Adding store and forward features to quantum key distribution space network for secure global and space communications with cubesats

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Abstract

At this moment, several space programs are under way to achieve the Technological Readiness Level (TRL) for the entanglement-based Quantum Key Distribution technique (QKD) in space, this technology is the corner stone in security for the next step towards a "Global Quantum Internet" in the near future. Space is the right scenario to deploy this technology because of the absorption problem with the Optical Networks on the Ground.

We will review some of the more important initiatives in this field which includes the Chinese QUESS (Quantum Experiments at Space Scale) mission, and the QEYSSAT Canadian Mission of COM DEV Ltd. Both of them based on conventional-sized satellites, and also the SPEQS program of the Centre for Quantum Technology in National University of Singapore, proposed with a cubesat constellation.

In this paper we will present a space program proposed between Quantum Aerospace Research Institute and the Ecuadorian Civilian Space Agency to develop and deploy an entanglement-based Quantum Key Distribution space based network to provide secure QKD communication at a Global Scale with Cubesat constellations, this technological infrastructure will also be the Core level for a QKD system for an Earth-Moon secure communications network.

Actually the QKD technology is restricted only to line of sight scenarios, the challenge of the program will be to develop miniaturized Quantum Memories to add store and forward capabilities to the cubesats network to transport the entangled photons to different space coordinates even without line of sight.

1 Introduction

For many years, the perspective of trying to create a global “Quantum Internet" [1], has been pursued for a new generations of scientific teams around the world [2]. This Global “Quantum Internet” will be based in a mature technology the for security: the Quantum Key Distribution (QKD) technique, than establishes highly secure keys between two distant points using single photons to transmit each qubit of the quantum key

Currently two approaches are been used to achieve this goal in parallel: fiber-based quantum repeaters and direct satellite links. The fiber approach needs “Quantum Repeaters”(QR) to extend the distance of elementary links by entanglement swapping [3, 4], While experimental demonstration of short-range quantum communications has been effective demonstrated [5, 6], long range repeater networks require the incorporation of fault-tolerant errorcorrection methods,and near zero temperature to function adequately, numerous designs of quantum repeaters have been proposed [7-13].

Terrestrial QKD networks using fibers optic cables or free-space atmospheric transmission are in operation today, however, truly global distances are still very difficult to achieve for repeatersbased on fiber links and quantum repeaters. This is true also for related approaches based on quantum error correction [14], whichtend to require repeater stations that are only a few kilometers apart.

Satellites in Earth orbit represent the only feasible way using currently technology to provide global distance QKD services, the advantage of quantum communication via satellites is that transmission loss is dominated by diffraction rather than absorption and thus scales much more favorably with distance. There has been a lot of progress in terms of feasibility studies and ongoing missions [15-23],even with new generation fiber-based networks and quantum repeaters than can establish long range quantum entanglement, most optimistic quantum repeater protocols may still only facilitate distance up to about1000 km [24] on terrestrial links while very recent results show that a quantum receiver based on satellite links are able to reach 10,000 km [25]

Finally a disrupted technology has appear in the horizon and is nothing less than sneaker-net network approach. This approach to quantum information, introducing a new network mechanism for the establishment of quantum entanglement over long distances based on the transport of error-corrected quantum memories [26].

Quantum memories may be transported to locations where entanglement is required or to intermediate locations to facilitate entanglement swapping between traditional quantum repeater networks, enabling a complete network structure without the full deployment of physicallinks. It is specially use fuel for transoceanic communication that presents a particular challenge for quantum networking, with this proposal the entanglement will be establishment by ship.

In section two of this paper we will take a closer look to this approaches and their implications in our proposal.

2 QKD Space Scenarios and ongoing Missions

A global, space-based network for distributing entangled photons will enable strongencryption keys to be delivered securely between any two points on Earth. Entanglement-based QKD is a mature technology. It has been demonstrated on multiple occasions and is the most established technological application of entanglement.

At the time of writing this paper, two mission have been launch with QKD mission objectives, one is the Chinese QUantum Experiments at Space Scale (QUESS) mission [27], and the other was the Small Photon Entangling Quantum Systems (SPEQS) mission integrated in the Galassia Nanosatellite[28].

