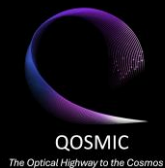


The Optical Highway

The On-Ramp to Quantum Communication

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Security guaranteed by physics, not by difficulty

1

No-cloning

An unknown quantum state cannot be copied. There is no passive tap on a quantum channel.

2

Measurement disturbs

Any eavesdropper leaves a statistical footprint in the error rate.

3

Forward secrecy

A key never transmitted as data cannot be harvested now and broken later.

This is the part of the story everyone in this room already believes.

First, the light has to land where it is meant to

Reliably. In daylight. Through turbulence. Onto a detector a few centimetres across.
From a satellite moving at several kilometres per second.

~7.5 km/s

LEO ground-track velocity

~5–10 min

usable pass over one station

μ rad

pointing precision required

0 dB

gain available from amplification

Quantum communication is a physics result standing on an engineering problem.

Where we are going

1 Why space

Why fibre runs out and the link has to go up

2 Optical link basics

Why light, and what an optical link is made of

3 The atmosphere

Divergence, turbulence, absorption, background

4 Pointing & the budget

Microradians, and where every photon goes

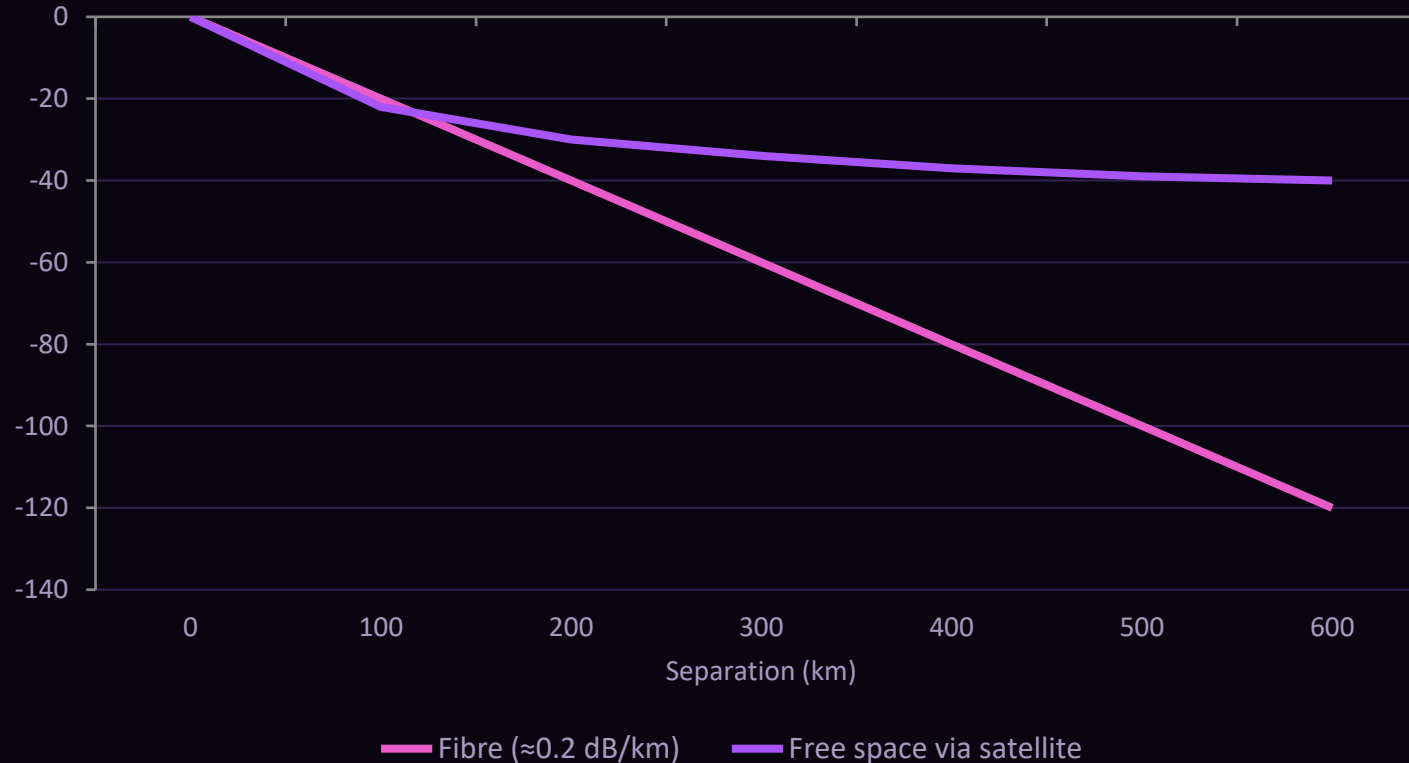
5 Classical → quantum

What changes when the signal is one photon

6 Digital trust

QKD, PQC, and what has to be built

Why this has to go through space



The trade

Fibre loss is exponential in distance — and a quantum signal cannot be amplified back up along the way.

Free-space loss is geometry plus the few kilometres of atmosphere near the ground. Above that, space is an excellent vacuum.

Beyond a few hundred kilometres, a satellite pass is the only channel that closes.

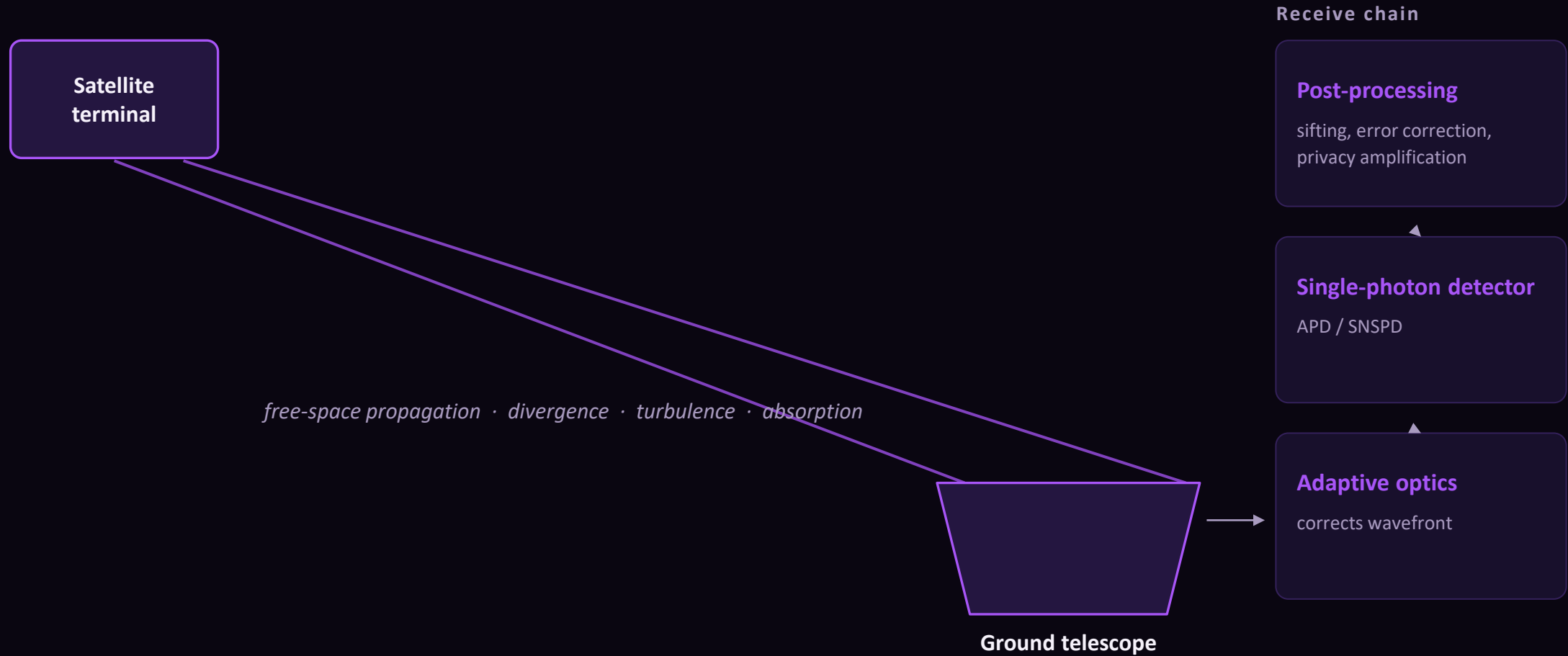
Schematic comparison of channel loss; illustrative, not measured data.

