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Bright Entangled Light Sources for Aerospace Applications

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Alexander Ling

ABSTRACT

A high brightness high quality entangled photon source which can be used to perform satellite to earth quantum communication has been developed using a liner design. A compact ruggedized version of the source is built for its application in field deployment. A measurement system to monitor the sky brightness is developed and it is used for the survey of potential ground stations for satellite to earth quantum communication.

Accomplishments

Research Objectives:

Entangled photon sources and the receivers are necessary technologies for quantum communication. For long distance and line of sight quantum communication, free space links are preferred. These are typically satellite-to-ground, satellite-to-satellite, or aircraft-to-ground communication links. One of the requirements for these implementations is a bright, high quality entangled photon source which needs to be deployed in the harsh environments such as satellite or aircraft. Though conventional Sagnac interferometer designs offer good performance the inherent instability of interferometers makes it harder to develop a compact ruggedized source.

Another major challenge in the free space quantum communication implementation is the background noise that reaches the quantum receiver. Urban environments have relatively bright night sky which pose a threat to the quantum communication. So before determining the location of a ground station, which is essentially a telescope coupled to a quantum receiver, one needs to do survey on the night sky brightness in order to ensure the signal to noise ratio is sufficient to establish the quantum communication. One possible mitigation strategy would then be to limit the Full Field-of-View (FFOV) of the receiver to reduce background noise by spatial filtering. A key design parameter would be to identify an appropriate size for the pinhole. The survey result will be crucial in designing a ground station at its location.

This project addresses both of these challenges. In the first objective, we develop a linear, compact, high brightness and quality entangled photon source which is ruggedized for field deployment. In the second effort for understanding the amount of stray light that will be received by a terrestrial quantum receiver we have built a dedicated instrument that involve a small aperture telescope and a single photon detector. This instrument can be used to measure the night-time sky brightness for an urban location such as Singapore. From the measurement result the noise levels of an actual telescope is predicted and this derives the requirement in terms of maximum field of view for achieving successful quantum communication.

- Please provide details of accomplishments during this reporting period.
 - Development of a source of entangled photons suitable for use in satellite to ground quantum communication. The fibre coupled source produces high quality entangled photon with fidelity 0.985. The observed brightness of the source is 450k pairs/s/mw which correspond to the generated brightness of 9.3M pairs/s/mw. With a laser of 40 mW one can reach upto a generated count rate of 372 M counts/s. This is suitable for any free space quantum communication as well as basic science experiments using entanglement.
 - The other major activity was the construction of surveying instrumentation that could be used to measure the sky brightness over tropical Singapore, during night time. This was important, because an optical receiver of satellite signals would see this background light. These results were also published as Conference Proceedings (see below).

- How were the results disseminated to communities of interest? If there is nothing significant to report during this reporting period, state “Nothing to Report.”
 - A. Lohrmann, C. Perumangatt, A. Villar, and A. Ling, Broadband pumped polarization entangled photon-pair source in a linear beam displacement interferometer, *Appl. Phys. Lett.* **116**, 021101 (2020).
 - Clarence Liu, Srihari Sivasankaran, Esther Wong, Peng Kian Tan, Moritz Mihm, Christian Kurtsiefer and Alexander Ling, Designing an optical ground station in an urban environment for satellite-based quantum communication, Poster at the Institute of Physics Singapore Meeting 2021
 - Clarence Liu and Alexander Ling, Considerations for satellite QKD in an urban environment, Oral Presentation at SPIE Defense + Commercial Sensing, Orlando, FL, USA 2022

Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

Development of the principal discipline(s) of the project

The primary contribution of this project has been in identifying a possible design for an entangled photons source fitted to a CubeSat capable of transmitting quantum-limited photons from a LEO satellite to an optical ground receiver. Since then, many groups around the world have also started reporting their designs for CubeSats. This project was one of the first to share its findings.

The other contribution is that sky brightness survey concluded that a tropical urban location such as Singapore, which is at sea level, had acceptably low levels of background light. This would enable satellite to ground quantum communication in the absence of clouds. It appears that urban solid state lighting does not emit a lot of light in the NIR and telecom regime, which is the preferred spectral range for quantum signals from satellites.