We think that the second of the two missions mentioned give us a clue of the path to be followed for a Latin-American Science Space Program using a revolution in the space industry where the use of very small spacecraft known as Nano-satellites are enabling access to space for a large number of organizations with only modest funding, challenging more traditional platforms for space applications.

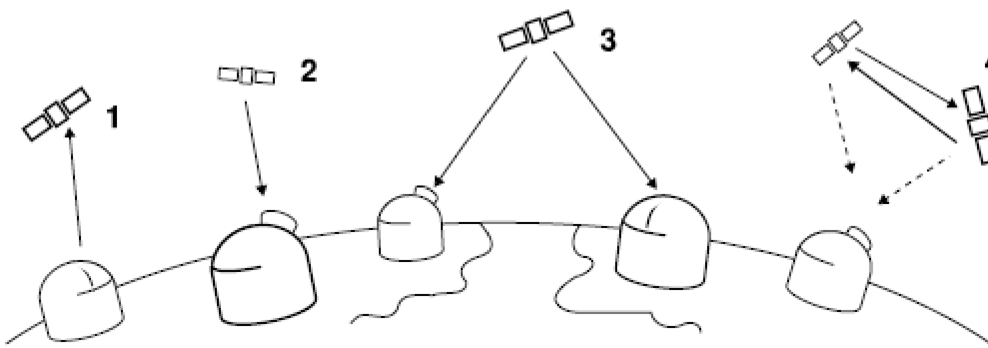

Fig. 1. Scenarios for QKD in space.

The scenarios used until now for QKD space missions are showed in Fig. 1 (Courtesy of EPJ Quantum Technology) [29].The possible satellite-based QKD implementations are: 1. Ground-to-space,where the photon source is on the ground and the satellite only carries detectors. 2. Space-to-ground, wherethe satellite carries a source and detectors. 3. A platform that can beam down to two ground stationssimultaneously. 4. Inter-satellite QKD which could be the building block for a long baseline test of quantumcorrelations. To enable configurations 2-4 with Bell violation-type measurements, a source of entangledphotons in space must be demonstrated.

Both the QUESSmission [27]and the SPEQS mission [29] uses the scenario number three for the QKD distribution, i.e. a space-based photon source platform that can beam photons down to two ground stations simultaneously on earth to create a QKD channel between the two points, and then perform a bell state measurement between then.Following this approach QUESS mission has achieved the creation of an "intercontinental" QKD channel of 1200 Km between Beijing and Vienna. [30]

A further theoretical work in this direction performed by a Canadian and Australian team [31], shows that with the adding of quantum repeaters (QR) to this architecture, truly global distances can be achieved. In this approach the satellites just need to be equipped with entangled pair sources, while the more complex components, such as quantummemories (QM) and quantum non-demolition (QND) detectors, are on the ground.

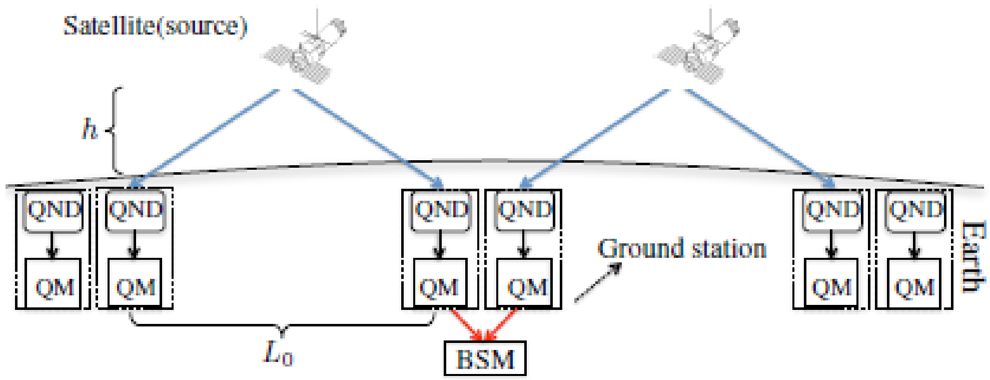

Fig. 2. Canadian-Australian Global QKD Satellite Network Architecture proposal.

