QKD IN SPACE

UNIQUE CHALLENGES IN SATELLITE-BASED QUANTUM COMMUNICATION

PANEL QUANTUM TECHNOLOGIES COMMUNICATIONS - 2023/06/29

MARCELL GALL, SYSTEMS ENGINEER AT OHB SYSTEM AG

AGENDA

1. Constraints in QKD - the reasons to go to space (2 min)
2. The limitations and challenges in space (10 min)
   1. **Orbits and link geometry**
   2. **Atmosphere**
   3. **Service organization and meeting user needs**
   4. **Space is hard – Space environment**
3. Possible solutions and OHB involvement (2 min)

MOTIVATION - SATELLITE-BASED QKD

- **QKD requires sending quantum states** / distributing quantum information over a quantum channel
- Quantum channels are sensitive to information **carrier loss**
  - No-Cloning theorem
  - Measurements influence quantum states

  → **No amplification possible** (good for security bad for loss compensation)

Fundamental upper limit of QKD link efficiency using point-to-point links [1]

$\approx$ **1.44·*T*** with channel transmission $T \rightarrow 0$

single-mode secret key capacity per channel, repeater-less bound

→ Losses cannot be compensated and limit performance even assuming **ideal** devices

[1] S. Pirandola et al., Nature Communications, 8, 2017.

MOTIVATION - SATELLITE-BASED QKD

- QKD requires sending quantum information over a quantum channel
- Quantum channels are sensitive to information carrier loss
  - No-Cloning theorem
  - Measurements influence quantum states

  → No amplification possible

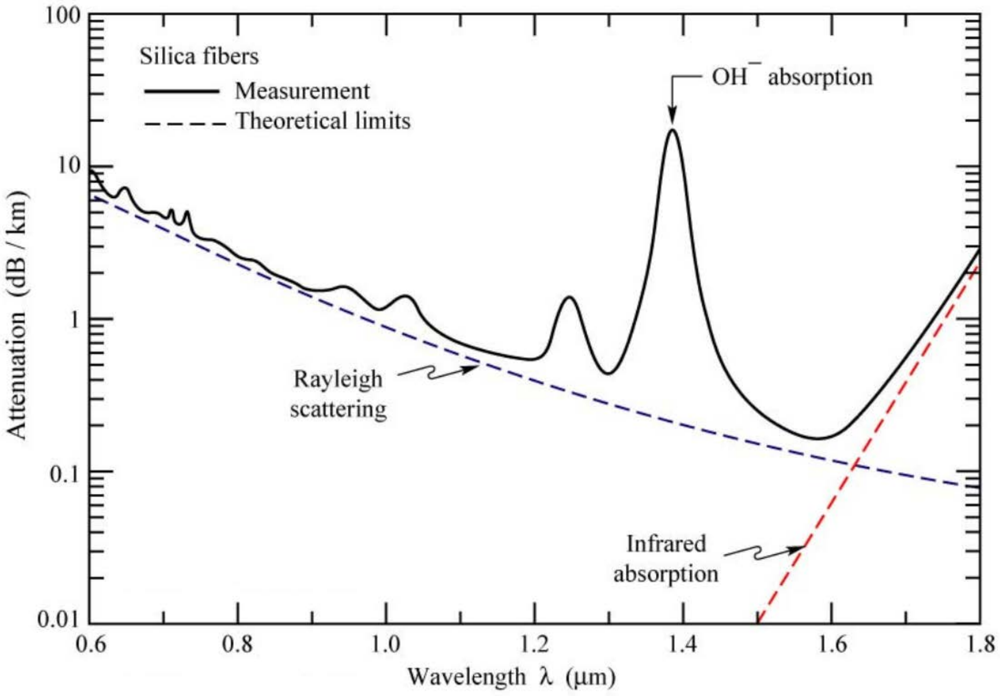
Fundamental upper limit of QKD link efficiency using point-to-point links [1]

≈ **1.44·*T*** with channel transmission *T* → *0*

- Optical silica fibers are optimized close to theoretical maximum transmission
- Current limit of fiber-based QKD: **P&M: 421km** [2] twin-field: 952 km [3]

