

Rapidly deployable mobile optical ground stations for operational satellite quantum key distribution

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ABSTRACT

Optical ground stations for satellite quantum key distribution have generally been implemented as fixed observatory-class installations, since pointing stability, low-loss single-photon coupling and thermal control are more readily achieved on a permanent foundation. As national and multinational QKD networks progress from demonstration to service provision, this approach constrains both the rate at which nodes can be added and the ability of the network to respond to weather. This paper describes the optical payload of the Configurable Mission Optical Ground Station (CMOGS), a road-transportable QKD and classical optical communications ground station developed by Honeywell under an ESA ARTES contract, and compares it against the fixed Optical Quantum Ground Station (OQGS) being delivered to the Canadian Space Agency for the QEYSSat mission. Parallel development of the two systems by a common engineering team permits the architectural elements intrinsic to satellite QKD ground terminals to be distinguished from those imposed by the deployability requirement. The principal penalties are quantified: 0.6 dB of collected signal attributable to a telescope selection constrained by container volume, 7 dB of eye-safety-limited uplink power per secondary aperture, and a polarization frame error budget of a few tenths of a percent QBER arising from removal of the closed-loop polarimeter. A Gaussian-copula treatment of cloud-free line-of-sight statistics gives 78 % usable pass availability for three stations separated by 1000 km, against 45 % for a single mid-latitude site.

Keywords: quantum key distribution, optical ground station, deployable systems, pointing acquisition and tracking, site diversity, QEYSSat, free-space optical communications

1. INTRODUCTION

Satellite quantum key distribution has progressed beyond initial demonstration. Micius established space-to-ground feasibility in 2016 [1], and the missions now approaching or in flight are directed at key delivery to users against a schedule: QEYSSat in Canada [2]-[4], Eagle-1 and the wider EuroQCI programme in Europe [5], and commercial systems including QKDSat. The field is reviewed in [6]. Development of the ground segment has not kept pace. Almost all optical ground stations constructed for QKD to date are permanent installations comprising a fixed pier, enclosure and foundation, preceded by a site selection study of duration comparable to the telescope procurement. This is appropriate where the objective is a single successful link, but scales poorly to a network required to add nodes on a timescale of months, and provides no mitigation against cloud, which remains the largest single cause of lost link time.

This paper describes the optical payload of the Configurable Mission Optical Ground Station (CMOGS), a deployable ground station being developed by Honeywell under an ESA ARTES contract, with the optical payload developed jointly by the Ottawa and Brno sites. CMOGS receives quantum downlinks from QKDSat and the QEYSSat QP2 secondary payload, supports the Craft Prospect ReFQ and OPS-SAT VOLT sources through a filter change, and transmits SDA-compatible optical communications to LEO partner spacecraft. The optical payload is carried on a lift occupying approximately half of a twenty-foot ISO container.

CMOGS has been developed in parallel with the Optical Quantum Ground Station (OQGS), a fixed installation Honeywell is delivering to the Canadian Space Agency for QEYSSat [3], [4]. The two programmes share engineering staff and software, and in several cases draw on the same procured hardware. This overlap permits the elements required of any satellite QKD ground terminal to be separated from those arising solely from containerization, road transport and rapid on-site commissioning. Section 2 sets out the two reference architectures. Sections 3 to 5 describe the optical, PAT and quantum channel designs, identifying mobility-driven decisions as they arise. Section 6 collects the resulting penalties and Section 7 evaluates them against the availability gain obtained from site diversity.

2. REFERENCE ARCHITECTURES

Table 1 compares the two systems. The principal structural difference is link direction. OQGS supports the primary QEYSSat mode, a quantum uplink from weak coherent pulse or entangled photon sources on the ground to a receiver on the spacecraft. That requires a narrow uplink beam near 780 nm, roughly 10 urad, with its own tip-tilt correction, sharing the main aperture with the receive path [4], [13]. CMOGS is a downlink receiver. The commercial case for deployable stations rests on downlink QKD as implemented by QKDSat, and an uplink source with its optical chain would exceed the available prototype volume. QEYSSat PAT compatibility was retained for tracking and commissioning campaigns. A quantum uplink variant based on the modular transmit architecture is under study with Heriot-Watt University.

