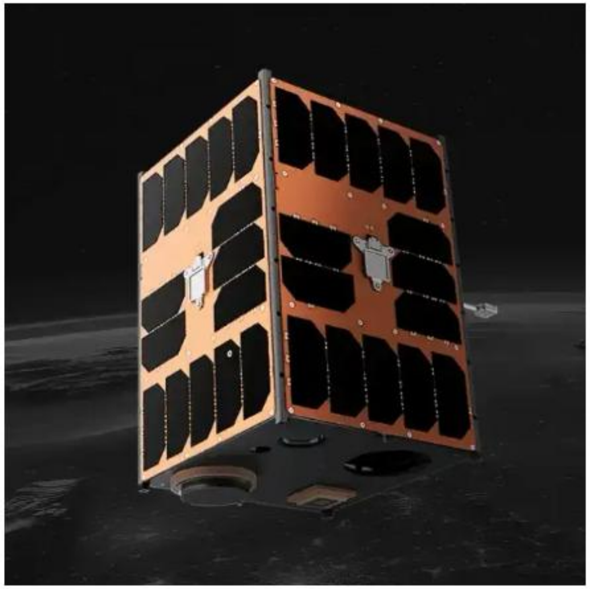
Scientific Reports **6**, Article number: 25603 (2016) | Cite this article

598 Accesses | **12** Citations | **12** Altmetric | Metrics

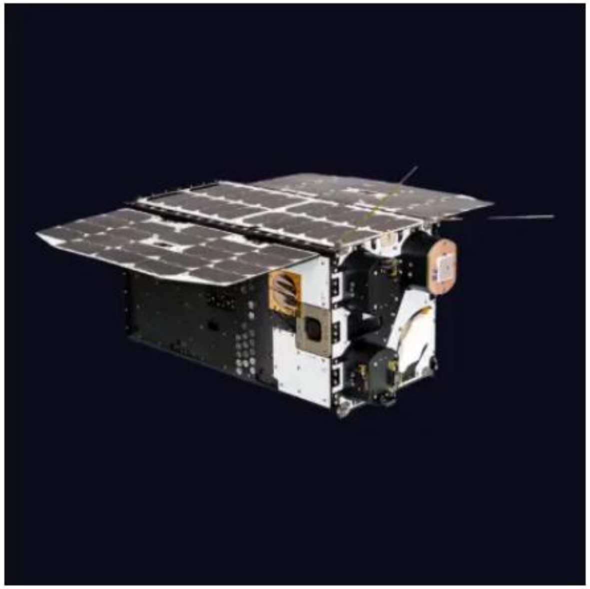
SPEQTRAL



SpooQy-1
2019

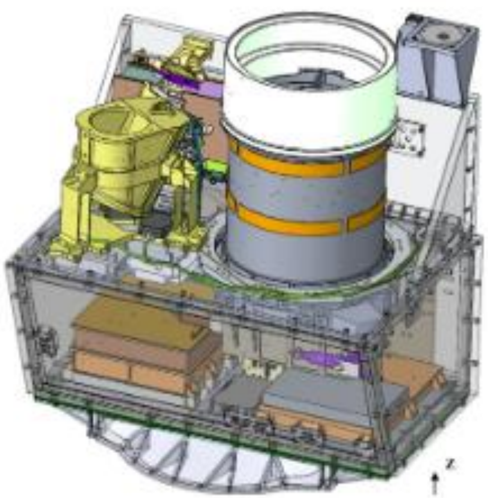


SpeQtre
2025



SpeQtral-1
2026

QEYSSAT-CANADA



Institute for Quantum Computing » Research » Research groups »

Quantum Encryption and Science Satellite (QEYSSat)

Principal Investigator Professor Thomas Jennewein

Institute for Quantum Computing (IQC) researcher Thomas Jennewein is pioneering new applications for quantum technologies, in particular quantum communications networks in space.

DOWNLOAD
QUANTUM SCIENCE HEADING TO SPACE »

Recent media

04/27/17 - Press release from Innovation, Science and Economic Development Canada

02/02/17 - Wired article by Sophia Chen

12/22/16 - "We've got photons!"