→ "Longer" QKD links can only be realized using trusted nodes

→ In general, **keep number of trusted nodes low (security considerations)**



W. Blanc et al., Journal of Optics 45, 2015

[1] S. Pirandola et al., Nature Communications, 8, 2017.
[2] Lucamarini, M., Physics, 11, 111 (2018)
[3] Liu, Y. et al., Physical Review Letters, 130(21) (2023)

MOTIVATION - SATELLITE-BASED QKD

Fundamental upper limit of QKD link efficiency using point-to-point links [1]:
≈ **1.44·*T*** with channel transmission $T \rightarrow 0$

Possible solution – satellite-based QKD

- Last ≈ 10km of photon travelling path in atmosphere only
- Losses dominated by beam divergence, BUT:
  - Beam divergence scales quadratic, absorption exponential

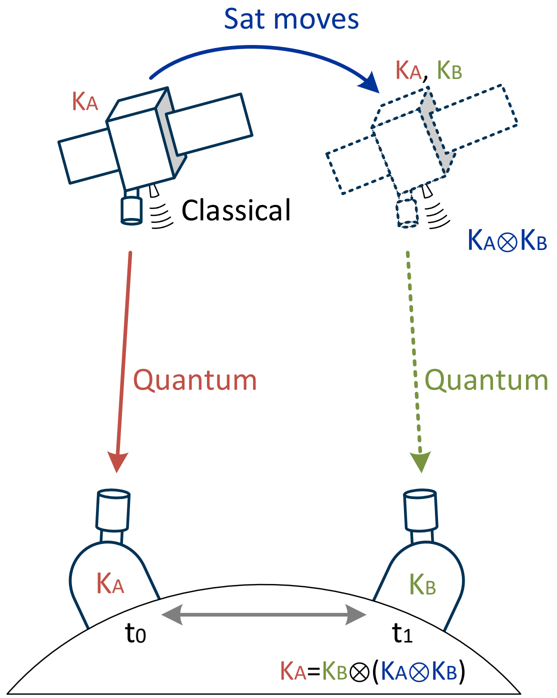
→ Cover large distances, throughout **Europe** & **globally**

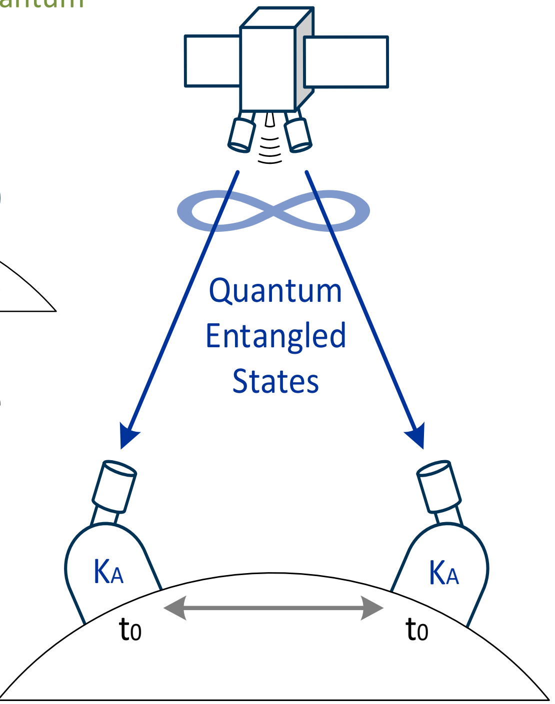
- Prepare-and-measure: Unlimited distance between ground stations with satellite as moving trusted node
- Entanglement-based: 1000 km orbit → ≈ 2700 km , 8000 km orbit → ≈ 8400 km limit

→ Key exchange with varying, distant and even nomadic optical ground stations

→ Connection of nodes of (future) quantum networks

Prepare and Measure (PM) based QKD





Entanglement-based (EB) QKD

[1] S. Pirandola et al., Nature Communications, 8, 2017.

ORBITS AND GEOMETRY

Where are the **dominant link losses** coming from?