Table 1. Fixed and deployable reference architectures.

Attribute	OQGS (fixed)	CMOGS (deployable)
Host structure	Permanent pier and enclosure	Lift in half of a 20 ft ISO container
Link direction	QEYSSat quantum uplink (WCP / EPS ground source) plus downlink	Quantum downlink only (QKDSat, QP2, VOLT); uplink retained for classical comms and beacon
Uplink launch	Sub-aperture of the 610 mm primary	Two or more 95 mm secondary telescopes (MUBS)
Polarization frame	Closed loop on a 980 nm linearly polarized downlink beacon, custom Rx polarimeter	Open loop from predicted relative yaw, with live ADCS updates where available
Site change	Not applicable	Road transportable, container mounted

3. OPTICAL ARCHITECTURE

3.1 Main telescope

The main telescope is a PlaneWave CDK24 on an L-600 azimuth-elevation mount: 610 mm aperture, 287 mm central obstruction, 3974 mm focal length at $f/6.5$, and 364.5 mm of back focus behind the tube. The mount carries 130 kg and slews fast enough for LEO passes away from zenith.

The alternative considered was the RC24, the same aperture in a Ritchey-Chretien rather than a corrected Dall-Kirkham form. Its central obstruction is 32 % of the primary diameter against 47 % for the CDK24, worth 0.62 dB of collected signal, which is significant for a photon-starved quantum downlink. It was not selected. The RC24 works at $f/10.6$ with a 6459 mm focal length, so holding the bench magnification would have required a redesign of the collimating eyepiece, and it needs 394 mm of back focus rather than 364 mm. Neither the longer optical train nor the extra back focus fits the volume the lift mechanism leaves inside the container. The telescope selection is therefore determined by the container volume. Recovery of the 0.6 dB would require a larger container or a lift concept providing additional depth behind the tube.

3.2 Receive bench

The Cassegrain focus of the CDK24 falls about 365 mm behind the back plate. This is convenient for an inline astronomical camera but poorly suited to a bench carrying four wavelength paths. The receive bench is therefore mounted on an aft plate roughly 200 mm behind the telescope back plate, on an imperial 1 in, 1/4-20 grid so that commercial mounts can be used throughout. A primary fold turns the $f/6.5$ cone parallel to the bench, a 60 mm collimating lens produces a 9 mm collimated beam at about 66x magnification, and a second fold turns the beam 90 degrees along the bench. That second mirror is also the fast steering mirror, and the two folds are oriented so that the polarization effects of the first are largely cancelled by the second. This is of greater consequence than on a fixed station, since CMOGS does not carry the closed-loop polarimeter that would otherwise measure and correct residual retardance (Section 5.3).

Wavelength separation downstream of the FSM is a cascade of long-pass and short-pass dichroics feeding four paths: the 851.5 nm quantum receiver, the C-RED 3 fine tracking camera, the 1527.99 nm time synchronization detector, and the 1536.61 / 1553.33 nm SDA communications receiver. The quantum path has priority and passes straight through the first dichroic in transmission. The bench supports a 2 mrad on-sky field of view, roughly plus or minus 67 mrad in collimated space.

A bench variant has been laid out for the Heriot-Watt optical ground station around an RA700 main telescope, which has 320.6 mm of back focus and requires a 100 mm collimating lens for 84x magnification. The substitution was accommodated by one lens change and one spacer change. A fixed installation performs such reconfiguration once; a deployable product line performs it repeatedly.

3.3 Transmit apertures

Fixed observatory-class stations, OQGS among them, generally launch the uplink through a sub-aperture of the main telescope, as the large NASA and ESA ground stations do. Recent deployable terminals, including NASA's LCOT and the earlier LLGT, mount a separate transmit optical assembly on the receive telescope structure [7]. CMOGS follows the deployable convention.

The principal driver is isolation. Detecting single photons at 851.5 nm while transmitting watts at 1536 nm through the same aperture calls for isolation on the order of 170 dB. Physical separation of the apertures removes the majority of this requirement independently of coating specification. Separate apertures also give eye-safe irradiance at each launch, largely uncorrelated uplink turbulence paths, local tip-tilt correction per beam, independent scanning during acquisition, and a modular interface for additional beams.

