

On-board QKD operations description of the Flight Segment of the In-orbit demonstrator for the Q-ANSER mission developed by INTA

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ABSTRACT

Q-ANSER is a Spanish technological in-orbit demonstration mission whose main objective is to advance the space-to-space Quantum Key Distribution (QKD) communication segment, using two CubeSats (Alice and Bob) to establish a Low Earth Orbit (LEO) QKD link and generate a cryptographic key.

In this mission, the first technological challenge starts by achieving the proper inter-satellite 50km distance, thanks to the propellantless formation flying control of the ANSER nanosatellites based on CubeSat standards developed by INTA. The key generation in the space environment will be implemented using an asymmetric BB84 protocol using two detectors and time multiplexing.

The eclipse phase covers the principal part of the QKD link which implies first a complex, time-limited and extremely accurate micro-radian pointing between both platforms and then, the single-photon transmission itself. Afterwards, post-processing operations and verification methods generate the final QKD key. In addition, other detailed on-board actions involving both platform and payload modules of each satellite are executed following systematic procedures.

This paper focuses on the QKD operation as well as the complementary activities needed to achieve the mission goals. Through the definition of four main operational modes and their operational states, the functional configuration of the mission will help to establish the operations, protocols, and flow diagrams for an appropriate performance of the satellites.

By successfully demonstrating an autonomous quantum inter-satellite link (ISL), Q-ANSER will prove that high-security key distribution is feasible using cost-effective nanosatellite clusters, overcoming technological challenges in satellite-to-satellite relays and providing flight heritage for future global-scale quantum constellations.

Keywords: Quantum Key Distribution (QKD); CubeSats; Inter-Satellite Link (ISL); Pointing, Alignment and Tracking (PAT); Formation flying; Space-to-space communications; BB84 protocol; Mission operations

1. Q-ANSER MISSION OVERVIEW

In terrestrial fibre-based systems, Quantum Key Distribution (QKD) communication distance is limited to a few hundred kilometres. As a result, signal intensity decays exponentially along an optical fibre. Satellite-based QKD overcomes this by leveraging free-space optical links, enabling long-range connections and global-scale distribution. The primary advantage is that signal loss in space is mainly due to beam divergence, meaning transmission efficiency decreases quadratically with distance rather than exponentially. Therefore, satellites are essential to achieving a global QKD network.

Q-ANSER mission's ultimate goal is to advance the space-to-space QKD link segment [1]. It utilizes two 16U CubeSat platforms flying in formation—based on the ANSER propellantless nanosatellites based on CubeSat standards previously developed by INTA—to establish a Low Earth Orbit (LEO) QKD link and generate a cryptographic key. To meet this challenge, it is essential to enhance the Technology Readiness Level (TRL) of all components so the mission must address a set of technological objectives, some of them appearing on Figure 1, such as:

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- Developing on-board QKD processing algorithms, protocols, and security analysis.
- Establishing and maintaining high pointing accuracy between both platforms and their respective Pointing, Acquisition, and Tracking (PAT) systems.
- Transmitting a synchronization signal through a beacon signal is paramount to coordinate a single-photon beam between both satellites.
- Development of a space-qualified photon source.

Furthermore, as extended objective, the project aims to study the performance of the quantum optical link by varying the distances between satellites. This study will help to understand how the distance between satellites affects the performance of the QKD link.

The Q-ANSER mission utilizes an asymmetric polarization-encoded time-multiplexed BB84 QKD protocol with two decoy states and two detectors, involving two parties: Alice and Bob. This protocol improves QKD security and range by sending light pulses of varying intensities (signal and decoy pulses). This technique identifies interception attempts by checking if the Quantum Bit Error Rate (QBER) in decoy pulses matches expectations, allowing the system to distinguish between natural channel loss and eavesdropping [2].