Figure 2 shows the proposed architecture of the Canadian and Australian teams with quantum repeaters on the ground and satellite quantum links. “. Each elementary link (of length Lo) consists of an entangled photon pair source on a low-earthorbit satellite (at height h), and two ground stations consisting of quantum non-demolition (QND) measurement devices and quantum memories (QM). The successful transmissionof entangled photons to each ground station is heralded by the QND devices, which detect the presence of a photon nondestructively and without revealing its quantum state. The entanglement is then stored in the memories until information about successful entanglement creation in two neighboring links is received. Then the entanglement can be extended by entanglement swapping based on a Bell state measurement(BSM)” [31]

An important variable to have in account in this architecture is that the satellite-based links are active only during each time period when the satellite is visible from both ground stations (the flyby time" TFB).For currently realistic quantum memory lifetimes all satellite links in Figure 2 have to be active simultaneously, which implies that the architecture requires a number of satellites equal to the number of links. However, the results show that four to eight links are sufficient to span global distances.

The last mission concept we will analyze in this document is the NanoQEY (Nano Quantum Encryption) a nanosatellite mission concept developed by the Institute of Quantum Computing at the University of Waterloo and the Space Flight Laboratory at Institute of Aerospace Studies in the University of Toronto that would demonstrate long distance QKD between two distant ground stations on earth.

The primary object of the NanoQEY is to successfully distribute at least 10Kbits of secure key between two optical ground stations separated by at least 400 Km during the life time of the mission, the secondary objective of the NanoQEY mission is to perform a bell test for entangled photons separated by at least 400 Km, where one photon shall be measured on ground and the other on the satellite.

In order to securely distribute encryption keys, the NanoQEY satellite act as a “trusted node” in wich the keys would be held during operations. The satellite would create a secure key between itself and Ground Station A during one or more passes, and then create another secure key between itself and ground station B during one or more passes. To create a secure key between Station A and Station B, a Boolean combination of the two keys is calculated on the satellite. The result is transmitted (classically) to one of the two ground stations. Using the combined key and the knowledge of its own key, a station can then calculate the other station key and use it for secure communications between themselves. [32]

After this review we can conclude that, Satellites in Earth orbit represent the only way using currently feasible technology to provide global-distance QKD services. In the simplest configurations, satellites could be used as complementary trusted nodes to bridge the distance between geographically dispersed QKD ground networks. In the future quantum repeaters may be developed which could establish long range quantum entanglement, however there will still be a role for satellites as the currently most optimistic quantum repeater protocols may still only facilitate distance up to about 1000 km [24] on terrestrial links while very recent results show that a quantum receiver based on satellite links and quantum memories on ground are able to reach 10,000 km and beyond. [25]. It is clear that to operate on continental and global scales, it is anticipated that future quantum networks would be similar to conventional data networks and employ both fiber-based solutions (quantum-repeater-equipped) and links with optical quantum communication satellites.

3 The QAS-EXA "QSNet Space Program"

Review of the state of the art low Earth orbit satellite quantum communication gives us the big picture necessary to develop the proposal of our QSNet Space Program. This proposal will be aligned with the major policy of our institutions:

- Democratization of space technologies.
- Develop of high efficient technology at a very low price to make it reachable for developing countries.

We will clearly choose the nanosatellite technology to implement our mission, reduce budged and fulfill our philosophy, in this line we find two major feasibility obstacles even with the best mission proposal (Quantum Repeaters + Satellite Links [25]): first the only mission that have successfully deploy a practical source of entangled photons in space until now is the Chinese QUESS, and it is clearly not a nanosatellite mission, the second mission that proposes an entangled photon source on space, the SPEQS mission, is a nanosatellite mission, not withstanding is still in the process of achieve the necessary technological readiness level (TRL). Second: even with a cheap and affordable nanosatellite quantum source, we still have a budged obstacle due to the operational costs, because in the most optimistic scenario we will need at least 8 ground stations and operations center on the Earth to operate a global QKD Network. This make this project only feasible for major telecom and satellite operator worldwide, leaving behind the emerging actors and developing countries forthis field.

