

Space-Ready DV-QKD Transmitter for Satellite Applications: A qualified compact polarization encoder for SmallSat missions and modern constellations

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ABSTRACT

Optical and quantum communications are emerging as key enablers of secure, high-speed global networks, with Quantum Key Distribution (QKD) playing a central role in next-generation cybersecurity. However, terrestrial fiber-based QKD systems are fundamentally limited by exponential attenuation, restricting transmission distances to a few hundred kilometers without trusted nodes. Satellite-based approaches, using free-space optical links and direct-to-Earth communication, overcome these constraints by reducing transmission losses, enabling global-scale key distribution. The feasibility of space-based QKD has been demonstrated through in-orbit missions such as Micius and Jinan by the Chinese Academy of Sciences. Despite these milestones, the technology remains largely experimental, highlighting the need for scalable, reliable, and manufacturable systems suitable for integration into operational satellite constellations and service-oriented infrastructures. In this context, this work presents the development and qualification of a polarization-encoded Discrete-Variable QKD (DV-QKD) transmitter within the QUDICE (QUantum DevIces and Subsystems for Communications in spacE) project, funded by the European Commission. The system is designed for downlink operation from a small satellite platform and is based on compact, scalable technologies compatible with modern optical communication architectures. The payload operates at 1550 nm in the optical C-band with a repetition rate of 200 MHz, implementing a three-state BB84 protocol with one decoy state optimized for free-space links. The fully integrated Engineering Model includes photon generation, intensity and polarization modulation, and control electronics within a volume below 6U, a mass under 4 kg, and peak power consumption below 20 W, making it suitable for next-generation satellite constellations. The system employs a polarization encoder based on the iPOGNAC architecture, enabling reliable generation of high-fidelity quantum states. Experimental results show a stable Quantum Bit Error Rate (QBER) below 1% under representative conditions, confirming robust performance for space-to-ground links. The transmitter has reached Technology Readiness Level 6 following qualification in accordance with ECSS standards, including thermal vacuum cycling and vibration testing at NASA GEVS levels. Radiation tolerance is ensured through a combination of rad-hardened components and selected COTS devices, supporting reliable operation in Low Earth Orbit. Overall, the system represents a significant step toward industrially viable quantum communication solutions, offering compactness, low power consumption, and compatibility with modern satellite platforms, and enabling scalable, secure, global QKD services.

Keywords: Quantum Key Distribution, QKD Payload, SmallSat, Free Space Optic

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1. INTRODUCTION

Cybersecurity in the age of the Quantum Computer will strongly rely on the adoption of proper technological solutions that can withstand attacks enabled by the unprecedented levels of computational power that will become available to adversaries.¹ One of such key technologies is Quantum Key Distribution (QKD) which allows distant users to distil cryptographic keys whose secrecy is ensured by the laws of quantum mechanics.² In this regard, several national and international activities have targeted the development and deployment of the first QKD networks, such as the EuroQCI initiative in Europe.³

To achieve continental and global scales, QKD networks will have to rely on satellites for key generation between distant nodes.⁴ This is mainly due to the exponential loss profile of optical fibers that limit the distance to hundreds of km.⁵ The feasibility of satellite-based QKD has been demonstrated by the Chinese Academy of Science with the Micius⁶ and Jinan-1⁷ missions. Despite these milestones, the technology remains largely experimental, highlighting the need for scalable, reliable, and manufacturable systems suitable for integration into operational satellite constellations and service-oriented infrastructures.

In this context, here we present a polarization-encoded QKD transmitter compatible with small satellite platforms developed within the QUDICE (QUantum DevICES and Subsystems for Communications in spacE) project, funded by the European Union. This QKD transmitter inherits from the scientific background of the University of Padova in the field of free-space and satellite Quantum Communications^{8–10} as well as ThinkQuantum's industrial expertise in the development of the commercial QKD modules, a turnkey QKD solution ready for deployment in fiber-based and free-space networks.^{11, 12} The philosophy behind the development is one inspired by the new space economy, exploiting robust and previously qualified components wherever possible. Additionally, the optical design of the QKD transmitter, which will be presented in detail in Section 2, exploits an efficient architecture based on the iPOGNAC polarization encoder.¹³

This work shows the development and testing of a DV-QKD transmitter up to a Technology Readiness Level (TRL) of 6. Section 2 offers an overview of the optical design at the base of the system, while Section 3 focuses on the functional design of the unit and its implementation. In Section 4, the tests performed and their results are presented. Finally, in Section 5, the conclusions and future work are drawn. In Fig 1, the QUDICE polarization encoder, together with some of the people that made it a reality, can be seen.



