ROKS QUANTUM COMMUNICATIONS PAYLOAD: FLIGHT MODEL DEVELOPMENT, TESTING & LESSONS LEARNED

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ABSTRACT

The Responsive Operations for Key Services (ROKS) mission is a UK Space Agency sponsored pathfinder for emerging quantum communication and onboard intelligence technologies. The mission is led by Craft Prospect Ltd, working across stakeholders in UK academia and industry.

The quantum technology payload consists of a near-infrared weak coherent pulsed source, quantum random number generator, ground acquisition and beamsteering, compact optical telescope, and high speed computing systems. These minaturised and modular technologies are being developed as products for application into future quantum communication networks such as quantum key distribution, where these smaller payloads and satellites are expected to augment larger systems in development and deployment. As such, the system will target technologies to demonstrate space-based trusted node quantum key delivery using an efficient asymmetric BB84 protocol. The quantum payload is coupled on the onboard intelligence side with a Forwards Looking Imager camera system running real-time neural networks for feature detection. This will investigate the opportunities for making best use of the limited resources of the payload, improving the link utilisation and ground station selection through local situational awareness of the upcoming subsatellite conditions, such as cloud and haze which can inhibit key delivery.

From October 2021 through to May 2022 under the National Space Innovation Program, the consortium team have been focussed on the delivery of payload flight models for integration into an off-the-shelf 6U CubeSat bus, and corresponding ground systems.

This paper provides an overview of the ROKS payload concept of operations, systems and development, and highlights some of the key challenges and lessons learned in progressing these new technologies from lab based experiments in UK universities to these flight models including security and assurance, optomechanical design, and system minaturisation. The paper further provides initial results from the integration and testing phase including with its mobile optical ground terminal, and implications for in-situ performance and operations. The ROKS satellite is being prepared for launch in late 2022.

1 INTRODUCTION

The ROKS mission was initially proposed in late 2018 by Craft Prospect Ltd, following a feasibility study with BT Plc looking at the opportunities for CubeSats to augment the deployment and delivery of future quantum key distribution and communication services, in addition to ground, air and larger space assets. The work built upon a technical assessment of a Quantum Research CubeSat (QUARC) led by University of Strathclyde [1, 2], and a partner in the mission. The mission study revealed a number of opportunities both in supporting the initial development of services, and later in enhancing the coverage and services offered globally within a network. A key feature throughout has been how more advanced concepts of operation could be integrated into the mission, applying more autonomous and ML-based techniques to maximise the utility of the limited resource CubeSat system, and improve the performance of optical systems [3].

In subsequent years the technology readiness of key subsystems have been raised from university test set-ups through now into flight models supported by the Universities of Strathclyde and Bristol, as well as more detailed business development studies, developing potential service level agreements and opportunities for hosted payloads, and understanding how the different elements developed could be utilised across future mission systems, and integrated into existing network infrastructure of telecommunication and data solution providers.

After a number of smaller developments, in late 2020, the company was able to initiate a National Space Innovation Program project within the UK followed by £1.35Mn in investment in 2021 to progress the technologies towards flight, the current phase of which is completing by June 2022 with an overall system readiness review. Beyond this further opportunities for progressing the payload both within the UK and beyond through launch and demonstration are being sought, leveraging the investment now secured, and looking at options to deliver variants of subsystems into upcoming missions such as the JADE quantum source on QEYSSAT [4], and with subsystems like the Forwards Looking Imager available as COTS items.

As a start-up the mission has provided Craft Prospect Ltd with a central focus for developing its own capabilities across the three legs of the business in Mission Architecture, Responsive Operations and Quantum Technology, upskilling and developing a team of interdisciplinary engineers across space systems, embedded & electronics, machine learning, optomechanics, and quantum domains.

2 CASE FOR CUBESAT QKD

Current security solutions, such as Public Key Infrastructure, are built on the premise that mathematical complexity and limitations of processing power are sufficient to protect our global networks and data. The emergence of new threats in quantum computing, coupled with the need for forwards security of data that retains significant value into the future and so is vulnerable to ‘record now, decode later’ attacks necessitates action now, particularly in an environment including hostile state actors and well resourced cybercriminals. A toolbox of new generation quantum safe techniques are required, and it is anticipated Quantum Key Distribution (QKD) will form part of the solution. As a result, ground-based QKD networks are already emerging limited by line of sight in free-space or fibre attenuation.

QKD using fast moving space assets in low Earth orbit as proposed in [5], presents a compelling opportunity to securely extend and scale-up emerging local or national infrastructure globally, bypassing third party infrastructure which may be vulnerable or disrupted. Coupled with the complementary capability of high throughput space-based optical communications, ground infrastructure is expected to emerge that will enable space-based key delivery into critical infrastructure networks efficiently and cost effectively.