- **Beam Divergence**: Optical beam sent in space over distances of >500 km diverges significantly, with spot-sizes on ground on the order of a kilometer
  - Using **smaller wavelengths** reduces divergence (see atmosphere)
  - **Reducing orbit height:** the distance satellite to ground station

- **Low earth orbit** (LEO: 400-2000km) leads to very fast movement of space craft (700m/s for 500km orbit good estimation)
  - Fast and **precise tracking is required** and a challenging task (angular velocity)
  - **little contact time** (overflight of Optical Ground Station)
  - EB limited in range (line of sight from satellite to both OGSs)
  - Fast movement also adds **Doppler shift** to the pulses, i.e. the timings of sent states and received states on ground needs to be synchronized!
  - **QKD basis changes** as well and needs to be stabilized (interferometer length (time-bin) or polarization basis)

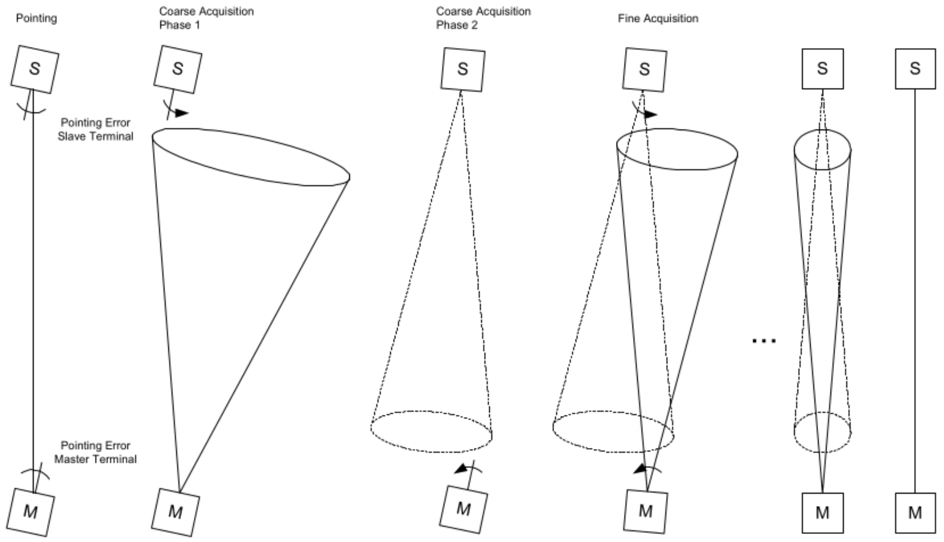


Fig. 3: Modes of beacon-less acquisition according to a master-slave approach

M: master terminal, S: slave terminal

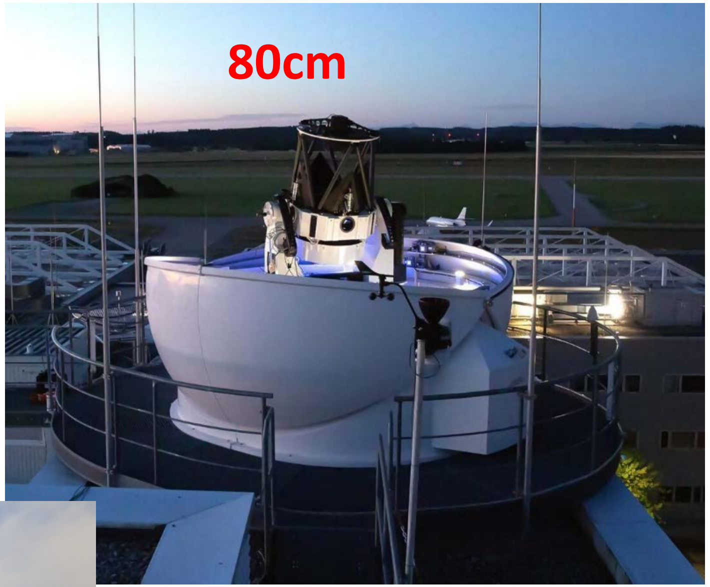
“In-orbit verification of optical inter-satellite communication links based on homodyne BPSK”, Proc. SPIE 6877, 687702 (7 February 2008)

ORBITS AND GEOMETRY

- Other extreme: **Geostationary Earth Orbit** (GEO) **@ ≈36.000km** - position relative to earth surface is constant
  - Nearly no Doppler shift
  - Very large EB range ≈ 8400 km
  - Very large divergence losses

- These losses can be reduced by **increasing the optical apertures / telescope sizes**
  - Increasing the size of telescope in space reduces divergence
  - Increasing the size of telescope on ground increases collection efficiency
  - Trade-off the telescope sizes:
  - Only few telescopes in space, a lot of telescopes on ground, where is the size increase more efficient?
  - Which sizes/budget can users **afford** to install on their premises?