Figure 1: The QUDICE polarization encoder, together with some of the people that made it a reality.

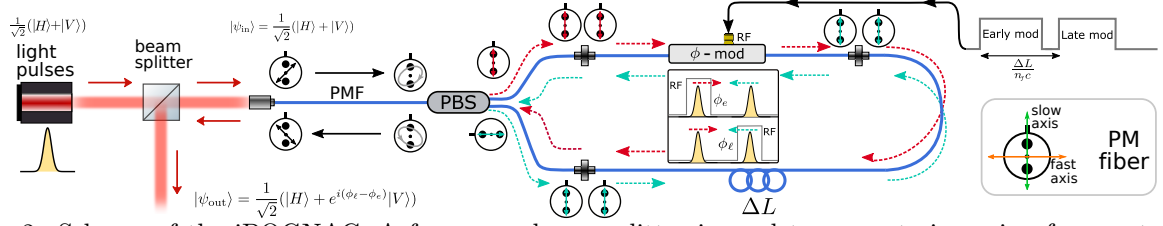


Figure 2: Scheme of the iPOGNAC. A free-space beam-splitter is used to separate incoming from outgoing light. A Sagnac interferometer including a fiber polarizing beam splitter, a phase modulator and polarization maintaining fibers (indicated in blue) is used to modulate the polarization state. Courtesy of M. Avesani *et al.*, Opt. Lett. **45**, 4706 (2020).¹³

2. OPTICAL DESIGN

The QUDICE polarization QKD source (DV-QKD) implements an efficient variant of the decoy-state BB84 protocol with 2 intensity levels and 3 polarization states (two in the key-generating basis and one in the control basis).¹⁴ The choice of this protocol was done mainly for two reasons: (i) The protocol outperforms other BB84 variants when considering finite-key effects, especially in the loss regime typical for satellite-to-ground QKD links;¹⁴ (ii) The reduced number of state and intensity levels substantially simplify the optical requirements, enabling a simpler design with fewer components.

The optical scheme of the QKD transmitter begins with a gain-switched DFB laser emitting optical pulses with temporal length < 100 ps Full Width Half Maximum (FWHM) at a wavelength of 1550 nm and 200 MHz repetition rate. The laser type and pulsing technique used in the project has been also subjected to a radiation testing campaign to ensure that its key characteristics such as phase randomization and short pulse emission are not degraded by radiation or ageing.¹⁵ The optical pulses pass through an Intensity Modulator based on the iPOGNAC polarization encoder.¹⁶ This design allow for tunable, patterning free and intrinsically stable intensity modulation. However, in this case the intensity ratio between signal and decoy μ/ν was fixed to around 2.2 which is close to optimal for the typical losses expected in a satellite scenario.¹⁴ After the intensity modulator, the emitted laser pulses encounter the iPOGNAC polarization encoder.

Since this polarization modulator, which can be seen in Fig. 2, is a key component of the design we present an overview of its workings adapted from M. Avesani *et al.*, Opt. Lett. **45**, 4706 (2020).¹³ After traversing a free space segment composed of a 50:50 beam splitter, the laser pulses with diagonal polarization, $|D\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$, are coupled into a polarization-maintaining (PM) fiber, whose optical axes are aligned with the horizontal and vertical polarizations. Due to the PM fiber birefringence, the two polarization components acquire an unknown relative phase δ , and the state reaching the fiber polarization beam splitter (PBS) can be described as:

$$|\psi_1\rangle = \frac{|H\rangle + e^{i\delta}|V\rangle}{\sqrt{2}}. \quad (1)$$

The phase δ depends directly on the fiber length and birefringence, as well as on environmental perturbations such as temperature and mechanical strain.

