Leap in Advancing of critical Quantum key distribution-spAce components (LaiQa)

Deliverable D10.1

First Report on Market Analysis, space QKD roadmap

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List of abbreviations

CV	Continuous Variable
EB	Entanglement-based
EC	European Commission
EPPS	Entangled Photo Pair Source
EU	European Union
EuroQCI	European Quantum Communication Infrastructure
FSO	Free-space optical
GEO	Geostationary Earth Orbit
NSR	ReSearch Nester
OGS	Optical Ground Station
OKD	Optical Key Distribution
OSI	Open Systems Interconnection model
P&M	Prepare and Measure
QCI	Quantum Communication Infrastructure
QKD	Quantum Key Distribution
QUIC	European Quantum Industry Consortium
QT	Quantum Technology
SaaS	Satellite-as-a-Service
SME	Small and Medium-sized Enterprise
SRIA	Strategic Research and Industry Agenda
TRL	Technology Readiness Level

Executive Summary

This document performs market analysis and road-mapping by identifying emerging trends and opportunities in the space quantum communication networks industry. In particular, the market analysis focuses on the European scenario, by keeping track of the world-wide space QKD progress in Space Quantum Communication Networks.

Keywords: market analysis, roadmap, quantum technologies, satellite quantum communications

1 INTRODUCTION

Second quantum revolution is underway and novel technologies using quantum resources to operate are the cornerstones of this process. Distribution of quantum resources encoded on single photons, like the entanglement, among remote quantum technologies is the core of many protocols enabling quantum communication, distributed quantum computing and sensing. Among the others, quantum key distribution (QKD) is the first fundamental step to achieve for distributing secret keys and enable unconditional secure communication. The suitable infrastructure to host all these protocols is still not available, and it is necessary to extend the range of quantum communication to achieve a successful global quantum network[1]. The development of large-scale optical quantum network is therefore a priority for the next years.

A satellite-based infrastructure would enable relatively quick implementation while addressing cost, availability, and sovereignty challenges associated with secure communication with foreign regions[2]. Space-based quantum network is the goal of different worldwide and European initiatives. Quantum technologies have been promoted within the European Union (EU) research and innovation framework programmes. In 2016, the European Commission (EC) proposed strengthening EU efforts through a long-term flagship initiative in collaboration with the private sector. This initiative is also reflected in the Quantum Manifesto[3].

Under the EU LaiQa project different technologies are being addressed for the development of space-based large-scale quantum network to be used for both on-board and on-ground network nodes.

This document reports the market analysis of the quantum technology context and the definition of a roadmap for the commercialization of the LaiQa-target technologies in European and worldwide market. The document will be maintained active and regularly updated with additional information or updates on the existing ones. The final updated version of this document will be released with D10.2 - Final Report on Market Analysis, space QKD roadmap, due in M36.

[1] O. Lee, Tom Vergoosen - An updated analysis of satellite quantum-key distribution missions , Singapore

[2] https://ec.europa.eu/defence-industry-space/eu-space-policy/space-research-and-innovation/quantum-technologies_en

[3] https://ec.europa.eu/jrc/en/research-topic/quantum-technologies?qt-news_events_tabs_on_topic_pages

2 GLOBAL QUANTUM COMMUNICATIONS CONTEXT AND OPPORTUNITIES

Governments have initiated numerous projects in the realm of quantum technologies. This surge in interest is driven by the potential for significant advancements in innovation and research, as well as the strategic benefits related to defense, enhanced communication security, and overall cybersecurity improvements.

This second quantum revolution will move quantum technologies (QT) from academic research to real-world applications in the coming years. Next sections illustrates the substantial effort and economic investment in QT, that will push its research and development, thus generating opportunities for technological innovation.

In particular, Section 2.3 documents the continuous annual growth of QT. This rapid development is expected to yield a significant socio-economic impact, influencing infrastructures as well. Quantum networks are currently under development (e.g., in Europe[4] and China[5]) which present opportunities for terrestrial and satellite quantum technology. Details about initiatives for space-oriented quantum network are also discussed in next sections.

2.1 Global Quantum Communications via Satellite Market

In 2017 and 2019, two satellite demonstrations, the Micius[6] and Spooky[7] satellites, respectively, were successfully completed. Although these were only demonstrative satellites, they served as catalysts for global initiatives in satellite quantum communication. Presently, numerous initiatives are underway in the field of space-based quantum communication via satellite.

According to 2022 data from Research Nester (NSR), the global market for quantum communication via satellite is rapidly advancing and is forecasted to reach at least $2,6B by 2020-2030 period[8]. This growth encompasses cumulative satellite orders, launch and service revenues, as illustrated in Figure 2-1. Specifically, service revenues are expected to cumulatively reach $1,8B by the end of the decade representing 69% of the total market, with $749,6M forecasted by 2030. Figure 2-1 details the cumulative revenues expected by region, showing that 48% of the revenues will comes from Asia, with orders valued at $632M. Here, China is leading due also to its successful in-orbit demonstrations.

The primary targets of the global quantum communication via satellite market include the banking, energy, and government/military sectors. These clients are interested in applications ranging from secure communication to positioning and navigation. The key satellite quantum applications for these sectors are:

1. Satellite-based quantum encryption (including QKD);
2. Quantum Communication Infrastructure: terrestrial & space segment linking network nodes;
3. Space-based Time and Frequency Transfer infrastructure;

[4] https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
[5] Chen, Yu-Ao, et al. "An integrated space-to-ground quantum communication network over 4,600 kilometres." *Nature* 589.7841 (2021): 214-219.
[6] Yin, Juan, et al. "Satellite-based entanglement distribution over 1200 kilometers." Science 356.6343 (2017): 1140-1144
[7] Villar, Aitor, et al. "Entanglement demonstration on board a nano-satellite." Optica 7.7 (2020): 734-737
[8] https://www.researchnester.com/reports/quantum-communication-market/5747

4. Earth-sensing and observation;
5. Fundamental sciences.

European projects involved in the realization of space-based quantum network are discussed in Section 3.1.

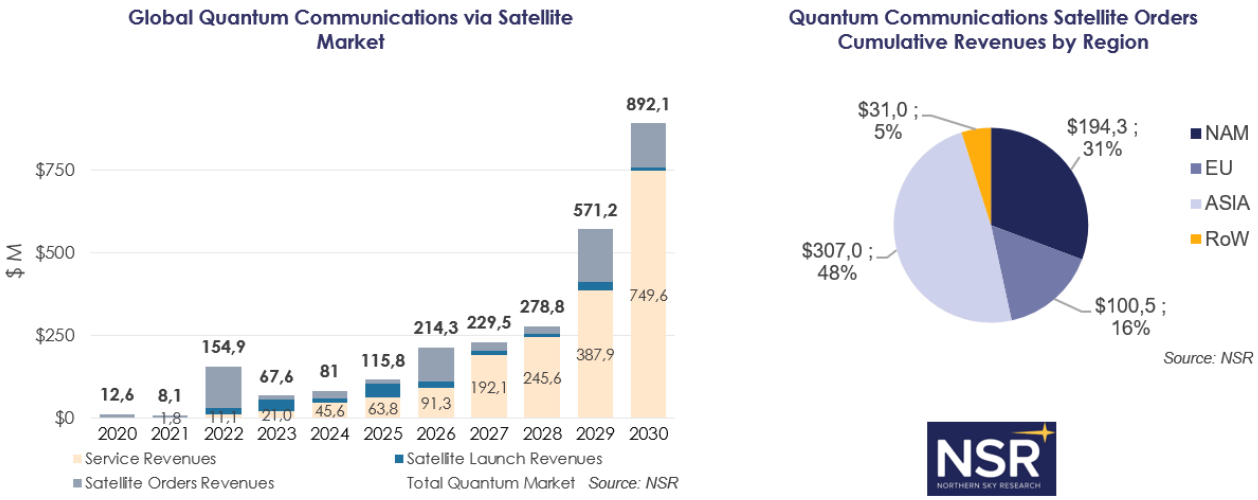

Figure 2-1 Quantum Communications Satellite Orders Cumulative Revenues by Region

2.2 Market Trends and Drivers

The government projects worldwide are driven by the potential for significant advancements in innovation and research, and particularly for the improvements brought from quantum technologies to communication security and quantum computing.