Other disciplines:

This work has also advanced a general appreciation for how laser communication from small satellites might be conducted to ground receivers in a tropical, urban location.

Describe the impact in this reporting period on the development of human resources

A young researcher, Clarence Liu, was working on various aspects of this project. He has

continued his interest in quantum technology and is now pursuing a PhD at the National University of Singapore.

The findings used in this project have also been used in various outreach materials by the University in its efforts to inform the public of the progress in developing quantum technology that can be deployed. Members of the project regularly use findings of the project in outreach activity.

Describe the impact on teaching and educational experiences

The instrumentation used for the sky brightness survey has been shared with colleagues interested in astronomy.

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

Outcomes from this project have been added to the growing body of evidence that quantum communication with satellites is possible. One positive outcome, has been the funding provided by other stakeholders to establish an optical ground receiver on the National University of Singapore campus, for receiving signals from satellites.

Impact on society beyond science and technology:

Not relevant.

Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the project or its direction. Sections may include:

Changes in approach

There were no changes in approach. The overall goal had always been to bring the technology to a point where satellite to ground quantum communication was possible. We also collected evidence that suggested that ground receivers in tropical, urban locations did not suffer from excessive background light and could conduct satellite to ground quantum communication.

Problems or delays

The major problem was the COVID-19 pandemic that made delayed a number of actions related to the project.

Expenditure Impacts

There were no significant impacts on expenditure.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards

Not applicable.

Changes to the primary place of performance from that originally proposed

Not applicable.

Technical Updates

Since the conclusion of this project, the PI and his team has continued to work on enabling satellite to ground quantum communication. A major development is that in Q12024, a dedicated optical ground receiver will be completed on the campus of the National University of Singapore. The AFOSR is invited to visit the site for further discussions to discuss possible future collaboration.

Attached is also the final report submitted in March 2021.

30th March 2021

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Period of Performance: 09/25/2018 – 31/12/2020

Abstract: A high brightness high quality entangled photon source which can be used to perform satellite to earth quantum communication has been developed using a linear design. A compact ruggedized version of the source is built for its application in field deployment. A measurement system to monitor the sky brightness is developed and it is used for the survey of potential ground stations for satellite to earth quantum communication

Introduction:

Entangled photon sources and the receivers are necessary technologies for quantum communication. For long distance and line of sight quantum communication, free space links are preferred. These are typically satellite-to-ground, satellite-to-satellite, or aircraft-to-ground communication links. One of the requirements for these implementations is a bright, high quality entangled photon source which needs to be deployed in the harsh environments such as satellite or aircraft. Though conventional Sagnac interferometer designs offer good performance the inherent instability of interferometers makes it harder to develop a compact ruggedized source.

Another major challenge in the free space quantum communication implementation is the background noise that reaches to the quantum receiver. Urban environments have relatively bright night sky which pose a threat to the quantum communication. So before determining the location of a ground station, which is essentially a telescope coupled to a quantum receiver, one needs to do survey on the night sky brightness in order to ensure the signal to noise ratio is sufficient to establish the quantum communication. One possible mitigation strategy would then be to limit the Full Field-of-View (FFOV) of the receiver to reduce background noise by spatial filtering. A key design parameter would be to identify an appropriate size for the pinhole. The survey result will be crucial in designing a ground station at its location.

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High performing entangled photon source for aerospace application:

Photon pairs that are entangled in energy and time or position and momentum, can be readily obtained using parametric down conversion where one high energy photon is split into two low energy photons. However, measurements of these degree of freedom are complex and often involves large interferometers. Polarization, on the other hand, can be easily measured using wave plates and polarizing beam splitters. For achieving polarization entanglement, SPDC photons produced from two pump decay paths with orthogonal polarization, need to be superposed [1].

Many designs for high performing entangled sources make use of a Sagnac interferometer. In this case, the phase stability of the entangled state generated is related to the alignment stability of the mirrors used in the interferometer with counter propagating pump beams. Moreover, Sagnac designs suffer from a relatively large footprint that is required for the interferometer. Therefore, instead of the common Sagnac source, we use a linear displacement interferometer based design [2] in which two displaced pump beams co-propagate inside a second order non-linear crystal. Such linear designs can be more compact and are particularly easy to align.