In this mission, Alice and Bob are each located on a separate satellite with an initial inter-satellite distance of approximately 50 km. This distance is driven by optical and pointing constraints, considering a 16U CubeSat structure. This limit accommodates the full QKD payload, including optical terminals, and PAT systems, which inherently restricts the maximum optical aperture size and pointing precision. Thus, the 50 km demonstration (plus a contingency margin) is the optimal compromise to validate QKD technology, optical terminals, and pointing algorithms within the CubeSat class, while providing a scalable path for future missions.

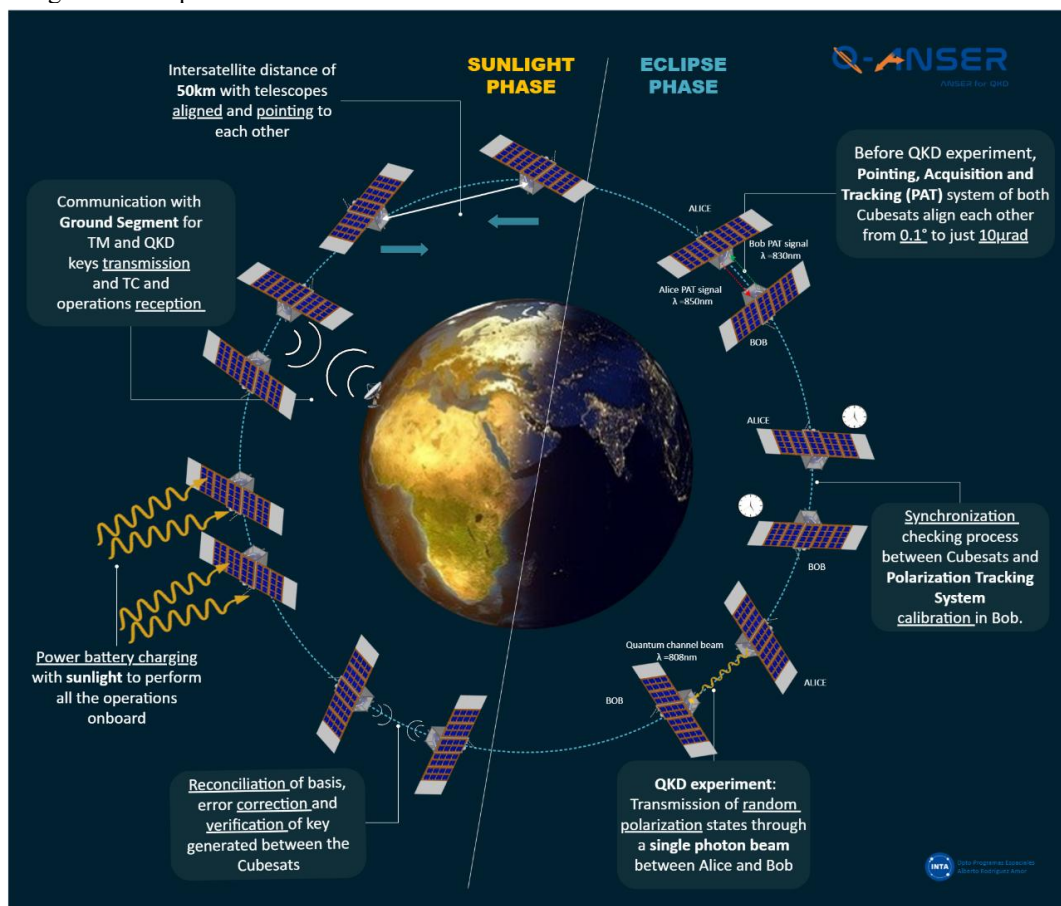


Figure 1: Q-ANSER mission operations and activities.