There are few examples of the role out of genuinely novel capabilities since CubeSats have reached the maturity levels required to support services. QKD is uniquely suitable given requirements around global coverage, rapid revisit, scaleable deployments, and responsiveness to emerging standards. As such nanosatellites offer several niche benefits when considered as an augmentation strategy for larger space or ground based networks, namely:

- Smoothing of demand where networks experience elevated key requests
- Gap filling capacity where infrastructure is unavailable or not yet deployed
- Alternate key channels where customers have bespoke security requirements
- Key delivery to locations outside of existing infrastructure
- Additional delivery opportunities to overcome environmental link constraints
- Redundancy in case of failure/attack of standard network, e.g. undersea cables
- Highly miniaturised systems capable of integration of secure nodes onto space assets

Longer term, based on the investment in these technologies, further benefits within a ‘quantum internet’ including networked quantum sensing and computing are anticipated.

3 MISSION GOALS

ROKS is a demonstration mission, both for the technologies and for the potential services these technologies can deliver. The mission objectives for ROKS are defined to be in staged levels of success, given the high risk nature of the developments. It is also recognised that CubeSats are highly unlikely to provide the only key delivery mechanism and therefore interoperability, augmentation and integration into emerging network infrastructure is viewed as critical, referred to as the QKD Augmentation Service or AQKD-S. At a high level the mission goals may be summarised as,

1.) Demonstrate the technologies and capacity for a QKD Augmentation Service to be implemented on a CubeSat
2.) Demonstrate the technologies and capacity for onboard intelligence to improve the responsiveness and utility of the QKD Augmentation Service on the resource limited CubeSat platform

4 CONCEPT OF OPERATIONS

The concept of operations is depicted in Fig 1 with the satellite as a trusted node. The mission considers a decoy state BB84 protocol for downlink QKD, operating during night-time to maximise the signal to noise at the ground receivers. This implies a Weak Coherent Pulsed quantum source onboard the satellite, driven by a true random number generator, in this case encoding photons into known but randomised sequence of polarisations. Decoy states ensure that should the WCP quantum source emit and encode a state onto more than an individual photon, security can be maintained. For a full QKD link, representing extended mission success for ROKS, raw keys would be transmitted to two receive stations, with secure keys between the satellite and ground stations (A and B) distilled through a reconciliation process, before a classical channel transmission of the product of the keys broadcast to both stations. This allows the ground stations to calculate the secure key of the other and so enables secure communication between each other via conventional means, without compromising security.

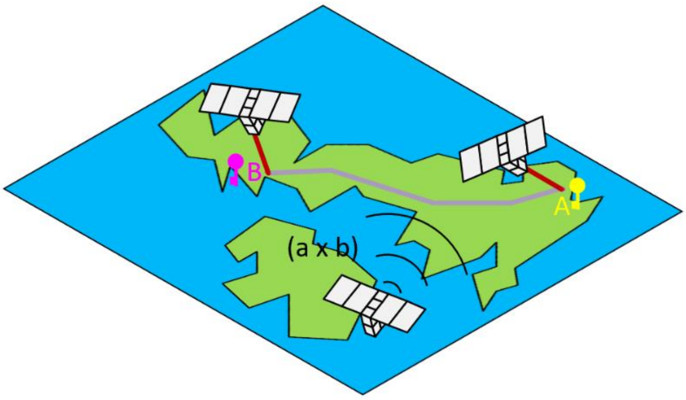


Figure 1. Trusted Node QKD

For ROKS, before these space to ground links are undertaken a number of progressive demonstrations of the underpinning technology are envisioned to build up to this capability. This will check out the technologies by assessing individual subsystem operation must be checked out into the space environment. For example, the quantum source has an integrated test mode to monitor the photon emission within the space environment, and the randomness quality must be checked to ensure that transmitted sequences remain truly random.

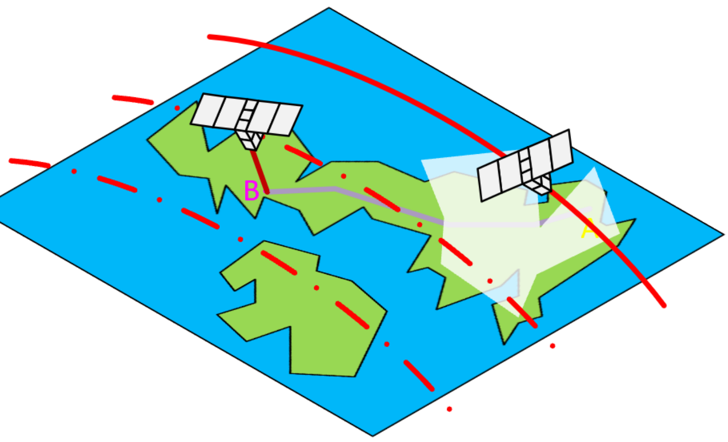


Figure 2. Cloud Cover Impacts on Optical Communications

Consideration must also be given to the impact of cloud cover on any potential service, as this can severely disrupt optical communications and hence key delivery as depicted in Fig 2. The mission considers that real-time observations and resource forecasts onboard the satellite, together with weather forecasting and ground reporting will be used to enhance future in-service performance. As such, the mission will also commission a near-IR Forwards Looking Imager with integrated neural networks trained for cloud detection, allowing onboard decision making as to whether to form a link with a particular ground station, targeting gaps in the cloud as resources allow or if blocked wait for future passes.