Design:

The source concept is given in Figure 1 . The pump beam with diagonal polarization is split into horizontal and vertical polarization component using spatial walk off from a birefringent crystal (BBO- beta barium borate). The horizontally polarized pump beam is converted to vertical polarization using a half wave plate. A periodically poled potassium titanyl phosphate (PPKTP) crystal kept at a constant temperature inside an oven is used as the second order non-linear crystal for SPDC. The crystal is oriented such that the vertically polarized pump photon with 405 nm wavelength is down converted to two vertically polarized daughter photons (type-0) with wavelengths 785~nm (signal) and 837~nm (idler). The phase matching is achieved by turning the temperature of the crystal using an oven. The polarization of SPDC photons from one of the pump decay path (the bottom path in Figure 1) is converted to horizontal and the two decay paths are superposed using another birefringent crystal of appropriate length.

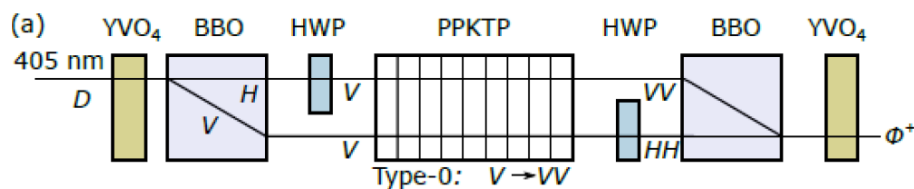


Figure 1: Linear design for entangled photon source.

Propagation of SPDC photons through the birefringent crystal can introduce a wavelength dependent phase between the orthogonal states. This reduces the entanglement quality. To compensate for the wavelength dependent phase a Yttrium Orthovanadate (YVO4) crystal is introduced. We also employ a pre-compensating crystal in the pump beam path, with which the phase introduced by different pump wavelength is always constant. This is helpful to ensure that the generated state is resilient to the changes in the pump laser wavelength that are generally associated with volume holographic grating laser diodes. Moreover, with this pre-compensation, one can use broadband free running laser as pump without compromising on the entanglement quality.

Fiber coupled entangled photon source

We have built a portable fiber coupled entangled. The design is given in **Figure 2**. In the source the photon pairs are separated into individual photons called signal and idler using a

dichroic mirror and coupled into single mode fibers. The output of the single mode fiber can be connected to the telescope interface or detection system for its use in quantum communication. The phase between two orthogonal polarization state is important and it needs to be kept constant over the period of the experiment. For this, a liquid crystal retarder (LCR) is inserted in the beam path which can nullify any phase offset. The entanglement quality is measured from the two photon polarization correlation (See Figure 3 (left)). The photo of the fully assembled unit is given in Figure 3 (right).

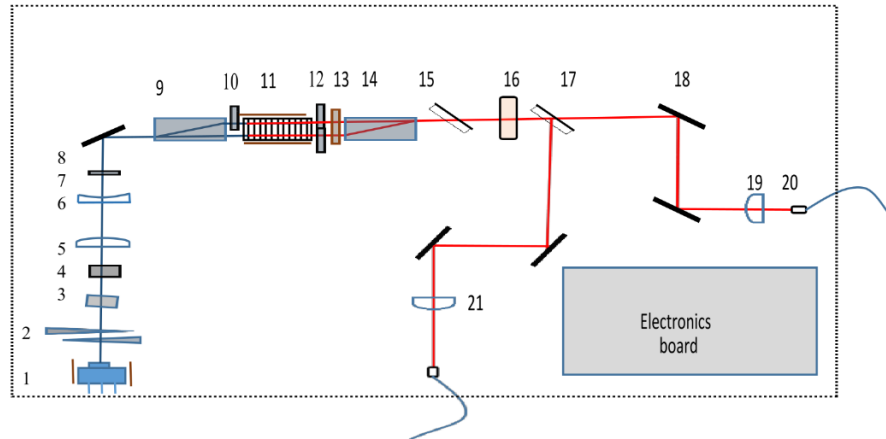


Figure 2: Design of the fiber coupled entangled photon source. 1- laser diode, 2-prism pair, 3- fluorescence filter, 4- neutral density filter, 5,6- focusing lenses, 7, 13- YVO4s, 8-mirror, 9,14- BBOs, 10,12- wave plates, 11-PPKTP in an oven, 15- dichroic mirror for removing the pump, 16- liquid crystal for adjusting the phase, 17- dichroic mirror that separate signal and idler photons, 18- gold coated mirror, 19,21 – achromatic lenses, 20 – single mode fiber (HP 780).