Why light, and not radio

Parameter	Radio frequency	Optical
Beam divergence	Wide — kilometres of spill	Narrow — diffraction sets the limit
Usable bandwidth	Congested, licensed spectrum	Unlicensed optical bands
Data per pass	Baseline	One to two orders higher
Interception footprint	Anyone under the beam	Must stand inside the spot
Quantum compatible	No	Yes — same physical layer

The last row is the one that matters for this talk: a quantum link is an optical link with a weaker signal.

Anatomy of a space-to-ground link



Every block in this chain exists whether the payload is a terabit downlink or a single-photon key. Only the tolerances change.

Five numbers decide whether a link closes

λ

Wavelength

Sets diffraction, detector choice and atmospheric transmission

D

Aperture

Transmit gain and receive collecting area both scale with it

θ

Divergence

$\approx \lambda/D$ at the diffraction limit — the tighter the harder to point

σ

Pointing error

Must stay well inside θ or the receiver sits in the beam skirt

η

Detection efficiency

Everything the photon survives after the telescope

Problem #1: Light spreads

$$\theta \approx \lambda / D$$

Diffraction sets a floor on how tightly a beam can be collimated.
A larger transmit aperture buys a narrower beam — and a harder pointing problem.

Illustrative

$\lambda = 1550 \text{ nm}$, $D = 10 \text{ cm} \rightarrow \theta \approx 15 \mu\text{rad}$

At 500 km slant range, the spot is several kilometres wide.



*The receiver collects a small fraction of the transmitted power.
This geometric loss dominates the link budget.*

Problem #2: The atmosphere is not still



Beam wander

Large eddies steer the whole beam off the receiver



Scintillation

Intensity fluctuates — deep fades lasting milliseconds



Wavefront distortion

The spot stops being a spot; coupling efficiency collapses



Angle of arrival

The apparent source position jitters, defeating fine tracking

The vocabulary

C_n^2 refractive index structure constant — how turbulent the path is

r_0 Fried parameter — the aperture size beyond which turbulence, not diffraction, limits you

σ^2_i scintillation index — the depth of the fading

A classical link rides out a fade with margin and coding. A quantum link loses the photons that were the key.

Problem #3: loss you cannot engineer away

Absorption & scattering

- Molecular absorption bands
- Aerosol and Mie scattering
- Transmission windows dictate λ

Cloud

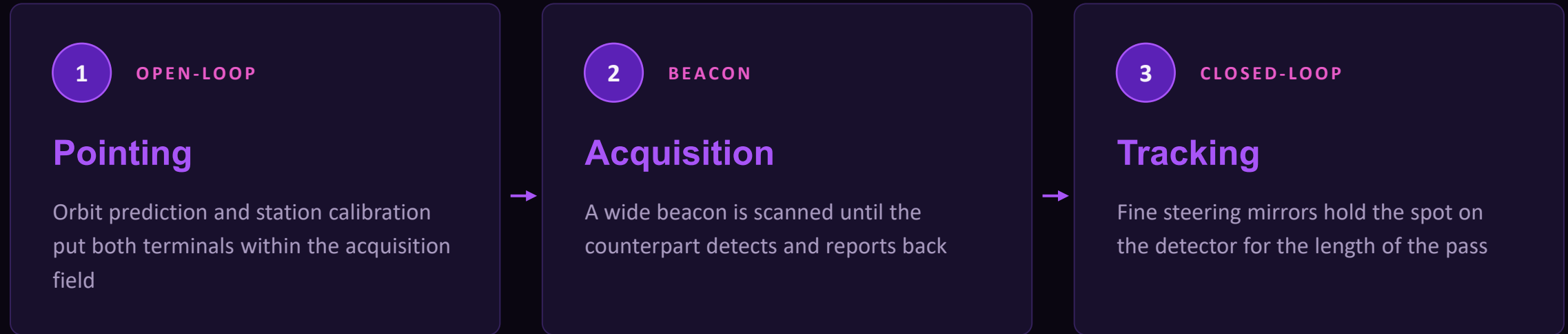
- An optical link does not penetrate cloud
- Availability is a siting and network problem, not an optics problem
- Diversity across stations is the only answer