The analysis of the main aspects that are driving the market of quantum technology is reported below.

Advances in Technology:

- R&D activities: Continuous improvements in technology are being achieved through dedicated research and development activities.
- Space-oriented sector growth: The space sector is expected to facilitate the market entry of quantum communication via satellite and other space-based quantum activities.
- Ground-oriented sector growth: The ground sector is expected to facilitate the market entry of quantum communication via fiber and other ground-based quantum activities.

Security Threats:

- Cybersecurity needs: In the digital age, where cyber threats are increasingly sophisticated and pervasive, there is an urgent need to ensure secure communication for various applications. These include protecting critical infrastructure, safeguarding state secrets, and securing financial transactions across borders. The introduction of quantum communications via satellite has the potential to revolutionize the telecommunications sector by providing a secure global communication network that is immune to eavesdropping and capable of detecting any interception attempts.

Quantum technology and quantum computing relevant funding:

- United States: The United States committed $1 billion in 2018 through the Quantum Act, with more funding expected to be announced. The country also benefits from substantial investments by commercial players such as Google, IBM, Microsoft, and AWS, all of which are heavily investing in quantum technologies.
- European Union: The European Union has launched several initiatives to support quantum technologies (see Section 3.1), including the Quantum Technologies Flagship, a 10-year, €1 billion initiative. Additionally, programs like Horizon 2020 and Horizon Europe have allocated significant funding for quantum research and innovation. EU countries, often in combination with private sector investments, support these technologies.
- China: China aims to maintain its leadership in global quantum technology development, supported by the funding outlined in their recent four-year plan. This includes significant investments to further advance research and development in quantum technology.

Specific to the space-oriented quantum technology market, further aspects of market drivers and restraints are also reported in Figure 2-2.

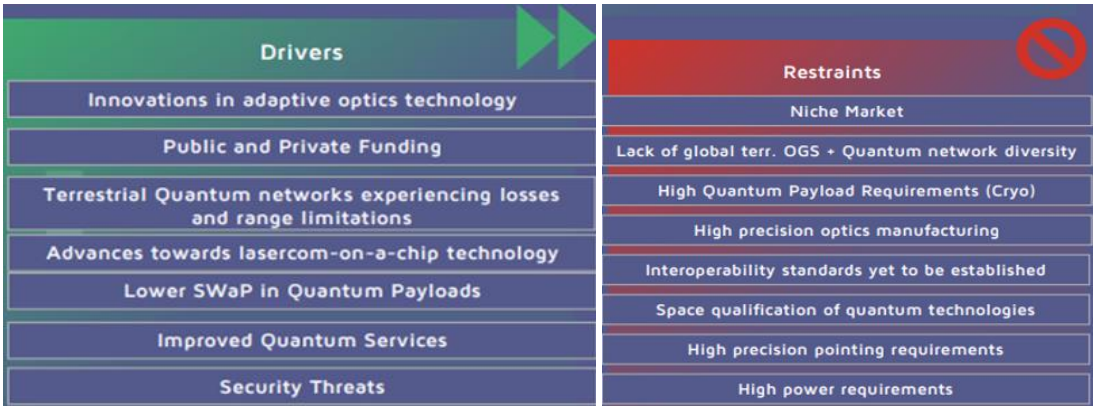

Figure 2-2 Driving and restraining aspects of QT market

As a result, new opportunities and challenges are emerging from the market trends activities of quantum technologies sector. In fact, as technology continues to advance and investments increase, the market is expected to grow, overcoming current challenges and unlocking new opportunities. In particular, quantum communications via satellite stand poised to significantly enhance the security and reliability of global telecommunications.

Different players are seizing the opportunities of quantum technologies, which are mainly related to the following factors:

- **The Satellite-as-a-Service (SaaS):** the SaaS business model is driving more quantum players into the market.
- **Banking and Security Segments:** they are early adopters of quantum communication technology.
- **Investors:** they are enabling significant funding rounds to bring the this news technology to fruition.
- **Government:** national strategies and funding initiatives are supporting the growth of quantum technologies.
- **In-Orbit demonstrations:** impressive advances, particularly from China, showcase the potential of quantum communications.

Despite the great opportunities, big challenges are still present, mainly deriving from the R&D development phase, such as:

- **Research and Development:** Quantum Key Distribution (QKD) is a game-changing technology but requires substantial government involvement for further R&D funding, certification, and accreditation.
- **Reliance on Optical Communication:** The industry still heavily depends on the optical communication value chain.
- **Lack of Commercialization:** Quantum communication technologies are not yet widely commercialized.

2.3 Quantum Communication Investments by Country

The global quantum effort leading to research and innovation in quantum science and technology is continually rising[9] with current worldwide investments exceeding $40B (from $30B in 2022). It includes rising investments on past initiatives and new ones (i.e. Philippines, South Africa, Brazil, Hungary, Switzerland). Overall, the market Quantum Tech. (incl. computing, TLC and sciences) is projected to reach $106B by 2040.

Figure 2-3 illustrates the substantial economic investment in quantum technologies (QT) for the years 2022 and 2024. These investments will push research and development on QT, thus generating opportunities for technological innovation.

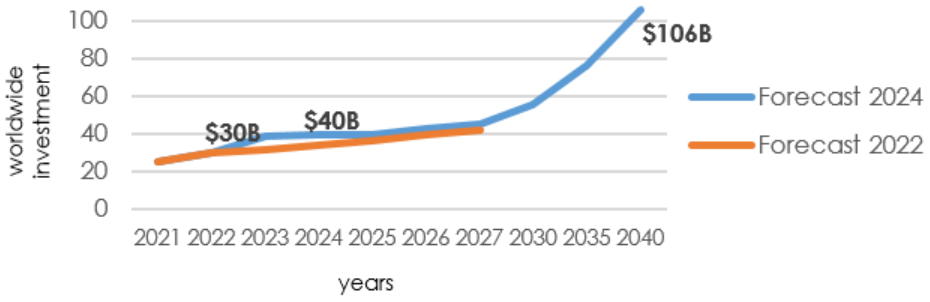

Figure 2-3 Global worldwide economic investment in quantum technologies

[9] https://www.qureca.com/overview-on-quantum-initiatives-worldwide-update-mid-2021/
https://www.qureca.com/overview-on-quantum-initiatives-worldwide-update-2022/
https://www.qureca.com/overview-of-quantum-initiatives-worldwide-2023/
https://www.qureca.com/quantum-initiatives-worldwide-2024/