Even more, the use of telescopes as ground stations of approximate 1,5-2m diameter [32]and a system of optical fine pointing in the satellite, lead us to nanosatellites with dimensions like 40x26x20 cm3, at least [31], and this is not the scope of our work.

We propose a major technological shift to approach the problem; this is the change of the frequency for the Quantum Chanel from optical domain to Radio Frequency Domain, specifically Microwaves in the X Band. This major technological approach permit us to solve not only the miniaturization of our spacecraft but also the miniaturization of the ground station, with the lower price that all that implies.

Additional to all of this, our system will add store and forward facilities to the satellites using Quantum Non Demolition Detectors (QND) and Radio Frequency Quantum Memories (RFQM)[33], and a *sneakernet approach* [25] for quantum networks.This will create Mobile Nodes in the space to transport entangled RF Photons from one place on Earth to a totally different location even in non-line of sight scenarios as we will see.

3.1.- Proof of Concept Mission

The QSAT (Quantum Satellite) is a Proof of Concept nanosatellite mission developed by Quantum Aerospace Research Institute (QAS) and the Ecuadorian Civilian Space Agency (EXA), which would demonstrate quantum entanglement between intercontinental distances by using a Mobile Quantum Repeater in Space. The quantum channel will be established with micro wave technology. The QSAT mission will also count with a QKD protocol that includes timing analysis, basis reconciliation, error corrections and privacy amplification, this QKD protocol will use classical channels for transmission, and would enable QKD transmission between the two ground stations on the ground.

3.1.1.-Mission Objectives

The scientific mission objectives of the proposed mission are the followings:

- Transmit an entangled RF photon from Ground Station 1 to QSAT Satellite.
- Transmit an entangled RF photon from QSAT Satellite to Ground Station 2.
- Perform a Bell State Measurement between RF photons in Ground station 1 and Ground Station 2.
- Distribute QKD Keys between Ground Station 1 and Ground Station 2.
- Perform scientific experiments of quantum teleportation between Ground Station 1 and Ground Station 2.

3.1.2.- Mission Architecture

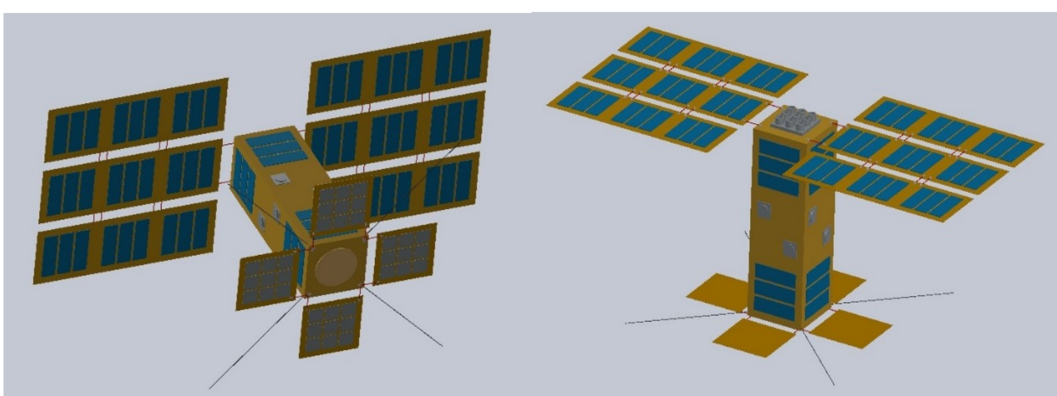

Fig. 3.1.2.1 Conceptual Design QSAT Proof of Concept Mission

The conceptual design of the space craft was achieved using the PEGASUS Class technology of the Ecuadorian Civilian Space Agency (EXA), that include on board computer and radios, GPS receiver system, IMU system, high capacity batteries, etc. with this technology the QSAT would be developed in a standard 3 cube sat U package of

10x10x30 cm3. The compound deployable solar array (DSA/3A) with six 3U solar panels will generate a peak power generation of 100.8 Watts, and the high capacity battery banks have a total nominal capacity of 427.2 Watts, having ample power to perform in eclipse.

