From NanoBob to RIQS: Towards the future Quantum Internet

2024-11-15 – Workshop distribution sécurisée du temps et systèmes spatiaux – Erik Kerstel

The Dream: A global Quantum Information Network

The quantum internet has arrived (and it hasn't), *Nature* **554**, 289 (2018)
On-demand entanglement could lead to scalable quantum networks, *Nature* **558**, 192 (2018)
Quantum internet: A vision for the road ahead, Science **362**, 303 (2018)

Distributed, cloud quantum-computing,
Entanglement-based sensing, clock synchronization,
Quantum physics measurements
Quantum communications, ...

credit:

Quantum information carried by single photons belonging to polarization entangled pairs

Optical fibers limited by absorption losses (~100 km, no-cloning),
Free-space optics on Earth limited to line of sight (~100 km)

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→ Global entanglement distribution ideally requires entanglement swapping with Q memories for synchronization purposes …

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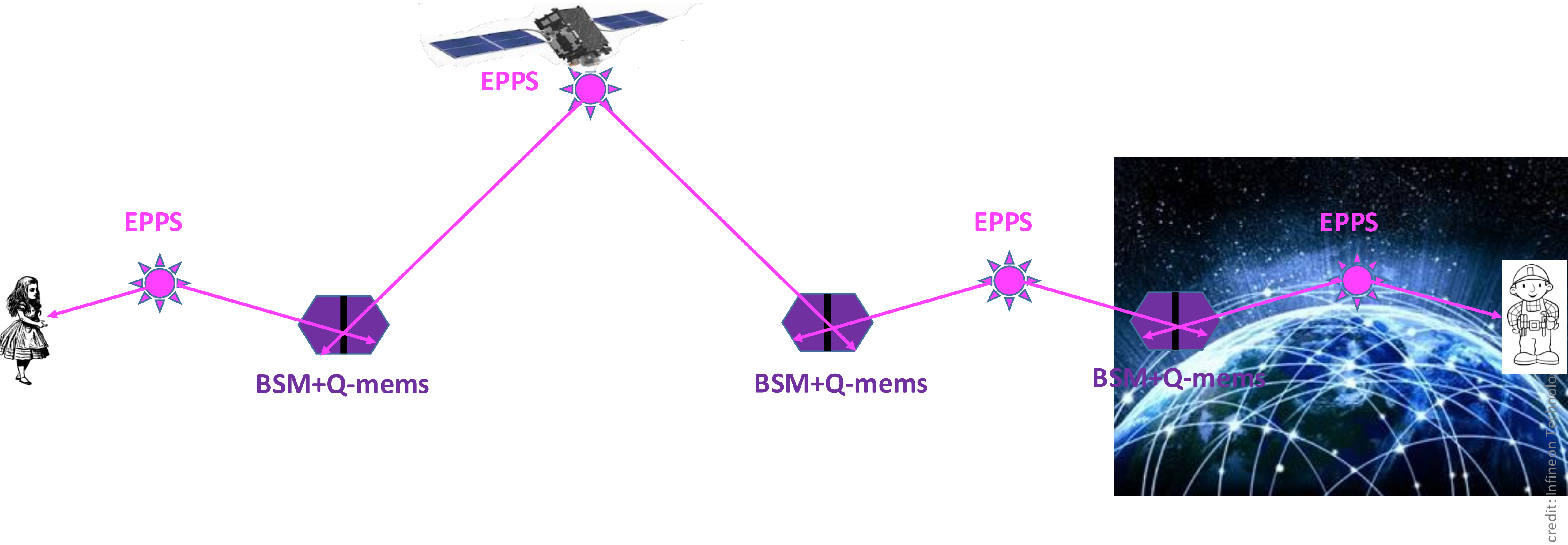

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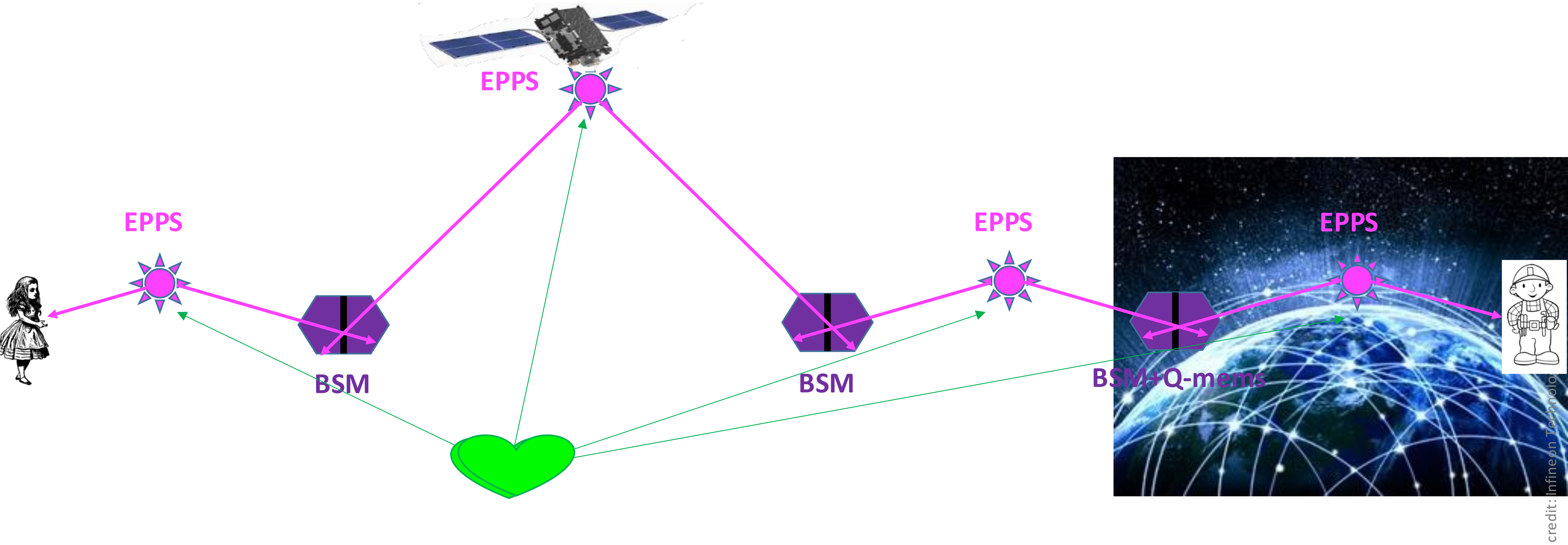
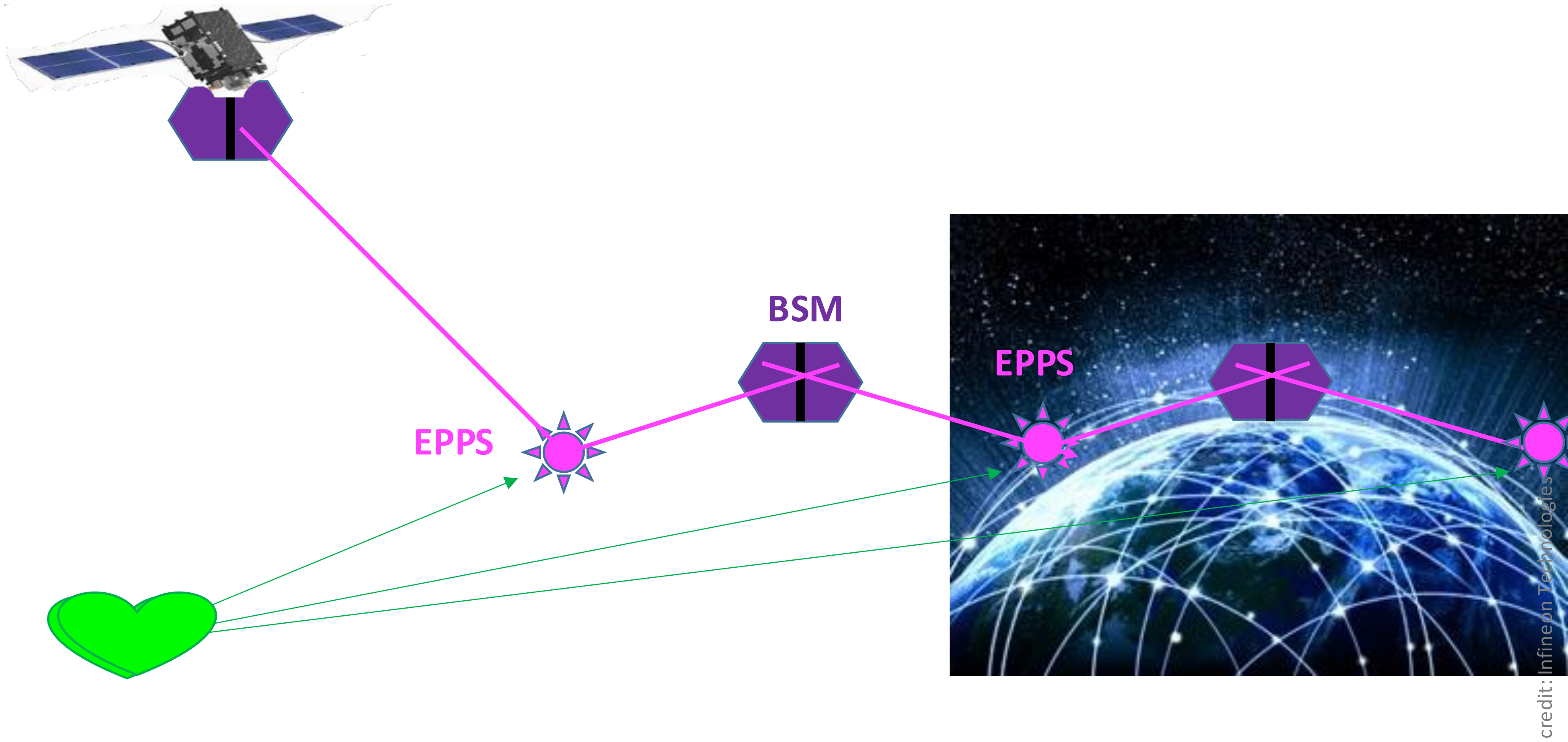


→ Global entanglement distribution (teleportation) ideally requires entanglement swapping with Q memories for synchronization …