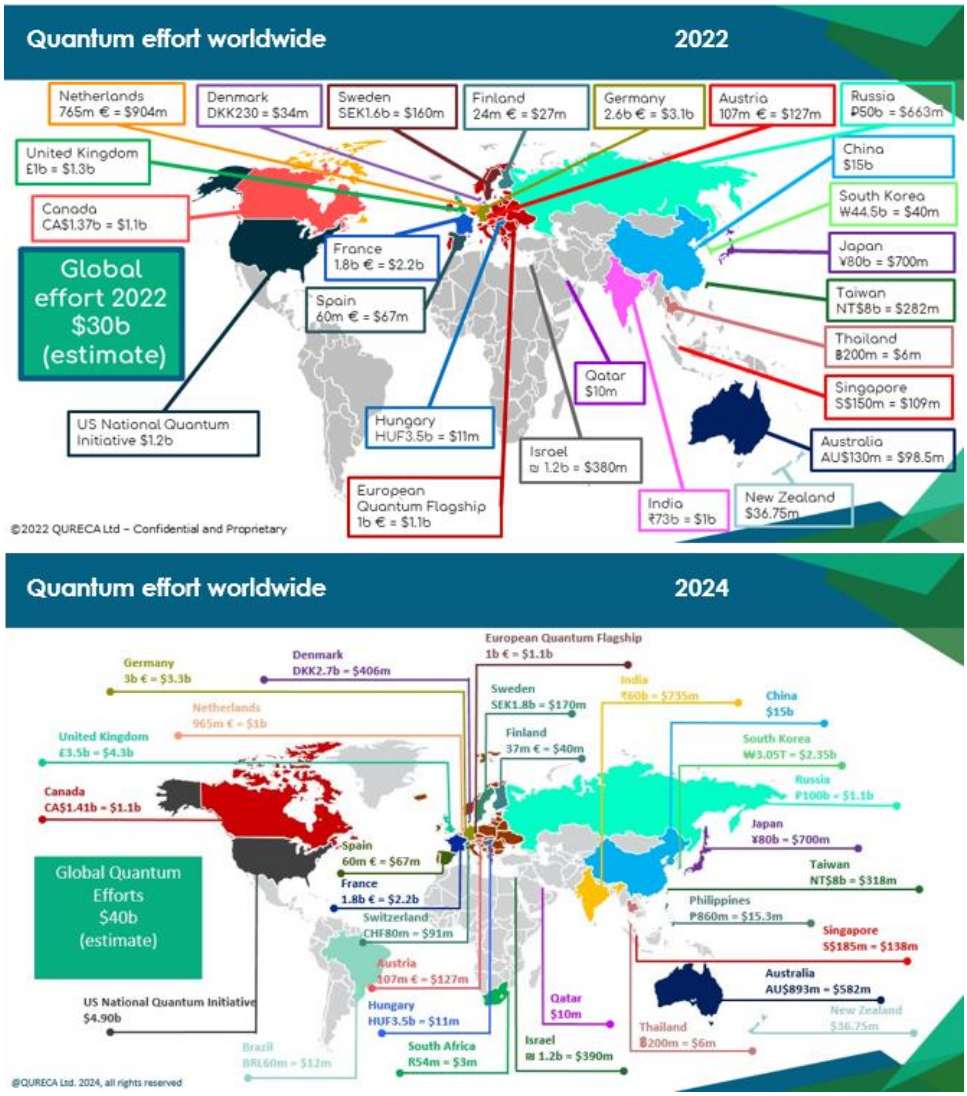

Figure 2-4 Worldwide economic investment by country in quantum technologies for the years 2022 (top) and 2024 (bottom)

As depicted in Figure 2-3 and Figure 2-4, a variety of countries are actively participating in this second quantum revolution. Table 2-1 provides a comprehensive list of worldwide initiatives undertaken by various players outside Europe. Specific European initiatives are discussed in next sections. All these initiatives are expected to move QT from academic research to real-world applications in the coming years.

Table 2-1 Worldwide initiatives on quantum technologies outside Europe

Country	Year	Player	Description
USA	**2019**	**Commercial**	Google, Amazon, IBM, Microsoft launch quantum cloud services
	2020	**Institutional**	The White House Office of Science and Technology Policy and the National Science Foundation and the Department of Energy announced a fund of $1 billion to establish 12 AI and quantum information science research centers nationwide

Country	Year	Player	Description
	2021	**Institutional**	The U.S. Senate passed the Innovation and Competition Act including funding for quantum technology
	2021	**Commercial**	CommStar Space Communications, which plans to launch its first satellite, CommStar-1, before 2023, has teamed with Quantum Xchange to provide quantum-safe encryption across the network
	2023	**Institutional**	The U.S. Department of Energy and partners announced the first round of participants dedicated to the Quantum & Space Collaboration.
	2023	**Institutional**	NASA's Cold Atom Lab Sets Stage for Quantum Chemistry in Space
	2023	**Commercial**	Lockheed Martin's Space 2050 report focuses on quantum computing, quantum communications and quantum remote sensing, technologies. ockheed Martin is developing "quantum algorithms to make use of quantum computers, quantum remote sensing and quantum communications,
Canada	**2024**	**Institutional**	EU and Canada discussed next steps for increased cooperation in cybersecurity, artificial intelligence (AI), quantum science and semiconductors, public policy related to online platforms, secure international connectivity, and cyber security.
	2023	**Institutional**	EU and United States enhance cooperation on cybersecurity
			The EU and the United States took an important step to further strengthen their mutual cyber resilience and foster a secure global cyberspace.
	2023	**Institutional**	development of the Quantum Encryption and Science Satellite – QEYSSat (demonstrate quantum key distribution (QKD) in space, launch in 2025-
			26), Dextre-Operated Camera–DOC (portable enhanced vision tool to inspect the ISS
China	**2020**	**Institutional**	Chinese scientists established the world's first integrated quantum communication network, combining over 700 optical fibers on the ground with two ground-to-satellite links to achieve quantum key distribution over a total distance of 4,600 kilometers for users across the country
	2020	**Institutional**	Chinese researchers developed the world's first mobile quantum satellite station; a quantum VSAT was fitted on a van and used during the 4,600 km QKD demonstration project that took place in 2020
	2020	**Commercial**	QuantumCTek goes public, largest IPO in STAR market history, QuantumCTek is a provider of terrestrial quantum equipment, it would be expected for QuantumCTek to supply and engage in space-based quantum services
	2023	**Institutional**	Chinese research institutes are working to construct a quantum communications network using satellites in low and medium-to-high Earth orbits.
	2024	**Institutional**	Two to three quantum communications satellites will be launched into low Earth orbit (LEO) next year
Korea/EU	**2023**	**Institutional**	EU and Republic of Korea Digital Partnership: strengthening our economic resilience. ROK-EU Forum for Semiconductor Researchers that intends to promote research in complementary areas. In the area of High Performance Computing (HPC), both partners agreed to join forces to

Country	Year	Player	Description
			develop applications for use in cases of common interest such as extreme weather events or material science.
Taiwan	**2024**	**Institutional**	Taiwan's 5-Qubit Superconducting Quantum Computer Goes Online Ahead of Schedule
Japan	**2023**	**Institutional**	Research group launches Japan's third quantum computer at Osaka University
	2023	**Institutional**	SKY Perfect JSAT Corporation announced the successful launch of the Quantum Cryptography Optical Communication Device, which was built in the "Study and Development of Satellite-based Quantum Key Distribution (QKD) and Cryptography Technology in Satellite Communication" for the Minister of Internal Affairs and Communications (MIC)evice
Singapore	**2024**	**Institutional**	Singapore aims to boost its capabilities in quantum computing with new initiatives to develop relevant skillsets and quantum devices. The Singapore government announced plans to set aside $23.5 million to support three national platforms, parked under its Quantum Engineering Programme (QEP).
Taiwan	**2024**	**Institutional**	President Tsai Ing-wen congratulated Academia Sinica on reaching a milestone in the development of Taiwan's quantum technology industry with the country's first 5-quantum-bit superconducting full-stack quantum computer.
India/EU	**2022**	**Institutional**	India and EU sign Intent for Cooperation agreement in high performance computing and quantum technologies
	2023	**Institutional**	First EU-India Trade and Technology Council focussed on deepening strategic engagement on trade and technology
India	**2023**	**Institutional**	ISRO makes breakthrough demonstration of free-space Quantum Key Distribution (QKD) over 300 m
	2024	**Institutional**	India Pioneering Quantum Communication; In a development that marks a significant leap forward in quantum communication, the Centre for Development of Telematics (C-DOT) and the Physical Research Laboratory (PRL) have achieved a milestone by integrating indigenous quantum key distribution (QKD) systems. This innovation seamlessly marries C-DOT's Fiber-based QKD system with PRL's Free Space QKD system, establishing an end-to-end quantum communication link spanning both fibre optics and free space as transport mediums.

