Optical noise in a free-space quantum communications link from natural and nuclear disturbed environments

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Abstract

Satellite communications at radio frequencies can experience a ‘blackout’ period following the atmospheric detonation of a nuclear weapon. The wavelengths used for free-space quantum communications will not incur the same ‘blackout’ effects from a nuclear detonation, but the optical systems will suffer from a phenomenon called redout. Redout occurs in an optical detector when ambient light scatters into the optical receiver, causing elevated background photon counts in the detector such that background noise overwhelms the signal. In this work, the duration of the redout effect is quantified from a nuclear disturbed environment on a ground-to-space quantum optical link. In addition, we comment on various techniques for reducing ambient and nuclear disturbed background counts in a quantum free-space optical link. For low-altitude nuclear detonations (i.e., under 50 km), the maximum interference time will be less than 1 min. Implementing a telescope, timing gate, and wavelength filter to the detector can reduce the background counts in the detector significantly. Aerosol levels and ground albedo are major contributors to background noise in a ground-to-satellite quantum channel, and ground station location should factor in both variables.

1. Introduction

The reliable transmission and collection of quantum signals between ground stations and satellites will be important for many large-scale quantum communications networks—and this will be a requirement if such networks are deployed before the practical implementation of quantum repeaters. Entangled photon sources used for quantum communications through the atmosphere typically operate in the visible or near-infrared (NIR) portions of the wavelength spectrum. Successful distribution of entanglement requires a quantum channel that preserves quantum state fidelity. State fidelity is affected not only by changes to the...
original state as it propagates, but also by the collection of light from other primary or secondary sources emitting photons into the channel. In fiber-optic channels, for example, these background photons can arise from Raman scattering \[1\] or light leakage (crosstalk) from adjacent optical signals. In a free-space channel between ground and satellite, the atmosphere acts as a secondary source, scattering photons into the quantum channel. As a result, the majority of space-based quantum communications experiments have been conducted during the night to reduce the background noise collected by the detector \[2–5\]. Recent research on daytime optical link communications has sought to reduce the effects of background light by using enhancements such as adaptive optics \[2\], a small field of view (FOV) telescope, wavelength filters, or a timing gate \[6\]. Although the continued development of techniques for distinguishing quantum signal from background will help to expand the operational range of quantum communications systems, background photons cannot be eliminated entirely. Thus, their presence imposes practical limits to the performance of a quantum communications system. It is therefore important to understand the underlying physical mechanisms for the ambient background photon rate and how certain atmospheric properties can affect the expected rate of background photons scattered into a quantum channel.

For a given quantum communications system, it is possible to estimate the impact of light scattered into the quantum channel for various daytime and nighttime conditions using established values for the brightness of sky background \[7\]. Unfortunately, these techniques are limited to typical atmospheric conditions since sky brightness data does not exist for atypical atmospheric events. This paper outlines a technique for estimating the background count rate due to light that is generated by atypical atmospheric events and subsequently scattered into a quantum channel. This technique is then applied to an atypical atmospheric event (a nuclear detonation), and various detector/optics setups and strategies are analyzed for reducing the background photon count rate in the channel. This manuscript covers only light interference in a quantum channel from a nuclear disturbed environment; studies considering the optical channel loss from a surface nuclear blast’s ejected material \[8\], as well as the increased dark count rate of satellite-based detectors from a high-altitude nuclear detonation \[9\] will not be addressed.

2. Method

2.1. Optical link

The problem considered herein is shown schematically in figure 1, which depicts an uplink quantum communications system consisting of a ground-based source and a satellite-based receiver (the downlink case is treated similarly). A bright atmospheric disturbance (in this case, a nuclear fireball) is located some distance from the quantum channel but is positioned outside the receiver’s FOV. That is, light from the external source can reach the receiver detector only after a scattering event within the FOV.