2. FUNCTIONAL ARCHITECTURE OF Q-ANSER FLIGHT SEGMENT

To provide a thorough overview of the flight segment, the functional architecture will be briefly described in this chapter prior the performance and operations that will be carried out by both CubeSats in space. The Q-ANSER flight segment is essentially composed of two CubeSats, Alice and Bob. INTA through the development of different ANSER missions has consolidated a sophisticated nanosatellite platform with subsystems devoted to achieve the ANSER flying formation philosophy [3]. This knowledge is centred on a cluster of CubeSats orbiting in a specific formation thanks to propellantless propulsion subsystems based on differential drag and lift aerodynamic effects still present in the faint LEO atmosphere. Thus, Q-ANSER CubeSats architecture will share those previous platform subsystems already consolidated plus the specific payload to achieve QKD communication in space.

2.1 Satellite Platforms & Common Subsystems

Both satellites utilize a standardized platform based on the INTA ANSER programme, including several subsystems that share common characteristics for both CubeSats:

- Structure and Mechanisms System (S&MS): comprising the 16U CubeSat framework as well as the deployable parts such as flaps and solar panels.
- Attitude Determination and Control System (ADCS): Sensors, actuators, controllers and estimators for satellite attitude determination and accurate pointing.
- Electrical Power System (EPS), Thermal Control System (TCS), and Global Navigation Satellite System (GNSS).
- Communication system (COMM) and On-Board Data Handling (OBDH): involving the classical communications with Ground Segment (GS), ISL (Inter-Satellite Link) communication between the two satellites, and the management and processing of data on board the satellites.

2.2 Payload Modules: O-Unit and E-Unit

The payload module provides the mission's differentiating feature and defines the role of each satellite during the QKD operations. It is composed essentially by an Optical unit (O-Unit) and an Electronic unit (E-Unit).

The design of the O-Unit consists of three main components: the expander—comprising a telescope and a collimator system—the channel splitter and the mechanical interface structure, connecting the expander and the quantum and beacon channels. Although Alice and Bob have different roles, in terms of the channel splitter, both CubeSats share a set of identical optical elements such as Fast Steering Mirrors (FSM), several Dichroic Beam Splitters (DBS), Beam Splitters (BS), Folding Mirrors (FM), detectors, optical harness, beacon sources and assemblies of Focusing and Collimating Optics when receiving or transmitting respectively the different light beams. And moreover, depending on the specific role of each CubeSat there will be more elements, like in Bob, highlighting the Polarization Tracking System (PTS), for the correction of the polarization states (i.e.: rotation and ellipticity) [4].

The Electronic-Unit is responsible for controlling the payload and performance of the different operational modes of the payload, to determine and distribute the power provided by the platform to the subsystems, to collect the data generated from payload, store it and transmit it to platform's On Board Computer (OBC) as telemetry, and to receive and execute the commands from platform's OBC for the operation of the payload. In both CubeSats the following elements can be found:

- Instrument Control Unit divided into two parts:
 - ICU-L: Managing satellite pointing. It aligns both CubeSats using the PAT system.
 - ICU-H: Managing QKD operation.
- QKD Processor.
- PAT Control: encompassing the control system of several elements such as FSM, Beacon transmitter, Beacon receiver and PAT thermal control in each CubeSat.
- Power distribution.

In Alice, furthermore, there will be the QKD Source comprising the Prepare and Measure (P&M) module, the control of the Quantum Random Number Generator (QRNG), the Quantum laser emitter and QKD source thermal control.

On the other hand, since Bob acts as the receiver, it will have instead, the Polarization control and PTS thermal control and the QKD Receiver control involving the performance of the QKD Rx detector and the associated Read-out electronics.

According to the common disposition of elements by the two CubeSats shown in Figure 2, platform S/S are located opposite to the payload module since the telescope aperture is located in the top face of each CubeSat. Solar panels transfer the energy captured from the solar radiation to power available by the EPS S/S where is located the battery packet and the Power Control and Distribution Unit (PCDU). It distributes the power generated to all platform S/Ss and the payload module to the Power Distribution Unit (PDU).