Background light

- Sky radiance, moonlight, city glow
- Every stray photon is a potential false detection
- Sets the daylight QKD limit

Background light is where classical and quantum part company: a bright sky is noise to a receiver that expects one photon.

Finding each other, then staying found



All three phases must complete inside a pass that lasts minutes — every pass, every night, unattended.

Microradians, from a moving platform

Point-ahead

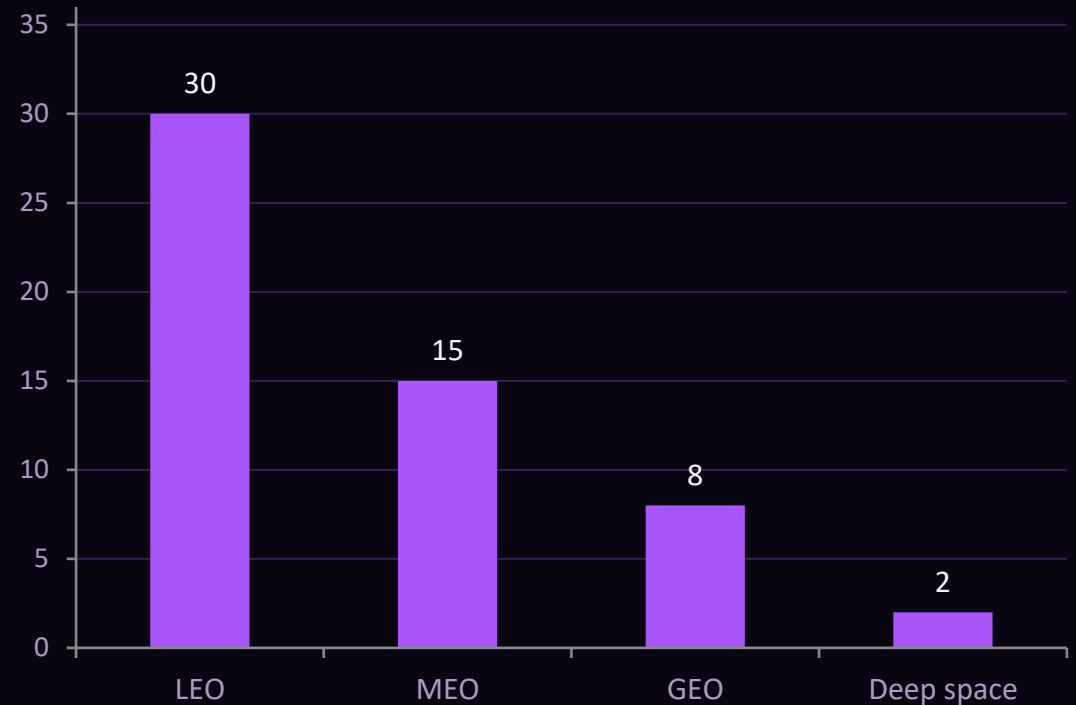
$$\alpha \approx 2v / c$$

Light takes milliseconds to arrive. You aim where the counterpart will be, not where it appears — tens of microradians away.