To calculate the amount of light reaching the receiver after being scattered, consider a thin horizontal slice of the FOV at altitude $h$ and thickness $dh$, as shown in figure 1. The radius of the FOV, $R(h)$, is assumed to be small compared to its distance from the external light source. In addition, the satellite is assumed to be directly over the source so that the optical axis of the quantum channel is normal to the slice.
The case in which the satellite is not positioned directly overhead is slightly more complicated by the inclusion of factors accounting for the inclination of the FOV.

When light from the external source is incident on this slice of the FOV, a small fraction is scattered toward the satellite’s receiver. The amount of light reaching the satellite is related to the brightness of the external source, as well as the number of scatterers in the slice, the scattering cross section, the distance from the receiver, transmittance of the light from the source to the scatterer, and the transmittance of the channel. Specifically, the irradiance, \( E_{\text{I,scatter}}(h) \), at a receiver on a satellite at altitude \( H \) is related to the irradiance at the disk, \( E(h) \), according to

\[ E_{\text{I,scatter}}(h) = \left[ \sigma_R(h)\rho_R(h) + \sigma_M\rho_M(h) \right] \frac{\tau(h)E(h)}{(H-h)^2} \pi R^2(h) dh, \]

where \( \tau(h) \) is the transmittance of the portion of the channel from \( h \) to the receiver; \( \sigma_R(h) \) and \( \sigma_M \) are the scattering cross sections for Rayleigh and Mie scattering, respectively; and \( \rho_R(h) \) and \( \rho_M(h) \) are the concentrations of the corresponding scatterers (for Rayleigh scattering, \( \rho_R(h) \) is the air density, whereas for MIE scattering, \( \rho_M(h) \) is the aerosol concentration in the air). The \((1 + \cos^2 \phi_{\text{scatter}})\) dependence of Rayleigh scattering is accounted for by noting that, for small source and receiver dimensions compared to the transit distances, the scattering angle, \( \phi_{\text{scatter}} \), can be expressed as a function of the height of the FOV slice. The \( h \) dependence is shown explicitly in the above expression because the geometry of the problem suggests that the amount of light scattered into the quantum channel will vary with altitude. However, it is understood that the irradiance may also depend on other variables. For example, if the intensity of the external light source varies in time, then that behavior will be evident in the scattered light and, by extension, in the irradiance at the satellite-based receiver.

The irradiance caused by light scattered in all portions of the FOV is found by integrating equation (1) over \( h \):

\[ E_{\text{I,scatter}} = \int_0^H \left[ \sigma_R(h)\rho_R(h) + \sigma_M\rho_M(h) \right] \frac{\tau(h)E(h)}{(H-h)^2} \pi R^2(h) dh. \]

In addition to the atmospheric scattering mechanisms described above, light from the external source can enter the quantum channel via reflection from the ground and infrastructure surrounding the quantum emitter. The irradiance, \( E_{\text{I,ground}} \), at the satellite caused by ground scatter is

\[ E_{\text{I,ground}} = \alpha_g \frac{\tau(0)E(0)}{H^2} \pi R^2(0), \]

where \( \alpha_g \) is the albedo of the ground area within the FOV.

The equations above make it possible to calculate the total irradiance at the receiver due to secondary sources (atmospheric scattering and ground reflection) in terms of the external source irradiance at points within the receiver FOV. The energy reaching the detector at the receiver can be determined by integrating the total irradiance from secondary sources, \( E_{\text{I,total}} = E_{\text{I,scatter}} + E_{\text{I,ground}} \) (typically given in units of Watts per square meter per nm) over the detector area, spectral filter width, and detector integration time. Then, a simple conversion yields the number of background photons from secondary sources. This approach is most useful for atypical light sources, but it is also valid for any external source located sufficiently far away, including typical background light sources such as the Sun or Moon. Indeed, when the irradiance of the Sun or full Moon are used for \( E(h) \) in the above equations, the background count rates are in good agreement with previously published estimates [7, 10]. Comparison of our method to Bonato’s [10] for the background photon count rate in an uplink scenario for both a clear, daytime transmission and a clear, nighttime, full Moon transmission can be seen in table 1. Both methods assumed a wavelength filter of 1 nm on the detector system, a 100 \( \mu \)rad telescope, a 30 cm receiver diameter and that the satellite was orbiting directly overhead at an altitude of 400 km. Values for daytime spectral irradiance are taken from SMARTS [11] and the full Moon spectral irradiance is taken from the MT 2009 model for 800 nm [12] and the GEMINI 7 lunar measurements for 1550 nm [13]. The difference in values is from Bonato’s [10] assumption that ground scatter dominates the background photon count rate and that air scatter can be ignored for uplink scenarios. In section 4, we investigate the contributions between ground scatter and air scatter to the background photon rate and show that the dominant scatter mechanism for the background photon count rate is dependent on wavelength of the channel and the concentration of aerosols in the atmosphere.