The mission will be launched as a secondary payload into Low Earth Orbit with parameters selected to provide a minimum of two night-time (between 2100-0300) passes over any UK site per day with at least one being greater than 40 deg elevation. Higher elevations ensure that minimum Quantum Bit Error Rates for assured security may be demonstrated, although are non-critical for the success of the mission itself. A baseline orbit for analysis has been taken as LTAN 1100 sun-synchronous orbit at 500 km with a Falcon 9. The fixed local time enabled through sun-synchronicity ensures that the satellite will experience eclipses each orbit favourable for QKD links to be formed. Given the location ground stations within UK, launch and operations avoiding the shorter nights in Summer are preferred.

5 MISSION ARCHITECTURE

The Mission Architecture is shown in Fig. 3. The CubeSat bus platform and corresponding ground segment has been procured from a space-as-a-service provider, allowing the consortium to focus on the development of the payload, optical ground station, prototype mission services, and considering integration into third party secure nodes for demonstration purposes.

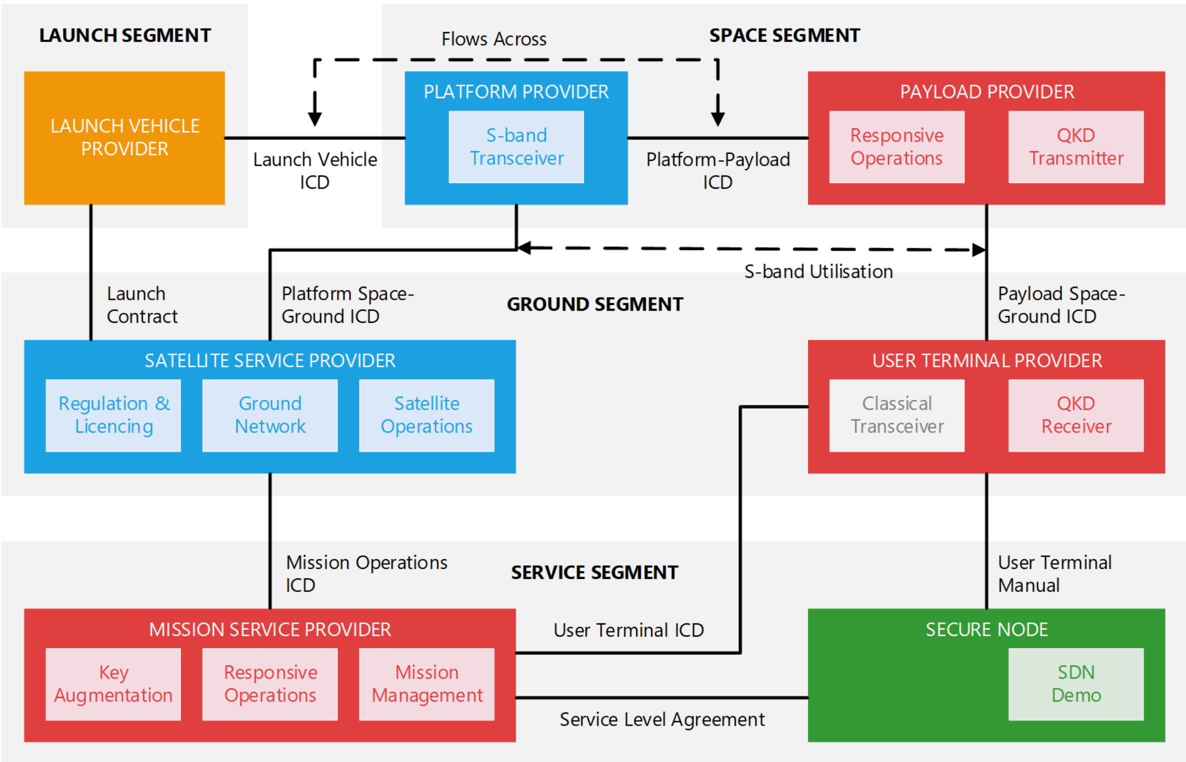


Figure 3. Mission Architecture & Key Interfaces

Model Based System Engineering practices have been applied to the mission in order to develop more rigorous design approaches necessary for assuring security and AI-based systems. Based on the differing capabilities of MBSE tools, two have been selected and evaluated in the development, Enterprise Architect for tracing through from high level enterprise and capability requirements through to architectures and operational flows, and Capella for mapping the onboard processing and behavioural components of ML. Examples of the outputs and process from Enterprise Architect is given in Fig. 4. Further information on the approach is provided in [6].