2.4 Market Landscape and Actors involved in Quantum Technologies

The quantum technology market is rapidly evolving, with a diverse range of companies and start-ups driving innovation in Quantum Key Distribution (QKD) and other quantum applications. The landscape features approximately 70 major companies and start-ups actively engaged in QKD projects, with varying levels of involvement in space-related activities.

The summary of the main actors involved is shown in figure below:

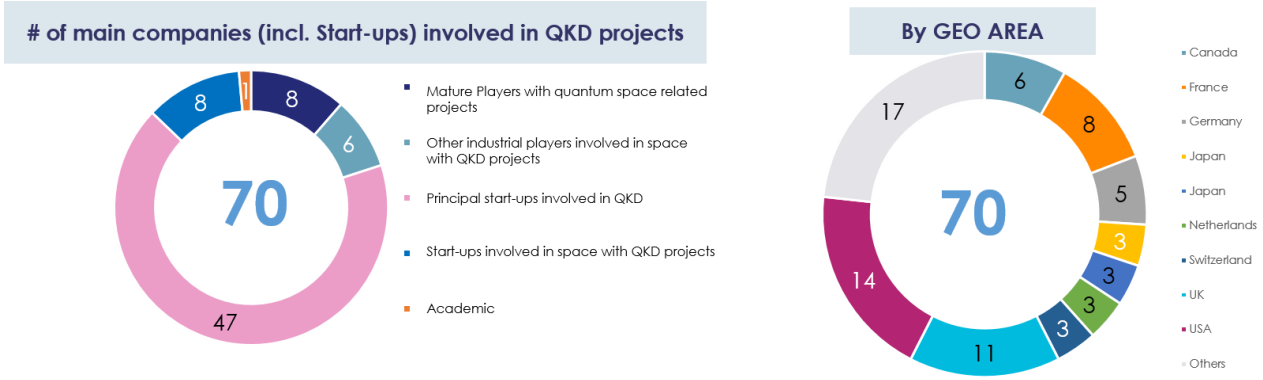

Figure 2-5 Description of main actors involved in QKD projects

According to the figure, the market can be segmented into several key groups:

1. Start-ups not yet involved in space projects: a significant portion of the market consists of several start-ups that are currently focusing on terrestrial quantum technologies and have not yet ventured into space projects. These companies are at the forefront of developing new quantum communication and computing technologies.
2. Mature players with space-related projects: there are a few established companies with notable involvement in space-related quantum projects. These include industry giants such as:
    - Thales Alenia Space (TAS)
    - Airbus Defence and Space (ADS)
    - Lockheed Martin
    - Northrop Grumman
    - OHB
    - Honeywell
    - SES
    - EUTELSAT GROUP
3. Start-ups involved in space projects: another dynamic segment includes some start-ups that are specifically engaged in space-oriented quantum projects. These companies are pioneering the integration of quantum technologies in space applications.
4. Non-space companies with space QKD projects: there are a few companies that, while not primarily focused on the space sector, are involved in space-related QKD projects. These firms are leveraging their expertise in quantum technologies to contribute to the advancement of space-based quantum communication.

The figures below reports NSR identification of the main actors of QT development divided by application domain.

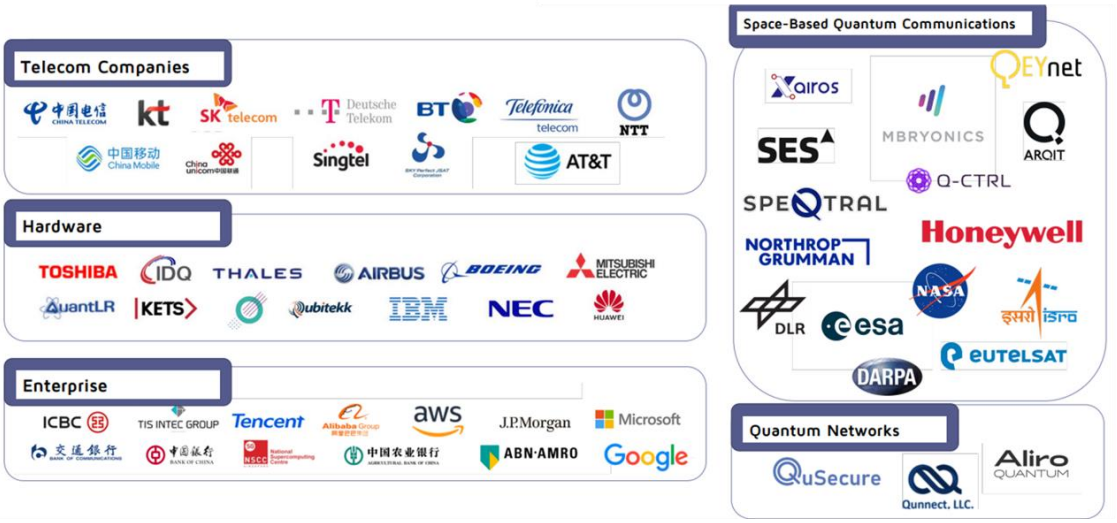

Figure 2-6 Categorization of the main actors involved in QT market

The collective effort of all these actors is driving the growth and commercialization of quantum technologies, positioning them as crucial players in the global market. As the industry progresses, the integration of quantum technologies in both terrestrial and space applications is expected to accelerate, fostering further innovation and collaboration across the sector.

This collective effort can be divided into some phases concerning the development of space-oriented quantum technologies, as reported in the following figure:

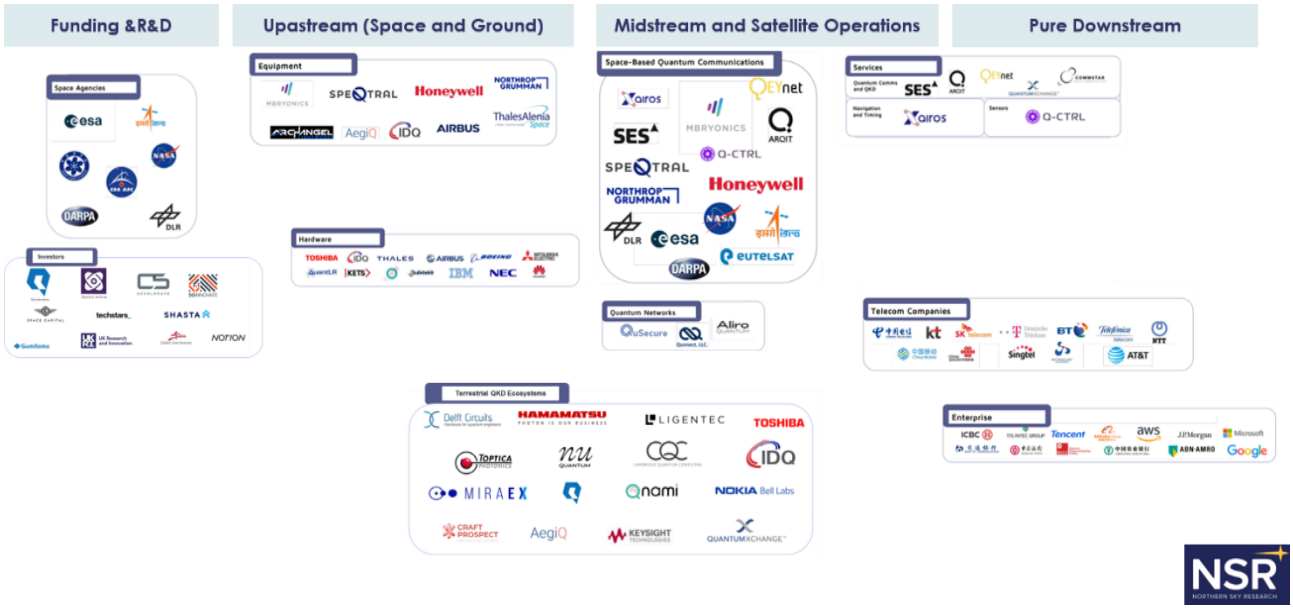

Figure 2-7 Relationship between development phases and key players involved.

It cover the main stages and activities involved in the value chain of space technologies, from initial funding and development (R&D) to the final processing and utilization of data (downstream). More specifically:

- Fundings R&D involves securing the necessary funding for the research and development of space technologies. It includes seeking investments from governments, space agencies, research institutions, and private investors. Activities in this phase involve feasibility studies, prototype development, testing of new technologies, and innovative approaches to enhance the capability and efficiency of space technologies.
- Upstream (Space and Ground) phase includes all activities leading up to the launch and operation of space missions. This encompasses the design, manufacturing, and launching of satellites and spacecraft. Additionally, it includes the ground infrastructure necessary to

support the launch, monitoring, and control of these space vehicles. Ground operations are crucial to ensure the successful deployment and ongoing functionality of the missions.

- Midstream and Satellite Operation phases focus primarily on the management and control of satellites once they are in orbit. It includes the calibration of onboard instruments, resource management of the satellite, monitoring its operational conditions, and implementing orbital maneuvers. Satellite operations also entail the collection, initial processing, and transmission of data acquired by the satellite's payloads to ground stations.
- Pure Downstream phase centers on the processing, analysis, and application of data collected by satellites. It includes distributing the data to end-users such as government organizations, private companies, and research institutions. Pure downstream operations aim to transform raw data into useful and actionable information.

3 DEVELOPMENT ROADMAP

The LaiQa project aims to elevate the Technology Readiness Level (TRL) of several critical technologies to facilitate the development of quantum networks. These technologies are tailored to support a quantum network that includes both space and ground segments.

Currently, various projects at the global, European, and national levels are in progress to advance quantum communication technologies. Specifically, the LaiQa project aims to align its development efforts with European objectives, focusing in the short term on first prototypes of satellite-based quantum communication, such as SAGA and EAGLE-1. In the longer term, the project aspires to contribute to the broader initiative known as EuroQCI, which envisions the establishment of integrated European quantum networks spanning both terrestrial and space segments.

This roadmap outlines the EU vision on quantum network development necessary to achieve these objectives, guiding the development of the LaiQa project towards supporting Europe's ambition in the realm of quantum communication.

3.1 European Policies

Europe has taken several concrete steps to support the development of Quantum Technologies[10]. A summary of the main programs is shown in Figure 3-1.

Figure 3-1 Main EU initiatives to support quantum technologies development

Quantum Technologies Flagship

The first main EU initiative is the Flagship program that involves an investment of €1B over 10years. The EU-funded Quantum Technologies Flagship is a collaborative long-term research and innovation initiative that was launched in 2018 and brought EU at the frontier of the quantum technological discovery by delivering first results in 2018-2022 (1st phase)[11]. Here, 24 projects across 31 European countries in the fields of quantum communications, computing, simulation, sensing and metrology, and basic quantum science have been supported. In funding both the Flagship and QuantERA,

[10] https://qt.eu/funding-opportunities/
[11] https://digital-strategy.ec.europa.eu/en/news/eu-frontier-quantum-technological-discovery-quantum-technologies-flagship-delivering-first-results

which supports quantum research across 31 European countries, the EU funded European quantum research with over €175M since 2016. These result in collaborative efforts of 1,654 scientists and 236 organisations, who have published 1,313 scientific papers (with a further 223 under review). It shows clearly that the Flagship projects have collectively made their mark in the scientific world. The ramp-up phase also saw significant steps being made towards the Flagship's main aim of bringing quantum research from the laboratory to commercial applications. 25 start-up companies have been founded and 105 patents have been filed, with 64 of those already granted.

Looking to the future, the Flagship will be key to achieving the goals set out in the Commission Communication "2030 Digital Compass: the European way for the Digital Decade": by 2025, the EU should have its first computer with quantum acceleration, paving the way for being at the cutting edge of quantum capabilities by 2030. The first of these goals is already in sight: in October 2022 the six sites that will host Europe's first quantum computers, to be integrated into the supercomputers of the European High Performance Computing Joint Undertaking, were announced.

Horizon Europe

Under Horizon Europe program, the EC will continue to support the Flagship in the period 2021-27 with funding of at least €500M. An update of Strategic Research and Industry Agenda (SRIA) of the Flagship has already been published, with enhanced targets for each of the initiative's four key pillars and a roadmap towards making them a reality. A number of new projects are already underway, with the aim of working towards these targets. Some projects are also laying the foundations for a pan-European quantum communication network that will be crucial to the development of the **EuroQCI**, i.e. a secure quantum communication infrastructure that will span the whole EU (Sec. 3.1.1). The updated SRIA also includes a focus on future industrial development and on strengthening links with other EU initiatives that cover quantum technologies: namely, the EuroQCI, the European High Performance Computing Joint Undertaking (EuroHPC JU) – which is already acquiring its first quantum computers – and the European Chips Act. This will ensure that the innovative applications developed on the basis of the Flagship's research will form the basis of a European quantum ecosystem and help Europe to maintain its leading position in this globally competitive field.

Within the European context, the **LaiQa** project represents a relevant EU initiative to develop quantum technologies oriented to a space-based quantum network implementation. LaiQa EU program is discussed more in detail in Sec. 0.

Despite EC funding, EU countries are contributing also individually to the second quantum revolution. Table 3-1 provides a list of some national and private initiatives undertaken by various players inside EU.