The PBS forms the input and output coupler of a polarization-maintaining Sagnac interferometer. It maps the two orthogonal polarization components onto counter-propagating optical paths: the vertical component propagates clockwise (CW), whereas the horizontal component propagates counter-clockwise (CCW). A PM fiber delay line separates the two pulses temporally at the phase modulator, allowing the application of independently controlled phases ϕ_e and ϕ_ℓ to the early and late pulses, respectively. Inside the loop, each pulse propagates along a single principal axis of the PM fibers, thereby avoiding polarization-mode dispersion in the modulator.

Upon recombination at the PBS, the Sagnac loop exchanges the horizontal and vertical polarizations. Consequently, during the backward propagation through the input PM fiber, each polarization component travels along the optical axis opposite to that encountered in the forward direction. The birefringent phase δ and group

delay accumulated during the first passage are therefore passively compensated, even when the differential delay exceeds the coherence time of the input pulses. The polarization state emerging from the device is

$$|\psi_{\text{out}}\rangle = \frac{1}{\sqrt{2}} \left(|H\rangle - e^{i(\phi_\ell - \phi_e)} |V\rangle \right), \quad (2)$$

and is thus determined only by the differential modulation phase. This double-pass compensation provides intrinsic stability and removes the need to characterize or actively stabilize the birefringence of the input PM fiber. The output of the device is reflected port of the 50:50 BS in the free-space segment of the device. It should be noted that this polarization modulator can reach GHz repetition rates.¹⁷

There are several advantages of the iPOGNAC. Firstly, it can be operated without requiring calibration. Secondly, it inherits the self-compensating characteristics of the Sagnac interferometer it is based on. However, for satellite-based QKD a key characteristic is its ability of generating polarization states that are fixed with respect to the transmitter's reference frame eliminating the need of calibration between the transmitter and the receiver. Additionally, given its free-space output, it can be easily interfaced with a telescope. This characteristic is exploited in designing the DV-QKD source since the free-space segment of the iPOGNAC acts as the optical gateway that interconnects the system to the optical head of the satellite.

3. FUNCTIONAL DESIGN

As previously explained, the QKD source generates and transmits qubits encoded in the polarization of single photons. At a high level, it operates as a module that receives a digital data stream from an external source, such as a Quantum Random Number Generator QRNG, and outputs a stream of qubits through a free-space optical port. Its primary role is to interpret the incoming digital data and generate the corresponding control signals for the electro-optical devices responsible for the qubit generation. The source is developed up to TRL 6 as an Engineering Model (EM), suitable for integration on a microsatellite class platform operating in Low Earth Orbit (LEO). The key functional, physical and interface characteristics, are summarized in Table 1;

The source is designed to survive temperatures between -20°C and 60°C and to operate between -10°C and $+50^\circ\text{C}$, to tolerate a total ionizing dose (TID) of 20 krad, and to operate at pressures below 10^{-5} mbar; parts are screened against the ESA and GSFC radiation and outgassing databases. Mechanical robustness is addressed through a quasi-static acceleration capability of 10 g and compliance with the sine and random vibration levels from NASA GEVS standard,¹⁸ applying the relevant safety factors, with an in-orbit lifetime target of at least 5 years. The payload provides dedicated interfaces for electrical grounding and bonding, consistent with the EMC design guidelines of ECSS standard.¹⁹

Table 1: Payload characteristics

Protocol & wavelength	efficient-BB84, 3 states, ≥ 1 -decoy; C-band
Qubit repetition rate	200 MHz
Intrinsic QBER	$< 1\%$
Data interface	Gigabit Ethernet, > 600 Mbit/s
Output beam waist	4.01 ± 0.04 mm, $M^2 \leq 1.05$
Mass / volume	3.45 kg; $270 \times 196 \times 110$ mm ³
Power	approx. 14 W
Environment	operative $= -10$ – 50°C , survival $= -20$ – 60°C

The payload is designed to exchange data with other subsystems of the satellite via Gigabit Ethernet. Additionally the payload is designed to be compatible with also SpaceFibre²⁰ for fast data exchange and SpaceWire²¹ for slower TM/TC as well as the SpaceFibre protocol, with a data interface sustaining at least 600 Mbit/s. The SpaceWire protocol is used for TM/TC instead. Timing is provided through a clock and a PPS signal, while power is received on a 12–28 V line protected against overcurrent and overvoltage. The optical output is specified as a Gaussian beam with a waist diameter of $4\text{ mm} \pm 0.1\text{ mm}$ and $M^2 \leq 1.05$; this beam shares a free-space interface with the satellite’s optical head, responsible of the Pointing, Acquisition and Tracking (PAT) procedure.