Regarding the payload module, it occupies most of the internal volume of each satellite (12U approx.). The power coming from the PDU is distributed to the E-Unit part of the payload. There, the ICU of the satellites governs the PAT and QKD functionalities. The ICU-L is connected to the PAT control module and the ICU-H to the QKD processor. At this point, Alice connects the processor with the P&M part responsible of generating the QKD transmission and Bob connects the QKD processor with the QKD receiver included in the Fibre-Optic Bob (FOBOB) module already included in the O-Unit.

The O-Unit part of the payload is composed by the previous elements mentioned in this document. QKD and beacon signals share the entrance/exit pupil of the system, i.e. the beam expander, the collimator system and the FSM. Although the QKD and PAT functionalities share the same optical elements through the channel splitter, for the sake of conciseness, these two principal functionalities of the CubeSat are depicted in the block diagram independently by distinguishing the QKD and PAT channels.

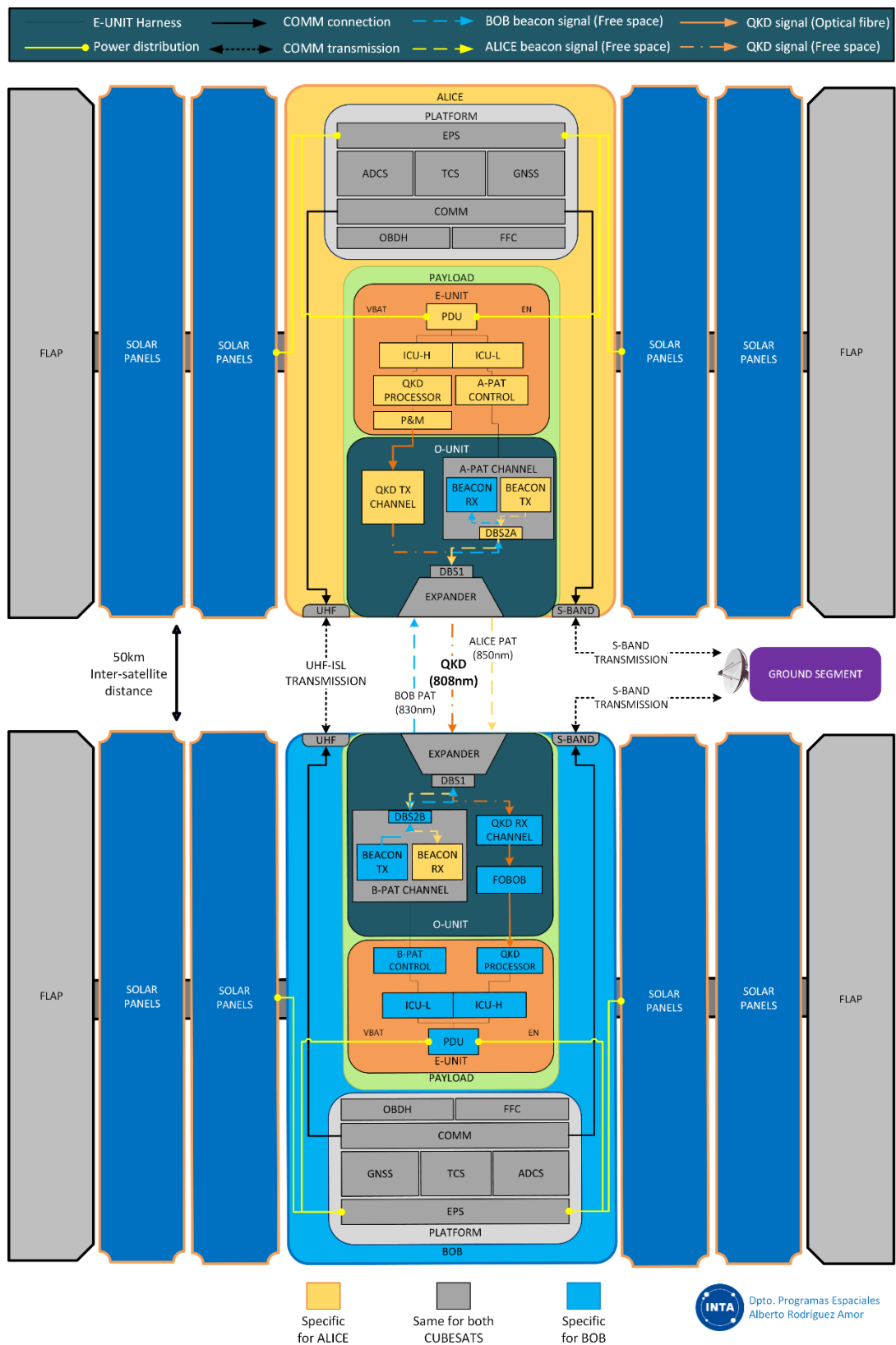


Figure 2. Block diagram of the functional architecture of the Flight Segment (Alice & Bob) of Q-ANSER mission.

3. Q-ANSER FLIGHT SEGMENT OPERATION

Previous Q-ANSER mission perspective needs a detailed set of operations in order to achieve the objectives defined throughout the whole operating life of the CubeSats. First, it is crucial to establish the operational modes of the satellites, as well as the states of operation encompassed by those modes and finally the activities and on-board operations carried out by each CubeSat in each state. Moreover, the relation and transition between each mode and state is essential to define later interfaces, protocols, and flow diagrams for an appropriate performance of the satellites.

Prior detailing the operational mechanism of the satellites, it is important to define important concepts to better understand the performance of the satellites in space:

- **Operational Mode:** a set of unique characteristics or circumstances that determine the behaviour and status of the satellite. Operational modes are mutually exclusive.