The spacecraft will have a four patch, X-Band antenna array in which would be allocated the 3 links necessary for the correct operation of the mission including the quantum link, the antenna array will be operated using artificial muscle technology from the EXA, specifically the MDH/R2 model so that it can be pointed inward in order to concentrate the transmission beam photon flux over a very small footprint and therefore boosting the gain in many orders of magnitude for the ground station 1 and 2. Fig.3 shows the conceptual design of the QSAT.

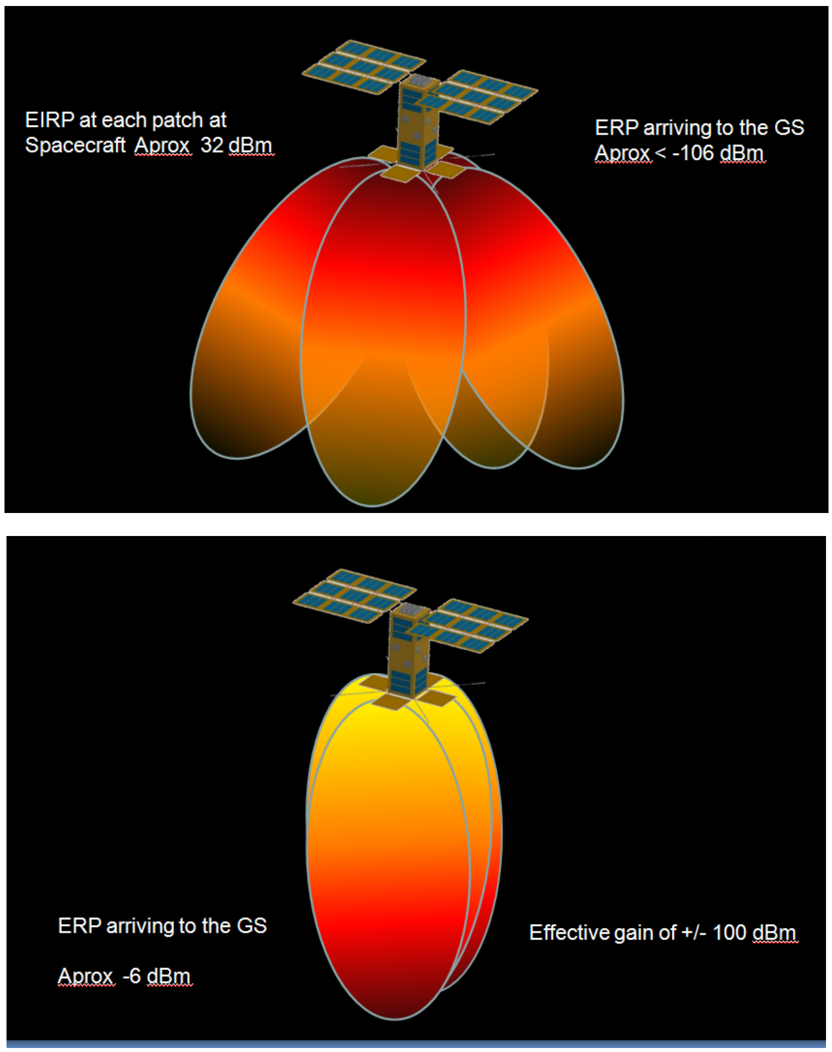

Fig. 3.1.2.1 QSAT Dynamic Comunications array based on artificial muscle technology boosting the gain of the array by concentrating the photon flux of the phasing beams

The QSAT would be launched into a 400 Km – 600 Km orbit and a 98 degree inclination mean LTAN (Local Time of ascending node) of noon +/- 11h00 to 12h00 The mission would employ the HERMES-A ground station in Guayaquil working as Ground Station 1 and a Ground Station in Holland working as Ground Station 2.