Credit: DLR/Erim Giresunlu



Credit: DLR (CC BY-NC-ND 3.0)

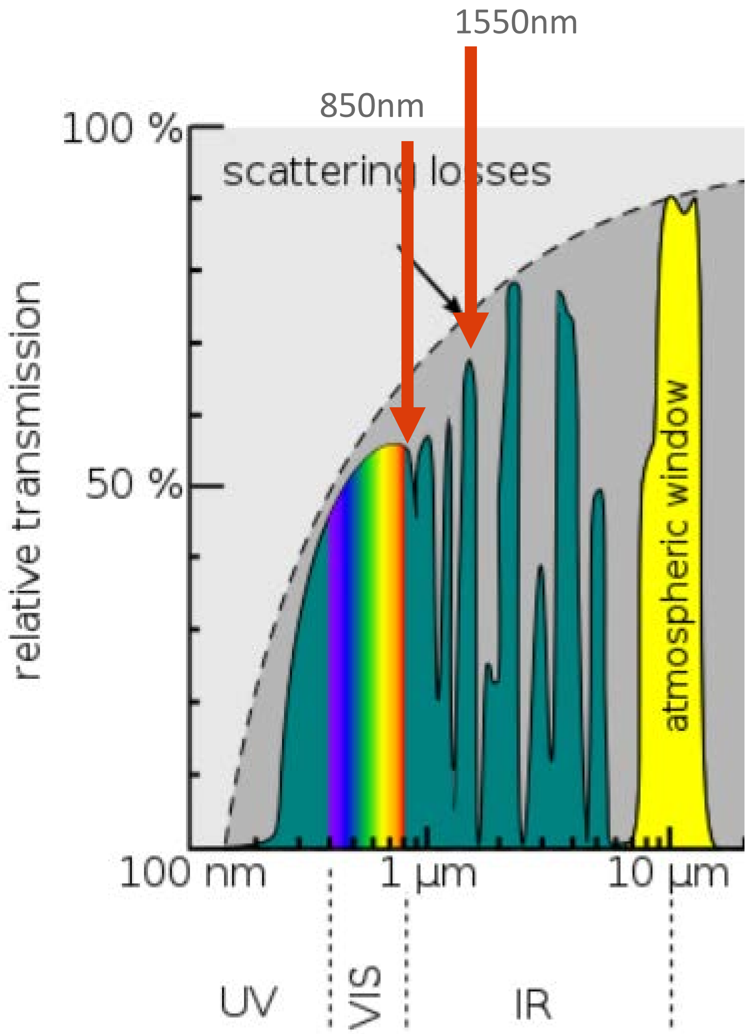
Credit: DLR (CC BY-NC-ND 3.0)

ATMOSPHERE

- **Atmospheric absorption**
  - Wavelength needs to be chosen to match atmospheric window
    - Wavelength in turn then determines divergence -> the smaller the better
    - But large wavelengths could be better coupled into fibers adding security

- **Atmospheric turbulence**
  - Wavefront distortion leads to pointing and thus coupling errors
  - **Adaptive optics** a possible solution
    - Measure the wavefront distortion from another high intensity source
    - Correct with a deformable mirror