- **Operational State:** a situation in which the satellite can remain executing a set of operational activities specifically for that operational state. At any time, a satellite is always in an operational mode and/or an operational state. This allows the satellite's behaviour to be defined deterministically. A satellite can remain in a specific operational mode without being in any operational state, or it can remain in an operational mode and transition between multiple operational states. Operational states are also mutually exclusive.
- **Basic operational activities:** an action executed by a satellite regardless of its current operational mode or state.
- **Specific operational activities:** an action executed by a satellite when it is in a certain operational mode or state.

3.1 Operational Modes

Q-ANSER mission operational modes are:

a) Booting Mode

It is associated with any power-up/reset of the satellite (controlled or uncontrolled) and has no operational states. In this mode, basic operational activities are not allowed and only are executed a set of defined activities such as:

- Switching on the OBC just after launcher separation.
- Initialize HW/SW modules.
- Self-tests execution.
- Identification of start-up (first power up, non-controlled switch-off, post SW updating power up, etc).
- Verify the On-board Time (OBT) maintenance
- Selection of the right operational mode and state and their transitions according to a specific algorithm.
- Boot report telemetry.

In this mode, distinct information is collected with the goal of transitioning, after applying a decision algorithm, to the appropriate operational mode and state. Thus, after an OBC reboot to execute a new version of the On-Board Software (OBSW), the booting mode is entered, and then, it transitions to the corresponding mode and state.

b) Initialization Mode

This mode enters automatically after Booting Mode (if all previous executed activities have been performed correctly). If a contingency occurs, Safe Mode will automatically enter and all states and activities programmed within the Initialization Mode will be executed in the Safe Mode.

The goal of the Initialization Mode is to execute all Launch and Early Orbit Phase (LEOP) activities and communicate with GS, by successfully uploading a GS contact schedule.