3.1.3. Concept of operations

The minimum mission duration would be one year from launch. The life time of the EXA PEGASUS Class technology in which the QSAT would be based in fact has proven at least 3 years of life time in space, but we think that one year will be enough time to achieve the scientific objectives of the mission.

To fulfill the mission objectives the system will have three links between Ground Station and Satellite, the TT&C link would operate in UHF band, the Data Link and Housekeeping, including QKD protocol will operate in S Band, andfinally the Quantum Channel will be implemented in X Band. Additionally the QSAT and the Ground Stations 1 and 2 would need GPS receiver technology to achieve the pointing degree needed for scientific application.

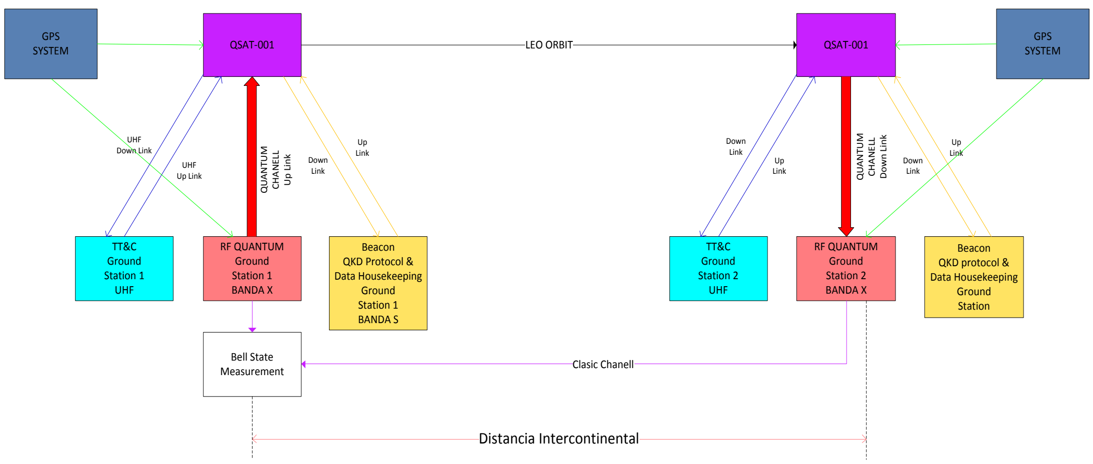

Fig. 4.QSNet proof of concept mission system overview

During nominal operations QSAT would be oriented for optimal power generation and thermal control. As the satellite approaches a ground station it will point it using the beacon if it is Ground Station number 1, the QKD protocol will set the RF Quantum Source on the ground station to emit a pair of entangled RF microwaves, the QKD protocol also will set the RF QND to start detection and the RFQM of the QSAT to store the RF Quantum photon emitted from the ground station. When QSAT arrives to Ground Station number 2, the QKD protocol will set the RFQM to emit the RF photon, and the will set the QND and the RFQM of ground station 2 to receive the RF photon. Fig. 4. Shows this operation concept.