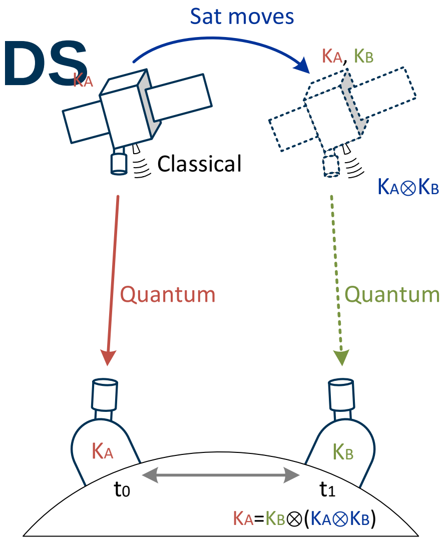
- **Weather, i.e. clouds, fog, smog**
  - Prohibit optical transmission
  - Straylight during day or due to light pollution of large cities also an issue
  - Ground station locations must be carefully chosen, next to demand, but in favorable conditions



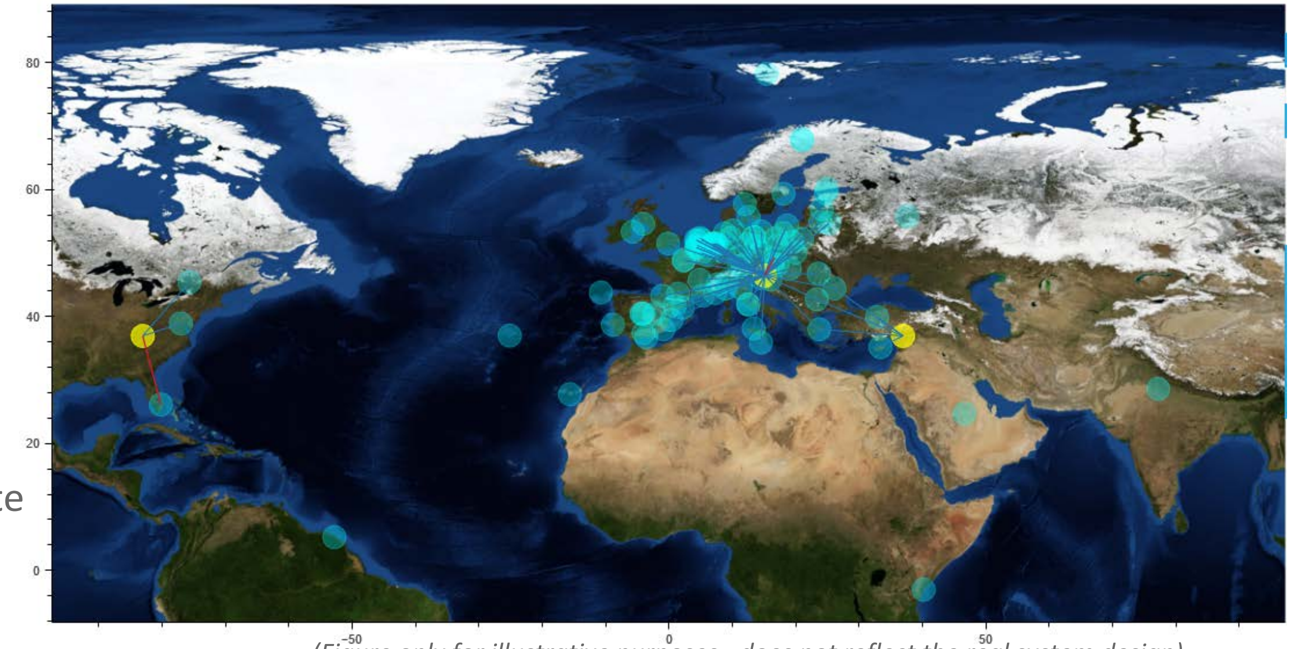
https://commons.wikimedia.org/

THE LIMITATIONS AND CHALLENGES IN SPACE

SERVICE ORGANIZATION AND MEETING USER NEEDS



- Many users, **keys between different users**:
  - PM: generate keys between satellite & user A and satellite & user B
- **Multiple users, single satellite**
  - priorisation of users and demand needs to be done
    - **Planning of the finite resource and link availability**
  - <u>BUT:</u> Weather only permits contacts in some locations at a time
    - long term planning needs to calculate probability
    - Short term planning needs to quickly adapt to weather
  - Assured service is difficult with dominating weather constraints
    - Keys might need to be created weeks before use (see stations in e.g. Norway)
- If **several satellites** in orbit, then for each link an optimal satellite needs to be chosen → scalability should be guaranteed!
  - Link availability in <u>constellations</u> needs to be calculated and simulated to provide the possibility of planned service