Or a master clock …

A global Quantum Information Network demo



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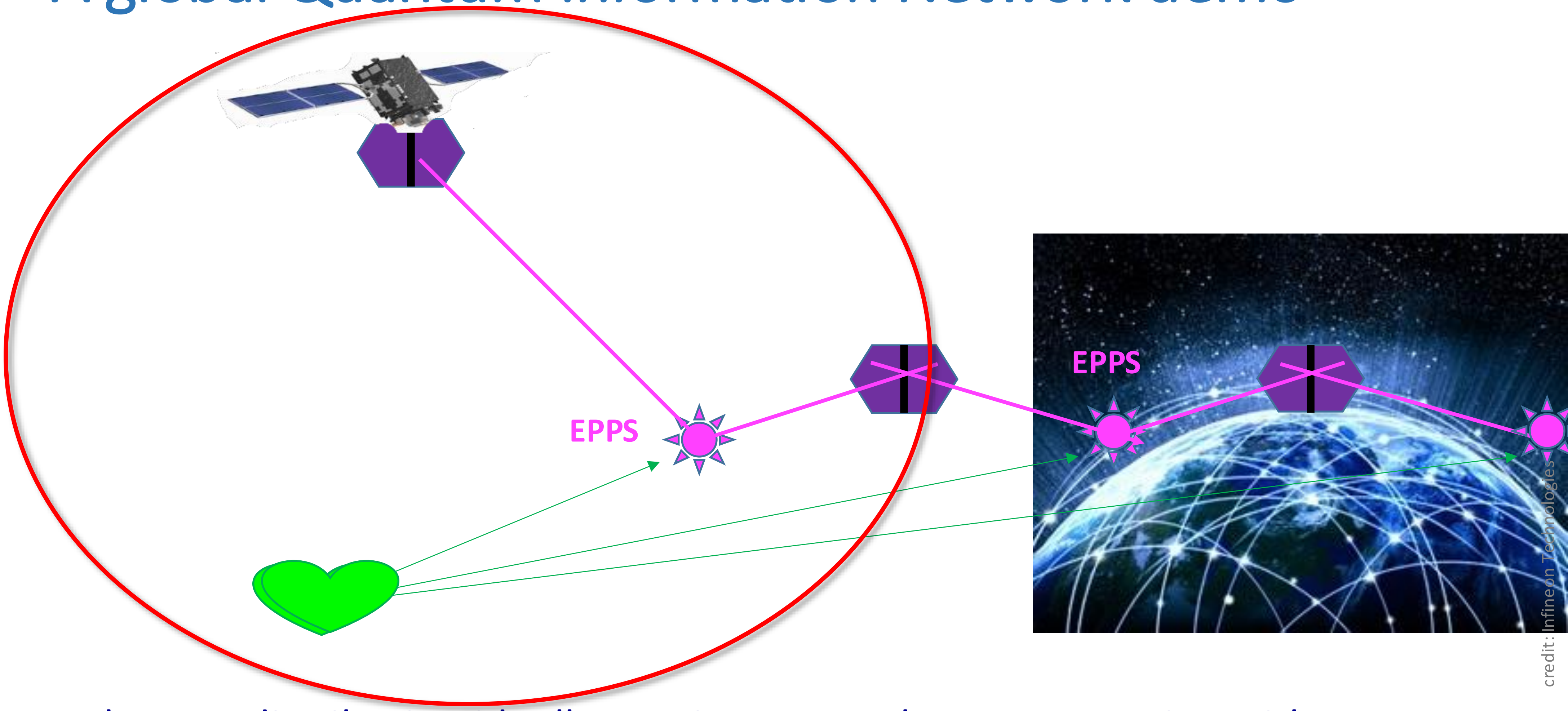
→ **2016:** NanoBob as a versatile prototype/early demonstrator for Space QKD and Q Physics **(IQOQI & CSUG Proposal**, following the Grenoble Workshop The Future of Nanosatellites)

A global Quantum Information Network demo



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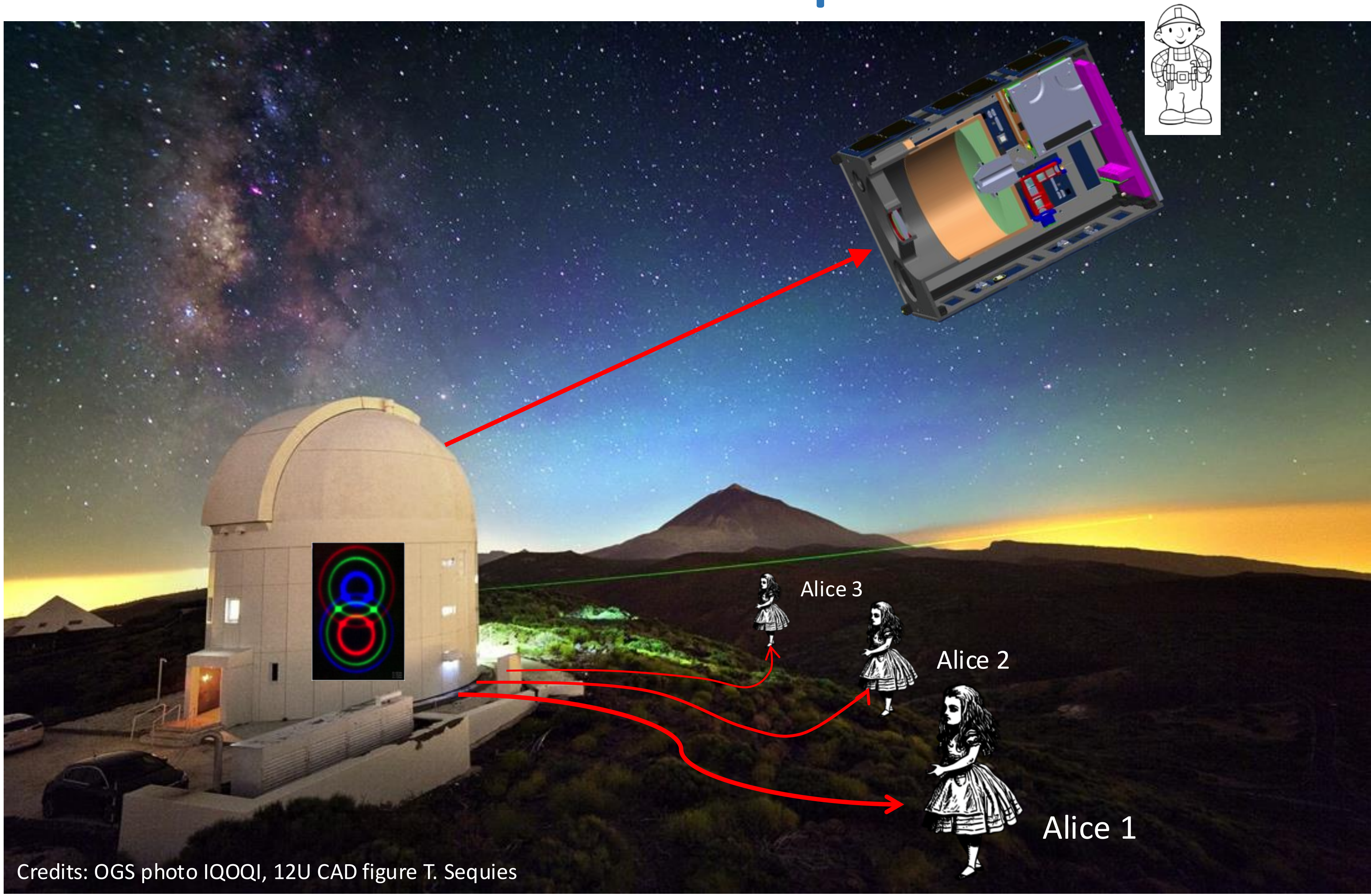
NanoBob QKD mission concept

QKD in uplink config using polarization entangled photon source on the ground

12U CubeSat with single photon detection unit

Synchronized quantum network to end-users (INPHYNI)

Global QKD



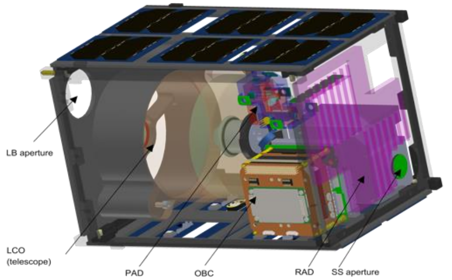
NanoBob Mission Definition Review: key elements

SWaP: Size, Weight, and Power

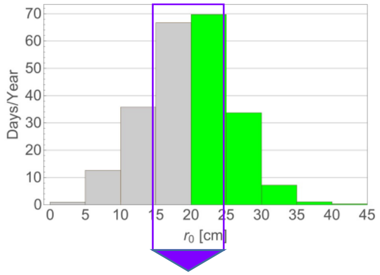
Item	Size (ml)	Weight (g)	Peak Power (mW)	TRL	Margin	Size Margin	Weight Margin	Power Margin
Payload	**5 045**	**2 680**	**14 500**			**1160**	**819**	**6850**
Quantum Optical Module (808 nm)	125	200	4 000	4	50%	63	100	2000
Beacon Receiver Module (1530 nm)	145	360	6 000	3	50%	73	180	3000
LCO-QKD	4 050	830	0	4	20%	810	166	0
Beacon Transmitter Module (1565 nm)	200	350	1 500	2	50%	100	175	750
Retro-reflector	125	340	0	7	20%	25	68	0
Detector cooling	100	300	0	2	20%	20	60	0
Time Tagging Module	100	100	2 000	2	50%	50	50	1000
Beacon Signal Processing	100	100	500	7	10%	10	10	50
Data storage	100	100	500	7	10%	10	10	50
Platform	**5 425**	**5 148**	**12 060**			**403**	**443**	**617**
OBC	110	94	500	9	5%	6	5	25
ADCS	750	1 225	2 470	9	5%	38	61	124
GPS	35	24	1 200	9	5%	2	1	60
UHF/VHF module	110	75	4 000	9	5%	6	4	200
S-Band module	130	62	3 800	9	5%	7	3	190
Antennes	110	128	0	9	5%	6	6	0
PMU & batteries	680	840	90	9	20%	136	168	18
Mechanical structure	3 000	2 000	0	9	5%	150	100	0
Detector radiators	200	400	0	5	20%	40	80	0
Solar panels	300	300	0	9	5%	15	15	0
TOTAL PAYLOAD & PLATFORM	**10 470**	**7 828**	**26 560**			**1563**	**1262**	**7467**

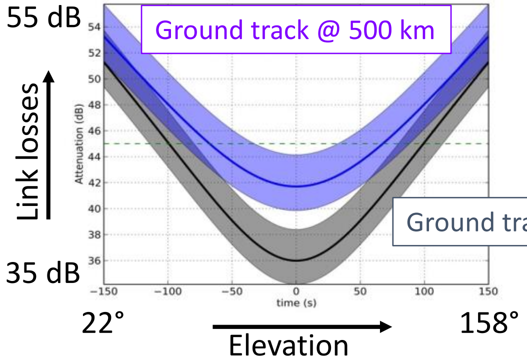
Detectors / Wavelength

	APD-Si	APD-InGaAs	SNSPD	SNSPD	MCT
Wavelength (nm)	**810**	**1550**	**810**	**1550**	**1550**
Photon Detection Efficiency	> 70%	> 25%	> 90%	> 90%	> 60%
Dark Count Rate (cps)	< 100	< 250	< 10	< 10	> 1000 ?
Timing jitter (ps)	< 100	< 200	< 80	< 80	< 100
Count Rate (Mcps)	> 100	> 100	~10	~10	
Complexity & cost (~ 1/maturity)	$	$$	$$$$$	$$$$$	$$$