12/21/16 - Researchers successfully demonstrate prototype for space-based quantum-secured communication

12/20/16 - Globe and Mail article by Ivan Semeniuk

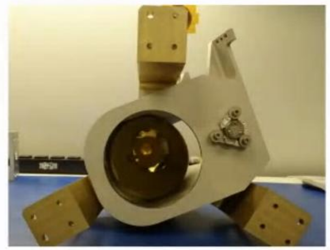
09/12/16 - IQC researchers successfully conduct airborne demonstration of quantum key distribution

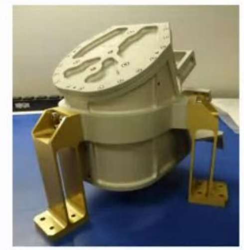
05/05/16 - IQC researcher awarded CSA grant to demonstrate quantum communications technologies aboard student space mission

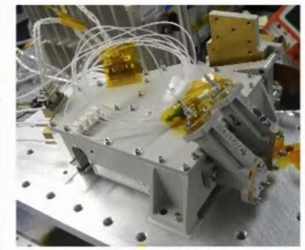
OISL TERMINALS FOR QKD

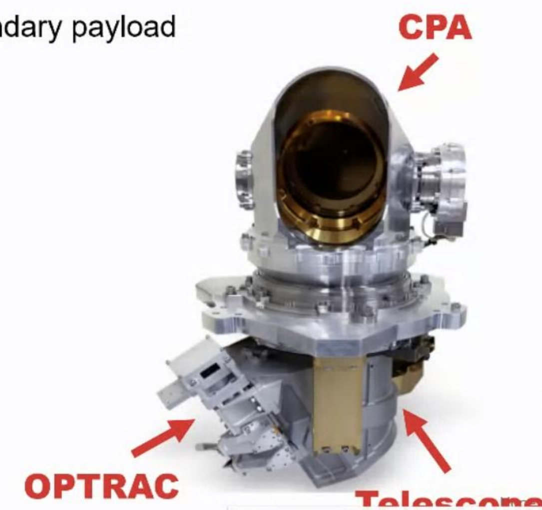
Optical intersatellite link terminal (LCT-100)

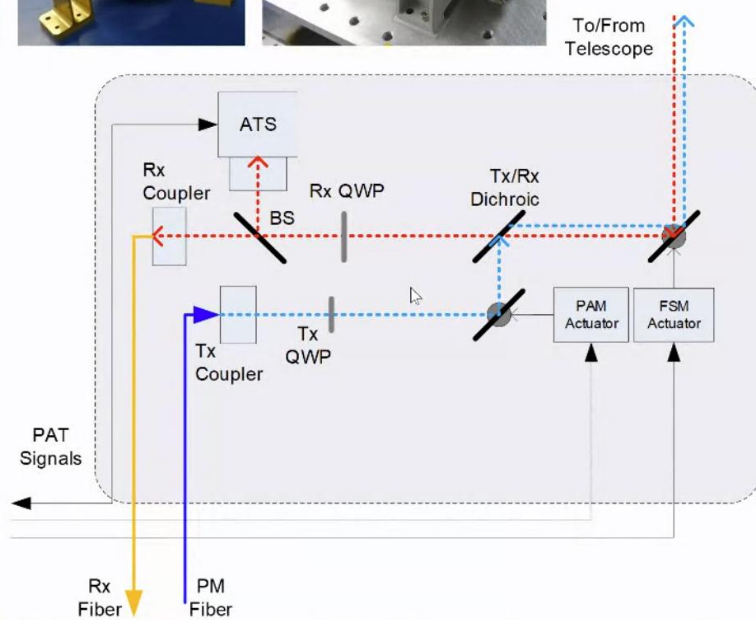
- 100 mm clear aperture
- Achromatic all-reflective system
- 7 year design lifetime
- OISL range >6000 km @ 10 Gbps
- Flight opportunity as secondary payload on QEYSSat