(Figure only for illustrative purposes - does not reflect the real system design)

Mars Climate Orbiter

Absturz wegen Leichtsinnsfehler beim Rechnen

Nicht wegen einer technischen Panne, sondern weil die beteiligten Wissenschaftler in verschiedenen Maßeinheiten rechneten, ist die 125 Millionen teure Marssonde Climate Orbiter abgestürzt. Ein klassischer Schülerfehler führte bei der Übersetzung vom amerikanischen ins metrische Maßsystem zur peinlichsten Pleite der Nasa. Eine weitere Sonde ist vielleicht mit denselben Fehlberechnungen zum Mars unterwegs.

01.10.1999, 12.24 Uhr

ALSO: SPACE IS HARD

Commercial

Astra Rocket 3.3 launch fails

Jeff Foust August 28, 2021

Private Japanese spacecraft apparently fails on historic moon landing try

By Mike Wall published 13 days ago

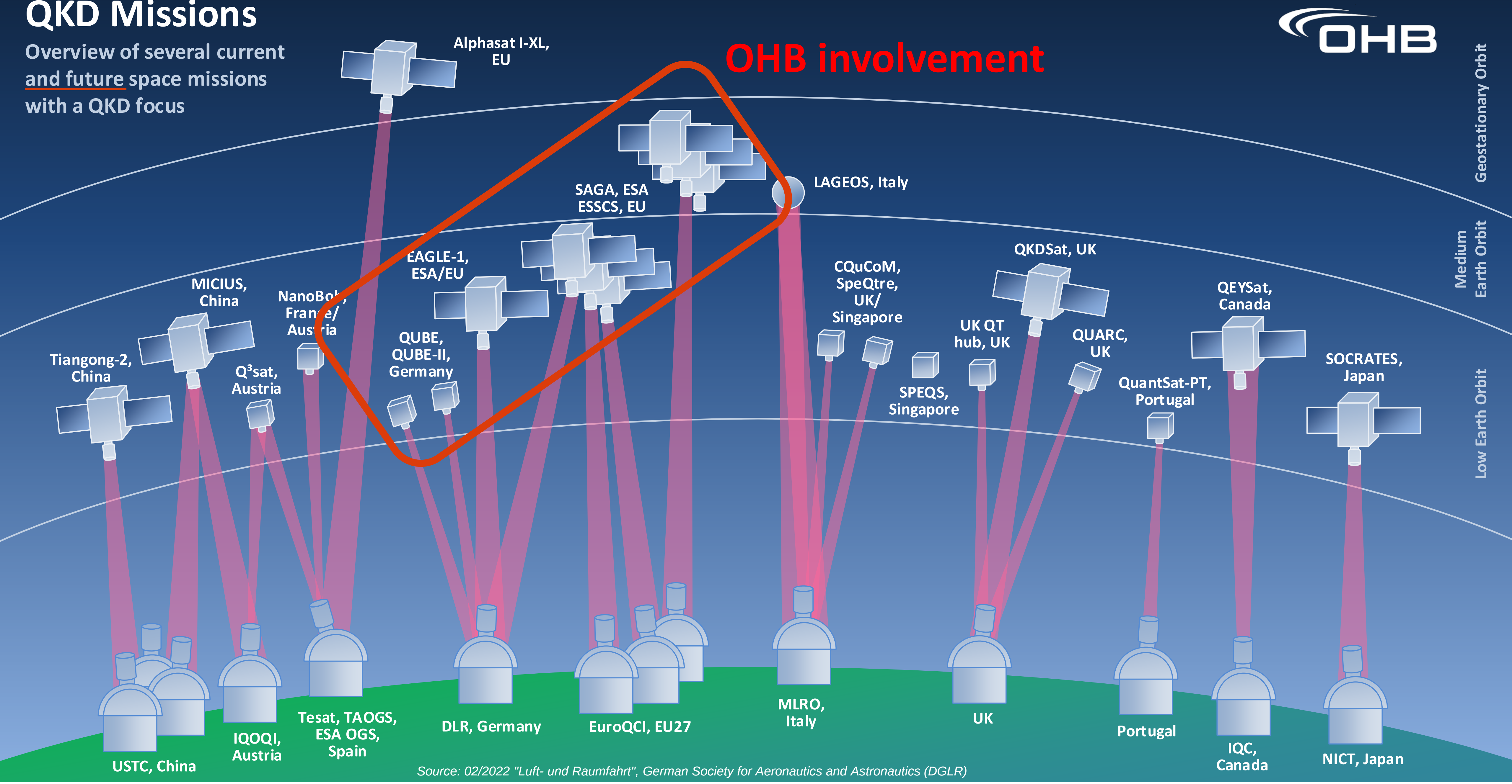
A Japanese moon lander likely came up short in its bid to make history today (April 25).