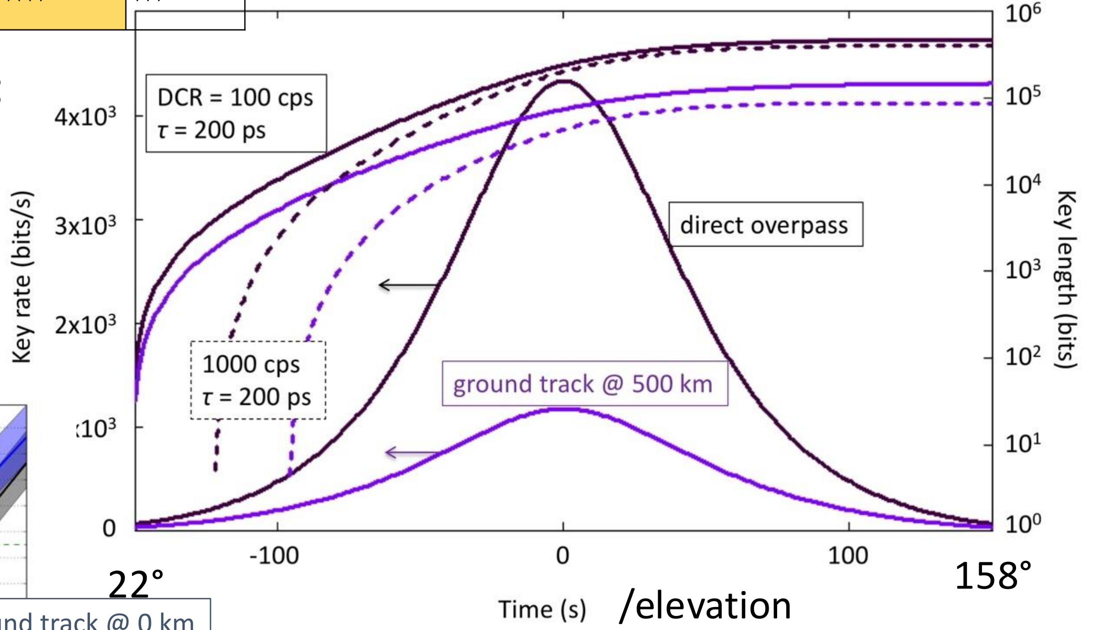


Atmospheric link budget



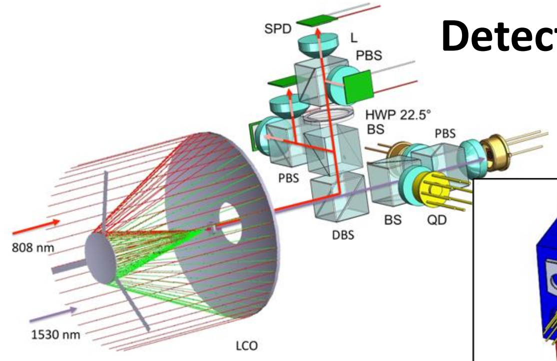


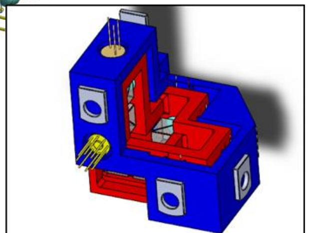
Quantum secure key rate and key length for one pass and for conservative instrument and link parameters:



→ key length per successful pass: 10^5 - 10^6 bits

Detection module & cooling





Key rate versus coincidence time window:

discrimination against dark- and background photon counts

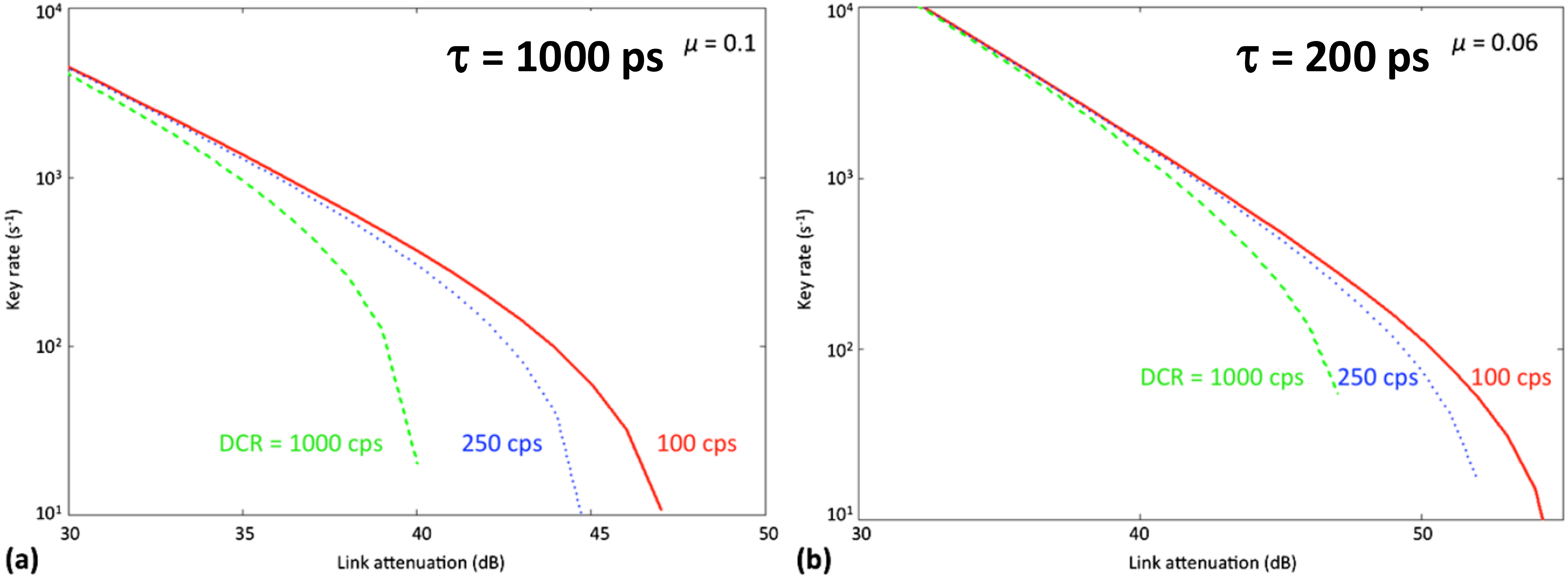
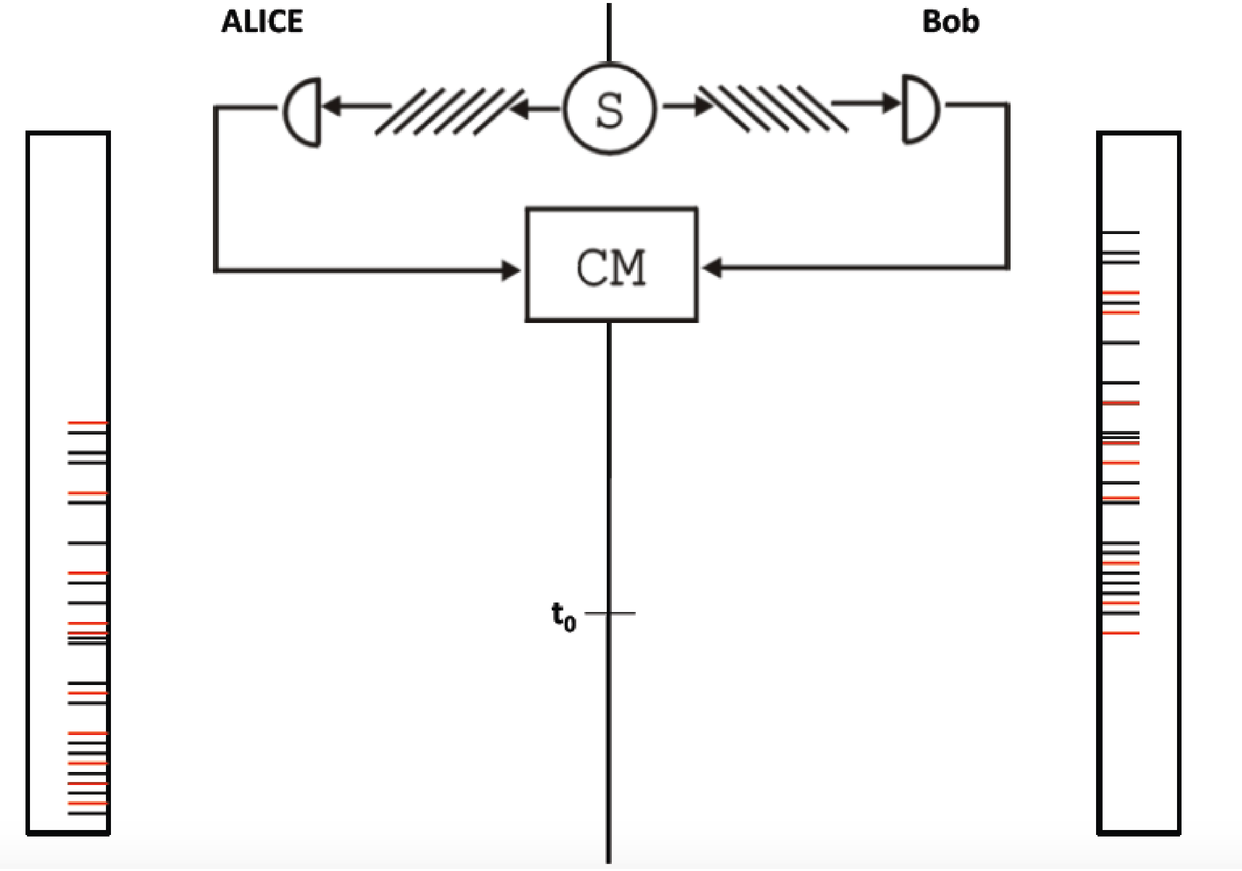
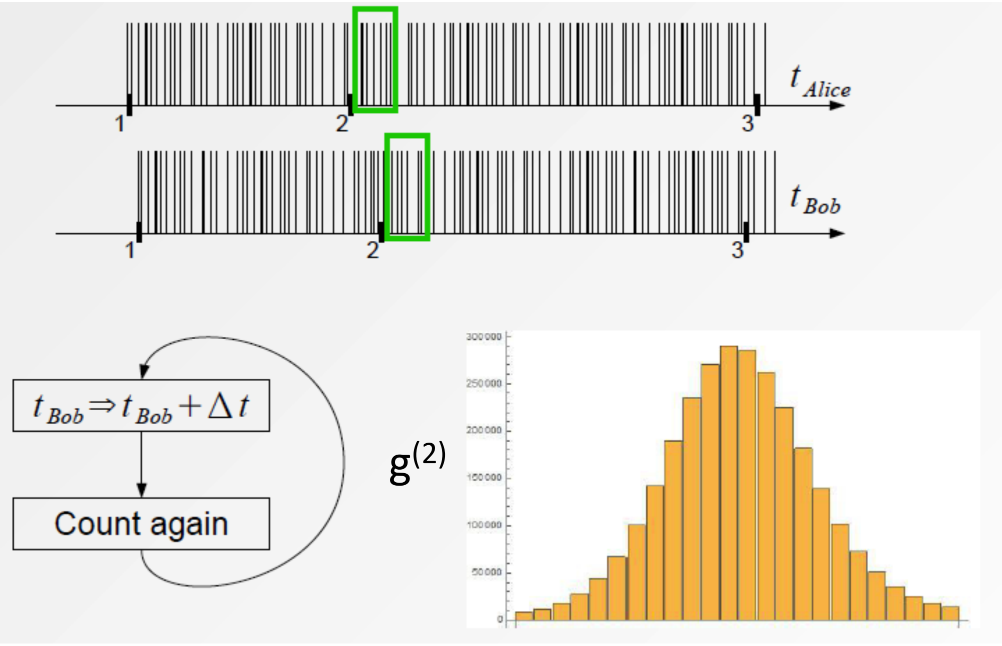