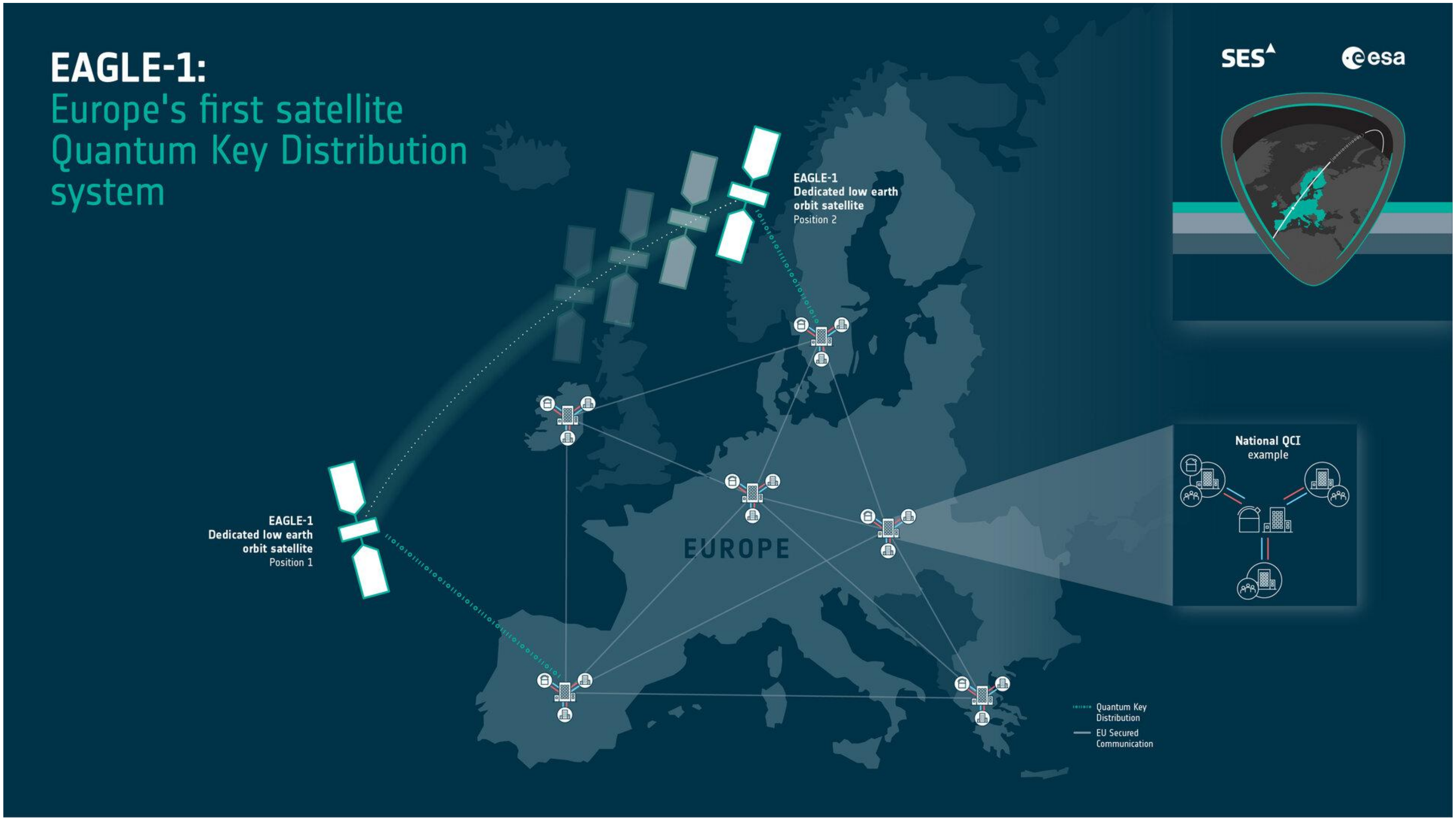




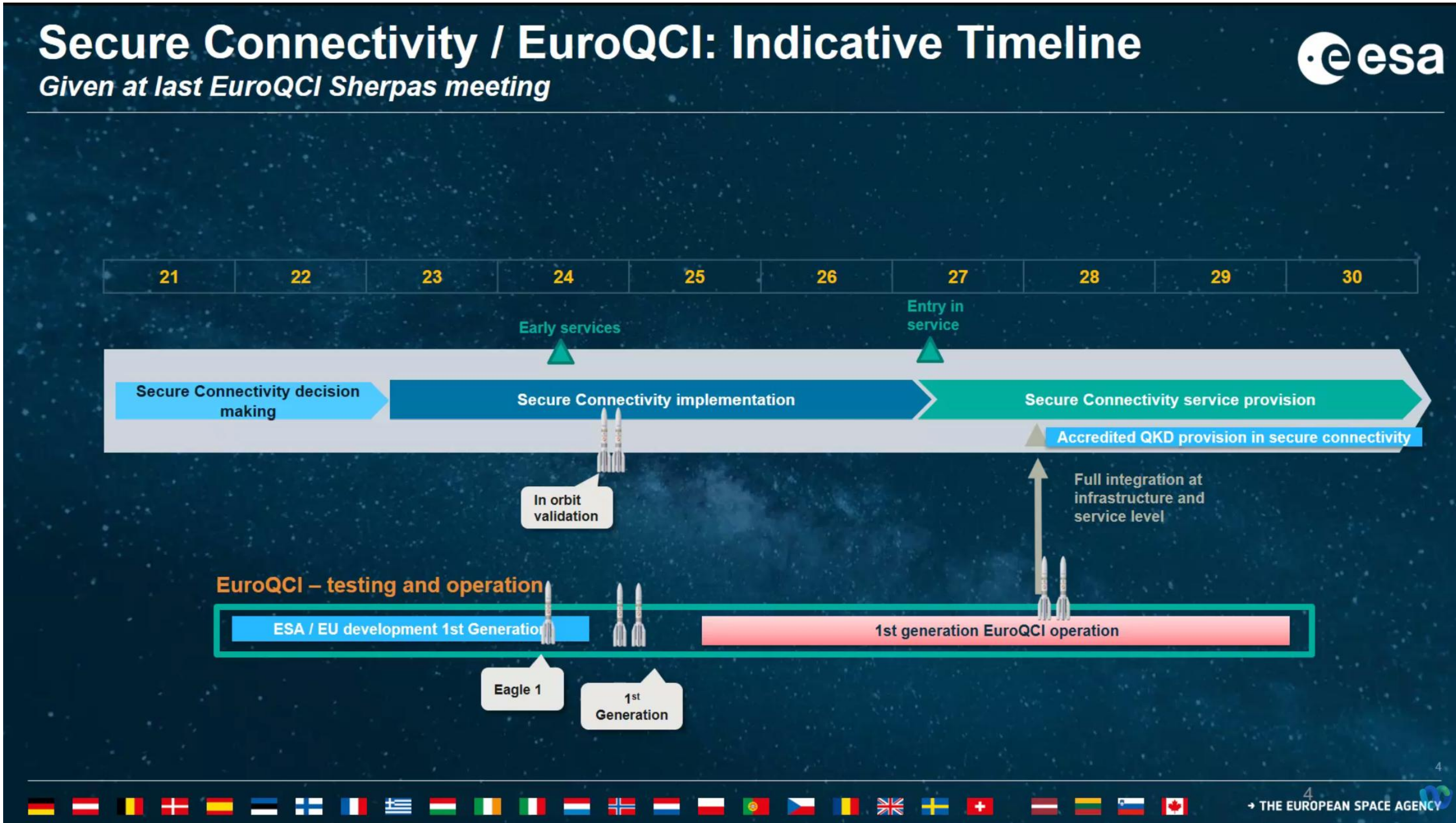


Honeywell

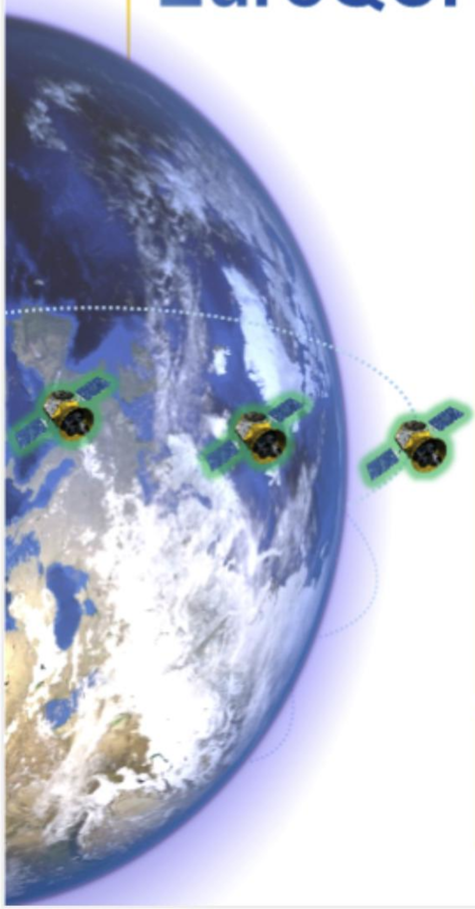
 13


EAGLE-1:
Europe's first satellite Quantum Key Distribution system
SES
esa
EAGLE-1
Dedicated low earth orbit satellite
Position 2
EAGLE-1
Dedicated low earth orbit satellite
Position 1
EUROPE
National QCI example
Quantum Key Distribution
EU Secured Communication

EU SECURE CONNECTIVITY



EuroQCI space segment



Eagle 1 – LEO satellite for in orbit demonstration and early tests
- Eagle 1 under development, led by ESA
- Funded by Horizon Europe / ESA / Industry
- Operations:
  - QKD proof of concept & testing interfaces with OGS

1st Generation - deployment of LEO satellites with EU technology
- First prototype satellite funded and led by ESA
- Next satellites funded by EU
- Possibly additional satellites by Member States
- Operations:
  - Exchange quantum keys between different sites on EU territory
  - First validation of end to end system: interconnected LEO satellites + ground stations + terrestrial systems
  - Initial coverage of user and security requirements – Incremental approach

2nd Generation - deployment of a fully operational system integrated with Secure Connectivity
Full coverage of user and security requirements