What fights you

- Platform micro-vibration and reaction wheels
- Mount flexure and thermal drift on the ground
- Atmospheric angle-of-arrival jitter

Required pointing accuracy tightens with altitude



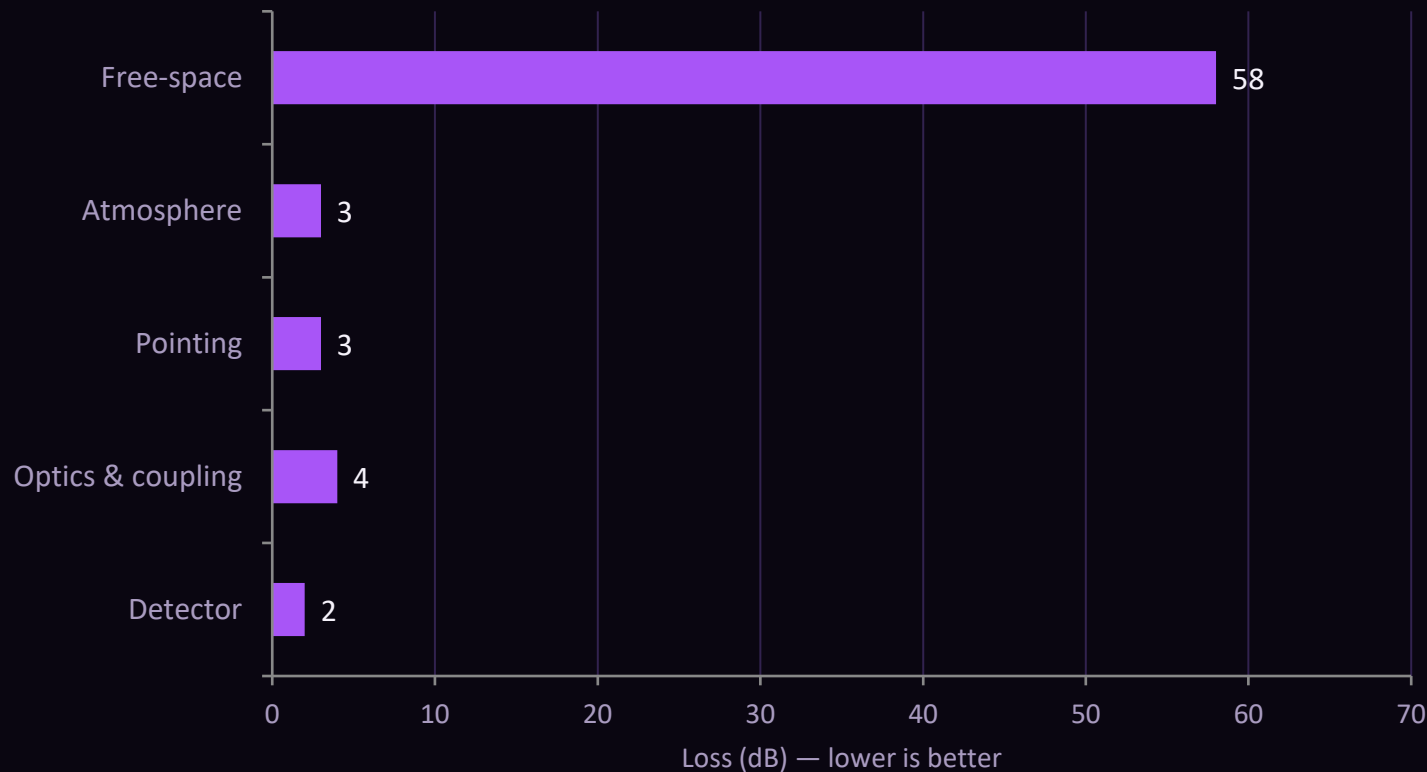
Illustrative orders of magnitude, not a specification.