2.2. Nuclear disturbed environment

The transmission of traditional radio frequencies (wavelengths of 1 m or more) between ground stations and satellites can be disrupted for several hours following a high-altitude nuclear detonation [14]. The
change in the electron density of the ionosphere (D, E, and F regions [15]) following a high-altitude nuclear detonation leads to the degradation of the propagation of radio frequency waves by altering the refractive index of the plasma in the upper atmosphere and through increased absorption [14]. The disruption of radio communications frequencies is commonly referred to as radio blackout. Although this blackout effect is not observed at the NIR wavelengths typically used for quantum communication, there is a concurrent effect called redout that can affect a quantum channel. Redout is a phenomenon in which the background levels of incident photons in a NIR detector are increased significantly from a nuclear disturbed environment such that the signal is obscured.

An enormous amount of electromagnetic energy is emitted by a nuclear fireball during a nuclear explosion. The exploding weapon reaches temperatures in the millions of Kelvins within the first few microseconds [14]. As a result, the weapon debris emits x-rays (along with UV, visible, IR, etc) that super-heat the surrounding air and material to form an isothermal plasma sphere. The large amount of electromagnetic energy emitted by the super-heated plasma can be quantified using Planck’s radiation law by treating the fireball as a black-body [16]. The spectral radiance of a black-body at temperature $T$ is given by

$$L_\lambda(\lambda, T) = \frac{4\pi\hbar^2}{\lambda^5} \frac{1}{\exp\left(\frac{\hbar c}{\lambda k_B T}\right) - 1}. \quad (4)$$

The spectral radiance of the fireball can be further simplified by approximating the fireball as a sphere of radius $R_{fireball}$. In this case, the irradiance at a distance $r$ from the fireball center is given by

$$E_\lambda(\lambda, T) = \frac{\pi R_{fireball}^2 L_\lambda(\lambda, T) \tau(r)}{r^2}. \quad (5)$$

In order to use this result in equations (2) and (3), it is necessary to determine the distance between the fireball and any given slice of the FOV (including the ground). For a fireball centered at an altitude of $H_{fireball}$ and a horizontal distance of $D$ from the quantum emitter, the distance at altitude $h$ in the FOV is simply $r = \sqrt{D^2 + (h - H_{fireball})^2}$. The transmittance of the photons over the distance $r$ is given as $\tau(r)$. Thus, the irradiance at an altitude $h$ in the FOV is

$$E(h) = \frac{\pi R_{fireball}^2 L_\lambda(\lambda, T) \tau(r) \cos \phi}{D^2 + (h - H_{fireball})^2}, \quad (6)$$

where $\phi$ is the angle that the rays from the fireball make with the vertical as they pass through the FOV. Noting that $\cos \phi = \frac{h - H_{fireball}}{\sqrt{D^2 + (h - H_{fireball})^2}}$, the expression above can be further simplified to

$$E(h) = \frac{\pi R_{fireball}^2 L_\lambda(\lambda, T) \tau(r)(h - H_{fireball})}{[D^2 + (h - H_{fireball})^2]^{\frac{3}{2}}}. \quad (7)$$

It is also worth noting that the scattering angle, $\phi_{scatter}$, and projection angle, $\phi$, are related via the expression $\phi_{scatter} = \pi - \phi$.

