

Lessons learnt from a 60 cm ground station (FEELINGS) to build a 2.5 m quantum Internet-ready ground station (PROVIDENCE)

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ABSTRACT

The exploitation of quantum entanglement as a basic resource for quantum communication protocols represents a crucial step in the development of the quantum Internet. Particularly, quantum entanglement sent from Space to Ground will allow the secured connection between two distant remote users, otherwise difficult to connect via fiber optics over large distances (> 150 km). The challenge lies in maximizing the qubit exchange rate and fidelity under propagation conditions that are particularly unfavorable for photon counting, due to diffraction losses, sky background influence and the propagation environment in general. However, specific receiver architecture choices can make a significant difference. Leveraging the first year of operation of the FEELINGS ground station, we propose here an initial dimensioning of the main stages of an entangled photon reception chain intended to equip PROVIDENCE, ONERA's future large-diameter station currently under development at the Haute Provence Observatory.

Keywords: Adaptive optics, entanglement, optical ground station, quantum communications

1. INTRODUCTION

The development of quantum computing raises the prospect of being able to break conventional encryption keys within a timeframe short enough to compromise the security of a significant portion of sensitive data exchanges transmitted across the globe for both the civilian (industry, health, security, finance, domains, administrations) and military (safe control/command, critical communications) applications. Relying on a security process based on the quantum properties of light, such as entanglement, could provide a solution, but this requires successfully transmitting entangled photons, in a photon-counting regime, between a satellite and the two communication nodes exchanging secure information located on the ground[1][2]. The frequency with which entangled photons pairs can be reliably transmitted that is currently achievable is particularly dependent on the link budget of the optical transmission. Even though a first demonstration of Quantum Key Distribution (QKD) exploiting entanglement sent from Space has already been carried out [3], the path toward developing the quantum information teleportation services required for the development of quantum Internet calls for a substantial increase in the qubits transfer efficiency and for demonstrating the reproducibility of this transfer with a view to service deployment. A particularly constrained link budget and the desire to limit the complexity of the space optical terminals encourage shifting the complexity to the ground, which in concrete terms translates into the use of metre-class ground segments, at least for the technological maturation phase. The use of small cryogenic single photon detectors (of the SNSPD type) and of an angular field as close as possible to the diffraction limit makes the use of adaptive optics with minimal and controlled losses essential. ONERA currently operates a first ground station, the FEELINGS station, dedicated to managing the propagation channel for optical links and space observation. This prototyping platform features unique characterization capabilities and the possibility of upgrading its diameter, making it an excellent candidate for future maturation activities involving optical links via quantum protocol. ONERA is also developing a large-diameter ground station, the PROVIDENCE platform. Exploiting a 2.5 m telescope supplied by AMOS and adaptive optics developed at ONERA, PROVIDENCE will, upon its first light in 2028, be the only European facility of this diameter equipped with AO correction capabilities dedicated to space observation and optical communications. By 2029, ONERA will therefore operate two ground stations, 362 km apart, equipped with state of the art means for characterizing the atmosphere and correcting atmospheric turbulence, dedicated to mastering the propagation channel. The aim here, building

on the approach presented in [1], is to assess the possibility of exploiting these two ground stations separately or jointly, in order to make progress in understanding the limitations imposed by the propagation channel on the development of the links required for the development of quantum information networks, so as to be able to provide proportionate responses to them. Section 2 is devoted to the characteristics of the FEELINGS and PROVIDENCE ground stations; Section 3 recalls the main outlines of the coincidence rate assessment method presented in [1]. An adaptation of the method to account for a very rough approximation of AO correction and a study of different link configurations are carried out therein to analyze the relevance of using FEELINGS and PROVIDENCE as prototyping ground segments for future field maturation of quantum internet technologies.