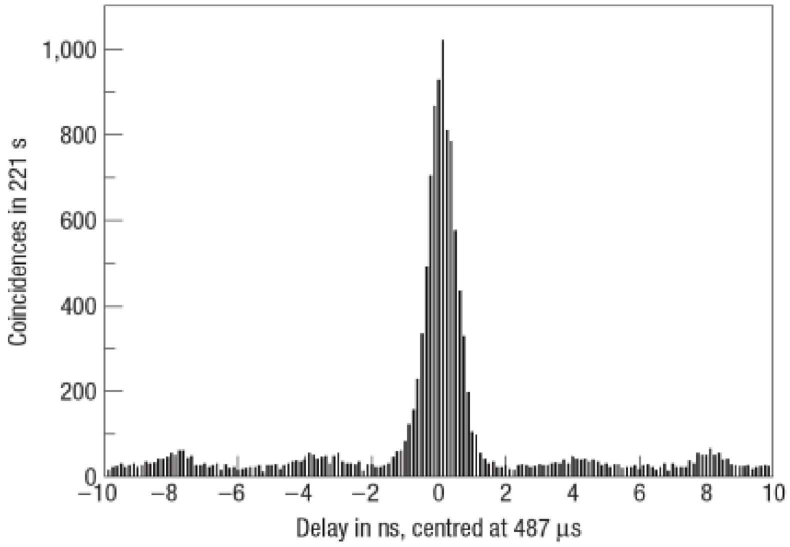
Figure 10 The secure secret key rate for three different values of the dark count rate as a function of the link attenuation (solid curve: 100 cps; dotted curve: 250 cps; dashed curve: 1000 cps per detector). (**a**) For the conservative parameters of Table 3 and $\tau = 1$ ns and $\mu = 0.1$ ($R_{pair} = 10^8$ s^{-1}), (**b**) same, except for $\tau = 200$ ps and $\mu = 0.06$ ($R_{pair} = 3 \cdot 10^8$ s^{-1})

Clock synchronisation

Timing of photon arrivals used to discriminate between entangled pair photons and background or dark counts.
But how to correct for clock drift?

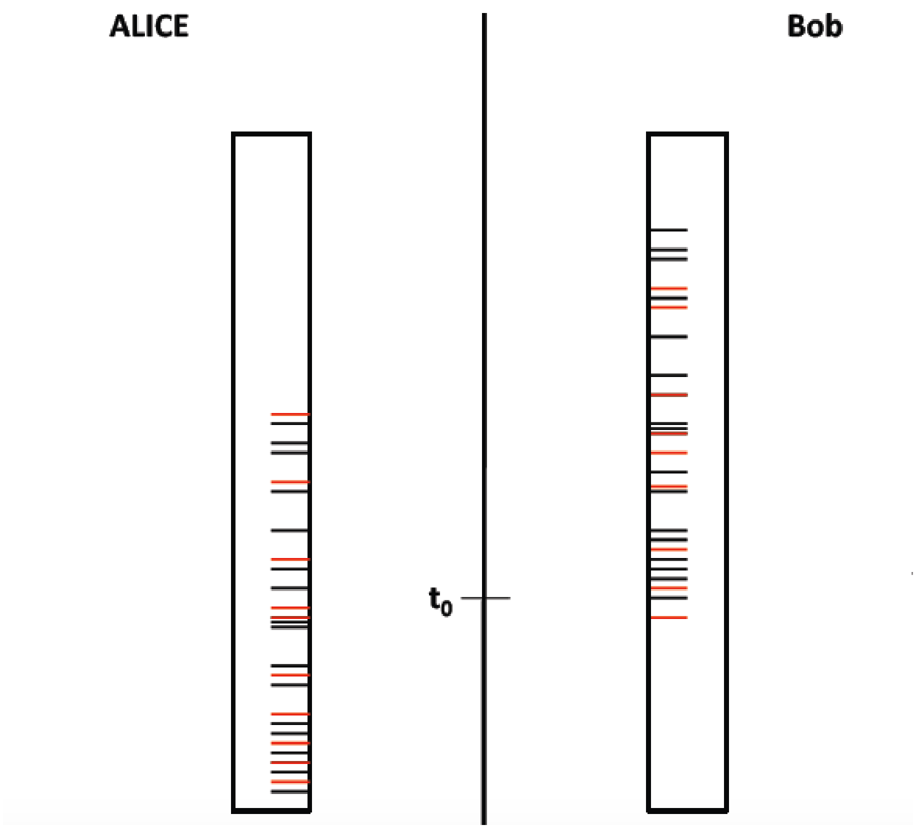


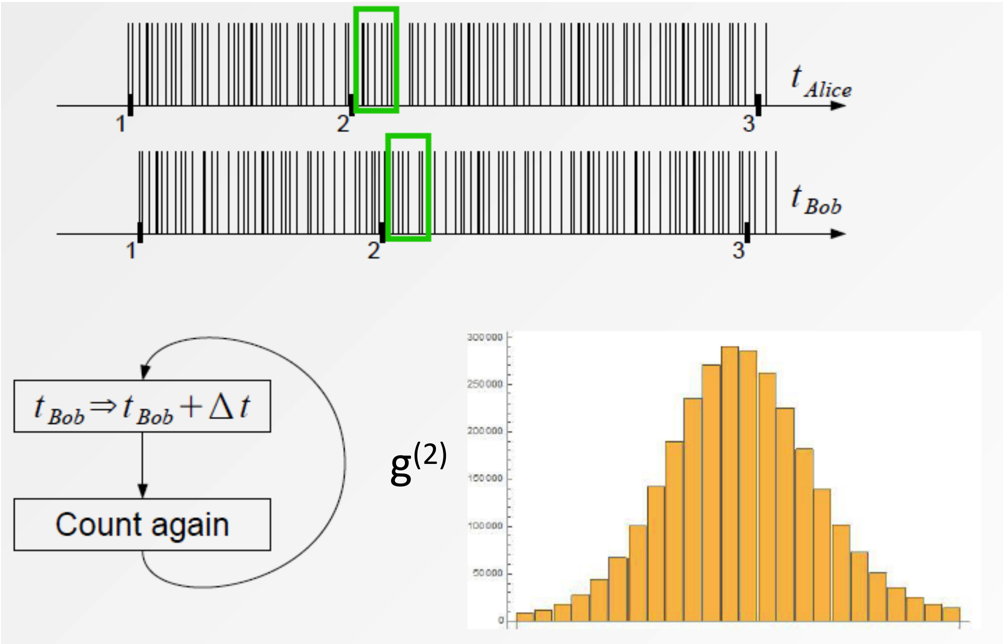


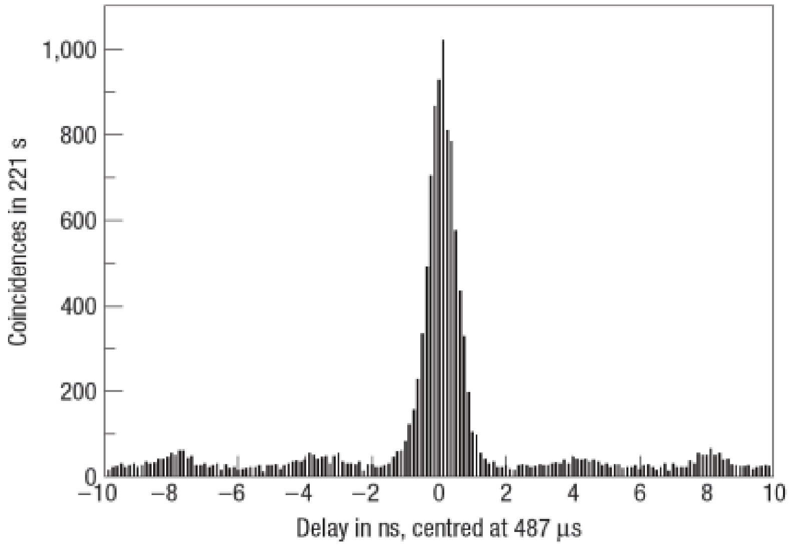


Clock synchronisation

Timing of photon arrivals used to discriminate between entangled pair photons and background or dark counts.
Maximize photon correlation to determine clock offset.







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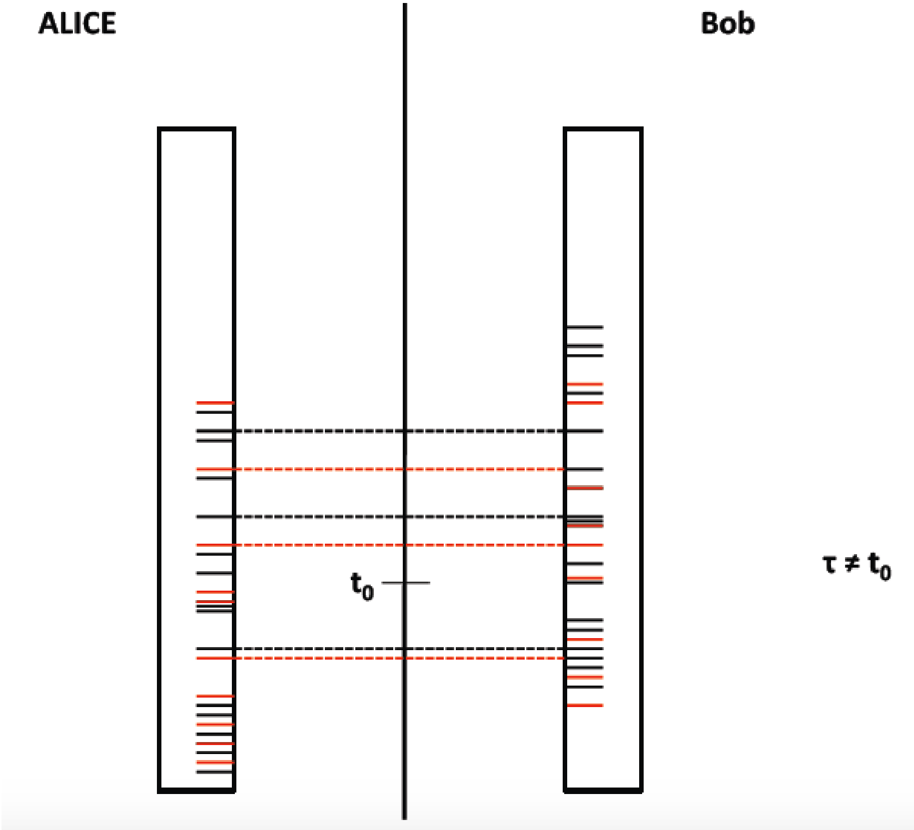