During the Initialization Mode, whenever the contact with GS is established, if the OBT is valid, Ground station contact schedule is available on board and the on-board health status is correct, the transition to Nominal Mode can be performed. This process can last several contacts with GS until the conditions previous mentioned are fulfilled, since maybe there is no available Two-Line Element Set (TLE) to generate a GS contact schedule. At this point, the satellite could transition

between two operational states (Ground Communication Attempt and Ground Communication) that will be explained afterwards. Then, the transition between states will be performed automatically, with the execution of the dedicated activity in those states.

c) Nominal Mode

This mode is entered automatically only if Initialization Mode has been performed correctly or by telecommand (TC) if Safe Mode has been exited. In addition, Nominal Mode is entered after SW update if Booting Mode is required. In the same way, different operational events with different severity levels associated with them trigger the automatic transition from Nominal Mode to Safe Mode.

This mode encompasses a series of requirements fulfilment to guarantee that the satellite is in a nominal situation:

- OBT maintenance.
- GS contact schedule loaded on-board.
- Nominal satellite health status.

d) Safe Mode

If the FDIR detects a high-severity system failure such as non-controlled switch-off, satellite failure that implies SW/satellite reset, Electrical Power System (EPS) failure, communication reset, Watchdog timer reset (WDT)...., a transition to Safe Mode will be executed. In addition, this transition may also be commanded via TC. The satellite may transition to this mode from any other operational mode. No other mode is allowed to be performed in order to safeguard the status of the satellite. However, exit from this mode and return to Nominal Mode can only be commanded from the GS via TC once the correct performance is ensured and the corresponding failure has been resolved. Hence, all the time required for guarantee the resolution of the failure and the conditions to have a nominal operation will be provided.

When Safe Mode is entered, usually payload performance is very limited or even directly switched-off until the problem on-board is analysed and solved and the permission to transition to Nominal Mode is conceded.

e) On Ground Testing

To be entered only on ground testing before launch to check all possible activities to be done in space by both CubeSats. This is a type of On-board SW (OBSW) start-up that infers functional activities and testing rather than an operational mode. This test enters if and only if it is connected to a dedicated Ground Support Equipment (GSE) for that aim.

3.2 Operational States

Q-ANSER operational states are:

a) Start-up state

This operational state enters automatically from the Booting Mode after the first power-up of the satellite (in either Initialization or Safe Mode). The aim of this state is achieving a stable scenario after the launch phase. Some of the specific activities associated to this state are:

- CubeSat specification post-launcher fulfilment in terms of Radiofrequency.
- Release of deployable components to establish communication with GS after CubeSat specification time fulfilment.
- Start-up of ADCS to acquire data and to command Detumbling manoeuvre from ground afterwards.

The satellite shall automatically transition from this operational state to Ground Communication Attempt state once the waiting period prior to any RF transmission has elapsed.

b) Ground Communication Attempt state

The main objective behind this operational state is to execute communication attempts with GS. This state enters automatically when there is no GS contact schedule uploaded to communicate with GS or that the maximum time between GS contacts has expired. Moreover, the transition to this operational state can be done from the corresponding operational state of, either the initialization or safe mode, due to several cases:

- Limit time reached before transmitting any radio beacon.
- No successful communication established with GS after communication attempt.
- No GS contact schedule uploaded after communication established with GS.
- End of GS contact schedule on-board the satellite.

The corresponding activities of this operational state are:

- Communication attempt development activities.
- Monitoring of time without transmissions with GS to execute recovery actions if needed after a set time is reached.
- Checking and release of deployable components to establish communication if not occurred yet.
- Management of radio beacon transmission sequence.

The transition to Ground Communication state will be done automatically once the communication attempt between satellite and GS has been performed successfully.

c) Ground Communication state

Operational state associated to link established with GS (scheduled or as needed) in which TM is sent to ground and TC are received. This state is reached once the Telemetry and Telecommand (TTC) subsystem is switched-on to communicate to GS either because the GS contact is schedule or there is no contact available and it is needed to transmit radio-beacons to connect with ground.