2. GROUND STATIONS

2.1 FEELINGS

The FEEDer LINKs Ground Station is a research facility developed in ONERA dedicated to the optical propagation channel characterization and management for various activities involving laser beam focusing through the atmosphere. Located in ONERA's site of Fauga (25 km South of Toulouse) FEELINGS is equipped with state of the art technologies and processing to provide a unique ability to understand propagation channel impact and test various correction capabilities. **See ~~Erreur ! Source du renvoi introuvable.~~** for a description of the atmospheric monitoring pipeline built in FEELINGS and [5] for an overview of recent activities on optical communications with FEELINGS. These past activities have made it possible to test the sizing assumptions of adaptive optics systems that lie at the heart of performance control for high angular resolution applications, and all the more so for optical communications. Until now used primarily for optical link needs with GEO satellites, FEELINGS is starting several optical link campaigns with LEO payloads in 2026, notably with the aim of characterizing the performance limits of downlink optical links at low elevation, testing control methods dedicated to the case of the deterministic slewing introduced by tracking LEO satellites, and testing the limits of uplink optical links toward LEO satellites. As a research platform, FEELINGS has upgrade capabilities of its own. The instrumental configuration, using a rotating M7 mirror, allows a new thermostatically controlled Coudé room to be added alongside the existing one without compromising ongoing activities. The space available around the infrastructure can accommodate cryogenic equipment, even bulky units. The broadband optical train (the 7 mirrors of the FEELINGS Coudé train are coated with protected aluminium) provides a per-surface transmission of 95%. The accessibility of the mirrors makes it possible to consider specific coatings for applications that would require them. The control room, located away from the restricted-access zone, together with an independent computer network, allows the facility to be operated independently, without depending on access constraints to ONERA's secure site. The architecture of the FEELINGS mount, currently equipped with a 60 cm mirror, is compatible with an 80 cm primary mirror, providing a 2.5 dB higher antenna gain at the expense of an opto-mechanical upgrade.



Figure 1 - FEELINGS ground station in Fauga. Dotted line points at available room for an additional Coudé room to host cryogenic detection.

2.2 PROVIDENCE

PROVIDENCE is a 2.50 m adaptive telescope, built in collaboration with CNRS, to be installed at the Observatoire de Haute-Provence (Figure 2) [6]. It is designed as an optical research platform optimized for high angular resolution and dedicated jointly to Space Domain Awareness, astronomy, laser applications, and characterization of the atmospheric

propagation environment [7]. Its main technical characteristics are summarized in Table 1. The project is supported by a complete digital twin, extending from the target and atmospheric models to the final science products, and is intended to be collaborative by nature, bringing together contributions from the national and international AO community to maximize the scientific and operational return of a shared sky-access facility.

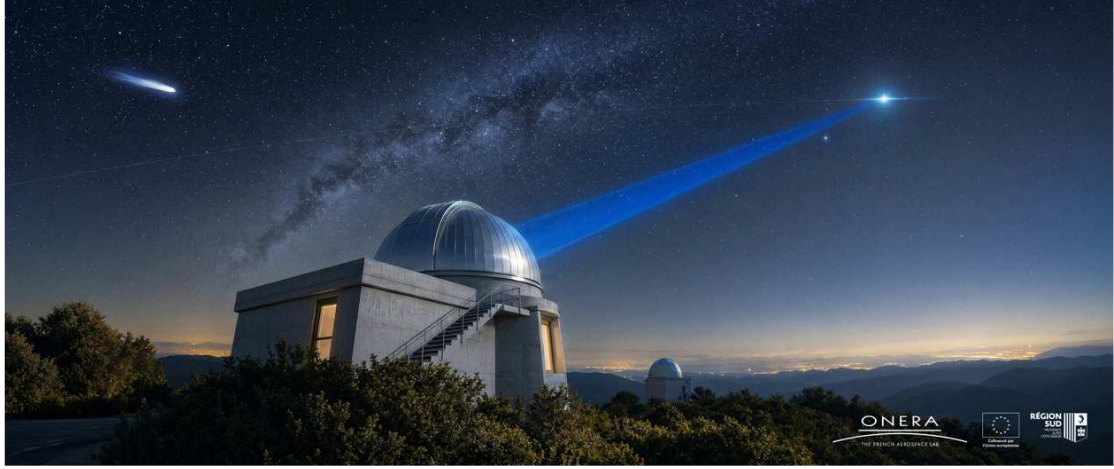


Figure 2 - The PROVIDENCE 2.50 m adaptive telescope (artist's rendering).

Parameter	Value
Telescope diameter	2.50 m, alt-azimuth mount, adaptive secondary mirror
Angular resolution	41 mas @ 0.5 μm (≈ 10 cm @ 500 km LEO; ≈ 7.5 m @ 36 000 km GEO)
Field of view	10 – 30 arcmin (including a 2 arcmin diffraction-limited field)
Tracking capability	Up to 5°/s (LEO satellite observation)
Spectral bandwidth	380 nm (goal 360 nm) – 2500 nm
Foci	Nasmyth, Cassegrain and Coudé
Laser guide star compatibility	Rayleigh and sodium
Operational mode	Toward a fully robotic telescope
Laser compatibility	Compatible with monostatic power-laser operation
Location	Observatoire de Haute-Provence (OHP), France
First-light instruments	INTERSTELLAR (AO-assisted, short-exposure, multi- λ high-resolution imager); MISTRAL (medium-resolution, $R \sim 700$, GLAO-assisted spectrometer)
Schedule	Realisation phase started June 2026; first light December 2028; start of operations April 2029

Table 1 - Main technical characteristics of the PROVIDENCE platform.