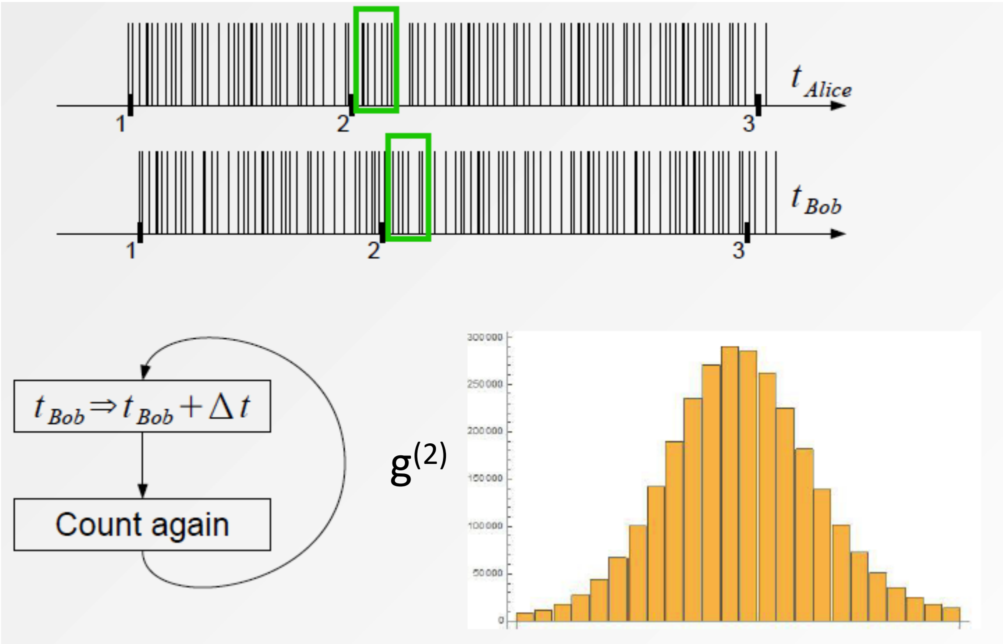

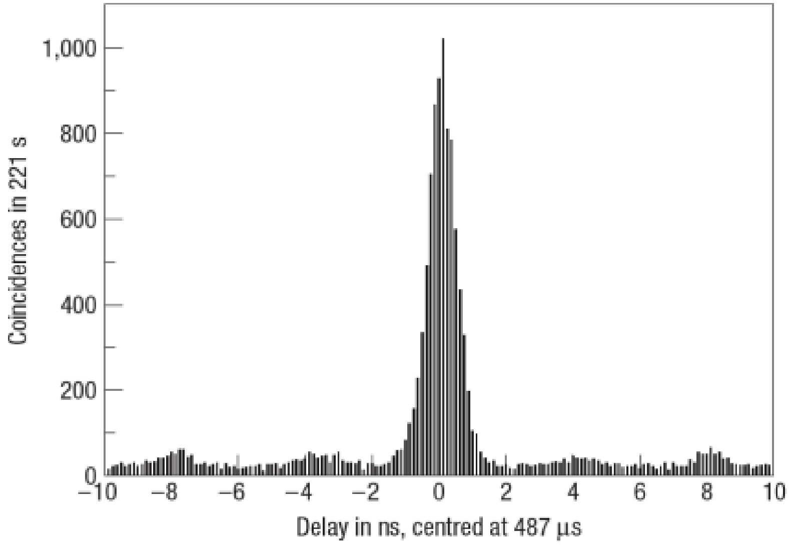

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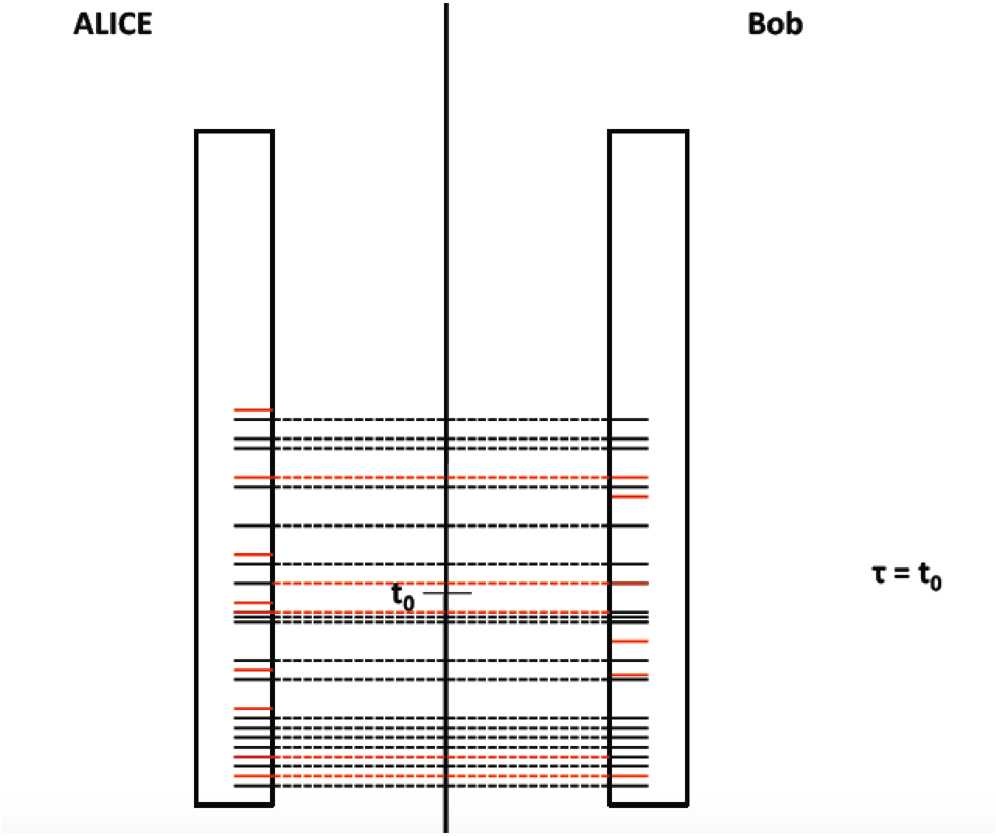
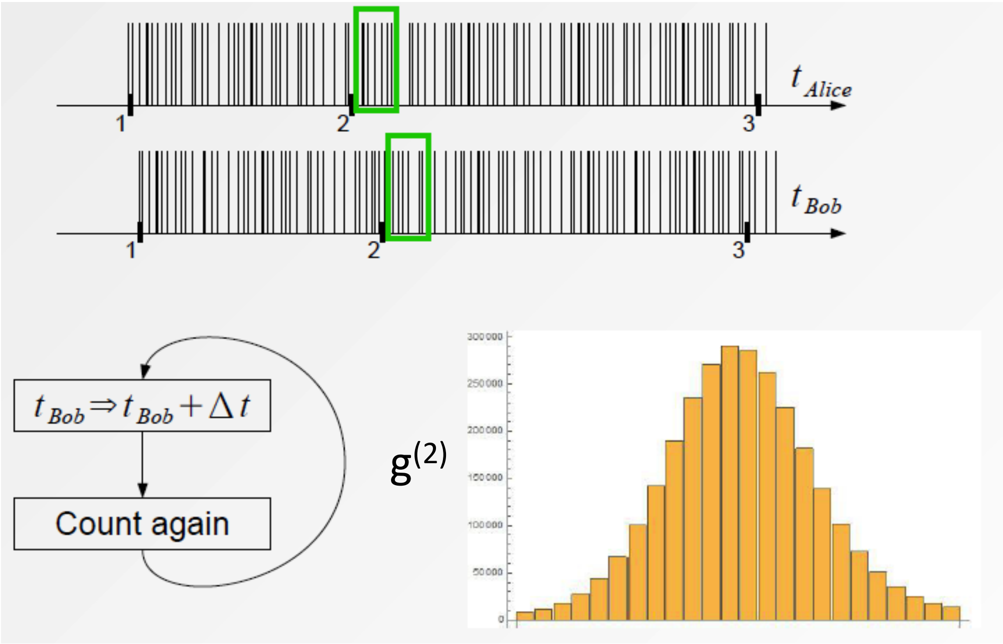
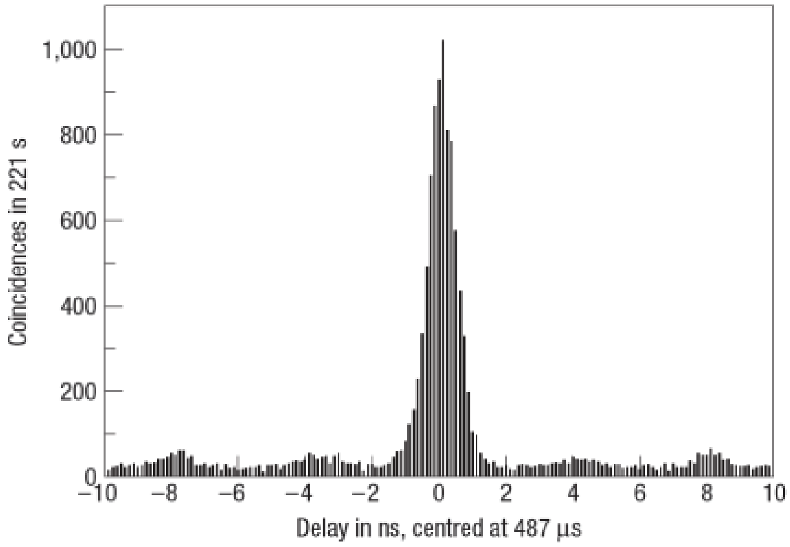
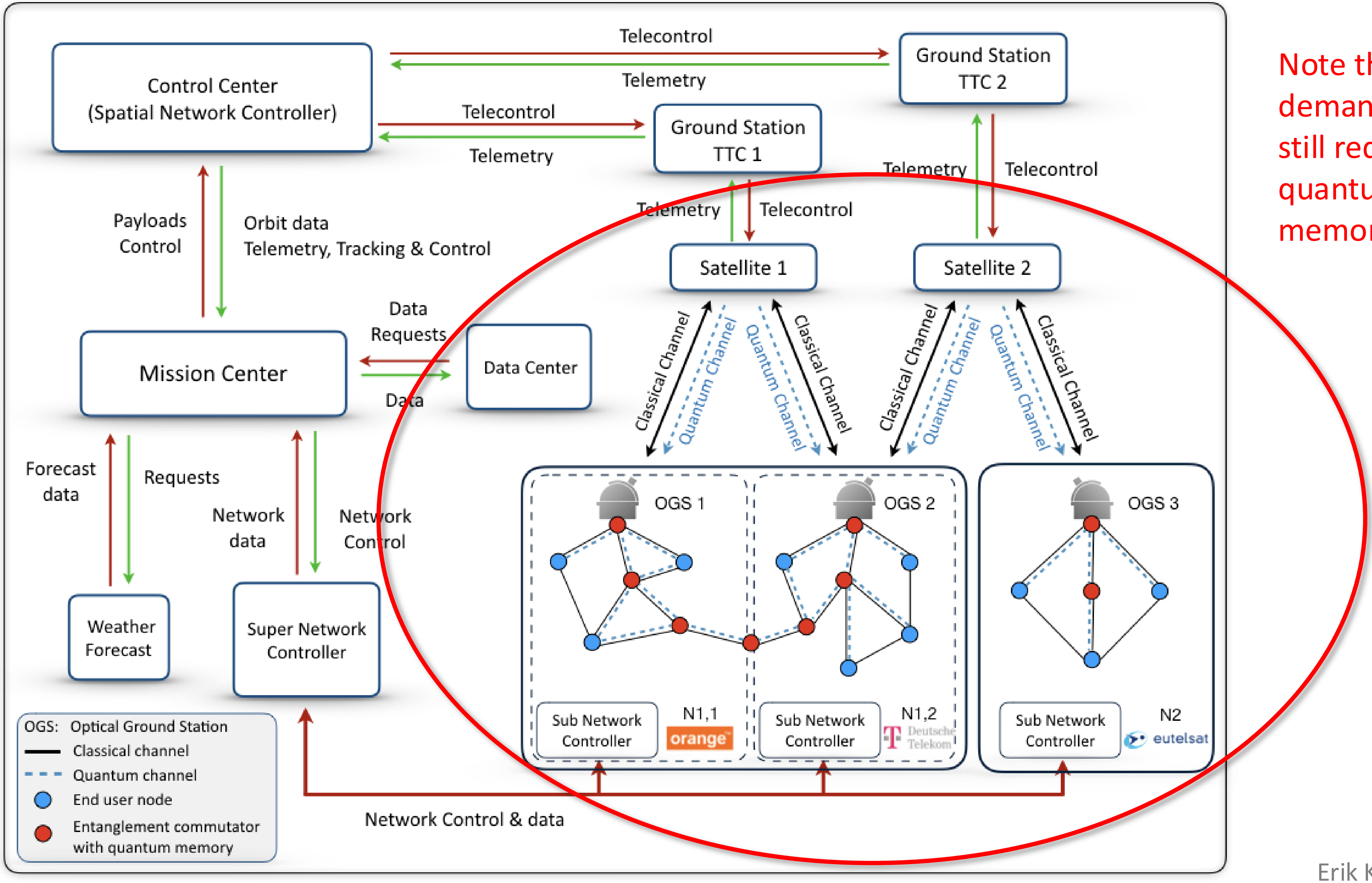