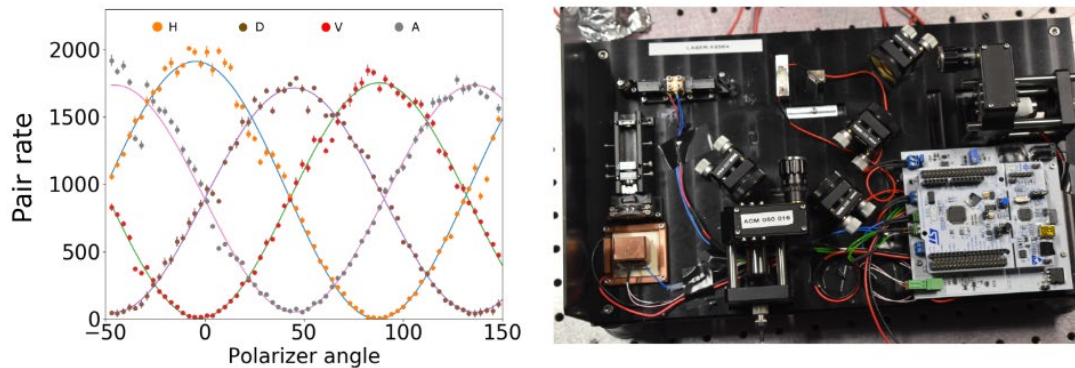


Figure 3 (left) Polarization correlation curves. H, D V and A correspond to horizontal, diagonal, vertical and anti-diagonal polarization projection on one photon. The state of the other photon is projected to different polarization states using a rotating polarizer and pair rate represents the coincident counts per second. The average visibility is 97% which corresponds to a fidelity of 0.985. The loss in visibility in the D and A curves are due to the polarization dispersion due to the dichroic mirror reflection. (right) Fully assembled entangled photon source. Dimension: 8cm x 20cm x 30cm and weight: 3.2 kg.

Performance of the source

The fibre coupled source produces high quality entangled photon with fidelity 0.985. The observed brightness of the source is 450k pairs/s/mW which corresponds to the generated brightness of 9.3M pairs/s/mW. With a laser of 40 mW one can reach up to a generated count rate of 372 M counts/s. This is suitable for any free space quantum communication as well as basic science experiments using entanglement.

Background sky-brightness estimation

The main objective of this experiment is to measure the background of the night-time skylight. This is in turn essential in estimating the signal to noise ratio for the optical ground

station (OGS). This section describes the experimental setup used for this measurement and the results obtained from the overnight measurements at various locations.

Requirements

We derive the requirements for the measurement from our OGS requirements, considering the quantum signal that is to be received by the OGS telescope.

- The spectral window of the measurement should overlap with the optical beam of interest from the optical payload on satellite.
- The measurement device should incorporate calibrated free space single photon avalanche detectors (SAP500T8)
- The interested elevation angle ranges from near horizon to zenith along the north-south direction, 20° – 90°.
- The measurement device should be light tight, i.e., should block out the stray light from entering the optical system.

Background

The background skylight is characterized [3,4] power which follows the equation,

$$P_b = H_B * \Omega_{FOV} * A * \Delta\lambda \quad (1)$$

Where, H_B is the brightness unit of the sky [$W/m^2/Sr/nm$], A is the effective area of the aperture of the objective lens [m^2], $\Delta\lambda$ is the spectral filter's bandwidth [nm], Ω_{FOV} is the solid angle field of view [Sr]. From the above equation, the background count rate [N_B] is,

$$N_B = \frac{[P_b * \lambda]}{[h * c]} \quad (2)$$

$$N_B = \frac{H_B * \Omega_{FOV} * A * \Delta\lambda * \lambda}{h * c} \quad (3)$$

$$\Omega_{FOV} = \frac{\pi}{4} [\theta_{FOV}]^2 \quad (4)$$

$$\theta_{FOV} = 2 * \text{atan} \left[\frac{d_{ph}}{2 * F_{eff}} \right] \quad (5)$$

Where, h is the Planck's constant [$J s$], c is the speed of light [$m s^{-1}$], θ_{FOV} is the full field of view [rad], d is the size of the spatial filter (PH) [μm], F_{eff} is the effective focal length of the optical system.