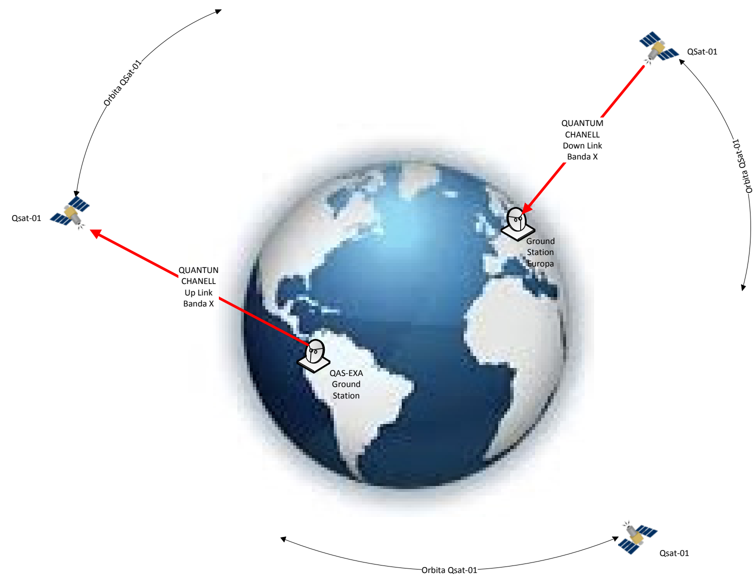

Fig.5. Intercontinental distance entanglement

This concept of operations will permit QSAT for the first time to transmit an entangled RF Quantum photon from Ground Station 1 (Ecuador - Latin America) to Ground Station 2 (Delft – Holland) over an intercontinental distance (approximate 10000 Km). Fig. 5. Shows this feature.

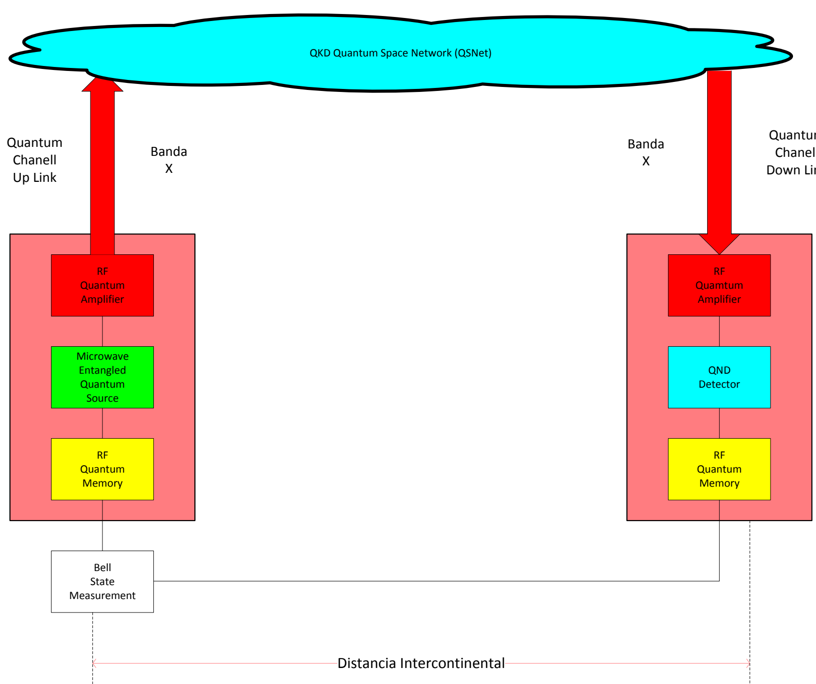

Fig. 6. Intercontinantal Distance BSM

The major concern in this topology will be perform the Bell State Measurement (BSM) between the RF photons in the two ground stations over a continental distance, this is something that still haven't been tested by any scientific team. Fig. 6 shows this schema graphically.

Quantum Payload Design

For the proposed QSAT Mission, QAS has designed a new technology quantum payload based on the RF quantum Technology [34] that would be compatible with the mass volume, power and performance constrains of a low-cost nanosatellite platform.

The technological basis of payload is adding RFQM and QND [33] to the nanosatellite, turning it in to a mobile quantum repeater, than can be used in a *sneakernet* approach [25]. The key research during the maturation of technology process will be focus on the development of a forward error correction technique to achieve a RF quantum memory storage period needed for the mission, also we would need a QND and RFQM on demand process based on the state of the art Micro wave Quantum Technology [34]