3.1 Engineering Model implementation

The QKD payload was designed around a modular architecture comprising a Main Unit and a separate Optical Gateway, as shown in Fig. 3. The choice to separate the Main Unit from the Optical Gateway, that provides the output beam, enables a more flexible positioning of the QKD payload inside the satellite, avoiding the constrain of a mechanical mounting near the PAT system. The Optical Gateway is a standalone unit with two PM fibre inputs and one free-space output, that can be installed as needed by the satellite architecture with a proper routing of the fiber, interfacing the quantum signal to the PAT subsystem. The EM was integrated in an ISO 7 clean room.

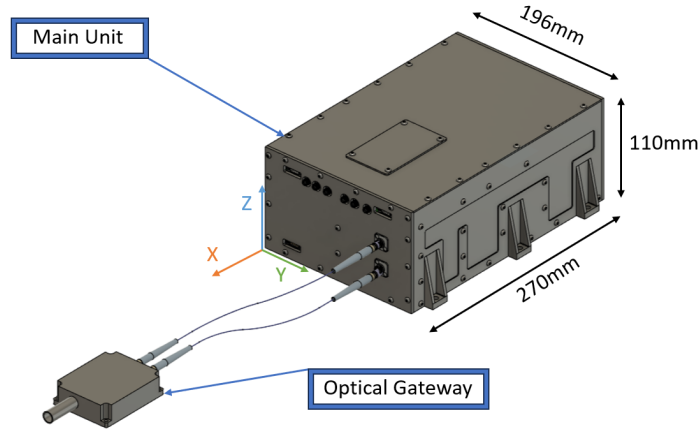


Figure 3: Architecture of the QKD payload: Main Unit and Optical Gateway

4. TESTS AND RESULTS

4.1 Functional Tests

Fig. 4 shows the experimental setup used for the functional tests performed on the payload. The receiver instrumentation comprised an optical breadboard to couple the free-space signal from the Optical Gateway into fibre, a dedicated QKD optical receiver, four single-photon detectors and a time-to-digital converter. The Device Under Test (DUT) was powered by an external power supply and controlled by an external computer. SNSPD (Superconducting Nanowire Single-Photon Detector) detectors were employed at the receiver during laboratory tests, while SPAD (Single-Photon Avalanche Diode) devices, more compact and easier to relocate, were used during the environmental test campaign conducted at Officina Stellare’s facilities. The QBER measured in laboratory environment over a 100s acquisition period is reported in Fig. 5, showing stable behaviour with a mean value of 0.40%.