European Commission

Quantum Communication at OHB

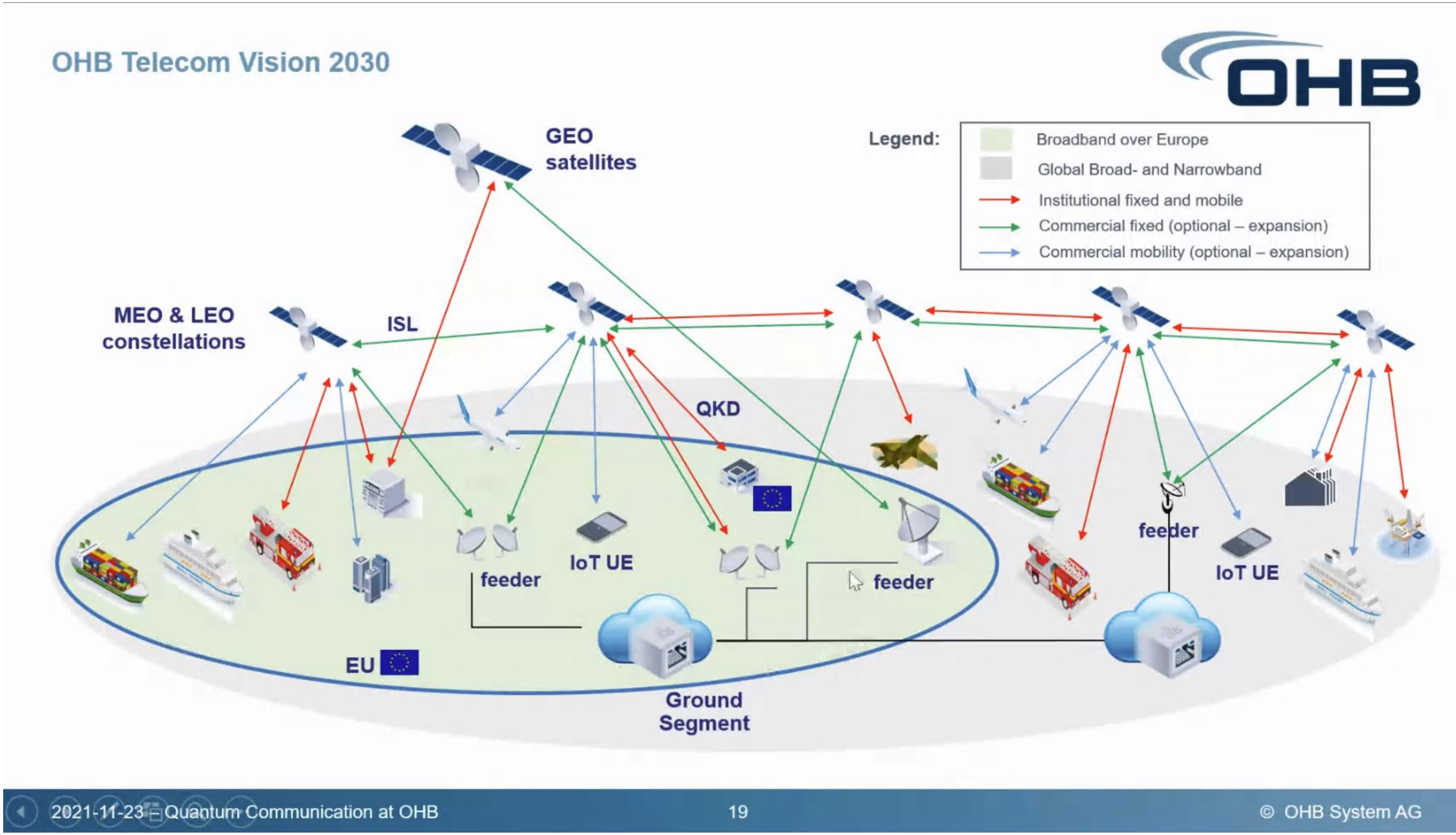
Project Overview – Upcoming Projects

QRNG (EU27) on Eagle-1 (with AntwerpSpace, FAU, AIT/fragmentix)

- Co-funded (ScyLight), Customer SES
- Objective: Deliver space qualified and certifiable **QRNG** for Eagle-1
- 2 QRNGs in development, OHB QRNG is **mandatory** for Eagle-1
- **In comparison** to other QRNG:
  - PIC based, smaller, lighter, more robust
  - Higher rate of random bit stream output
  - EU27 source

QUBE-II (with DLR-IKN, FAU, LMU, ZfT)

- For BMBF (VDI/VDE): **OHB** as **Prime**
- Follow-on project of QUBE
- Objective: Establish **Quantum Key Distribution in orbit** based on **CubeSats**
- CubeSat launch in early 2025
- Demonstration of successful **Quantum Key Distribution** planned **in late 2025**