Although the expression above does not show an explicit dependence on time, the physical properties of the fireball evolve over the course of several minutes. The super-heated air of the fireball has a much lower density than the colder surrounding atmosphere and rises rapidly into the sky. The rapid ascent causes an entrainment of air underneath the rising fireball, which gives it the distinct mushroom cloud look. The entrainment of the surrounding air cools the fireball as it rises in the sky. As a result, the photon emission decreases, and the spectrum of light moves farther into the infrared portion of the electromagnetic spectrum. Besides black-body emissions, there are other mechanisms for photon emission during a nuclear blast: chemiluminescence (UV, visible range), vibraluminescence (4.3 $\mu$m emission typically), fluorescence

| Method              | Uplink, 800 nm | Uplink, 1550 nm |
|---------------------|----------------|-----------------|
| Light conditions    | Daytime       | Nighttime, full moon | Daytime | Nighttime, full moon |
| Bonato et al [7]    | $2.10 \times 10^8$ | $7.60 \times 10^7$ | $1.20 \times 10^6$ | $7.40 \times 10^2$ |
| This paper, PM10 level of 5 | $3.34 \times 10^8$ | $1.21 \times 10^5$ | $1.30 \times 10^6$ | $7.99 \times 10^2$ |
| This paper, PM10 level of 25 | $4.07 \times 10^8$ | $1.47 \times 10^5$ | $1.49 \times 10^6$ | $9.17 \times 10^2$ |
| This paper, PM10 level of 50 | $4.62 \times 10^8$ | $1.67 \times 10^5$ | $1.68 \times 10^6$ | $1.03 \times 10^3$ |
Figure 2. COMSOL simulations of the temperature, spatial, and temporal evolution of a nuclear fireball for a 100 kT detonation at a height of burst of 1 km.

(UV given off by interactions of the surrounding air with ionizing radiation) and plasmonic frequencies (RF wavelengths). Since we chose the NIR range for our detector and optical link, the only effects of concern are the black-body emissions from the fireball. In the next section, we use the commercial computational fluid dynamics code COMSOL [17] to model the time-temperature profile of the fireball as it rises into the atmosphere (and the resulting photon output).

3. Results

3.1. Low-altitude nuclear photon interference

To model the disturbance to a free-space quantum optical link in a nuclear disturbed environment (the redout time), a simulation of the temperature–size–time profile of a 100 kT (arbitrarily picked yield) fireball was created in COMSOL. We simulated a 100 kT detonation at 1, 10, 25, and 50 km heights of burst (HOB). For the COMSOL fireball simulations, the model incorporates the Navier–Stokes equations to solve for conservation of momentum and the continuity of mass, the $k−ε$ turbulence equations for air turbulence effects, and the radiative, convection–diffusion equations for heat transfer. The initial conditions of the fireball were set as an isothermal sphere with a temperature of 5000 K. The radius of the sphere was determined by the ideal gas law and Glasstone’s thermal partition of the yield versus altitude [14]. The composition of the atmosphere (temperature, humidity, and pressure conditions as a function of altitude) in the COMSOL model was taken from the US standard Atmosphere model [18]. The model was created in 2D axisymmetric geometry with a mesh size set at 10 m. The isothermal contours from the fireball rise, and expansion can be seen in figure 2 for a few time stamps for a 100 kT, 1 km HOB scenario.