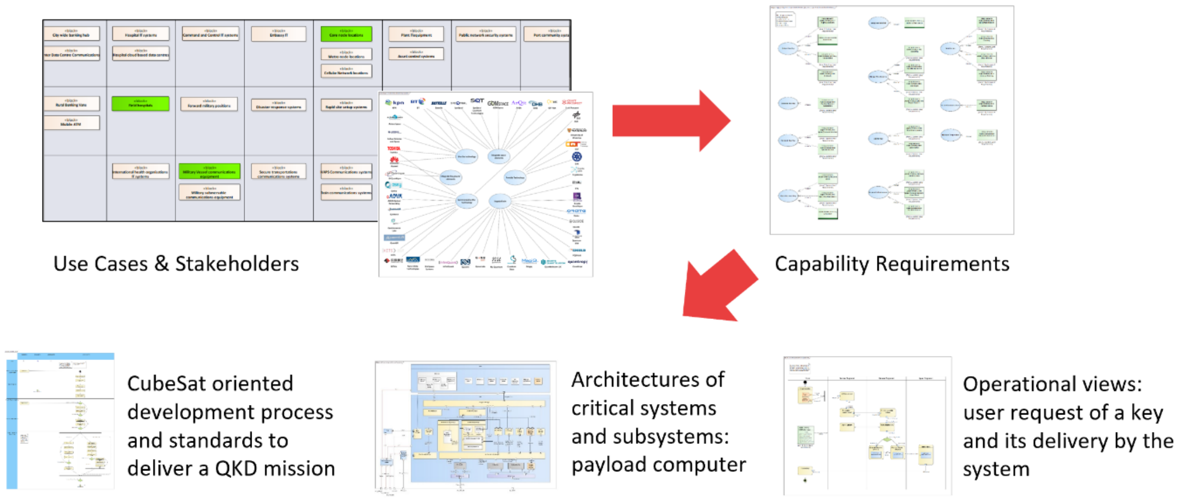
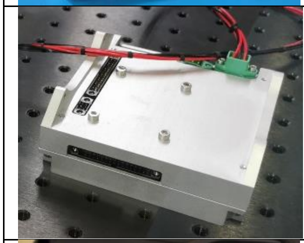


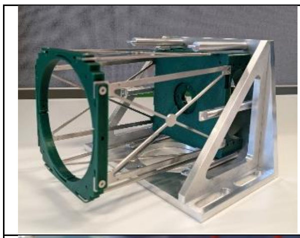
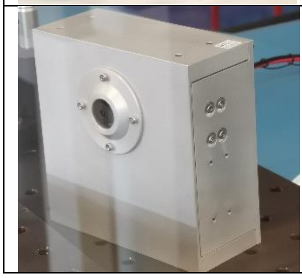
Figure 4. MBSE Approach using Enterprise Architect

6 PAYLOAD SOLUTION

6.1 Subsystem Modules

The payload system consists of five modular hardware subsystems, with software components operating on the Bright Ascension GenOne flight software providing portability to different computing solutions. The technology for the quantum communications has been developed in partnership with the University of Bristol and Strathclyde, while the optical telescope has been developed with Fraunhofer UK; throughout Craft Prospect hold all necessary licences for commercialisation. In this way a configurable set of enabling products for the company have been developed addressing different market opportunities as illustrated in Fig. 5, together with a component based software package for QKD (e.g. reconciliation) and responsive operations (e.g. real-time feature detection).

	**JADE Quantum Source**, Craft Prospect The quantum source integrates with a number of off-the-shelf quantum random number generators to provide a polarisation based WCP QKD solution with configurable wavelengths. It features thermal control, with in-situ signal power output and alignment monitoring.
	**OBSIDIAN Payload Computer**, Craft Prospect The payload computer provides interfacing to all subsystems using a Zynq based FPGA, runs the GenOne flight software with CPL components for responsive scheduling and QKD. Includes high speed throughput to the RF transceiver for reconciliation and distillation of the secret key.
	**APATITE Beamsteering**, Craft Prospect Provides a MEMS mirror based solution with uplink beacon camera to provide closed loop control of the look-ahead downlink, based on the ground station beacon received. Utilises design approach to minimise the interdependencies of the components for optical alignment and thermal mismatch.

	**GARNET Optical Telescope**, Fraunhofer UK licenced to CPL High performance/low distortion compact <2U, 1U aperture Cassegrain telescope designed for integration into CubeSats for QKD or optical communication.
	**FLINT Forwards Looking Imager**, Craft Prospect Wide field of view imager using detector for low light conditions, and running an FPGA-based neural network for real-time feature (cloud) detection. Configurable to provide up to 120 s look ahead in advance of the satellite in Low Earth Orbit.