Table 3-1 Relevant EU and UK national and commercial initiatives on quantum technologies

Country	Year	Player	Description
Sweden	**2024**	**Commercial**	IBM partnership gives Swedish firms and researchers access to large quantum test bed
	2024	**Commercial**	The Gothenburg based company ConScience AB has delivered its first quantum technology components to a US based quantum computing company.
Belgium	**2023**	**Institutional**	Federated Quantum System (FQS) satellite-based quantum technology encryption network under development to

Country	Year	Player	Description
			share communications securely with allies; 1st sat to launch in 2023
Netherlands	**2024**	**Institutional**	Over €10 million handed to projects looking into benefits and threats of quantum developments→Dutch funders have handed out more than €10 million to 19 quantum technology research projects covering a wide variety of topics—from improved magnetic sensing to superconducting microwave resonators.
Austria	**2023**	**Institutional**	A consortium of machine learning and quantum computing experts – Gradient Zero, Anaqor, QMware and PQML – is launching Quantum Connect, Austria's first national quantum machine learning initiative.
Germany	**2024**	**Institutional**	Qube, a German cubesat, is preparing to test quantum key generation and distribution via optical link. The Germany institutions are already planning Qube follow-ons. QUBE-2, a six-unit cubesat with "a much stronger laser payload," is slated to launch in the second half of 2025.
	2023	**Institutional**	New Institute of Quantum Technologies in Ulm. DLR project 3D-LoCoS has demonstrated that additive manufacturing play a major role for space propulsion systems.
	2023	**Institutional**	Mynaric has been selected by German government for three technology development projects related to quantum communication
Spain	**2023**	**Institutional**	Caramuel GEO sat. mission for quantum key distribution, study funded by ESA and led by Hispasat
Luxembourg	**2022**	**Commercial**	The University of Luxembourg's Interdisciplinary Centre for Security, Reliability and Trust (SnT), in collaboration with the Department of Media, Connectivity and Digital Policy (SMC) of the Ministry of State, announces the development of the Luxembourg Quantum Communication Infrastructure Laboratory (LUQCIA). The 5-year project is funded by the European Union's Recovery and Resilience Facility in the context of the NextGenerationEU initiative, to build a national testbed in 2023 to enable advanced and applied research in quantum key distribution and quantum internet – a vital stage in the next generation of computing and internet usage.
Switzerland	**2022**	**Institutional**	The Swiss Quantum Commission (SQC), a group of leading experts from ETH Zurich and EPFL, the universities and other higher education institutions, the private sector and government agencies, is responsible for coordinating the expertise of Swiss research institutions. As an umbrella organisation, the Swiss Academy of Sciences (SCNAT) hosts this commission, which is responsible for the implementation of the initiative and aims initially to strengthen research.
Denmark	**2024**	**Institutional**	The Danish Quantum Communication Infrastructure is the national Danish contribution to the pan-European infrastructure EuroQCI. The project is funded by the European Commission under the Digital Europe Programme as well as by the Danish government. It is a collaboration between Danish universities, companies, and public authorities. In QCI.DK we will establish a quantum secured metropolitan network between 5 Danish public authorities and 2 associated data centres in the Copenhagen area. In

Country	Year	Player	Description
			addition the infrastructure will encompass a 200 km long-distance link connecting three participating university partners via the metropolitan network. QCI.DK will combine three different QKD technologies in one network and thereby enable a broad range of tests and applications. To explore applications of QKD, the project devotes large attention to the development of use cases in the public authorities network and analysis of best implementations.
United Kingdom	**2024**	**Commercial**	Providing a platform for its 50-strong network of members, UKQuantum supports the entire quantum ecosystem, spanning computing, sensing and communications. Members of the consortium range from early-stage startups to large end-users, with all benefiting from the national and global engagement that UKQuantum strives to offer.
	2023	**Commercial**	Sky and Space (SAS) to Embed World's First Quantum-ResistantEncryption Solution for Its Satellites and Ground Terminals
	2021	**Commercial**	ArQit SPAC: UK startup goes public with $400M funding

3.1.1 Focus on EuroQCI

The European Quantum Communication Infrastructure (EuroQCI) Initiative will be a secure quantum communication infrastructure spanning the whole EU, including its overseas territories.

The European Commission is working with all 27 EU Member States, and the European Space Agency (ESA), to design, develop and deploy the EuroQCI, which will be composed of a terrestrial segment relying on fibre communications networks linking strategic sites at national and cross-border level, and a space segment based on satellites. It will be an integral part of IRIS², the new EU space-based secure communication system.

The EuroQCI will safeguard sensitive data and critical infrastructures by integrating quantum-based systems into existing communication infrastructures, providing an additional security layer based on quantum physics. It will reinforce the protection of Europe's governmental institutions, their data centres, hospitals, energy grids, and more, becoming one of the main pillars of the EU's Cybersecurity Strategy for the coming decades.

The EuroQCI will make use of innovative quantum communication technologies such as those developed by the researchers of the EU-funded Quantum Technologies Flagship, and building in particular on the activities of the Horizon 2020 OPENQKD project[12]. The involvement of European industry partners and Small and Medium-sized Enterprises (SMEs) is also crucial to ensuring that the critical components of EuroQCI are based on European technologies, and ultimately to boosting Europe's scientific, technological and industrial capabilities in cybersecurity and quantum technologies. The initiative will thus contribute to European digital sovereignty and industrial competitiveness, and help to meet Europe's Digital Decade target of being at the cutting edge of quantum capabilities by 2030.

Towards an operational EuroQCI

The EuroQCI was launched in 2019 with the EuroQCI Declaration, initially signed by seven Member States: all Member States subsequently joined the initiative. Since then, work has continued, under

[12] https://openqkd.eu/

the supervision of the Commission and implemented by the Member States in the case of the terrestrial segment, and by ESA in the case of the space segment.

Terrestrial segment

For the terrestrial segment, the Commission first funded two industry consortia to conduct system design studies defining the EuroQCI's architecture. The findings of these studies are now paving the way to the deployment of the EuroQCI.

The EuroQCI's first implementation phase started in January 2023 with the support of the Commission's Digital Europe Programme[13], with a focus on the following areas:

- A set of industrial projects (see Table 3-2) to develop and mature the key technological building blocks for the EuroQCI, with the aim of developing Europe's quantum communication ecosystem and industry.
- National projects (see Figure 3-2) allowing Member States to design and build the national quantum communication networks that will form the basis of the terrestrial segment, testing different technologies and protocols and adapting them to the specific needs of each country.
- A coordination and support action, **PETRUS**[14], to act as a link between all projects, facilitate collaboration, and identify standardisation needs.

These first Digital Europe projects will together make it possible to take the first steps towards services offering operational quantum key distribution (QKD), a highly secure way of delivering encryption key material.

Alongside this, the Connecting Europe Facility[15] (CEF) will provide funding for projects developing cross-border links between national networks, and interconnections with the EuroQCI's space component.

In addition, with the support of the Digital Europe Programme, a testing and evaluation infrastructure[16] will be built that will enable QKD-based technologies and services to be assessed and validated, so that users can be confident that they will not be vulnerable to attacks. This infrastructure was expected to start becoming available from mid-2024 onwards.

Table 3-2 Industrial projects related to EuroQCI[17]

Project	Description
MDI QUEEN	At MDI QUantum Equipment for European Networks (MDI-QUEEN) we will develop and industrialize next-generation QKD devices and crucial elements for future quantum networks that will enable a transition to a quantum-safe and secure communication infrastructure. Furthermore, we will strengthen the European ecosystem by building a resilient value chain for the upcoming quantum communication market.

[13] https://digital-strategy.ec.europa.eu/en/activities/digital-programme
[14] https://petrus-euroqci.eu/
[15] https://digital-strategy.ec.europa.eu/en/activities/connecting-europe-facility
[16] https://digital-strategy.ec.europa.eu/en/funding/testing-and-evaluation-infrastructure-european-quantum-communication-infrastructure-euroqci
[17] https://petrus-euroqci.eu/industrial-qkd-projects/