Design:

Based on the requirements, we design an optical system described in Figure 4. A plano-convex lens of 1-inch diameter is used as the primary lens of the optical setup. A spatial filter (pinhole) of 50 μm is introduced at the focal plane of the objective lens. An aspheric lens is introduced to collimate the beam output from the spatial filter. A bandpass filter is placed within the collimating section, as per the required spectral window. The light is then focused onto a free-space single photon detector using another aspheric lens.

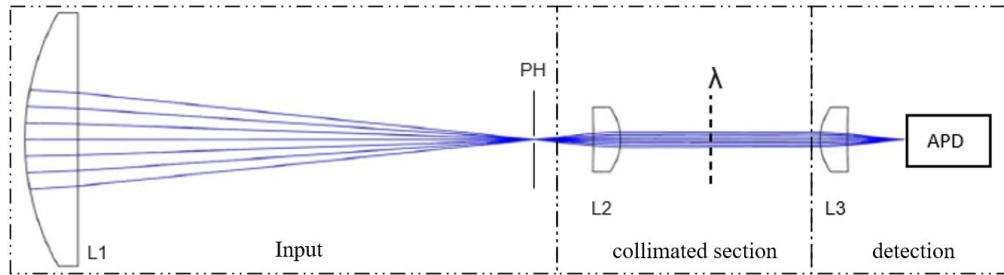


Figure 4: Optical layout of a single telescopic setup for the measurement of background light. L1: Plano-convex lens LA1131-B (f=50mm, dia: 25.4mm), L2 & L3: aspheric lens A397TM-B (f:11mm, dia: 9mm), λ : bandpass filter (optional), PH: spatial filter (pinhole), APD: Free-space single photon detector (SAP500 T8)

Setup & alignment:

For the experiment, we build two setups as described in the design. Each setup has an identical twin setup design where the only difference is that the second setup has no bandpass filter. Figure 5 shows the experimental devices assembled based on the design given in Figure 4.

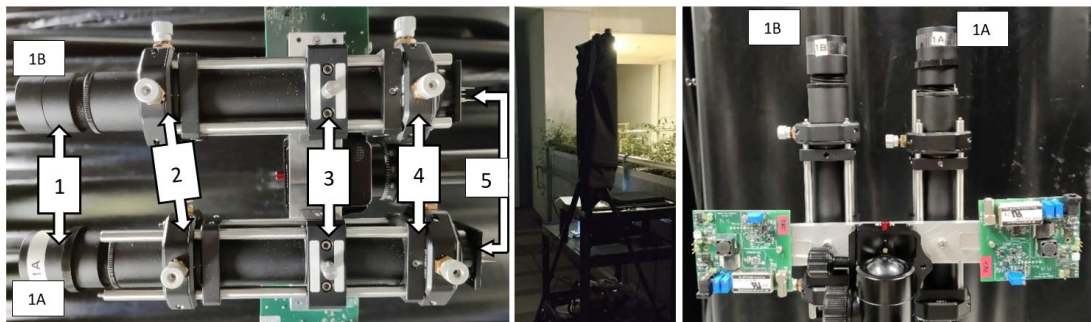


Figure 5 : The figure illustrates the measurement developed. (a) *left* – the two setups developed 1A and 1B are identical except the device on the top of the picture has no bandpass filter in slot 3. The components are based on the optical design layout, [Slot 1]: L1 (Plano convex lens), [Slot 2 & 4]: XY stage, [Slot 3]: bandpass filter, [Slot 5] SAP500 APDs in a XY stage. (b) *center* – depiction of the experiment setup after assembling the components onto a tripod stand. (c) *right* – setup image along with the quenching circuit.