Each Modular Uplink Beam Scope (MUBS) is a 95 mm aperture, 580 mm focal length IR-optimized refractor with a 60 mm collimating lens for 9.7x magnification, giving a 9.8 mm collimated beam onto a 1 in tip-tilt mirror at the exit pupil. The transmit beam leaves the aperture at 6.6 mm diameter, the collimator set slightly convergent for a 50 to 100 urad half angle, through a quarter-wave plate at 45 degrees for circular output. Point-ahead of up to 50 urad is applied as

a look-behind bias on the tracking setpoint rather than through a separate mechanism, which eliminates an actuator from a payload subject to road transport.

The eye-safety limit is a direct consequence of the small transmit apertures. Each MUBS is optically capable of 5 W but is restricted to 2 W to hold peak irradiance below 0.1 W/cm² at the aperture under ANSI Z136.1 [9], which gives a nominal ocular hazard distance of zero for long-term exposure. A fixed station launching through a 610 mm aperture distributes the same power over approximately forty times the area and is amplifier-limited near 10 W. Two MUBS recover 3 dB of the resulting 7 dB deficit and a third a further 1.8 dB. The penalty applies to the classical uplink and acquisition beacon, not the quantum downlink.

Separating transmit from receive by aperture solves the isolation problem and creates a smaller one inside each Tx scope, where the transmit beam and the received beacon share a beamsplitter. A dichroic is the natural answer, but SDA compliance requires switching between 1536.61 and 1553.33 nm on transmit, and a switchable dichroic needs tight angular repeatability in a unit shipped by road. Polarization splitting is unavailable because the beacon polarization is not controlled, and time-division splitting is unavailable because the transmit beam is continuous. The design uses spatial multiplexing: an annular beamsplitter formed from an elliptical AR-coated transmission region within a gold reflector on the 45 degree interface of a right-angle prism pair. The Gaussian transmit beam passes the central clear region with minor clipping and the flat-topped beacon is picked off from the surrounding annulus. Scatter control is the principal difficulty, since the AR coatings can return transmit light to the quad cell at levels orders of magnitude above the beacon; wedged interfaces, geometric masking and a two-position slider carrying 1535/3 and 1550/3 nm filters are used together to keep it off the sensor. A volume Bragg grating on a tilt stage is under evaluation as a single-element alternative.

4. POINTING, ACQUISITION AND TRACKING

Acquisition assumes ephemeris no better than a 24 hour old TLE, which is about 1.5 mrad of position uncertainty, and searches a 3 mrad radius region using the SDA 3.x / 4.x spiral algorithm [8]. The assumption is deliberately conservative and follows from the deployability requirement, since a recently relocated station may lack current ephemeris or a completed site survey.

Three fields of view are nested. A wide guide scope, a 100 mm NIR lens on an InGaAs camera sensitive from 400 to 1600 nm, gives roughly 16 by 13 mrad for plate solving, mount frame alignment and first beacon capture. The C-RED 3 fine guidance camera on the receive bench, re-imaged to about 2.3 m effective focal length, covers a few mrad with sub-frame readout to 20 kHz. Each MUBS carries a 1 mm quad cell with a field near 2 mrad and a linear tracking range predicted between 100 and 250 urad. The quad cell field must be co-aligned with the fine guidance field centre to about 50 urad and the spiral scan centred on it to about 10 urad. A fixed station establishes this alignment once during commissioning. Maintaining it across a road move is a requirement specific to the deployable case.

Because the transmit apertures steer independently of the main mount, the wide guide and fine guidance cameras can watch for a downlink beacon while the Tx scopes scan the uplink uncertainty region. Two MUBS executing nested Archimedean spirals over the same 3 mrad radius, arranged so that each beam overlaps its partner's track but not its own, halve the scan time at equal dwell and beam width. Once a spot appears on a receive camera, uplink pointing is corrected onto the spacecraft, mount tracking is adjusted to bring the spot into the Tx scope fields, and tracking hands over to the quad cells locally and the fine guidance camera for the mount.