Project	Description
equo	At European QUantum ecOsystems (EQUO), we will design, develop, and test QKD systems with high TRL level using cutting-edge European technology ready for integration into telecommunication networks. EQUO will demonstrate the QKD solution in use cases, ensuring interoperability between quantum and traditional cybersecurity systems. We will also identify current and future use-cases and investigate socio-economic trends in quantum communications. EQUO will disseminate results through scientific publications, contributions to standardization bodies, and industrialization plans.
eCausis	eCAUSIS (European, Certifiable, Affordable, User-oriented, Secure, Integration-able, Scalable quantum key distribution solutions) will design, develop and industrialize key components for quantum key distribution (QKD) systems. The main focus of the project will be an interoperable DV-QKD module and key management system (KMS). To elaborate on this, we want to reach an easy to implement and use, certifiable and scalable QKD systems, establish a resilient European supply chain for DV-QKD technology and reach a cost-efficient and repeatable serial manufacturing on an industrial level
QKiss	Quantum Key Industrial SystemS (QKISS) develops QKD systems for industrial encryption using CVQKD. They prioritize security and reliability with early and continuous analysis of potential vulnerabilities. Field demos precede industrialization, where QKISS optimizes systems to meet clients' needs. Their complete QKD systems offer clients highly secure data protection, making them a key player in quantum information technology.
QUARTER	QUAntum CRyptography Technology for EuRope (QUARTER) will increase the maturity level of quantum cryptography technology, including QKD systems, photonic-integrated components, and classical security solutions to allow for industrialization, network integration, and will assist with the deployment into the EuroQCI. Furthermore, QUARTER pushes the readiness level of quantum communication technology for its large-scale deployment in secure environments and networks.
SEQRET	Secure and Industrialized Quantum Key Distribution for European Telecom Networks (SEQRET), led by KEEQuant and including Rohde & Schwarz Cybersecurity, SMART Photonics, Dacoso, EXATEL, Poznan Supercomputing and Networking Center, and CESNET, advances European telecommunication with an industrialized, certifiable TRL8 QKD and an integrated photonics based TRL7 QKD system, setting a benchmark in quantum security standards and cybersecure system integration.

Figure 3-2 National projects related to EuroQCI

Space Segment

For the space segment, the Commission is currently working with ESA on the specifications of a first generation constellation of EuroQCI satellites. This will build on the first prototype satellites called Eagle-1 and SAGA.

Eagle-1 is developed by ESA and an industrial consortium, and due to be launched in late 2025 or early 2026. Specifically, the European Space Agency (ESA) announced[18] that SES will lead a consortium of 20 companies to develop and launch a secure quantum key distribution (QKD) satellite in 2024 for European secure communications. SES and partners will build the first sovereign European end-to-end space-based QKD system, with a Low-Earth Orbit (LEO) satellite, and an operations center in Luxembourg. The consortium will develop the QKD payload, terrestrial optical station, scalable quantum operational networks, and key management system to interface with national quantum communication infrastructures (QCIs). This project will provide mission data to support future EU sovereign quantum secure communications networks. ESA Director General Josef Aschbacher said the Eagle-1 project is toward future European quantum communications that are secure and scalable.

In particular, The SES-led consortium of European companies, responsible for development of the quantum secure space-based EAGLE-1 system and working in close collaboration with the European Space Agency (ESA), is joined by TNO and Airbus Netherlands B.V., to design and build an optical

[18]https://www.satellitetoday.com/cybersecurity/2022/09/22/ses-esa-announce-eagle-1-quantum-key-distribution-satellite/

ground station (OGS) for the mission[19]. The OGS for EAGLE-1 represents a highly advanced and complex system which will be able to receive quantum encryption keys from the EAGLE-1 satellite, and will have at its core a system that integrates fast adaptive optics, accurate mirrors, a robust fiber coupling, a novel laser beacon system, and a stabilised telescope. Other organization involved in the collaboration are Officina Stellare, Celestia-STS, TESAT and Demcon.

Co-funded by the European Space Agency (ESA) and the European Commission (EC), together with the space agencies of Germany, Luxembourg, Austria, Italy, the Netherlands, Switzerland, Belgium and the Czech Republic, and the industry, the EAGLE-1 programme will demonstrate the feasibility of quantum key distribution (QKD) technology via satellite within the EU and beyond, enabling next generation cybersecurity for the Member States. It will also provide valuable mission data for the future deployment of a secure quantum communication infrastructure for the EU (EuroQCI).

The development of terrestrial components of the quantum communication infrastructure will be under the responsibility of the EC's Directorate-General for Communications Networks, Content and Technology (DG Connect)[20]. It would comprise a series of quantum communication networks, linking institutional users and their critical infrastructures, and sensitive communication and data sites in Europe.

The space-based component, known as **SAGA** (Security And cryptoGrAphic mission), would be developed under ESA's responsibility and consists of satellite quantum communication systems with pan-European reach. The ESA, through its SAGA programme, is responsible for designing the space backbone of the EuroQCI. The objective is to produce a EuroQCI demonstrator and offer an initial operational service by 2027. It will be an integral part of IRIS², the new EU space-based secure communication system[21].

Besides boosting European autonomy and scientific leadership in this strategic field, creating a quantum communications infrastructure fits into ESA's strategy of helping to develop new business opportunities for European companies, by stimulating the development of innovative technologies and systems. ESA's programme of Advanced Research in Telecommunications Systems (ARTES) supports such innovation in the development of new products, services and applications, including SAGA as part of the strategy for Space Systems for Safety and Security (4S).

In addition, some information describing ground interfaces and the QKD protocol has been partially made public[22] in order to enable the development of associated technologies that do not have direct visibility into projects.

3.1.1 Quantum Technology Road to 2035

The EuroQCI will integrate QTs and quantum systems into terrestrial fibre-optic communications networks. Early field-deployed fibre-based QKD demonstrations have been realised, including crossborder QKD links between EU Member States. The EuroQCI will also include a space-based segment to ensure full coverage across the EU and other continents. The ESA, through its SAGA programme, is responsible for designing the space backbone of the EuroQCI. The objective is to

[19] https://www.ses.com/press-release/ses-led-eagle-1-onboards-tno-and-airbus-deliver-ground-station-quantum-key

[20] https://www.esa.int/Applications/Connectivity_and_Secure_Communications/European_quantum_communications_network_takes_shape

[21] https://defence-industry-space.ec.europa.eu/eu-space-policy/iris2_en

[22] https://connectivity.esa.int/sites/default/files/2024-10/saga-satellite-advanced-global-architecture-2014.pdf

produce a EuroQCI demonstrator and offer an initial operational service by 2027. It will be an integral part of IRIS[2], the new EU space-based secure communication system.

To this end, several European consortia have been established under the EuroQCI initiative to advance the maturity level of QKD and related technologies. An important project is the PETRUS consortium coordinating the EuroQCI, which will ensure the interoperability of the quantum network and alignment across deployments by the different EU Member States.

A very detailed recent roadmap on quantum technologies considering both space and terrestrial segment can be found by European Quantum Industry Consortium (QUIC)[23]. In the following, a LaiQa-oriented summary of QUIC roadmap is provided.

Immediate future (to 2025)

By 2025, QKD products will be industrialized, allowing for the manufacture of tens to hundreds of QKD links per year. QKD networks with dozens of links will be established, with some continuing in test mode and a few being used in production. QKD network architectures will be demonstrated and ready for validation in governmental applications. Products will enter the market with general-purpose certifications according to EU directives, and QKD security certification preparations will be underway. The adoption of quantum keys by encryptors operating at Open System Interconnection (OSI) layers[24] 1 to 4 will begin, and CV and EB QKD products will reach TRL 9.

Near-term (2025-2029)

Between 2025 and 2029, QKD networks will expand to hundreds of nodes, replacing testbeds with production networks. QKD products will evolve from general-purpose devices to specialized products, ranging from low-cost and low-performance devices for access networks or local private networks to high-key-rate devices for long distances. Integration of optical and electronic components will become advanced enough to allow for medium-scale production. The first QKD products will be certified, and quantum keys will be adopted or integrated by devices operating across various OSI layers. The initial stages of quantum internet will begin by connecting two quantum computers within the same metropolitan area, offering limited benefits compared to the standalone computational power of individual devices.