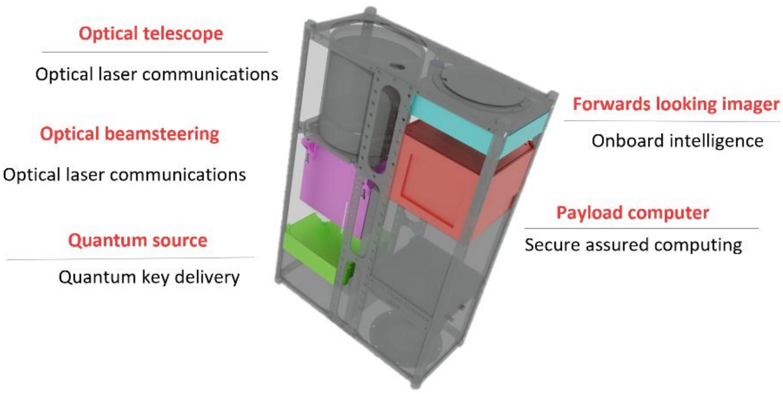


Figure 5. ROKS Enabling Products configured within 6U CubeSat Structure

6.2 System Specification

The baseline system specification, based where possible on the as measured performances of subsystems to date is described below. Work will continue to confirm these figures based on the as-built system during the payload test phase now underway.

Parameter	**Specification**	**Comment**
Total Mass	2730 g	Excluding harnessing
Total Volume	3.5 U nominal	< 4U based on structure
Peak Operating Power	22 W	14.5 W nominal ex thermal
Operating Temperature	-10 to 40 degC minimum	-20 to 50 deg target (TBC)
Thermal Control	TEC to ~20 degC (TBC)	Integrated in source
Operating Wavelength	785 nm	Configurable
QKD Protocol	Polarisation-based WCP BB84 2-decoy state	Asymmetric preferred
Source Rate	100 MHz	200 MHz potential
Pass Secure Key Rate	> 10,000 key bits	Unobscured, finite key
Telescope Aperture & Length	80 mm, < 160 mm	Including mounting
Telescope Field of View	0.25 deg	
Space to Ground Link Loss	37 dB	
Pointing Requirement	> 0.1 deg	3-sigma preferred
Stability Constraint	< 2 urad @ > 150 Hz	TBC

7 DEVELOPMENT CHALLENGES & LESSONS

From October 2021 through to March 2022 the payload progressed from engineering models through to flight model Payload Test Readiness Review. With this phase complete, from April functional and environmental testing of the system will commence. Delivering the PTRR in 6 months represented a significant undertaking for the team and organisation, particularly given partial lockdowns due to COVID limiting access to the company facilities, completion of a ISO9001 full audit with no NCs, and chip shortages necessitating careful stockpiling and BOM monitoring. Figure 6 shows the full flight model integration onto the test bench against the subsystems identified in Fig. 5.