We aligned each of the optical setup by introducing a collimated beam at the input of the objective lens. The pinhole and the APD were aligned to optimal position using a XY stage. Light collected is detected using a passively quenched avalanche photodiode with inbuilt TEC (SAP500T8s). The detection efficiencies of these passively quenched APDs were pre-determined by comparing their count rates with a commercial single photon counting module.

A bandpass filter, λ , centered at a wavelength of 810 nm with a Full-Width-at-Half-Maximum of 20 nm is included in device 1A. 1B acts as a reference telescope monitoring the sky without any filter.

Experimental procedure:

The setup is isolated from the background scattered light using a black cloth. The dark count of the apds are measured initially by recording the count rate with the lens covered. Removing the cover over the aperture, the device is exposed to the night sky and the count rate is recorded over the course of a night which lasts for about 6-8 hrs. In addition, photographs of the night sky using a camera were taken at hourly intervals to monitor the changes in the sky condition. The photographs can then be used to correlate with changes in the counts observed. A higher counts observed in the detector usually correlates with clouds passing over the sky reflecting off the light from the ground, which can be verified with the corresponding images.

Sites:

The measurements were conducted at the vicinity of the Centre for Quantum Technologies (NUS) and at other locations as part of our optical ground station survey. Photographs of the sites where the measurements were conducted, are given in Figure 6. Our measurements were mainly conducted on reasonably clear nights, resembling to the conditions at which optical ground station would operate.

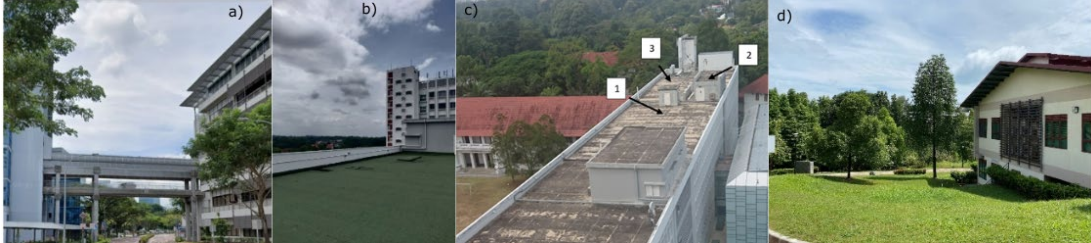


Figure 6: Site locations – (a) left: Centre for Quantum technologies, NUS (1.2973078078390918, 103.78033971392504), (b, c) Bukit Timah Campus, NUS (1.3191342758271596, 103.81704721349182), (d) St. Johns island site (1.217164636811086, 103.850138)

Results & discussion:

Figure 7 shows the background count rate observed by the instrument plotted against the observation time. For example, on 20th August 2020, we started the experiment at around 10 pm (SGT) and ended the experiment at around 5 am (SGT) the next day morning. The background count rates are scaled up for compensating transmission losses and relative detection efficiencies.