The acquisition and tracking sensor is a 1 mm diameter InGaAs quad cell near a 50 mm focus, defocused by about 1.2 mm to produce a 200 μ m spot at 97 % encircled energy across the four segments. The noise-equivalent angle target is 2.5 urad RMS, taken as half of the 5 urad RMS jitter allocation. The front end is a 4.7 MOhm transimpedance amplifier with 2 pF of feedback, mapping the 1000 nW maximum spot power onto a 5 V converter range while holding 10 kHz of bandwidth with adequate phase margin, followed by a buffer and a differential stage into a 24-bit converter at 52 kSa/s. At the nominal 250 nW per segment the shot-noise-equivalent current is about 30 pA RMS over 10 kHz and simulation puts the integrated input-referred front end noise below 10 pA, so the chain is shot-noise limited as intended. The electronics are entirely analogue up to the converter, with local low-dropout regulation and differential inter-board signalling. This is driven by mobility as much as by noise. A containerized station locates HVAC compressors, lift motors and drive electronics within a few metres of a picoampere-class front end, whereas an observatory installation can site them remotely.

Tip-tilt correction on each Tx scope uses a piezoelectric steering mirror with 35 mrad of range and measured bandwidth above 300 Hz, driven from a 16-bit converter through a low-noise gain and level-shift stage; over the 70 mrad mechanical range at 11x optical magnification this resolves better than 0.1 urad in real space against a 0.5 urad requirement. A transmissive element was considered for the receive bench, a tilting 10 mm BK7 plate giving about plus or minus 36 urad at 10 Hz, attractive because it avoids the polarization effects of a reflective mirror on the quantum path. It was rejected in favour of a conventional fast steering mirror, because the bench needs range across a 1 mrad field and bandwidth nearer 100 Hz. Measured servo error from an L-500 prototype at 1 and 10 deg/s falls inside the correction range of either device, and the selection was therefore determined by bandwidth rather than stroke.

The L-600 is a two-axis azimuth-elevation mount and therefore has a keyhole. Reorienting the axes to move the keyhole toward the horizon was considered and not adopted for the prototype, because the optical payload is large and the interface to the lift mechanism was prioritized. An 85 degree keyhole excludes 0.38 % of the hemisphere by solid angle. This figure understates the operational impact, since near-zenith passes have the shortest range and lowest airmass and therefore the highest key yield. Alternative mount geometries are on the roadmap for the next iteration.

5. QUANTUM CHANNEL

5.1 Photon detection module

The quantum receiver is the Photon Detection and Time Tagging Module (PDTTM) supplied by Craft Prospect, who also built the ReFQ flight source that QEYSSat will demonstrate through the Honeywell QP2 terminal. The module contains a high extinction ratio four-state polarization analyzer splitting the input into H, V, A and D bases, with a motorized quarter-half-quarter waveplate stage at the input that can realize any unitary polarization transform and is calibrated against the as-measured, wavelength-dependent retardance of the CMOGS receive path. A second quarter-half-quarter arrangement on the A/D arm cleans up beamsplitter error. The target QBER contribution from the module optics is below 0.5 % at 851.5 nm.

Ahead of the module the beam is reduced to the module clear aperture and passes a rotating achromatic half-wave plate on a motorized stage for frame alignment, then a narrow line filter in a multi-position wheel. The baseline filter is nominally centred at 852 nm and angle tuned to the mission wavelength, 851.5 nm for QKDSat or 850 nm for QP2; a second position carries a 785 nm filter for OPS-SAT VOLT. Reconfiguration for a different quantum source requires a filter wheel position change and a calibration run.

5.2 Fiber coupling and detector placement

The analyzer outputs couple into four 105 μm core step-index multimode fibers feeding single-photon avalanche detectors and a time tagger. Step-index fiber is the right choice for coupling a beam that is moving under atmospheric turbulence, but it carries 20 to 50 ps per metre of modal dispersion. Graded-index fiber would reduce that to 0.1 to 0.2 ps per metre and couple far worse off axis. Holding fiber-induced pulse spreading below 200 ps at GHz source rates therefore caps the run at about 4 m in the worst case, and the design uses 2 m.