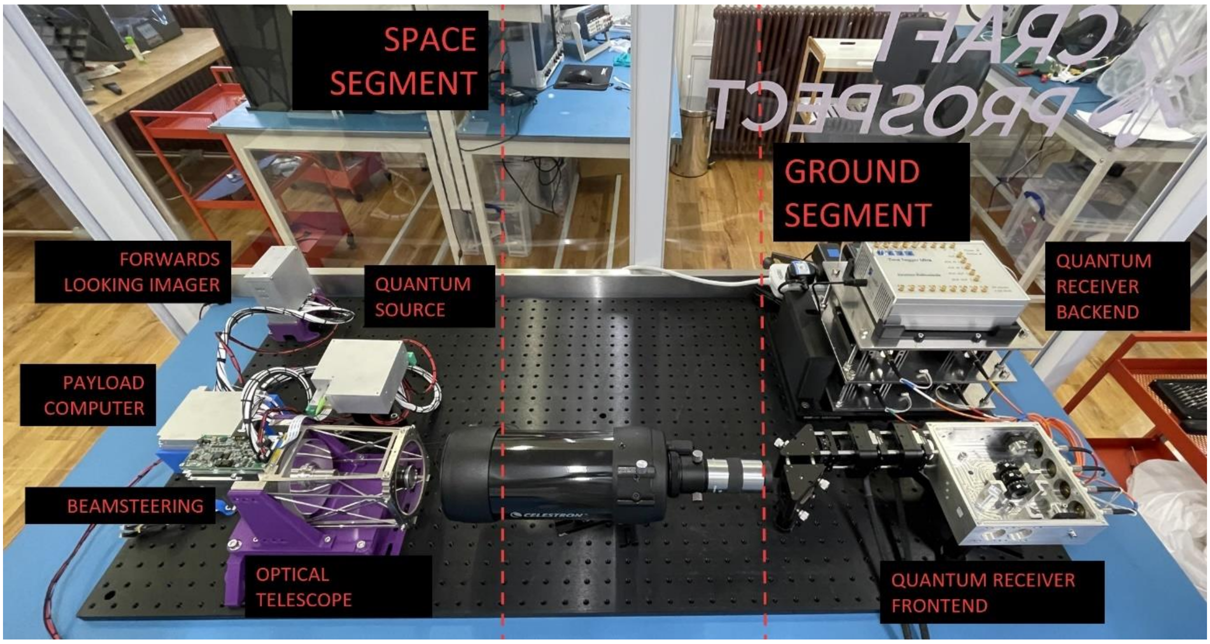


Figure 6. Payload Test Bench with all Flight Model Subsystem Integrated

Despite taking the approach to design the payload to be bus agnostic, challenges were encountered with respect to interfacing and particularly due to the variability of structural design philosophies across different CubeSat 6U structures. While data and power interfaces could be accommodated through modifications to the interface boards, structural compatibility and the thermal and optical implications of different approaches were more difficult and time consuming to address due to availability and variability of mounting points and keep outs in addition to the CubeSat standard. This was particularly problematic for the compact telescope given the already tight constraints.

It was found that supplied optical components in particular varied significantly in quality. Given the highly specialised nature of optical components used and the application, it was found that components frequently failed to perform in line with datasheets or expectations of the supplier, especially with respect to polarisation maintenance. Clear communication of the end use with suppliers and therefore individual component expectations, together with improvements to goods in processes and the need to procure specialised test equipment to perform incoming acceptance prior to integration, helped to resolve these issues, however additional rework and characterisation is needed across the space environment as part of the next steps.

Maintaining a focal point of a test bench for the payload development, into which subsystem components could be swapped in and out helped to maintain momentum in the later stages of the integration. Given learning from the rapid development cycle, the team is now looking to integrate sprint developments of 2-3 mo iterations following establishment of a baseline solution for R&D to more progressively build up capability. This is anticipated to save money in production, as front-ends a number of complex manufactures and interface challenges ensuring that production issues are identified and addressed early and as part of a 'first pass integration' rather than at a single crunch point close to review.

The value of automated testing, although still an ongoing development, and strategy for the production of multiple models became apparent during this phase. The former ensured that tests became more standardised, with less variability between engineers, despite being somewhat exploratory at this phase. Together with multiple models it allowed both (a) that a discipline engineer could focus on a particular issue at a subsystem level independently while the system test bench could continue end to end integration, and (b) that issues with a indiscernible root cause in hardware/software could be more easily established.

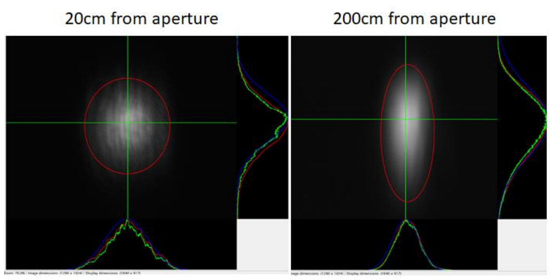
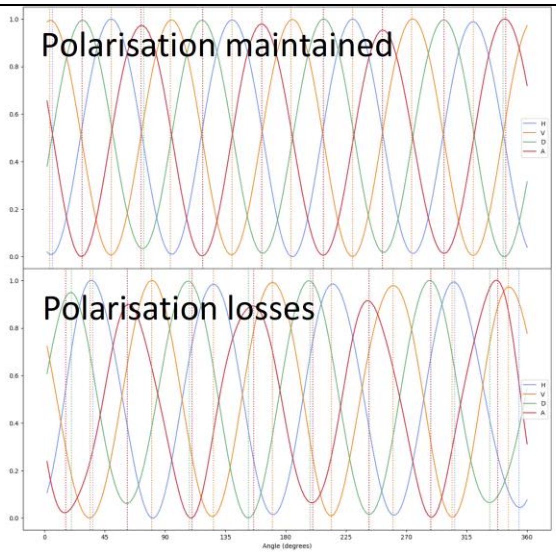
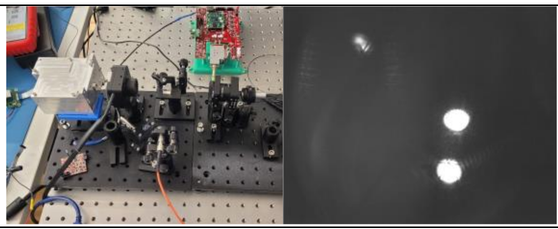
Prior to this phase the company invested in 3DP capability. Throughout integration, we found that the ability to rapidly prototype fixings for the subsystems for integration and test highly valuable. Based on this success, we further investigated additional prototyping options such as PCB milling, but given the high turnaround of PCB prototypers we considered that this would not add significant value. During this evaluation it was identified that creating standardised test points for repeat acceptance of incoming PCBs and assemblies would accelerate this stage and provide additional acceptance repeatability.