3. COMPATIBILITY WITH QUBIT EXCHANGES

3.1 Communication scenario

We investigate in this section the opportunity to exploit both FEELINGS and PROVIDENCE as Optical Ground Segments (OGS) for Quantum Information Networks technology demonstration. The analysis is built upon the approach described in [1] (see section IV) that is slightly adapted to take into account adaptive coupling losses. The principle of the model is summarized below. It relies on the calculation of the coincidence detection of entangled photons between two OGSs $Q(\mu, \eta_1, \eta_2)$ proposed by Ma et al. [8] where μ is the average number of photon pairs per time

window of interest and η_1 , respectively η_2 corresponds to the quantum channel efficiency between the satellite and OGS₁ respectively OGS₂. AO coupling efficiency degradation with elevation θ is taken into account through a multiplicative attenuation term T_{AO} to the channel transmittance efficiency for OGS_x ($x=1,2$) reported in [1]:

$$\eta_x(\theta) = T_T \cdot T_R \cdot (1 - L_p) \cdot T_{optics} T_{AO}(\theta) \cdot PDE/A_x(\theta) \quad \text{Eq. 1}$$

Where T_T is the transmitter transmission factor, T_R is the receiver telescope transmission factor, L_p stands for pointing losses contribution, T_{optics} corresponds to the overall optical losses of the optical train detection module (from telescope output to coupling into the single mode fiber), T_{AO} stands for the coupling efficiency degradation related to the evolution of atmospheric turbulence conditions with elevation, PDE corresponds to the single photon detector efficiency and A_x is the total line-of-sight channel attenuation:

In Eq. 1 the coupling efficiency degradation due to turbulence influence is assumed to be dominated by spatial errors (limited number of degrees of freedom of the correction with respect to the number of coherence areas in the receiver aperture), the bandwidth of the correction being chosen high enough for the temporal effects to be neglected, and the flux available to drive AO correction being assumed high enough thanks to the use of a dedicated beacon, T_{AO} is therefore approximated by (see for instance [10]):

$$T_{AO}(\theta) = \exp\left(-\sigma_{fitting}^2(\theta)\right) \quad \text{Eq. 2}$$

The fitting error variance $\sigma_{fitting}^2$ is calculated according to :

$$\sigma_{fitting}^2(\theta) = 0.458(n_r + 1)^{-\frac{5}{3}} \left(\frac{D_R}{r_0(\theta)}\right)^{\frac{5}{3}} \quad \text{Eq. 3}$$

where D_R is the receiver diameter, n_r corresponds to the maximum Zernike radial order of the correction brought by AO and r_0 is the Fried parameter at elevation θ calculated from its value at zenith r_0^{zenith} according to :

$$r_0(\theta) = r_0^{zenith}(\sin(\theta))^{3/5} \quad \text{Eq. 4}$$

Restricting AO residuals to the spatial error term is a very restrictive hypothesis, particularly for applications requiring LEO tracking due to the apparent wind velocity. It presents however the advantage of incorporating a $(D_R/r_0)^{5/3}$ dependency common to most of the key contributors for strong Signal to Noise Ratio AO downlink with satellites. It and must be considered as a

The total line-of-sight channel attenuation is calculated according to (see [1]):

$$A_x(\theta) = \frac{L_x^2 \theta_{diff}^2}{D_R^2} 10^{A_{atm}(\theta)/10} \quad \text{Eq. 5}$$

with $\theta_{diff} = 2.44 \lambda/D_T$ the diffraction limited divergence angle, D_T being the transmitter aperture diameter, and $A_{atm;x}$ the atmospheric attenuation due to scattering and absorption, expressed in dB. A_{atm} is a function of the elevation angle $A_{atm}(\theta) = A_{atm;0}/\sin(\theta)$, with $A_{atm;0}$ the atmospheric attenuation at zenith.

Parameters for the calculation of the distilled coincidence between entangled photons pairs are reported in Table 2. A single detection modality based on the use of a fiber coupled superconducting single-photon detectors (SNSPD) at 1550 nm is considered further as this modality provides by far the best performance in terms of coincidence evaluation according to [1], mostly due its high photodetection efficiency and a smaller stray light contribution at 1550 nm. Typical atmospheric turbulence conditions observed on FEELINGS for daytime are considered [4] with a 15 cm Fried parameter at zenith.