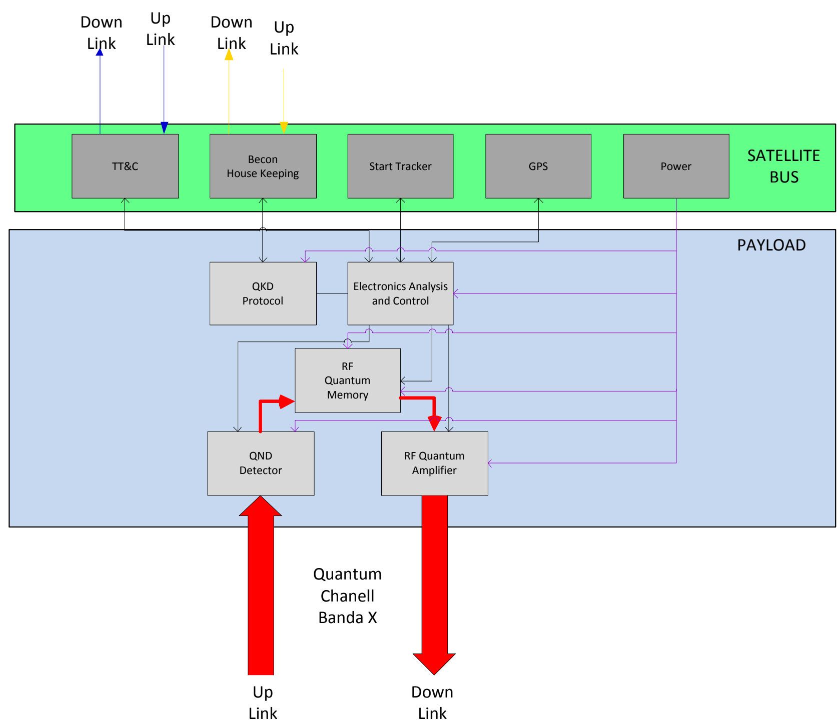

Fig. 7. Quantum Payload Block Diagram

Fig. 7 provides a simplified Block Diagram of the Quantum payload of QSAT, in this diagram the Forward error correction circuit is inside the electronics analysis and control block.

A further Global QKD distribution space network will be designed in base of the result of the Proof of Concept mission, this will also include the possibility to distribute QKD on to the space.

4. Programmatic

The proposed Space Program will be supported for all the Nano Satellite Space Technology developed by the Ecuadorian Space Agency (EXA) and the INSPIRE consortium, it would permit a rapid deployment of the Space Program. Notwithstanding the Payload and the Optical Ground Station will need additional maturation technology process.

The milestones for the Technology Readiness Level (TRL) of the proposed Space Program is shown in Table 1

YEAR	QSNet SPACE PROGRAM MILISTONE	LOCATION
2017	Payload Technology Maturation	QAS Laboratories
2017	Ground Station Technology Maturation	QAS Laboratories
2018	Drone Test / High Altitude Test	Aerospace / High Altitude
2019-2022	Proof of Concept Mission	Low Earth Orbit
2023-2027	QSNet Technological Deploy	Low Earth Orbit

Table 1.QSNet Space Program Milestone

The low cost, high efficient and mature Nano satellite space technology of EXA would allow to develop the proposed QSAT Proof of Concept Mission in 2.75 years from project kick-off to launch of space craft, followed by 1 year on-orbit mission. Table2 shows a summarized project schedule for QSNet proof of concept mission.

	YEAR 1				YEAR 2				YEAR 3				YEAR 4			
TASK	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
Mission Funding																
Preliminary Design																
Detailed Design and Miniaturization																
Manufacture, Assembly, Test																
Launch																
On Orbit Operations																

Table 2. Quantum Space Network QSAT proof of concept mission schedule

5. Conclusions

The feasibility study performed by QAS and EXA show that a nanosatellite mission to demonstrate quantum entanglement over intercontinental distances is feasible and practical with a maturation process of current technology. QSAT will employ proven space technology from EXA to implement the space craft and a innovative compact QKD Payload designed by QAS that would be compatible with the mass, volume, power and performance constrains of low cost nanosatellite platform.

If it is constructed under the high efficiency approach of EXA, after one year of technology maturation, the proposed QSAT mission would be developed in 2.75 years, from kick-off to launch of the spacecraft, followed by one year on orbit mission.

If the mission achieve all the scientific mission objectives, first it would be a new world record for quantum entanglement, second it would demonstrate de feasibility of a Global QKD Space Network based on this technology, adding to this that with the RF used in the project we will open the possibility that any parson could afford a low-price ground station to securely communicate point to point with any other place in the world, with all that this means.

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