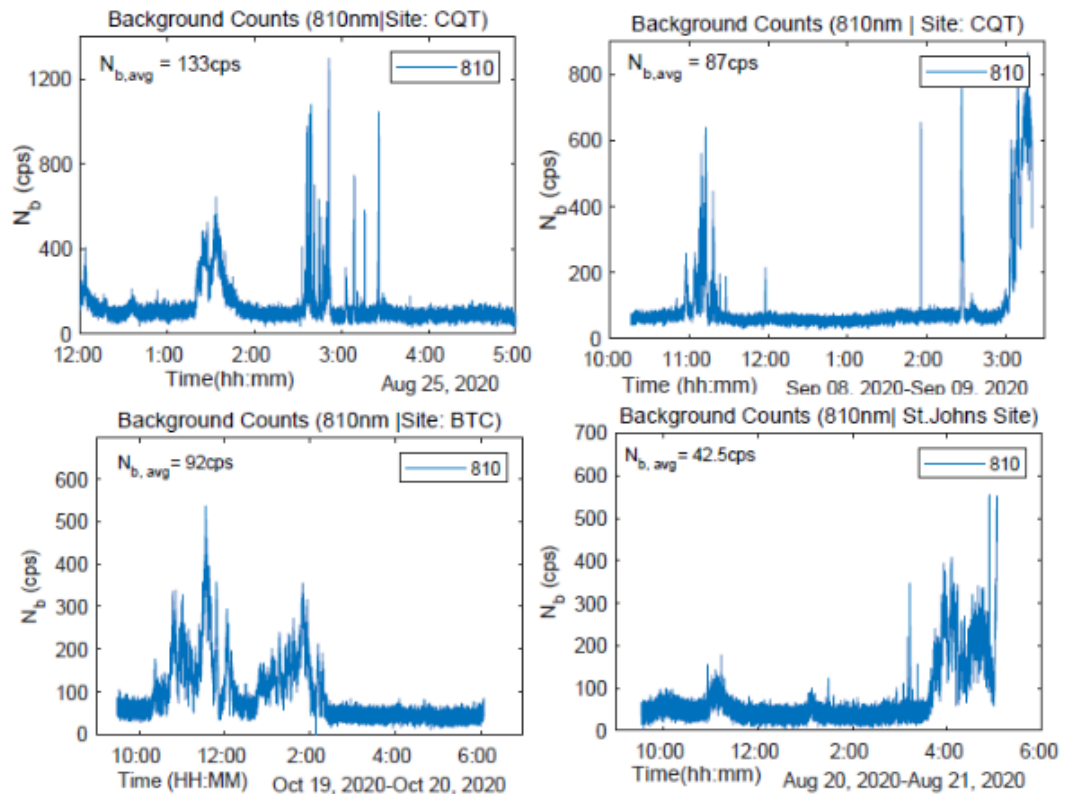


Figure 7 The plots show the observed count rate from the night sky within the field of view of 1 mrad (~200arc sec). Each plot represents the experimental data measured at different location (as mentioned in the plots).

Considering the measurements taken on 20th Aug 2020 at St. Johns site, we see a rise in the count rate around 11.30pm, similarly from 4am we observe higher count rates up to 600cps. Correlating these change in count rates with our hourly photographs logs monitoring the local variation in the night-sky, we observe few clouds passing by around 11.30pm and also around 4am (Figure 8 – b,e,f). This could mean the increased counts observed are contributed by the clouds reflecting back the photons from the ground. The average background count rate over the course of each experiment is indicated, ranging between 42 counts per second (cps) to 133 cps with varying weather conditions. The experiments were conducted at a total of three unique sites over Singapore, with the Saint John’s Island being an offshore location. From the measurements, we see no significant difference in background count rate at the different sites, which could be confirmed with more measurements at these sites on other days. Spikes in the instantaneous background count rate were found to correlate with instances where a cloud loomed or passed over the instrument’s field of view.

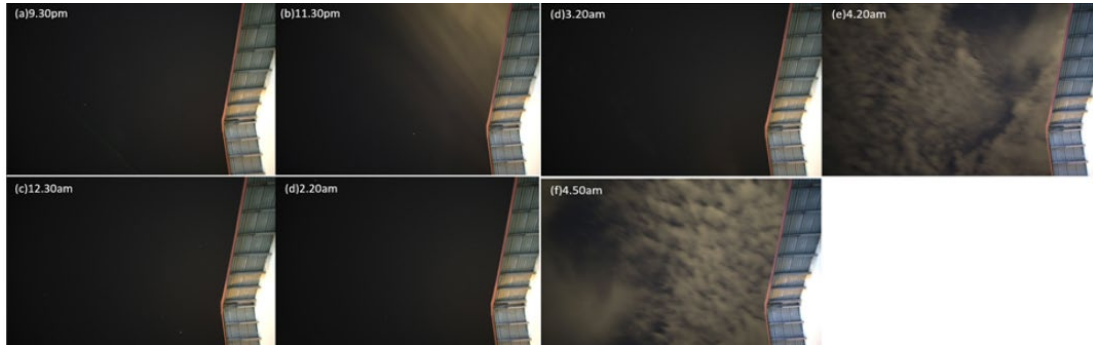


Figure 8: Pictures representing the hourly monitored photos of the night-sky from 9.30pm to 4.50am. These pictures correspond to the measurement conducted on 20th Aug 2020, at St. Johns site (refer Figure 7 plot – top left). The photos taken are representative of the sky that the experiment setup is pointing at.