Parameter Description	Value
Quantum channel wavelength	1550 nm
Satellite altitude LEO	600 km
Ground receiver telescope diameter	see Table 3
Onboard transmitter telescope diameter	30 cm
Atmospheric attenuation at zenith	2 dB
Receiver transmission factor (T_R)	0.8
Transmitter transmission factor (T_T)	0.8
Optical module transmission factor (T_{optics})	0.35

Pointing losses (L_p)	0.2
Basis reconciliation factor for BBM92	0.5
Bidirectional error correction efficiency	1.22
Coincidence time window	200 ps
Average number of photon pairs per pulse	0.02
Detector dark count rate	100 cps
Background (stray light)	100 cps
Single photon detector efficiency (SNSPD)	0.9
Error probability for dark- and background counts	0.5
Error probability of photon arriving on wrong detector	0.01
Daytime zenith Fried parameter@1.55 μm	15 cm

Table 2 – Parameters for distilled coincidence evaluation.

Key contributions to the channel transmittance efficiency are plotted Figure 3 for a 600 km altitude LEO satellite, a $D_R = 80$ cm receiver and an adaptive optics able to correct the first $n_r=17$ radial orders of the atmospheric turbulence. As expected geometrical losses clearly dominate the transmittance degradation, the influence of coupling degradation due to atmospheric turbulence remaining marginal here. In practice a spatial error limited assumption for AO correction is however very optimistic with LEO satellites, at high elevation angles due to the apparent velocity of the satellite that raises challenges for the loop bandwidth and for low elevation angles (below 20°) when scintillation effects on wavefront sensor efficiency becomes non negligible [9]. The residual AO error budget shall therefore not be taken for granted but should rather be considered as a first and straightforward attempt to fix order of magnitude for residual phase variance to draw trends on AO requirements. This very preliminary approach must be completed with a more accurate AO error budget that will have to take into account the major limitations of existing (FEELINGS) and yet to come (PROVIDENCE) AO systems.

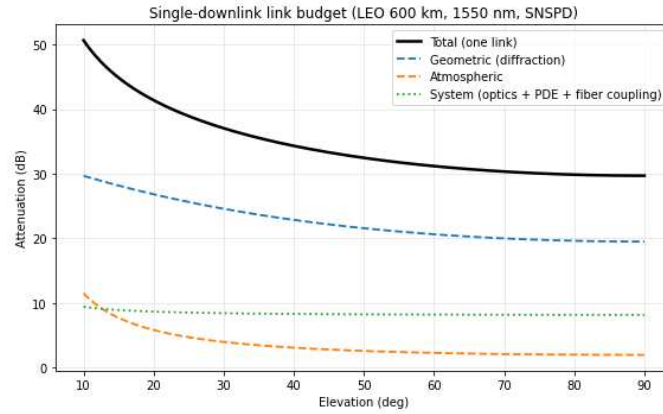


Figure 3 - Contributors to the quantum channel transmittance efficiency as a function of elevation for a 600 km altitude LEO pass. The Geometric term corresponds to the first term of Eq. 5, the Atmospheric one to the second term, the System term incorporates the other contributors to Eq. 1.

3.2 Preliminary results

Three ground stations configurations are considered for the evaluation of the distilled coincidence. They differ from their diameter and their correction level. The parameters are synthesized in Table 3.

Parameters	Config 1		Config 2		Config 3	
	OGS_1	OGS_2	OGS_1	OGS_2	OGS_1	OGS_2
D	0,8	0,8	0,6	0,8	0,8	2,5
n_r	17	17	17	17	17	40

Table 3 – OGS configurations considered for the photon pair distilled coincidence evaluation.

The first configuration is symmetrical (same diameter and number of degrees of freedom for AO correction for both cases) with $D=0.8$ m and $n_r = 17$. This configuration is used as a reference case. When neglecting AO correction it corresponds to the SNSPD case @1.55 μm of [1]. Considering a single LEO pass and assuming a trajectory which trace on ground is equidistant to each of the OGSs the total number of distilled coincidence reaches 3979. The distilled coincidence rate reaches a peak of 36.31 bit/s as illustrated in Figure 4. Taking into account AO correction and its degradation with elevation the coincidence total number drops to 3435, (peak distilled coincidence rate of 31.97 bit/s). Turbulence degradation influence remains very limited thanks to the considered AO design.

The second configuration aims at quantifying the distilled coincidence number over a single pass while considering existing FEELINGS characteristics for OGS₁ ($D = 60$ cm, $n_r = 17$) and ($D = 80$ cm, $n_r = 17$) for OGS₂, which would correspond for instance to the use of a subaperture within PROVIDENCE's diameter. The total number of distilled coincidence over the pass drops to 1985 and distilled coincidence reaches a peak rate of 18.41 bit/s. The 2.5 dB drop of the link budget due to the reduction of the receiver diameter translates into a comparable drop of the per-pass distilled-coincidence count (3435 to 1985, i.e. 2.4 dB).