SPACE IS HARD – SPACE ENVIRONMENT

- **Challenging SWaP**
  - Size
  - Weight (and)
  - Power
    - Devices on Satellites need to be as miniaturized as possible, while consuming little power.
- **Temperature cycling**
  - Variations due to orbits, passing from direct sun exposure to earth shadow -> -20 to +60 degrees in 2h cycles possible
  - Temperature emission of devices, as air for cooling not available
- **High Energy Radiation**
  - Gamma rays, heavy ion radiation etc. is affecting electronics, semiconductors, optics, etc.
- **Vibrations at Launch**
  - Launch with a rocket applies stress strong enough to break mirrors and destroy aligned optics if not designed well
- **Cost**
  - Launching a satellite is extremely expensive but (usually) not as expensive as:
  - designing and manufacturing the satellite or developing or verifying the technology
- **No after launch changes**
  - Once launched, no servicing can be performed
  - Very extensive tests are performed to ensure proper function and performance

QKD Missions

Overview of several current and future space missions with a QKD focus



Source: 02/2022 "Luft- und Raumfahrt", German Society for Aeronautics and Astronautics (DGLR)

PROJECT OVERVIEW – HERITAGE & INVOLVEMENT

QUANTUM COMMUNICATION AT OHB

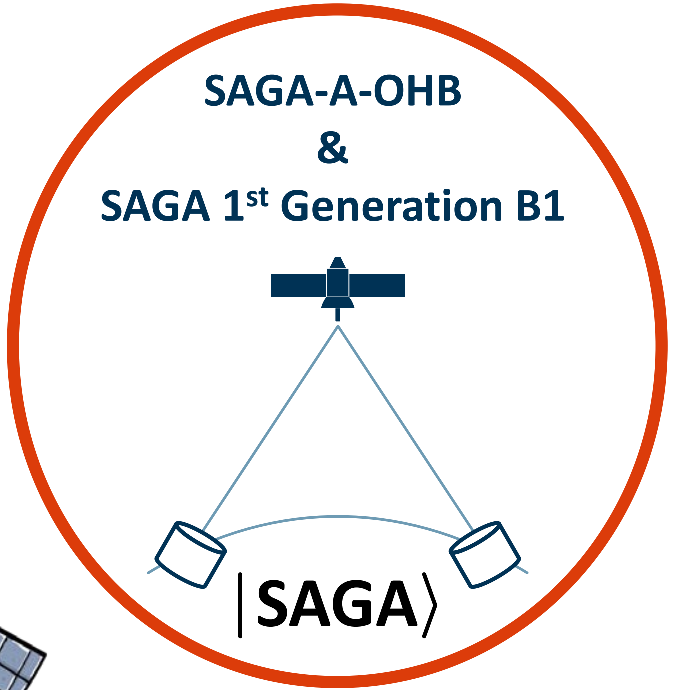
OHB

QKD4ECI