This constraint has a substantial architectural consequence. The detectors cannot be racked at the base of the container; they are mounted on the receive bench and therefore move with the gimbal. Every gram of detector, cooler and time tagger counts against the 130 kg mount capacity, must survive the slew profile, and must be thermally managed on a moving structure within a container rather than in a climate-controlled room. A fixed station satisfies the same dispersion constraint by locating the detector package on the pier within a short cable run, where mass and thermal management are effectively unconstrained. On CMOGS the constraint propagates into mass, thermal and cable-wrap budgets on the moving payload.

5.3 Polarization frame alignment

Polarization-encoded QKD requires the ground reference frame to track the source frame to within a few degrees through the relative yaw excursion of a pass. Two approaches are in use. OQGS closes the loop optically, tracking a linearly polarized 980 nm downlink beacon with a custom receive polarimeter and correcting through the rotating half-wave plate. QKDSat instead pre-computes the relative rotation from pass geometry and the spacecraft attitude profile, the method demonstrated on the European ground receivers during the Micius campaign [1], with provision for live attitude updates over the classical optical link.

CMOGS uses the pre-computed approach. The driver is cost and schedule on the custom polarimeter optic, and the bench layout retains space for the OQGS polarimeter should closed-loop operation prove necessary. The resulting penalty is quantifiable. A residual frame misalignment of θ contributes $\sin^2 \theta$ to the QBER, which is 0.12 % at 2 degrees and 0.27 % at 3 degrees. Against the 0.5 % allocated to the PDTTM optics, an open-loop solution accurate to 2 or 3 degrees approximately doubles the instrumental QBER floor while remaining well below the security threshold. Whether the predicted rotation retains this accuracy on a station whose azimuth reference has recently been re-established after a road move remains to be verified, and is a primary measurement objective of the first deployed campaign.

6. SUMMARY OF DEPLOYABILITY PENALTIES

Table 2 collects the penalties identified above. Most are recoverable or bounded: the uplink deficit decreases with each MUBS added, the polarization QBER contribution can be removed by fitting the polarimeter for which the bench retains space, and the keyhole is a mount geometry decision rather than a physical limit. The only irreversible penalty, 0.6 dB from telescope selection, is set by container volume. The aggregate is below 1 dB of collected signal and a few tenths of a percent of QBER.

Table 2. Quantified penalties attributable to the deployability requirement.

Penalty	Magnitude	Origin and comment
Collected signal, quantum downlink	0.6 dB	Container volume forced the f/6.5 CDK24 over the lower-obscuration f/10.6 RC24. Permanent.
Classical uplink power	7.0 dB per aperture, 4.0 dB with two	Eye-safe irradiance over a 95 mm aperture, 2 W against roughly 10 W amplifier-limited. Recoverable by adding MUBS.
Polarization frame QBER	0.12 % at 2 deg, 0.27 % at 3 deg	Open loop frame prediction in place of the OQGS polarimeter. Comparable to the 0.5 % PDTTM optical allocation.

Penalty	Magnitude	Origin and comment
Sky access	0.38 % of the hemisphere	85 deg keyhole on the L-600 Az/El mount. Small in solid angle, weighted toward the highest-yield passes.
Residual tracking jitter	5 urad RMS allocated	Allocation for a payload carried on a lift rather than a pier.
Detector placement	Design constraint, not a loss	Step-index MMF dispersion caps the fiber run at 4 m, so the SPADs ride on the gimbal.

7. SITE DIVERSITY

Cloud cover is the dominant cause of lost key. The standard remedy in the classical optical communications community is a network of geographically separated stations [10], [11]. The argument applies with more force to QKD, where a lost pass is lost key that cannot be retransmitted later; Anipetdi et al. reach a similar conclusion for a four-station Irish network using five years of measured weather data [12].

We model the cloud-free line-of-sight state of a station as a binary variable with single-site probability p , and correlate sites through a Gaussian copula with an exchangeable correlation matrix. Correlation between two sites separated by distance d is taken as ρ equal to $\exp(-d/d_0)$, with d_0 set to 600 km to represent mid-latitude synoptic scale weather systems. Network availability for N stations is one minus the joint probability that all N are blocked, evaluated from the multivariate normal distribution function. Table 3 gives results for p equal to 0.45, a representative mid-latitude value, together with the independent-site upper bound.