The nominal activities developed during this operational state are:

- Monitoring of the communication (control of the time of communication process...).
- TM transmission to ground.
- TCs, GS contact schedule and list of operations reception.
- Post-communication process activities (TTC S/S switch-off...).

The exit of this state can be to two different states, depending on the operational mode it is in and what happened during the GS contact.

d) Maintenance state

This operational state aims to preserve the nominal situation of the satellite, understood as the fulfilment of the requirements mentioned in previous Nominal Mode section. A list of operations to be done on-board can be loaded but it is not essential in order to stay in this state.

This state is reached only if Ground communication has been successful, and all activities defined to be performed by the satellite can be done nominally. On the other hand, if contingency happens, Safe Mode is activated and the aim is to perform the corresponding actions sent by GS to solve the contingency created and finally checking all platform S/S and payload electronics are adequate to be used nominally.

Other nominal activities done in this state are:

- GS contact schedule acceptance (including initialization of communication process).
- List of operations execution.
- Payload on-board operations after Ground communication state:

- Power Charging operation: both satellites orientating the solar panels towards the sunlight to charge the batteries for performing all the payload and platform operations.
 - Intersatellite Distance operation: both satellites shall navigate in formation with both telescopes aligned and pointing to each other at the target inter-satellite distance (50km) and 1deg pointing accuracy is constantly checked. This will be achieved by means of ADCS and Formation Flying Computer (FFC) on-board.
 - QKD operation (QKD activities) explained afterwards.
- In Safe Mode, list of operations execution after Ground communication state to solve contingency and TC to exit Safe Mode.

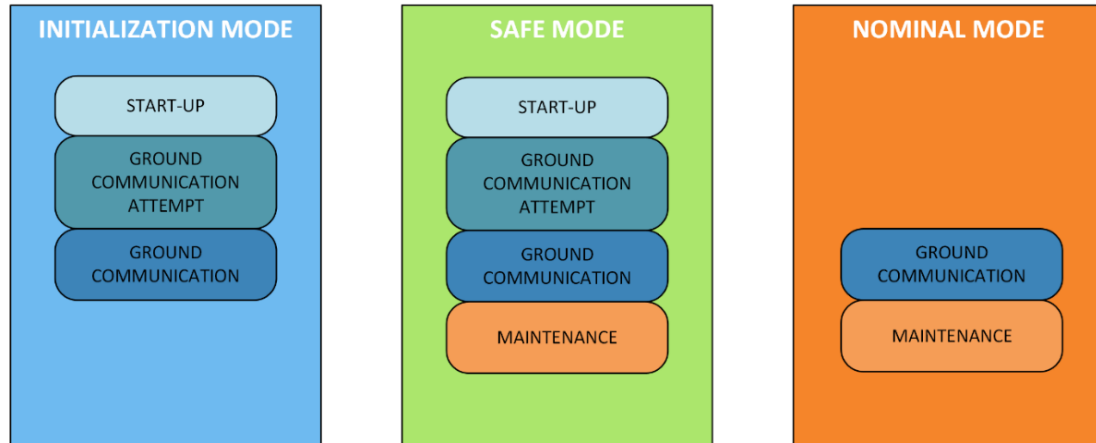


Figure 3: Operational states within each operational mode.

3.3 Basic operational activities

Apart from the appropriate activities developed by the satellites in each operational state, according to the operational mode in which it is operating, there is other type of basic activities that are essential for the correct development of the performance of the satellite and they have to be done independently of the state and mode (except for the Booting Mode) and simultaneously to the corresponding action of the state in which it is operating.

These basic activities encompass:

- OBT maintenance.
- Housekeeping and fundamental parameter monitoring.
- Reset WDTs.
- FDIR monitoring for an adequate health status of the satellite.
- GS contact schedule loaded on-board.

3.4 QKD Operation

Regarding Payload activities, generating a secure key is the core of Q-ANSER. For that ambitious goal, it is necessary to perform well previous mentioned activities such as positioning both CubeSats at the required distance of 50km and having the power available within the defined threshold.