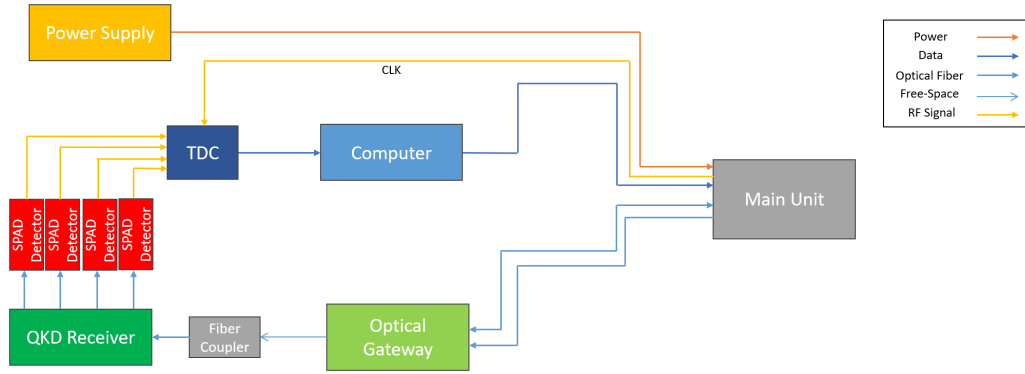


Figure 4: Schematic of the test setup for the QKD payload

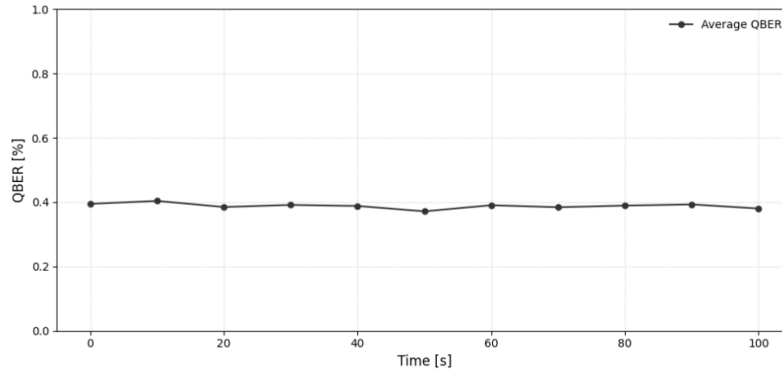


Figure 5: QBER of the QKD payload during functional tests

4.2 Environmental Tests

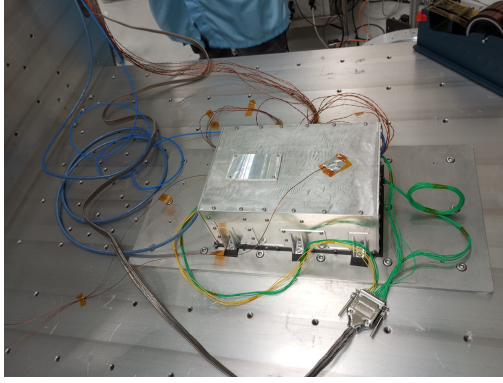
A complete thermovacuum test campaign was conducted on the DUT to verify its functionality and survivability. The TVAC profile was organized in eight cycles, being the operative range -10 to $+50^{\circ}\text{C}$, and the survival range -20 to $+60^{\circ}\text{C}$. A temperature gradient of $0.5^{\circ}\text{C}/\text{min}$ was applied for the rising and falling profiles, while a 3-hour plateau ensured thermal uniformity between the environment and the DUT. QBER measurements were acquired during the different hot and cold plateaus, once the Thermal Reference Point on the device confirmed thermal balance with the chamber.

During the TVAC cycles, the temperatures of the relevant components were monitored using T-type thermocouples, verifying that all subsystems operated within the declared temperature range. DUT performance was measured before, during, and after the test to monitor for potential degradation.

The robustness of the payload against the vibrational environment during launch was assessed through a shaker test campaign. After an initial resonance search to identify the natural modes of vibration of the device, it was excited along the three axes with loads derived from the NASA GEVS¹⁸ standard. Both sine and random vibration tests were conducted at qualification levels, and the repetition rate and QBER measured after the structural solicitation were consistent with the pre-test values, confirming the robustness of the design.

5. CONCLUSIONS

This work presented the design, development and qualification of a polarization-encoded Discrete Variable QKD transmitter for space applications, based on a modular Main Unit and a separate Optical Gateway design.



(a) QKD payload installed into the TVAC



(b) QKD payload installed on the shaker

Figure 6: QKD payload environmental testing

The Engineering Model was subjected to a rigorous verification campaign spanning individual components, subassemblies and the fully integrated payload. Functional tests demonstrated a stable QBER of 0.40%, confirming the robustness of the efficient BB84 protocol implementation and of the iPOGNAC-based polarization encoding. The payload further demonstrated its resilience to the space environment, successfully completing a thermal vacuum campaign of eight cycles across the full operative and survival temperature ranges, as well as a shaker test campaign at qualification levels compliant with the NASA GEVS standard. In both cases, the repetition rate and QBER measured after environmental solicitation remained consistent with pre-test values, with no observable performance degradation.

These results confirm that the QKD source has reached TRL 6, demonstrating a fully functional and robust quantum key distribution payload validated in a representative operational environment. The compactness, low power consumption and modularity of the design make the system directly compatible with integration on smallsatellite platforms, marking a significant step from laboratory demonstration towards an industrially viable, flight-ready quantum communication payload for operational LEO constellations and EuroQCI-compatible services.

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