The third configuration corresponds to ($D = 80$ cm, $n_r = 17$) for OGS₁ hence emulating FEELINGS diameter upgrade to 80 cm and ($D = 2.5$ m, $n_r = 40$) for OGS₂ corresponding to the use of the full diameter of the PROVIDENCE ground station. For this configuration the number of distilled coincidence increases by nearly an order of magnitude compared to the first configuration to reach 31929 bits (peak distilled coincidence rate of 299.11 bit/s) on a single pass thanks to the 10 dB gain brought by the use of the 2.5 m diameter.

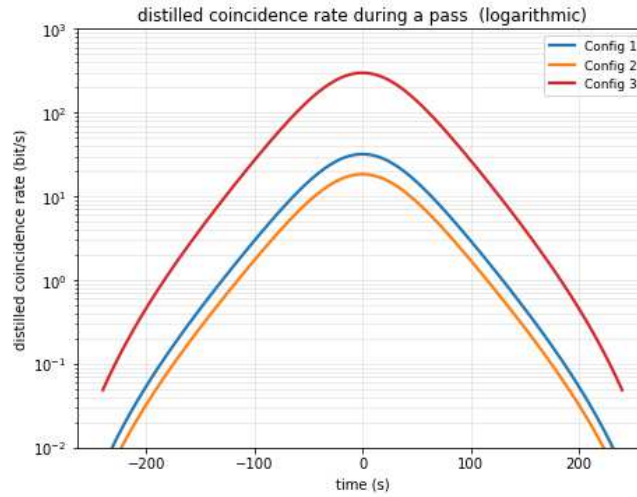


Figure 4 - Distilled coincidence rate during a pass for a 600 km altitude LEO satellite on a trajectory whose ground track is equidistant from the two OGSs.

These evaluations confirm the relevance of using the FEELINGS and PROVIDENCE ground stations for future maturation activities of ground-satellite optical links for the quantum internet. Increasing FEELINGS to a diameter of 80 cm while maintaining an AO sizing comparable to the one already deployed should make it possible to benefit from the 2.5 dB provided by the larger collector diameter. Using PROVIDENCE at its full collection diameter will yield an additional gain of 10 dB. The analysis carried out here nevertheless deserves to be refined by incorporating all the limitations of the AO correction chain—notably the errors specific to the wavefront sensor and the temporal error. The influence of the ambient background signal generated by the coupling of solar photons scattered by the atmosphere could also be consolidated, if necessary by leveraging FEELINGS's existing infrastructure to confirm the assumptions considered in [1] and adopted here.

4. CONCLUSION

Assuming an architecture based on the detection of entangled photons in the C band and single-mode injection, the work presented here lends credibility to several scenarios for secure optical links using a quantum protocol between two ground stations 362 km apart. The work presented builds on the approach published in [1], adapted here to account for the coupling losses at the focus of the adaptive optics. The distilled-coincidence count reaches 1985 bits for a pass whose ground track is equidistant from the two stations. Increasing the diameter of FEELINGS to 80 cm and developing a dedicated AO system, combined with the use of a fraction of the PROVIDENCE receiving pupil, makes it possible to obtain a symmetrical configuration emulating two stations 80 cm in diameter. Using the upgraded version of FEELINGS together with an 80 cm subaperture of PROVIDENCE (the symmetrical configuration), and exploiting two passes per day, makes a daily distilled coincidence number of 6870 conceivable. Using PROVIDENCE full aperture and a dedicated AO system could increase this number of an order of magnitude. These preliminary results remain to be consolidated by a detailed AO error budget to incorporate other limiting AO contributors (such as wavefront sensing errors and temporal error). They however fix a limiting residual phase variance for future AO system implementation dedicated to this kind of application.

By the end of 2028, ONERA will commission the PROVIDENCE platform, a multipurpose infrastructure dedicated to high angular resolution instrument prototyping. The development of future generations of secure optical links is a priority for ONERA: with the commissioning of PROVIDENCE and the FEELINGS platform operational since 2024, ONERA will have, by the end of 2028, two optical ground stations 362 km apart. These facilities, developed with a link-performance-mastery approach, will, whether operated separately or jointly, provide the opportunity to have — for future international demonstrations at the European or global scale — a first network of stations equipped with harmonized correction and characterization capabilities. The analysis carried out here demonstrates the relevance of using each of these ground segments, considered together or separately, for the maturation of quantum optical links, which are essential building blocks of future quantum information networks.

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