From the above plots we observe a maximum of 133 counts per second as the average count rates for clear sky segments. From equations (3) - (5), we derive the following relation that would enable us to translate the observed count rates to be scaled up to any similar desired optical setup.

$$N_B = \frac{H_B * \frac{\pi}{4} * (2 * \text{atan}(\frac{d_{ph}}{2 * f_{eff}}))^2 * A * \Delta\lambda * \lambda}{h * c} \quad (6)$$

$$\frac{N_b}{N'_b} = \left(\frac{d_{ph}^2 * A}{f_{eff}^2} \right) * \left(\frac{F_{ph}^2}{D_{ph}^2 * A'} \right) \quad (7)$$

where, N_b observed count rate of the system and N'_b is the count rate of the OGS setup scaled up from our measured count rate. The expected count rates for the OGS setup can be estimated using Eq. (7). The relevant parameters for the OGS parameter are referred in table 1. From the measured count rate of 133cps, we use the relation (7) to estimate count rate for the OGS setup to be about ~ 450 counts/sec.

Table 1: Table of optical parameter of the measurement device and OGS setup

Measurement Device		OGS Setup	
d_{ph}	50 μ m	D_{ph}	300 μ m
f_{eff}	50 mm	F_{eff}	3972 mm
θ_{FOV}	1 mrad [~200 arc sec]	θ_{FOV}'	15.6 arc sec
A	20.27 cm ²	A'	1.168 m ²
N_b	133 counts/sec	N'_b	~ 450 counts/sec

D_{ph} (μm)	θ_{FOV} (arc sec)	N_B (counts/sec)
50	2.59	12.33
60	3.11	17.76
100	5.19	49.35
150	7.78	111.04
200	10.38	197.40
250	12.98	308.45
300	15.57	444.17
350	18.17	604.56
400	20.77	789.63
500	25.96	1233.8

Table 2: OGS setup's estimated background counts for varying full field of view.

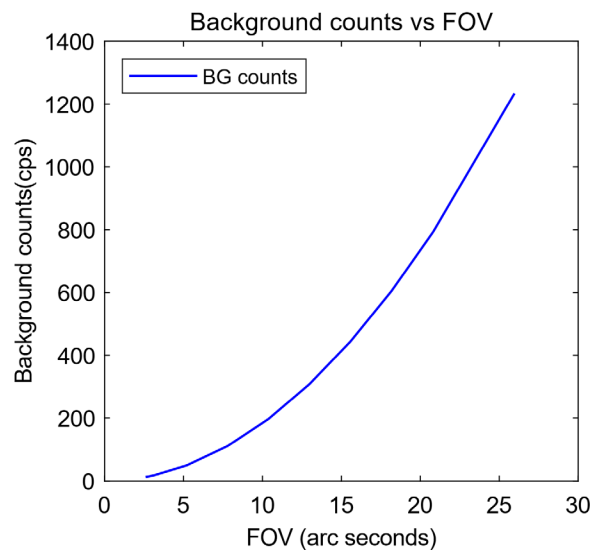


Figure 9: Estimated background count rate and Signal to noise ratio against OGS's . This estimation is based on our measured count rate for the experiment setup.

The estimated background count rates for change in FOV and the corresponding SNR are shown in table 2 and Figure 9.

List of Publications and any Significant Collaborations that resulted from your AOARD supported project: No publications have been made yet, but we have started a very productive collaboration with the research team of Prof Keri Cahoy of MIT. Prof Cahoy's team will be developing a design for a CubeSat telescope that can be used to transmit entangled photons from our source to ground. This is complementary to our ongoing research effort with RALSpace (UK). We expect a joint paper at the SmallSat conference later this year, and an extended report on the night sky brightness survey.

Reference:

- [1] A. A. M. Abdulla, C. Perumangatt, F. Steinlechner, T. Jennewein, and A. Ling, ArXiv 1 (2020).
- [2] A. Lohrmann, C. Perumangatt, A. Villar, and A. Ling, Appl. Phys. Lett. **116**, (2020).
- [3] E. L. Miao, Z. F. Han, S. S. Gong, T. Zhang, D. S. Diao, and G. C. Guo, New J. Phys. **7**, 0 (2005).
- [4] C. Bonato, A. Tomaello, V. Da Deppo, G. Naletto, and P. Villoresi, New J. Phys. **11**, (2009).