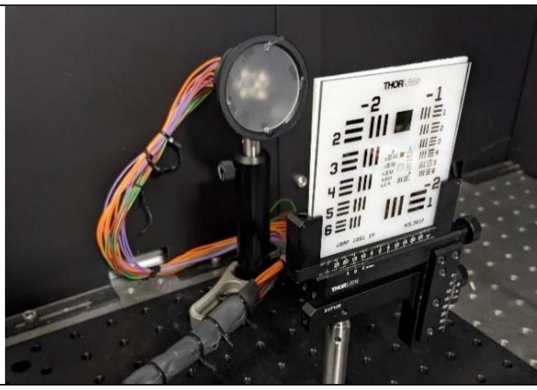
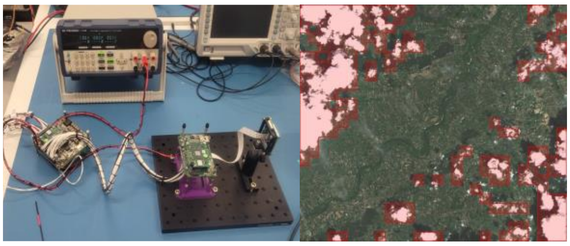
During this phase, and with a less experienced team we also undertook team-wide training on the realities of system integration and testing for space for CubeSats. We monitored the issues that arose, and tried to classify root cause and in doing so reinforce practical guidelines and key messages to help the team avoid repeats. Over this phase by focusing on continuous improvement within behavioural and process aspects we saw avoidable issues reduce significantly ~1/3 with the majority of issues arising as a result of normal integration challenges and with 76% closed out within the phase. The current key messages developed with the team may be simplified to,

1. Have spares of everything
2. Photograph/video everything
3. Serial number everything
4. Keep a record card with kit
5. Record test configurations
6. Invest in test set-ups
7. Maintain and keep tidy set-ups
8. Automate repeatable functional tests
9. Get to end to end testing early
10. Check supplied parts against spec
11. Plan testing to an appropriate level
12. Design for handling
13. Continuously communicate to team
14. Plan for forgetfulness and stupidity
15. Get to prototyping early
16. Verify and update budgets
17. Record steps taken in detail
18. Plan for subco production issues
19. Plan for multiple models
20. If it gets too much, speak up

8 INITIAL RESULTS

Throughout engineering model development and flight model integration, initial system testing has been performed, with further results in [7]. Further results are anticipated in the April/May time through ongoing testing of the payload and will be reported as available at the time of the conference. Selected tests from this phase are described below which led to changes in the as-built system over the period.

Testing	Purpose & Results	Representative Image
Beam Divergence	*Characterising the through system beam divergence and matching between modules to minimise any losses, found that some clipping occurred and corrected through rework of optical links between telescope and beamsteering*	
Beam Polarisation	*Confirming that polarisation is maintained through to the exit, in particular by the beamsteering and dichroic optical components, found that some optical components where not polarisation maintaining per their specification. Corrected within source, further actions within beamsteering required.*	
Beam Tracking	*Confirming that alignment and downlink beacons can be received onto the uplink detector and this can drive the MEMS mirror for downlink*	
Beamsteering Robustness	*Confirming that the MEMS component selected and the processes for packaging and integrating the beamsteering system are robust to the vibration environment, found that packaging and process is key following damage through handling and overdrive*	

Lens Distortions & Alignment	*Looking across the telescope assembly to ensure that the beam expansion by the telescope is uniform and that alignment of the lenses does not modify the mode*	
Bonding Testing	*Confirming that the bonding materials and processes do not distort the optical path and considered across the thermal range, found that settling of components into mounts could significantly change throughput leading to modification of assembly processes and tooling*	
Image Processing	*Confirming that the imaging systems are able to capture images and run neural networks for detection of clouds within a variety of low light images, found that faster frame rate capture for confirming the performance needed and implemented*	