This implies not only raw key generation through a single photon beam laser between Alice and Bob, but also prior activities that are fundamental for the correct performance of the QKD experiment, such as precise alignment and pointing through ADCS and PAT subsystems. Whereas the former one is able to achieve a relative pointing between two satellites in the order of 0.1° per axis, the latter one handles the additional accuracy achievement up to microradian range needed by the mission for maintaining the optical single photon link at a 50 km distance between Alice and Bob telescopes. Each payload plays an active role in fulfilling the mission's pointing performance objectives. Both Alice and Bob will be

equipped with two beacon channels. Alice will send its own beacon signal at 850 nm, being able to receive Bob generated beacon at 830 nm. For Bob, the assignment of wavelengths for the emitted and received beacons will be the opposite. Furthermore, each PAT system will have two pointing sensors. A first sensor with coarse field of view and the second one with fine field.

Other important activities take place at the same time such as stabilization of photon sources, synchronization of both CubeSats and calibration of instruments.

Once previous activities are accomplished, the raw key generation can be performed. The QKD operation starts in Alice, managing the protocols and pulse timing in the QKD processor and generating the QKD laser beam of 808nm (orange arrow in Figure 2) in the P&M module by encoding quantum states. From this point, the laser beam is driven via optical fibre (continuous orange arrow in Figure 2) to the QKD Tx channel block. Inside this module there is a Collimating Optics Assembly where the photon beam is transmitted via free space (orange dot-dashed arrow in Figure 2) onwards to the FM. Afterwards, at the entrance of the expander block the DBS1 joins the QKD with the two beacon beams explained previously. Then, it goes to the FSM and then through the expander throughout the collimator and telescope respectively (not depicted these sub-assemblies in Figure 2 for simplicity).

Once the single-photon beam has travelled the 50km intersatellite distance, it reaches the Bob expander. Then it goes through the DBS1 separating the QKD beam from the beacon signals. Afterwards, the QKD beam enters to the QKD Rx channel. This assembly encompasses a series of optical elements that the single-photon beam is going to pass through, such as the filters, the PTS, where the polarization is corrected, and Focusing Optics Assembly to collect the incoming photon beam from Alice and inject it to an optical fibre (orange continuous arrow in Figure 2). Once, the QKD beam is contained in the optical fibre, all the assembly including the QKD detectors is called FOBOB (Fibre Optic BOB), a series of devices containing the optical fibre where the QKD polarized beam is corrected, retarded and separated randomly into the corresponding bases and transmitted to the QKD receiver.

After the eclipse phase, reconciliation and verification process of the QKD key generated is done and no time-limited period is necessary to complete it. Since all this process has a high degree of complexity and execution, each activity and sub-task will be monitored and checked on ground before passing to the next step. Moreover, Figure 4 depicts the sequence of activities involving the QKD operation, the phase of the orbit in which they are performed and the S/S from platform and modules from payload that required to be active in each of those processes.



Figure 4: QKD operation activities sequence, with the phase they occur and the S/S from payload and platform that requires to be active.

4. CONCLUSIONS

This paper presents the comprehensive operational architecture and operations for the Flight Segment of the Q-ANSER in-orbit demonstration mission. By organizing the satellite behaviour into four operational modes—Booting, Initialization, Nominal, and Safe—and their respective states, the mission achieves a high level of autonomy. This structured operational design successfully balances the platform activities during the sunlight phase, with the critical payload tasks during the eclipse phase. Specifically, it coordinates the high-precision PAT alignment and the single-photon transmission required for the BB84 protocol over a 50 km distance. In conclusion, the operational modes, protocols, and sequence of activities defined in this study prove that secure quantum key distribution is feasible using cost-effective 16U CubeSat. This work provides a clear and scalable baseline for future global quantum satellite constellations.

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