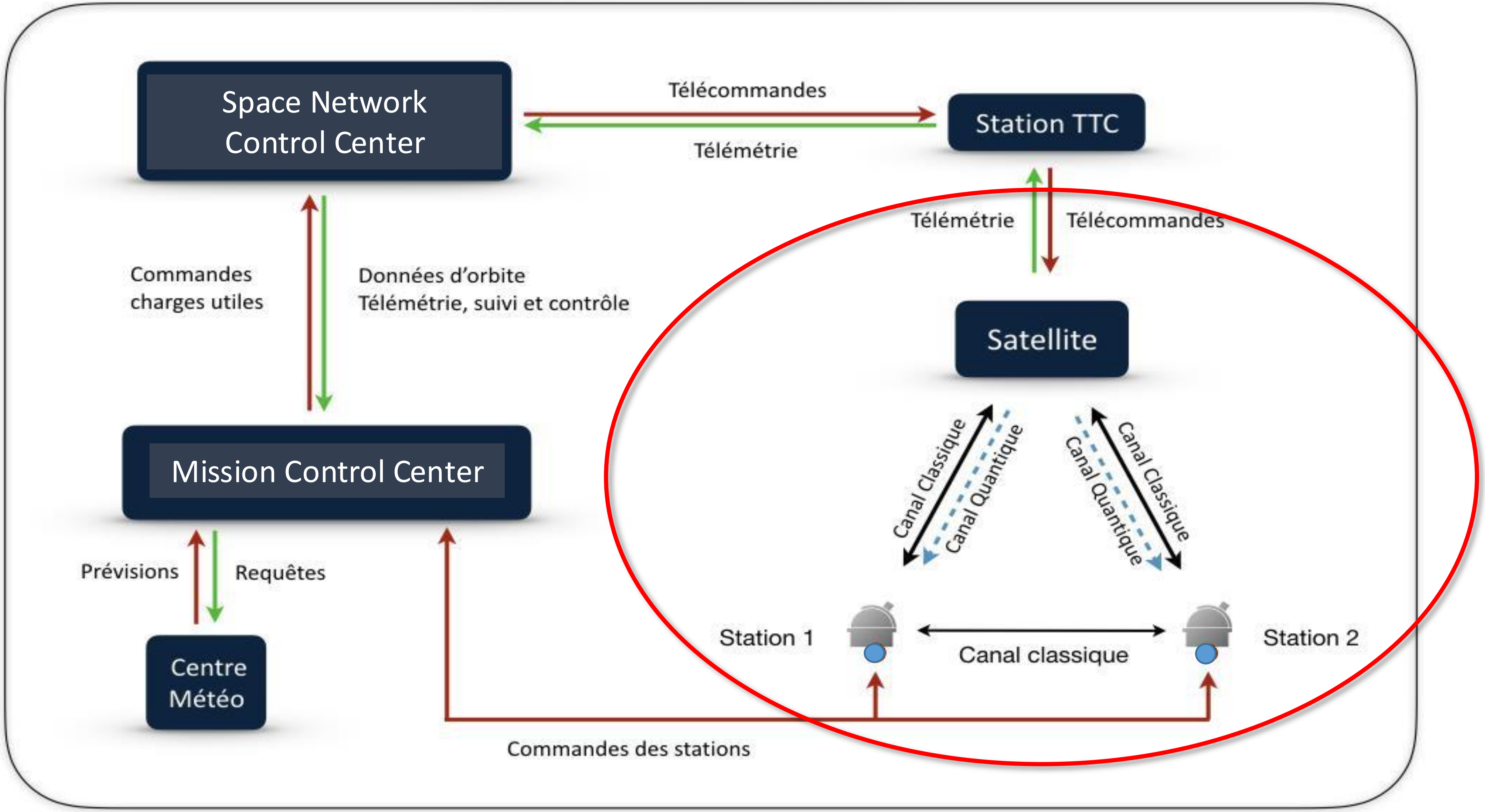


G-QIN: Satellites distribute entangled photon pairs



Note that an on-demand network still requires quantum memories (●)

Demonstrator Simplified Diagram



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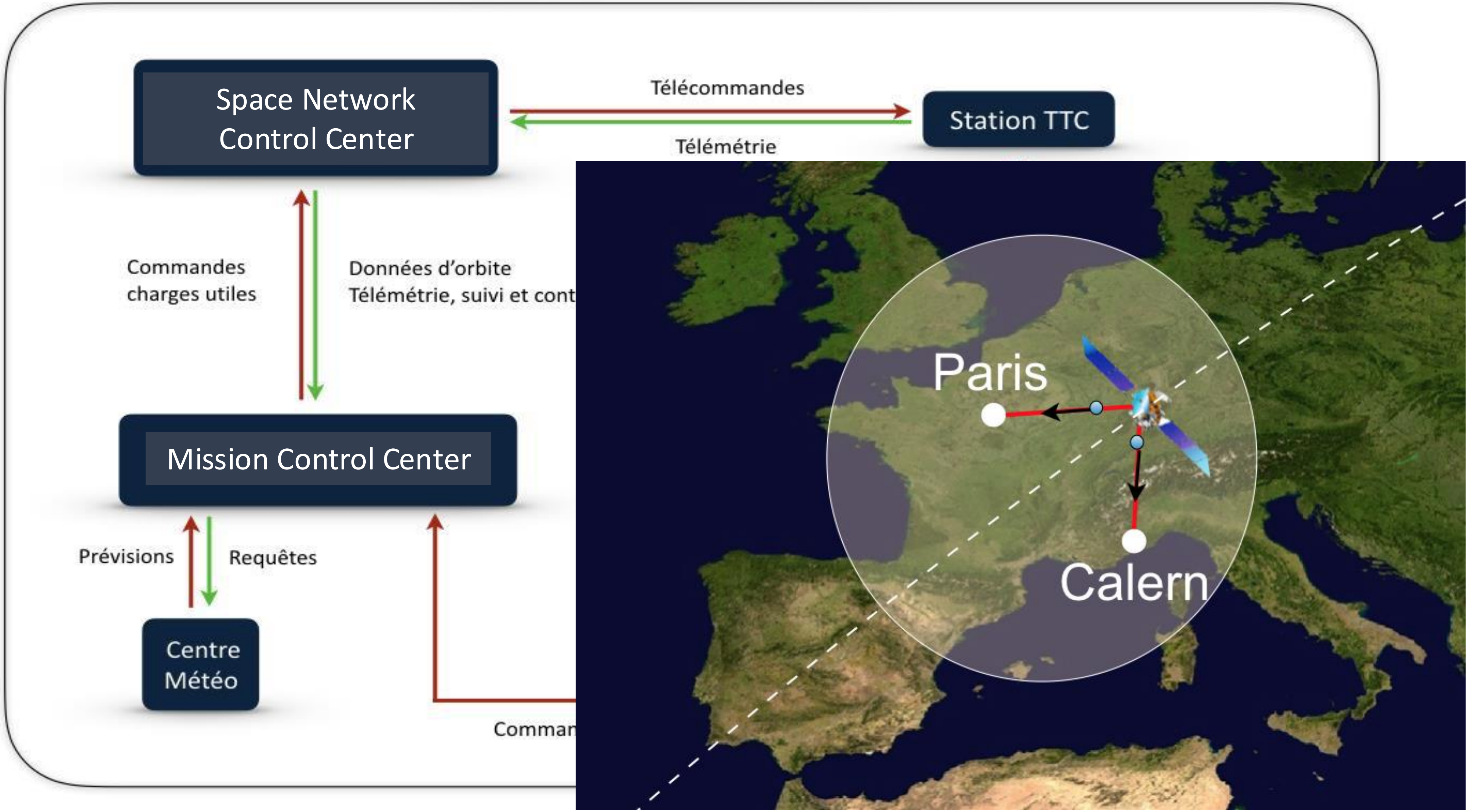