Accounting for every photon

$$P_{rx} = P_{tx} \cdot G_{tx} \cdot L_{free} \cdot L_{atm} \cdot L_{point} \cdot G_{rx} \cdot \eta$$

G_{tx}	Transmit gain	grows as $(\pi D/\lambda)^2$ — the reward for a big, well-figured aperture
L_{free}	Free-space loss	the dominant term; geometry, not technology
L_{atm}	Atmospheric loss	absorption, scattering, cloud; varies by site and elevation
L_{point}	Pointing loss	how far off boresight you sit, averaged over the pass
η	Receive efficiency	optics, coupling, filters, detector quantum efficiency

Where the photons actually go



The shape of the problem

One term dwarfs the rest, and it is pure geometry. You cannot invent your way out of free-space loss — you can only build a bigger aperture or fly lower.

What margin buys you

In a classical link, spare decibels absorb fades. In a quantum link, they are the difference between a key and no key.

Illustrative figures for a LEO downlink; exact values depend on aperture, wavelength, elevation and site.

Now make the signal one photon

	Classical optical link	Quantum link
Amplification	Optical amplifiers, repeaters	Forbidden by no-cloning
Retransmission	ARQ, coding, buffering	The photon is gone
Detection	Photodiode, high SNR	Single-photon detector, dark counts matter
Background light	Filtered, tolerable	Directly limits the secure key rate
Timing	Bit-level synchronisation	Sub-nanosecond gating to reject noise

Every classical constraint becomes sharper, not softer.

The same theorem gives and takes

What it gives

- An eavesdropper cannot copy the state
- Interception is detectable, not merely improbable
- Security does not rest on a computational assumption
- Keys are safe against future computers

What it costs

- No amplifiers, no repeaters on the optical path
- Loss translates directly into key rate
- Range is limited by what one clean line of sight allows
- Which is exactly why the link has to go through space

The property that makes quantum communication secure is the same property that makes it hard to engineer.

What actually crosses the link

1

Transmit

Photons prepared in randomly chosen bases

2

Detect

Receiver measures in its own random bases

3

Sift

Public discussion keeps only matching bases

4

Estimate

Error rate bounds what an eavesdropper could know

5

Distil

Error correction and privacy amplification yield the final key

Only the quantum stage needs the optical link. Everything after it is classical networking over an authenticated channel — which is where PKI walks back into the room.

From demonstration to infrastructure

Micius (China)

2016 →

First satellite QKD demonstrations, entanglement distribution over ~1200 km, intercontinental key exchange

QYSSat (Canada)

in development

National quantum satellite mission for uplink QKD experiments

Eagle-1 (Europe)

in development

ESA / SES precursor for a European QKD system

SpeQtral (Singapore)

in development

Commercial satellite QKD, building on the CQT nanosatellite line

Selected programmes; status as publicly reported. Every one of them is, at heart, an optical terminal programme.

QKD and post-quantum cryptography are not rivals

Post-quantum cryptography

- Software — deploys over existing networks
- Scales to every endpoint, including devices
- Security rests on a computational assumption
- Available now; migration is the hard part

Quantum key distribution

- Hardware — needs a physical channel
- Point-to-point, or trusted nodes in between
- Security rests on physics and on implementation
- Strongest where keys must survive decades

Migrate to PQC because the threat is already here. Build the optical layer because QKD cannot be retrofitted later.

The ground segment is the long pole

1 Optical ground stations

Telescopes, mounts, PAT, adaptive optics — built and operated as a network, not as one-off experiments

2 Site diversity

Cloud is a hard stop, so availability comes from geography and from scheduling across stations

3 Indigenous components

Optical front ends, fine steering, detectors — supply chains that a national trust architecture can rely on

4 Standards and integration

Key delivery interfaces, authentication, and how a quantum key reaches an existing PKI

None of this is quantum work. All of it is prerequisite to quantum work.

CONCLUSION

- 1 A quantum link is an optical link with an unforgiving signal.
- 2 Free-space loss, turbulence and pointing are the real gatekeepers.
- 3 No-cloning gives security and takes away amplification.
- 4 PQC and QKD answer different questions on different timescales.
- 5 **Build the optical highway first — the quantum highway runs on top of it.**