OHB Telecom Vision 2030
OHB
GEO satellites
Legend:
Broadband over Europe
Global Broad- and Narrowband
Institutional fixed and mobile
Commercial fixed (optional – expansion)
Commercial mobility (optional – expansion)
MEO & LEO constellations
ISL
QKD
feeder
IoT UE
feeder
feeder
IoT UE
EU
Ground Segment
2021-11-23 Quantum Communication at OHB
19
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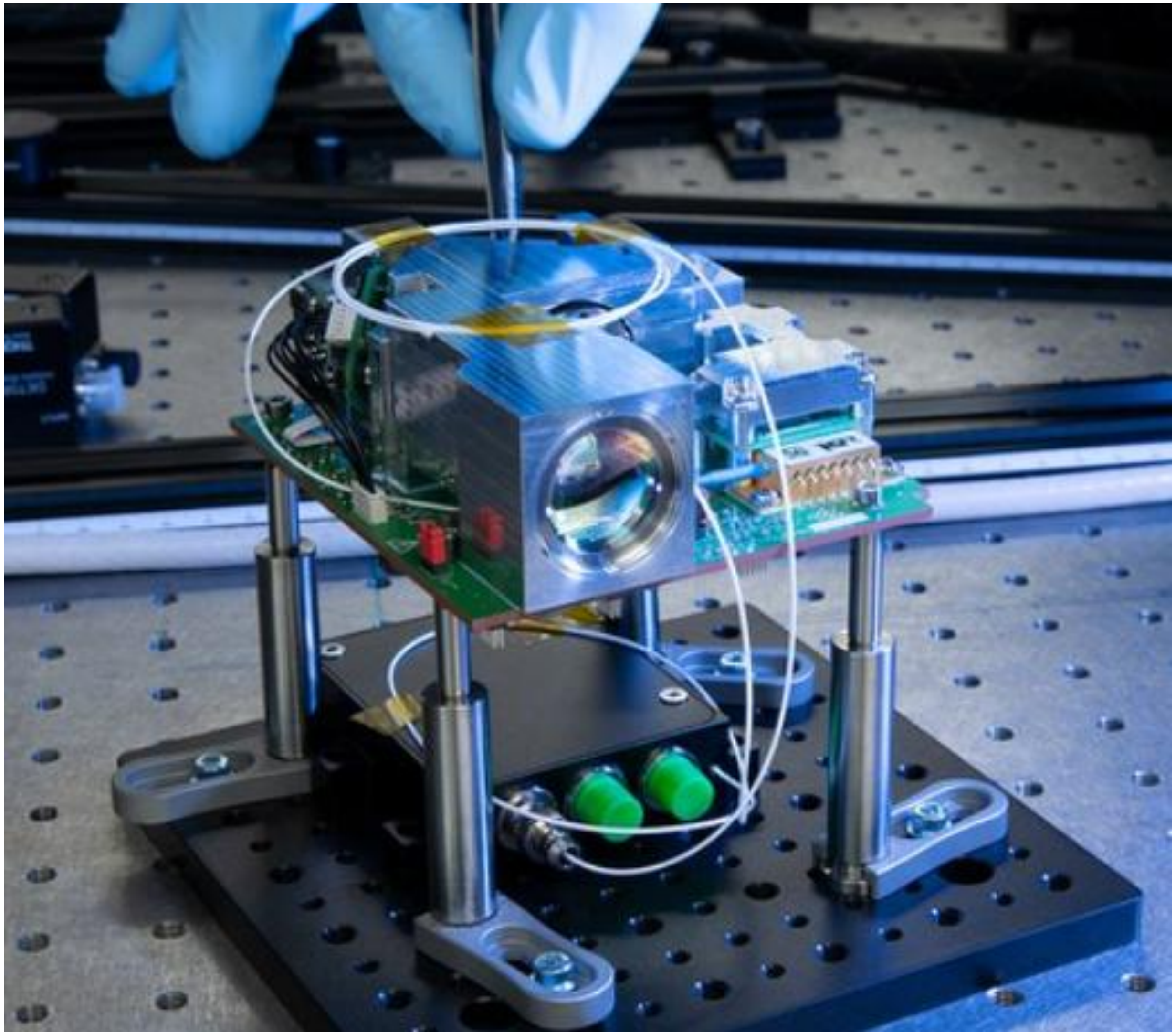
QUBE SATELLITE - DLR



Future free-space quantum channel:

- minimizing atmospheric interference
- increasing the free-space distances (proper amplification of the signal)
- building appropriate transmitting and receiving equipment
- successful experiments could lead to advances in space communications
- the free-space model is operational we can achieve a shift in the history of space communications as great as the shift from analogue to digital

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