« RIQS » Atmospheric dual link and SKR

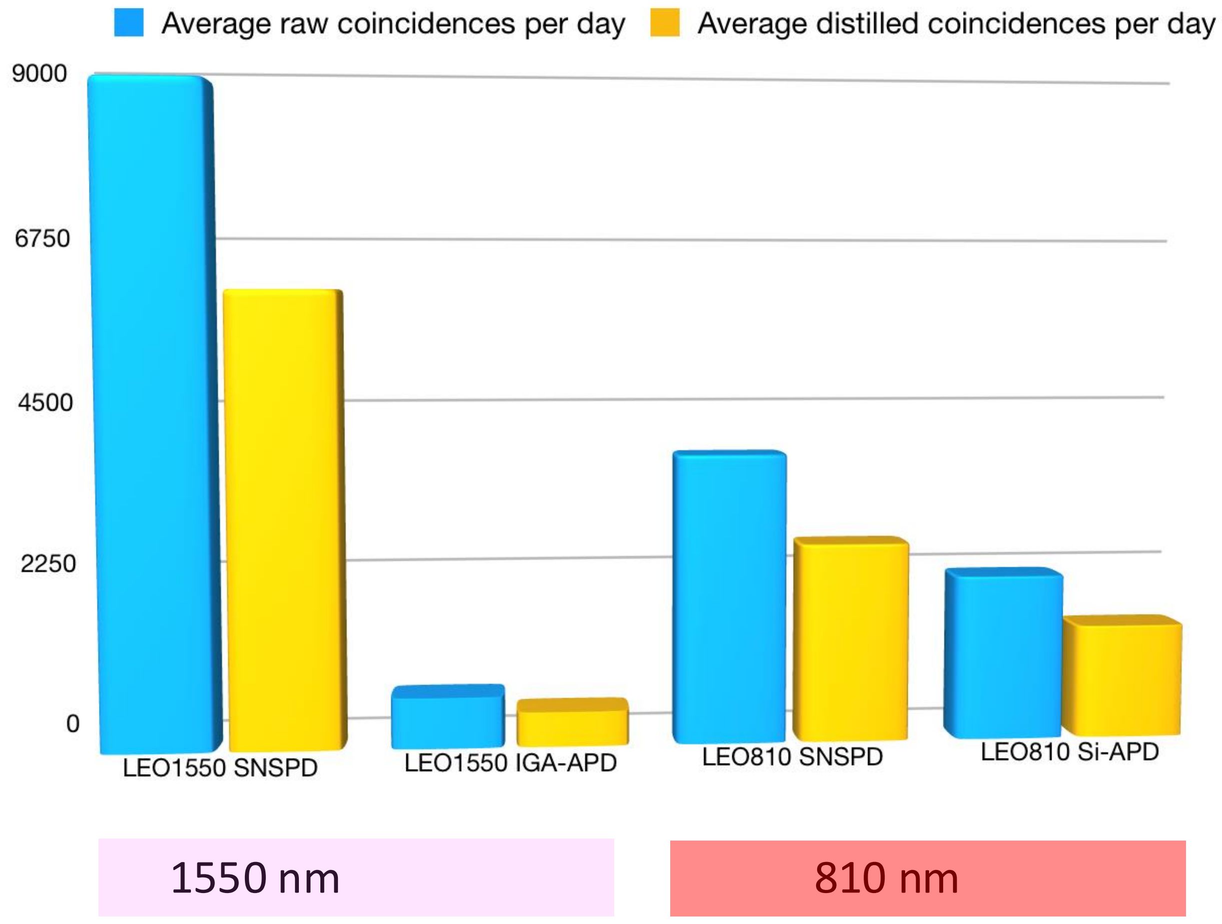
Simulation input parameters:

h	Satellite altitude (LEO / MEO)	600 / 7625	km
q	basis reconciliation factor	0.5	
f(E)	bidirectional error correction function	1.22	
τ	coincidence time window	200	ps
μ	average number of photon pairs per pulse	0.02	
D_R	OGS telescope diameter (LEO / MEO)	80 / 100	cm
D_T	Sat telescope diameter (LEO / MEO)	30 / 50	cm
D	OGS dark count rate per detector	100	cps
B	OGS background count rate (810 / 1550 nm)	400 / 100	cps
N_{det}	number of detectors	4	
PDE	Photon Detection Efficiency (SNSPD / IGA-APD / Si-APD)	0.9 / 0.25 / 0.68	
$\eta_{1,2}$	$\eta_{1,2} = T_{opt} \cdot T_R \cdot T_T \cdot (1-L_P) \cdot PDE \cdot 10^{-A1,2/10}$, with A1,2 the quantum channel 1,2 atmospheric link attenuation in dB		
$A_{atm,0}$	Atmospheric attenuation at zenith (810 / 1550 nm)	3 / 2	dB
L_P	Telescope pointing error (810 / 1550 nm)	0.3 / 0.2	
T_R, T_T	Telescope transmission factors	0.8	
T_{opt}	Combined optics efficiency (OGS & Sat) (810 / 1550 nm)	0.2 / 0.35	
e_0	error probability of dark- and background counts	0.5	
e_d	error probability of photon arriving on wrong detector (polarization error)	0.01	

Entangled photon source models by Ma, Fung, and Lo (2007), Neumann et al. (2021)

« RISQ » Simulations: some results

- Realistic orbital modeling
- Long-term simulations (1 yr)
- QKD metrics as proxy for entanglement distribution efficiency
- Timing requirements for a dual link are technically feasible: 200 ps timing jitter quite acceptable: small losses due to distillation (= discrimination against dark- and background counts + classical error correction, using arrival timing to identify entangled photon pairs).



TAS-F (Mathieu Bertrand, Laurent de Forges de Parny, Mathias Van Den Bosche)
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IQOQI (Rupert Ursin, Siddarth K. Joshi, and Matthias Fink),
INPHYNI (Sebastien Tanzilli, O Alibart),
LIP6 (Eleni Diamanti, M Schiavon),
OCA (E Samain, C Courde, J Chabé),
Bristol (SK Joshi, John Rarity),
Onera (Nicolas Vedrenne),
and other industrial partners

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EPJ-QT 2018. https://rdcu.be/1uEO
Nature Comm Phys 2023. https://rdcu.be/c3xo9

The CSUG NanoBob *Student* and Staff Team:
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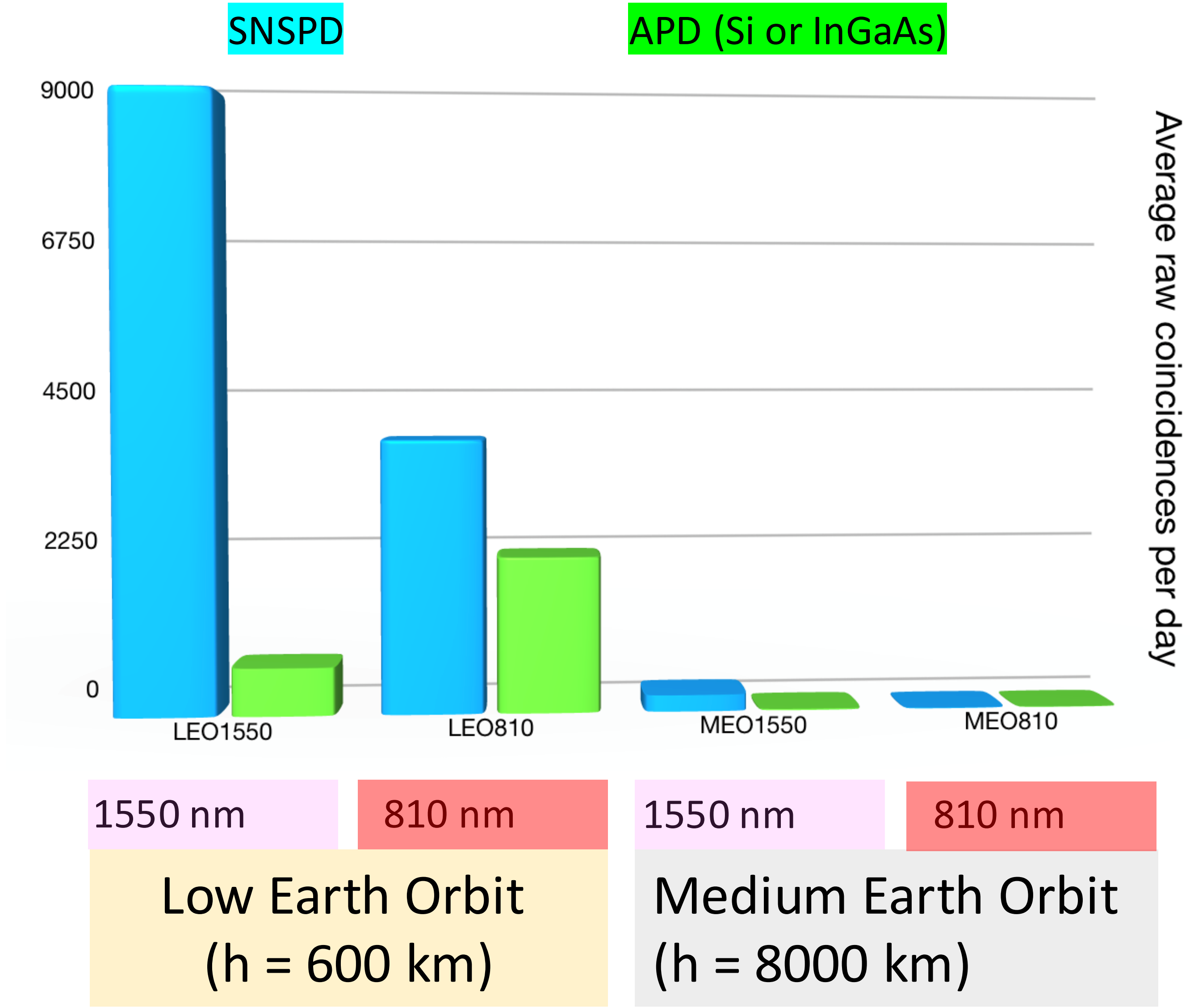
Vincent Borne, Guillaume Bourdarot, Jean-Yves Burlet, Alexis Christidis, Alexandre Metrat, Fabien Montagne, Paul Payraudeau, Melanie Prugniaux, Mathieu Roccia, Etienne Rolland, Jesus Segura.
Benoit Boulanger, Veronique Boutou, Mylene Bouzat (Air Liquide), Mathieu Chabanol, Laurent Fesquet, Hassen Fourati, Michel Moulin, Jean-Michel Niot (Air Liquide), Rodrigo Possamai Bastos, Bogdan Robu, Sylvain Toru

« RIQS » Simulation results



Conclusions:

If cost plays no role:
SNSPDs at both wavelengths

If cost/complexity/cooling is a concern:
Si-APDs at 810 nm

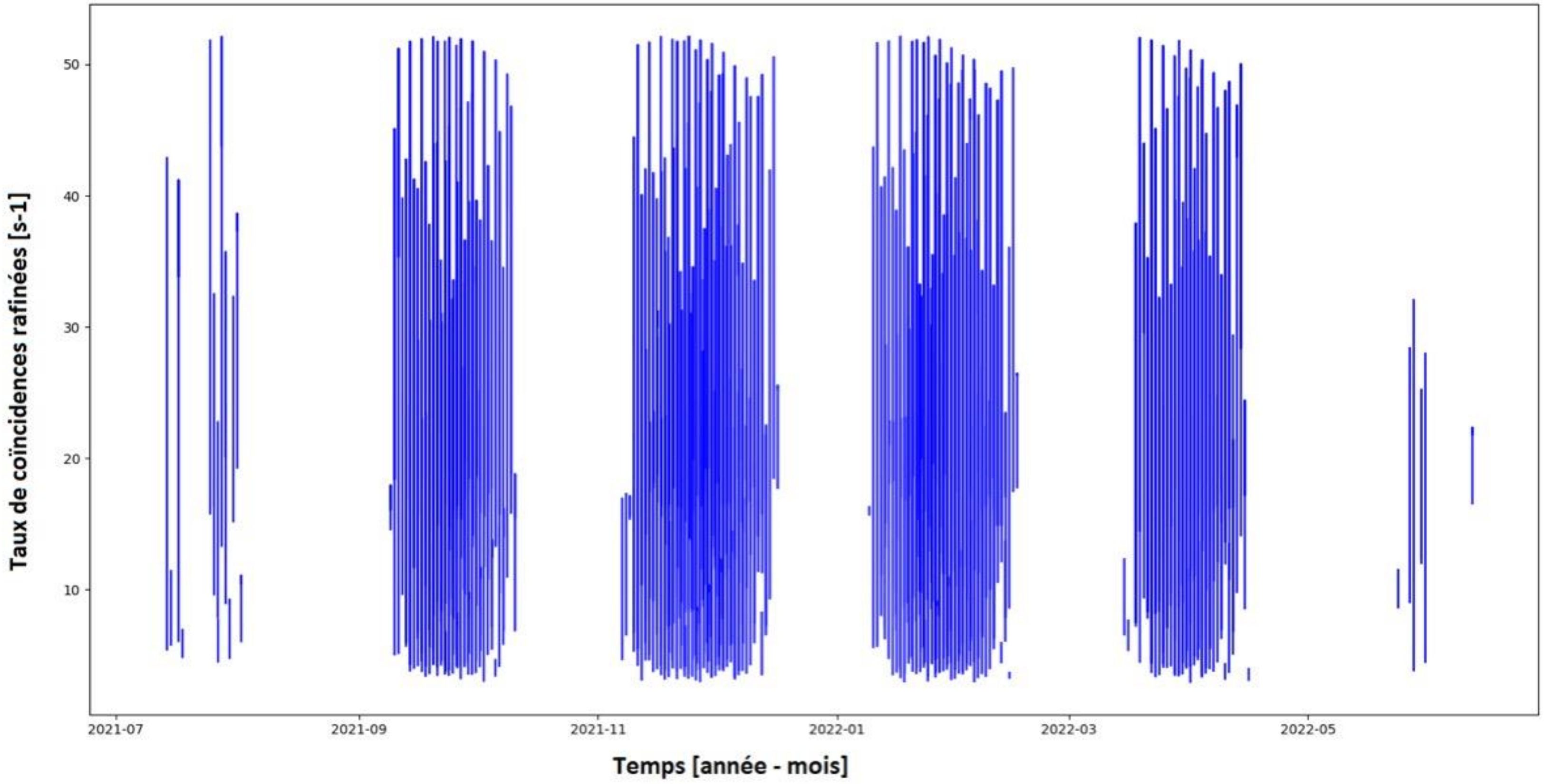
Note: No daylight communication at 810 nm:

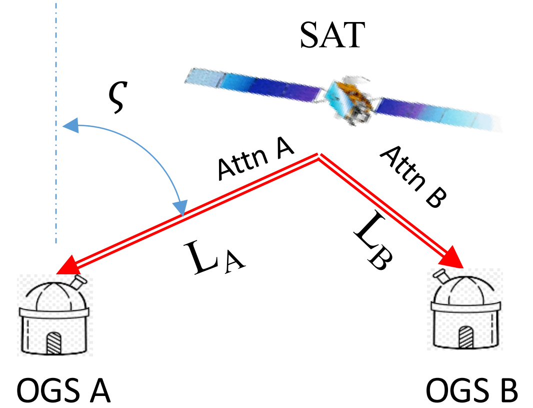
Average comm time 9.3 min/day at 1550 nm, versus 2.3 min/day at 810 nm

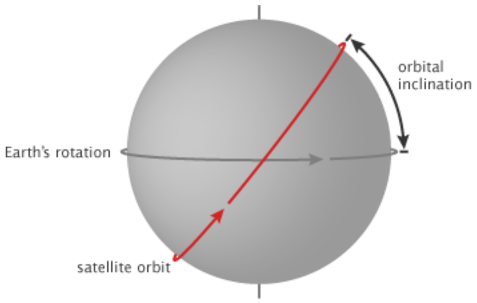
LEO orbital is always to be preferred

Highest SKR for LEO at 50° inclin.

But … if communication is possible only during nighttime (810 nm) :







Dual link Paris-Calern: <u>Night-time only</u>

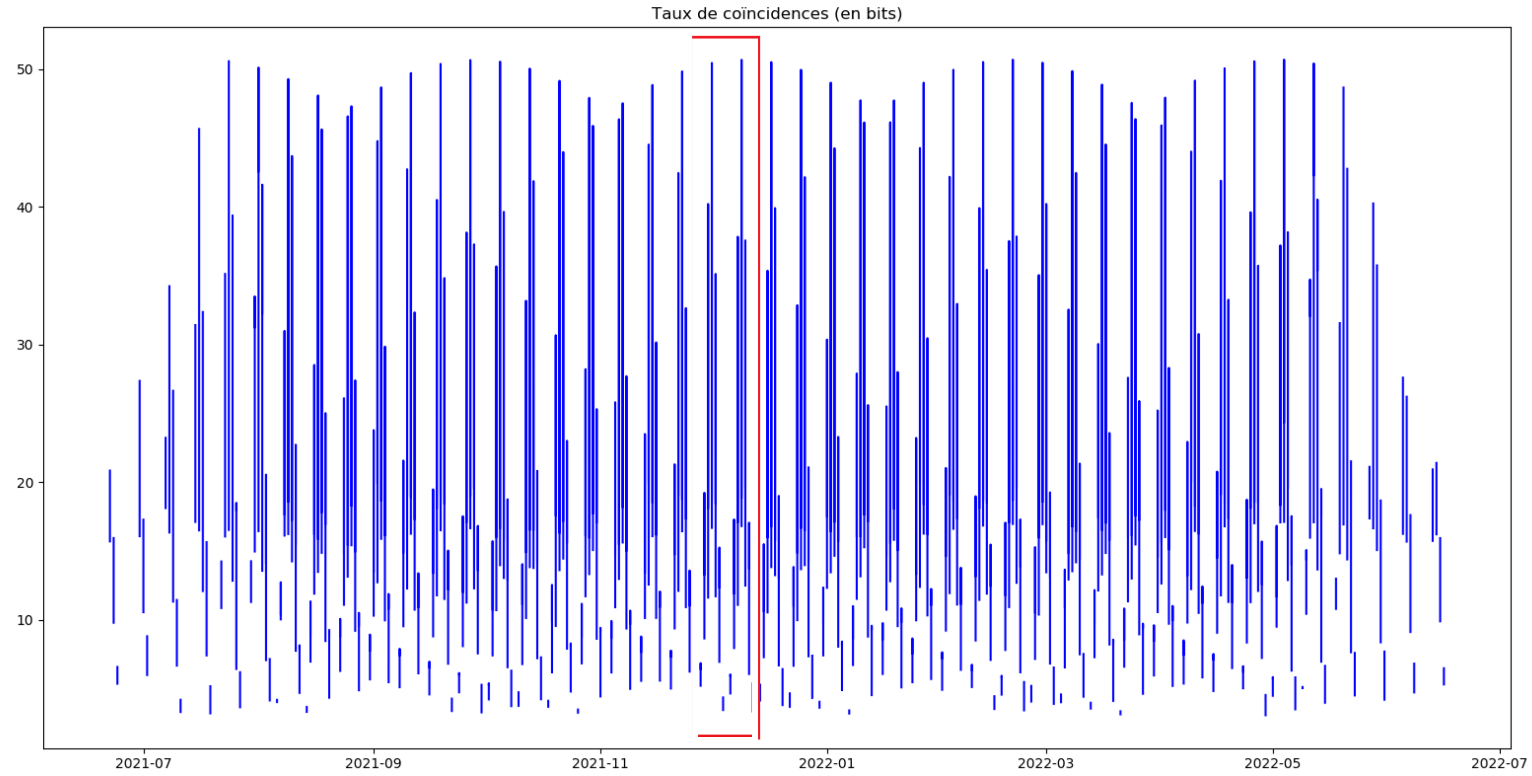
λ = 810 nm
SNSPD

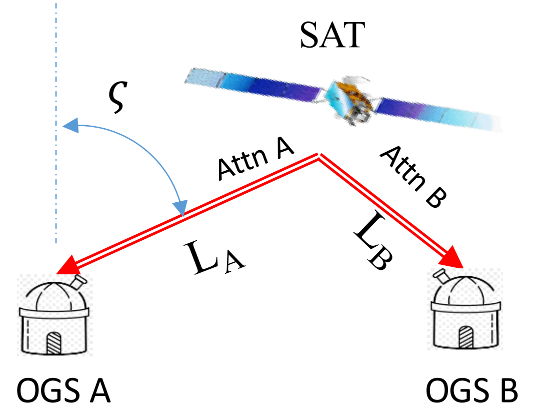
	LEO 50° inclination				LEO SSO			
	1550 nm SNSPD	1550 nm IGA	810 nm SNSPD	810 nm Si	1550 nm SNSPD	1550 nm IGA	810 nm SNSPD	810 nm Si
Total Time (min)	9.29	9.29	2.27	2.27	2.97	2.97	1.19	1.19
Coincidences/day	8 752.94	676.08	3 858.30	2 202.92	2 795.92	215.96	2 051.50	1 171.32
Distilled coincidences/day	6 038.24	462.29	2 656.00	1 514.00	1 928.74	147.66	1 414.27	806.40

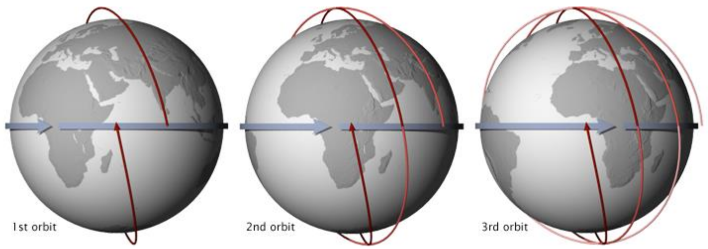
Sun-synchronous orbit (SSO)

SSO h = 608 km, inclin. 97.8°

dual,link, 365 j, communication only during nighttime







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