8.1 Optical Ground Station

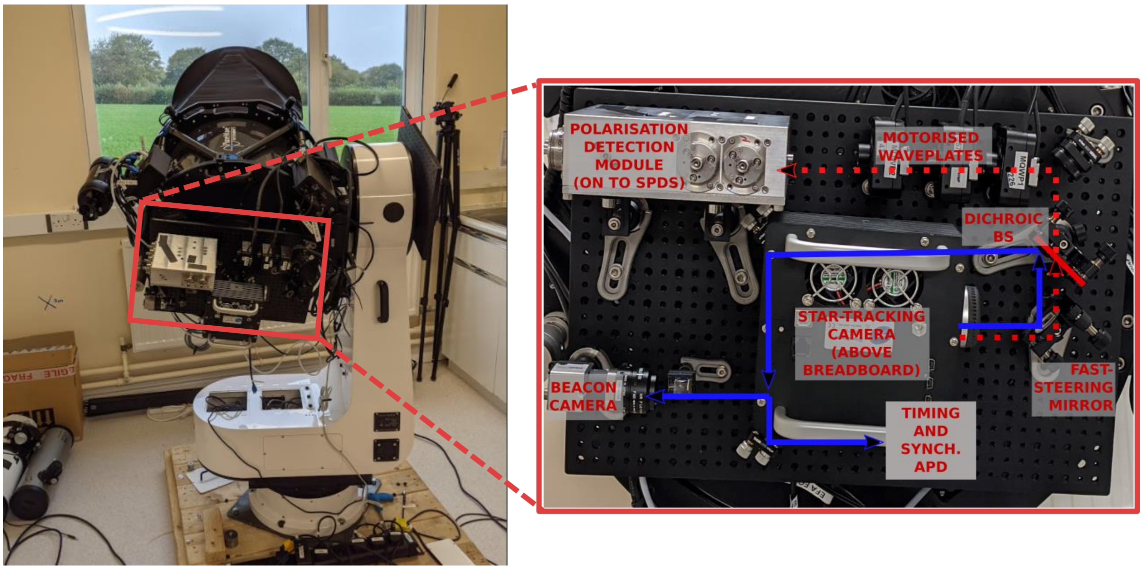


Figure 7. Baseline Optical Ground Station (courtesy University of Bristol)

The corresponding baseline Optical Ground Station for the mission is being developed with consortium partner University of Bristol and is shown in Fig 7. The system incorporates an off-the-shelf telescope with custom quantum receiver optics, in a form factor rapidly deployable using a standard half shipping container. Due to COVID, there have been delays to integrated testing with the completed flight model payloads. A representative receiver system has been established within the Payload test bench in order to facilitate interim results as seen in Fig. 6.

8.2 QKD Link Performance Assessment

Based on the space and ground segments described, University of Strathclyde has been supporting the consortium with analysis of the link performance [8]. Performance curves typical for the symmetric (solid) and asymmetric (dashed) BB84 implementations are given for a given system link loss (for ROKS 37 dB is targeted), and minimum ground track offset from the OGS over the pass. A number of potential routes to improve the baseline key rates significantly have been identified through this analysis and are on the roadmap to be implemented within this mission, or subsequent iterations based on available resources.

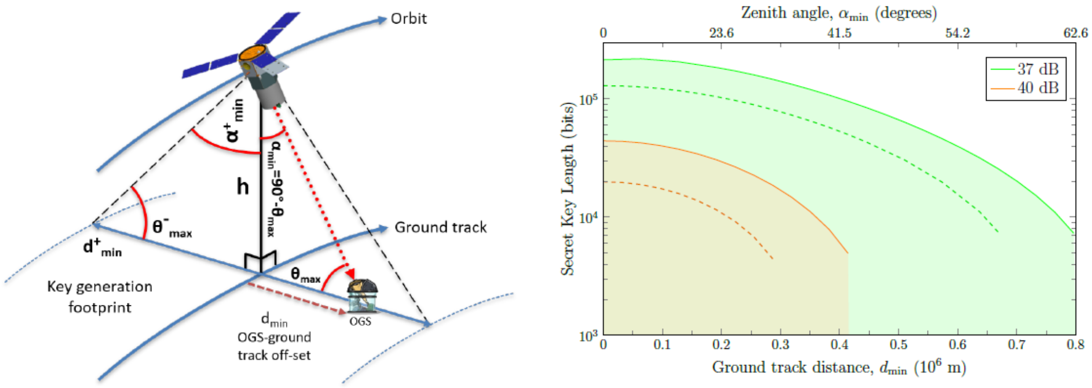


Figure 8. Representative Link Budget Performance (courtesy University of Strathclyde)

9 CONCLUSIONS

The ROKS Payload development to date represents a significant milestone for Craft Prospect, and has resulted in the production of flight model modules for a range of subsystems which will be made available to market as configurable products across quantum technology and onboard intelligence. The learning for the mission and systems engineering team has been equally important, developing the capacity of the business to extend its offering from feasibility studies for future missions through into payload and system delivery.

With a baseline payload system, ongoing work will now focus on environmental characterisation and functional testing of the payload system, end to end integration with the OGS developed by our partners, and continued iteration of the software, particularly to improve the beamsteering maturity. This will lead to Satellite Integration Readiness Review, and integration with the space-as-a-service bus systems for qualification testing for a Flight Readiness Review before the end of 2022.

Supported through ESA Business Applications, an initial cybersecurity service study 'Augmenting QKD with CubeSats for Cybersecurity Services (AQKD-S)' was completed in

2021 engaging with organisations in a diverse range of sectors including data service providers, international finance, oil and gas, telecommunications and network operators. Through the next phase, a service demonstration with the ROKS mission and other deployments of the payload systems is planned. With a number of international organisations signed up for the demonstration, Craft Prospect would welcome any further approaches to further engage on a product or service basis by contacting hello@craftprospect.com.

10 ACKNOWLEDGEMENTS

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