Table 3. Modelled probability that at least one of N stations has a cloud-free line of sight. $p = 0.45$, decorrelation length 600 km.

Site separation	$N = 1$	$N = 2$	$N = 3$	$N = 4$
250 km	45.0 %	58.4 %	65.4 %	69.8 %
500 km	45.0 %	62.7 %	72.0 %	77.8 %
1000 km	45.0 %	66.8 %	78.5 %	85.4 %
2000 km	45.0 %	69.2 %	82.4 %	89.8 %
Independent limit	45.0 %	69.8 %	83.4 %	90.8 %

The increment from one station to two is 18 to 24 percentage points depending on separation. The marginal gain is largest for the second station and diminishes beyond three. Beyond approximately 1000 km of separation the correlation term becomes negligible, and little is gained from spacing stations further apart than a typical synoptic system. A three-station network at 1000 km spacing reaches 78.5 % against 45 % for a single site, which is a factor of 1.74 in usable passes and, to first order and neglecting the elevation dependence of key rate, a comparable factor in cumulative key.

Two effects are not captured, both of which favour diversity. Separated stations observe partly distinct pass geometries, so the network gains coverage in addition to redundancy; and a deployable station can be repositioned seasonally or in response to forecast, which is not available to a fixed network. The model is, however, static. It uses a single decorrelation length, ignores persistence and diurnal structure, and assumes identical stations. Substituting measured multi-year cloud climatology at candidate sites, in the manner of [10] and [12], is the natural next step and is planned as part of UK site selection.

Comparison with Section 6 gives the central result. The deployable architecture forgoes 0.6 dB of aperture and a few tenths of a percent of QBER, while three such stations return a factor of approximately 1.7 in delivered key. On the assumption that three deployable stations can be fielded for cost and schedule comparable to one fixed installation, the trade favours deployment.

8. OPERATIONS

The optical payload stows on a lift occupying roughly half of a twenty-foot container, under a closed roof. For on-sky work the roof opens and the lift raises the payload clear of the container for an unobstructed field of regard. Available volume for the receive bench and peripherals is set by the lift platform area, this is the constraint governing the telescope selection of Section 3.1.

Control is distributed. Each MUBS runs its own pointing and tracking loop on a local single-board computer, with an FPGA carrying the real-time control, and reports telemetry to a payload computer that also drives the receive bench, wide guide scope and mount. Software is organized as microservices over a publish-subscribe message bus, so that a peripheral can be added, replaced or run standalone without modification elsewhere. This matters more for a system reconfigured between deployments than for a fixed installation.

The payload state machine has four modes: standby, calibration, observatory and acquisition. Calibration mode exists specifically for deployment: it plate-solves through the wide guide scope to establish the mount coordinate frame, then co-aligns the Tx scope, fine guidance and quad cell fields against a star field. On a fixed station this is a commissioning

activity performed once. On CMOGS it is executed on every site change, and probably on every clear night; its duration is a principal contributor to the deployment timeline.

A site deployment consists of transport, levelling, power and network connection, roof and lift checkout, and optical calibration, executed in that order. Only the last of these is specific to a quantum station, and it is the item over which the design has any control.

9. CONCLUSION

Designing a satellite QKD ground station for relocation rather than permanent installation affects a specific and enumerable set of decisions. Container volume selected the telescope, at a cost of 0.6 dB. Eye-safe operation over small transmit apertures costs 7 dB of uplink power per aperture, the majority of which is recovered by adding apertures. A fiber dispersion budget of 200 ps places the single-photon detectors on the gimbal. Cost and schedule constraints on a custom polarimeter led to the replacement of closed-loop polarization frame tracking with prediction, at a cost of a few tenths of a percent QBER. The rest of the architecture, including the dichroic cascade, the quad-cell tracking chain, the four-state analyzer and the spiral acquisition, is what any satellite QKD ground terminal would need.

These penalties are small relative to the availability gain obtained from geographic distribution. Under a conservative correlated-cloud model, three separated stations raise usable pass availability from 45 % to approximately 78 %. For operational QKD services, for which key delivered per month is the relevant figure of merit rather than best-case key rate under clear skies, the deployable architecture is preferred. Breadboard integration is under way and the first deployed campaign is planned for the UK site.

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