Long-term (2030-2035)

From 2030 to 2035, there will be widespread deployment of QKD. It will become possible to connect quantum computers within the same region into networks that have a combined computational power substantially greater than the sum of individual devices. The adoption of entanglement-based communication and new quantum communication services, such as the quantum internet, will occur in niche applications where high costs and limited key rates are acceptable.

[23] https://www.euroquic.org/wp-content/uploads/2024/02/PUBLIC-version-Strategic-Industry-Roadmap-2024.pdf

[24] The OSI model is a seven-layer framework that standardizes networking protocols, with layers 1-4 focusing on the physical transmission of data (physical layer), error detection and node-to-node data transfer (data link layer), logical addressing and routing (network layer), and reliable data transfer with error correction and flow control (transport layer).

3.2 Strategic Plan of LaiQa

LaiQa[25] (Leap in Advancing of critical Quantum key distribution-space components) is a 36 - month Research Programme part of the HORIZON Innovation Actions funded by the European Commission, through the European Health and Digital Executive Agency (2022-23 calls: 2023-62 Quantum Communication Technologies for space systems: €5M for 2 projects incl. LaiQa and QuTechSpace[26]).

LaiQa was launched on 1 January 2024 and it is expected to run for 3YY. The TNO and the Institute of Communication and Computer Systems (ICCS) and a consortium of other European partners, joined forces in the project. The other involved partners are Quantum Technology Laboratories GmbH (Austria), Quantum Space Systems GmbH (Germany), the National Observatory of Athens, Eindhoven University of Technology, the National and Kapodistrian University of Athens, Thales Alenia Space Italia.

LaiQa comes as a technology intensive research and innovation action aiming to develop and enhance critical components and technologies necessary to build a global spaced-based quantum network. LaiQa envisions to realize unconditionally secure quantum communications over long distances integrating functional QKD components with advanced system integration techniques, into deployable space-QKD systems. The project's objectives include the development of space-deployable, high-brightness 1550 nm entangled photon pair source (EPPS), a space-suitable Decoy State - BB84 Prepare and Measure (P&M) source, a photonic integrated EPPS for next-generation on-board sender stations, a quantum memory for long-distance entanglement distribution, an advanced fibercoupling/ adaptive optics system for converged space/terrestrial QKD segments, and software components towards the optimization of LaiQa architecture. The project will demonstrate P&M- and entanglement based QKD systems both in lab/terrestrial FSO testbeds and in field demonstrations in Helmos optical ground station (OGS). LaiQa will also mobilize its consortium to prioritize standardization activities with focus on space components for P&M- and entanglement-QKD.

A preliminary strategic plan of LaiQa project has been already presented in the LaiQa proposal. This plan summarized in the following and the related timeline envisioned is shown in Figure 3-3.

Figure 3-3 Envisaged timeline of the LaiQa roadmap

LaiQa actors: the consortium consists of 8 partners, among which 3 academic organizations (ICCS, TU/e, NKUA), 1 applied scientific research organisation (TNO), 2 SMEs (QTLABS and QSSYS), 1 National

[25] https://www.tno.nl/en/newsroom/2023/09/laiqa-european-quantum-internet-space/
[26] one more project (CARIOQA PH) received €1.5M for the 2023-63 Quantum Space Gravimetry Phase-A Study

Observatory (NOA) and 1 Industrial Aerospace Organization (TAS-I) originating from 5 European countries (Austria, Germany, Greece, Italy, The Netherlands).

Strategic vision: To work in parallel with the global and EU context and be competitive in the QT market, LaiQa's technology development aims at the following goals:

- optimizing the performance of satellite QKD downlinks by focusing on the design and development of on-board sources with improved KPIs and adaptive coupling/optics (AO) systems to optimize coupling performance of space segment with the terrestrial, fiber-based infrastructures
- boosting the transition towards entanglement-based protocols by focusing on the design and development of on-board entangled photon sources and quantum memory.
- providing space-oriented quantum technology solutions, by seeking low-power consumption, low-footprint, enhanced stability, alignment-free operation
- delivering new OGS paradigms by introducing novel hybrid classical/QKD ground receiver systems for accessing urban metropolitan areas, and it will also promote hybrid QKD/Optical Key Distribution (OKD) solutions to significantly enhance the SKRs.

To align the development with the EU context, LaiQa foresees to foster synergies with national and international initiatives, including:

HellasQCI[27]: LaiQa will use the deployed dark fiber infrastructure segments in Helmos OGS to demonstrate converged wireless/fiber experiments using LaiQa's space-qualified sources and the array of SNSPDs available in OGS. LaiQa will also use the expertise from its partners involved in Aristarchos telescope activities to deploy an innovative Quantum Communication testbed in Helmos OGS for performing P&M- and ENT-based experiments.

QSNP[28]: in synergy with the Quantum Secure Networks Partnership (QSNP) project, LaiQa partners involved in multi-user entanglement-based quantum key distribution activities are contributing to the creation of a sustainable ecosystem for quantum cryptography in Europe based on convergent entanglement distribution networks across space and fiber.

QUARTZ[29]: in synergy with the QUARTZ project, LaiQa partners are contributing to development of novel free space to fiber coupling systems for optical ground terminals that support QKD.

Any additional contributions of LaiQa activities that emerge during the course of the project to the European ecosystem will be continuously monitored and included in the final version of the document.

[27] "HellasQCI – Quantum Communication Infrastructure for Greece ", https://grnet.gr/en/business-directory/hellasqci-en/
[28] "Horizon Quantum Flagship QSNP", https://qsnp.eu/
[29] "QUARTZ", https://connectivity.esa.int/news/10-new-business-and-research-partners-join-quartz

4 CONCLUSIONS

This document represents the first version of the Market Analysis and space QKD roadmap defined by LaiQa consortium in the first twelve months of the project.

A comprehensive analysis of the current state, opportunities, and development roadmap for quantum communication technologies have been provided, with a specific focus on the space-based Quantum Key Distribution (QKD) market. The surge in global and governmental investments highlights a recognition of the potential impact of these technologies.

The second quantum revolution, characterized by its capacity to drastically enhance communication security and infrastructure, presents unprecedented challenges and opportunities. Space-based quantum communications, notably through QKD, are emerging as pivotal in providing advanced encryption solutions essential for the future of global cybersecurity.

In Europe, initiatives and programs such as the Quantum Technologies Flagship, Horizon Europe, and the EuroQCI outline a clear path toward developing and deploying these quantum technologies. The EuroQCI, in particular, aims to establish a secure quantum communication infrastructure covering the entire EU, becoming a cornerstone of the EU's cybersecurity strategy for decades to come.

The LaiQa project stands out as a crucial endeavor aimed at advancing space-based QKD technologies. By developing and integrating critical components, LaiQa seeks to contribute to a global quantum network, advancing elements of both space and ground segments. Collaboration with national and international initiatives, such as HellasQCI, is vital to the project's success and the broader European ecosystem.

The roadmaps detailed in this document for the development of quantum technologies predict a steady maturation and industrialization of QKD technologies. As technological integration advances, we expect to see increasingly sophisticated quantum systems embedded into global communication infrastructures.

In summary, the future of quantum communications is promising, offering significant opportunities for innovation and enhanced global communication security. Continued research and development efforts, backed by substantial investments and robust international cooperation, position quantum technologies as crucial in constructing a secure and resilient global infrastructure. Europe, through various initiatives and projects such as LaiQa, is poised to play a leading role in this technological revolution.

This document will be updated during the project lifecycle, in order to reflect any possible changes and additions in market analysis, as well as any refinement in the QKD roadmap of the project outcomes. In particular, the final versions of the document will be released at the end of the project in M36.

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