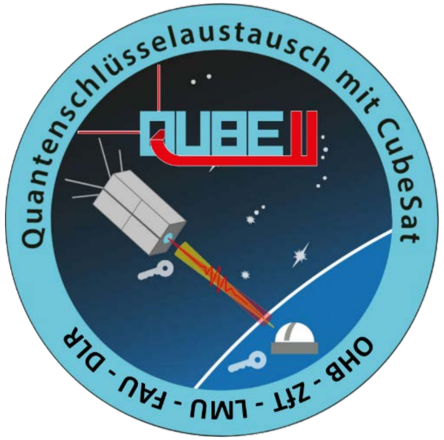
QCI4EU

QCI4EU QSAFE

System / Constellation Level



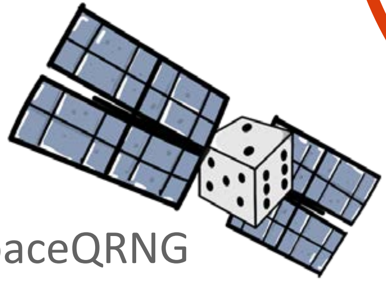
Microsatellite QKD system



- 6U CubeSat for QKD key generation
- ZfT, DLR, FAU, LMU as Partners
  OHB coordination and systems engineering
- Precise body pointing (ZfT) and 80mm telescope (DLR) for optical link
- Two Quantum Modules (FAU/LMU)
  with different bases and different wavelengths

QKD Component Development

Q R N G FOR



SpaceQRNG

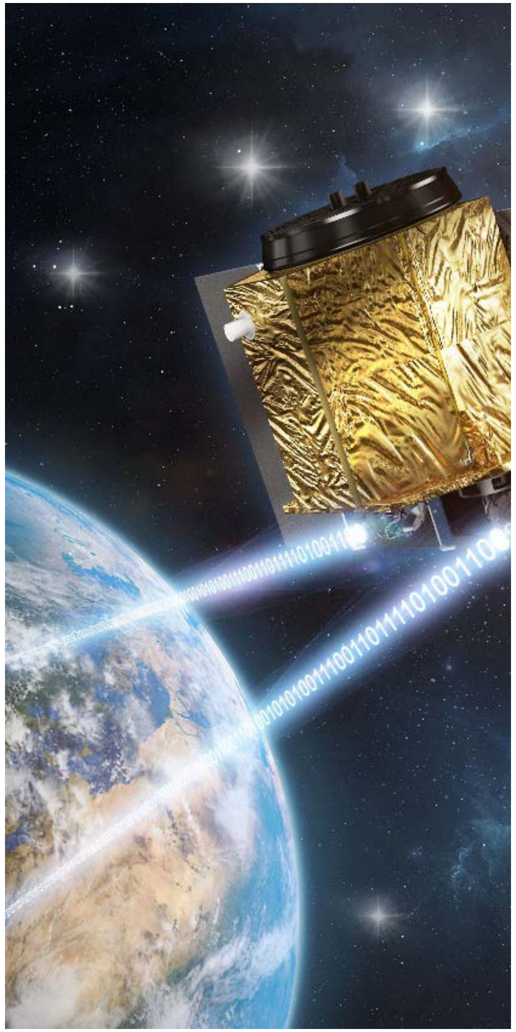
QuSync

Deutscher Industrieverbund für Quantensicherheit

ADVA, KEEQUANT, qutools, ROHDE & SCHWARZ, DB, OHB, T, TESAT, evolutionQ, IABG, QuantiCor, QUANTUM OPTICS JENA, TOPTICA PHOTONICS

QUANTUM COMMUNICATION AT OHB

CONTACTS



OHB System AG
Manfred-Fuchs-Straße 1
82234 Weßling / Oberpfaffenhofen
Germany
Phone +49 8153 4002-0

Dr. Marcell GALL
marcell.gall@ohb.de
Phone +49 8153 4002-607

Dr. Bettina HEIM
bettina.heim@ohb.de
Phone +49 8153 4002-298

Norbert M.K. LEMKE
norbert.lemke@ohb.de
Phone +49 8153 4002-168

OPN Feature Article
February Issue 2018
Satellite-Based QKD
Imran Khan, Bettina Heim, Andreas Neuzner and Christoph Marquardt

Space-based Quantum Communication, Luft- und Raumfahrt, Issue 2 / 2022
Norbert M.K. Lemke, Bettina Heim, Imran Khan, Thomas Sichert

Open positions!
Contact us or check OHB.de