The temperature of the fireball was input into Planck’s law (equation [4]) to determine the spectral radiance of the fireball as a function of time (the emissivity of the fireball was assumed to be 1). The spectral irradiance, size, and altitude of the fireball were then used as inputs into the equations from section 2 to determine the background photon count rate at the detector as a function of time. Photon scattering by air molecules was calculated using the Rayleigh scattering cross section from Bucholtz [19]. For scattering by aerosols, the Mie scattering cross sections were calculated using the PyMieScatt Python package [20]. The particle size distribution for the aerosol content of the atmosphere was calculated for four different geographic locations: (1) urban (2) desert (3) marine and (4) remote continental [21]. The particle size distribution for all of the locations were represented by a tri-modal lognormal distribution with altitude dependent concentrations up to 10 km [21]. The total concentration of the aerosol in the environment was quantified as a PM10 concentration. Aerosol PM10 concentrations are the mass of fine particulates in the air that have a diameter of less than 10 μm per cubic meter (the units are in 1 μg m$^{-3}$). Because optical links suffer high attenuation losses if clouds are present, generally rendering the link inoperable, analysis was restricted to clear days (no clouds); thus, geometric scattering from larger cloud particles was neglected. Besides the Rayleigh and Mie scattering from the air, ground scattering was included for the uplink calculation (albedo for ground scattering was set at 0.3 [22]).

Approximate values of the transmittance $\tau_{\text{channel}}$ from the FOV to the receiver were used (a uniform value per wavelength) to simplify the calculation. The transmittance $\tau(r)$ from the fireball to the FOV was explicitly calculated, as it is typically the dominant loss mechanism. Unless the fireball is located very close to the FOV, any light traveling from the fireball to the receiver via a scattering event in the FOV will experience significantly more attenuation on the first leg of its journey than on the second. This is because a
significant portion of the path from the fireball to the FOV is close to the surface of the Earth, where the air density and aerosol level—and thus the attenuation—is much higher. The $\tau_{\text{channel}}$ is usually a secondary effect (clouds and weather events can change this assumption), so this assumption changes the results by only a small margin.

The photon count rates at the detector from the fireball can be seen below in figures 3 and 4 for both the uplink and the downlink scenarios as a function of height of burst and time. To simplify the problem, we assumed that the satellite and FOV were fixed in the same location during the fireball evolution. Both figures assume the fireball is 10 km outside of the FOV during a clear, low-aerosol (PM10 level of 5) day. Scenarios involving different atmospheric conditions and distances away from the detonation are evaluated in the following paragraphs. The detector and optical link setup for the problem is based on the NASA MASCOT free-space optical link specifications [23, 24]. A single-photon detector on a satellite (International Space Station for NASA MASCOT mission) orbiting at 400 km (uplink scenario) or a detector at a ground station observing a satellite at 400 km (downlink scenario) using a telescope with a 100 $\mu$rad FOV and a 100 cm receiver. A wavelength filter of 1 nm (799.5–800.5 nm filter) was assumed to be implemented (not specified yet for NASA MASCOT mission). Scenarios involving different receiver setups are explored in the Discussion section.

The height of burst of a weapon significantly affects the duration of the disturbance to a ground-to-satellite quantum channel. At heights of burst above 25 km, the air density is low such that the fireball is not rapidly cooled by the entrainment of the surrounding air. In addition, the partition of thermal energy compared to blast is greater as the altitude increases due to the decreased interaction between the expanding fireball and the surrounding air. At a 10 km HOB, the fireball cools more quickly than at a 1 km HOB due to the relatively cooler air in the upper atmosphere. The background photon rate at 800 nm is initially higher than at 1550 nm, but as the fireball cools, the peak of the black-body spectral distribution shifts to longer wavelengths so that the 1550 nm disturbance has a longer duration. The downlink noise from the fireball is less than that of the uplink due to smaller FOV volume at lower altitudes, where scattering is more prevalent.

The distance between the FOV and a nuclear detonation has a significant impact on the amount of light scattered into the quantum channel. In figure 5, the background photon rate is calculated for an 800 nm uplink for various distances between the quantum channel and fireball. The distances include 1, 10, and 100 km away (still assuming a PM10 level of 5—visibility of 50 km) as well as a scenario where the fireball is in a quarter of the FOV. The fireball in the FOV is a worst-case scenario, as the photons emitted do not have to scatter first to affect the quantum channel; the fireball was placed in only a quarter of the cross section of the FOV as the quantum signal cannot penetrate through the fireball cloud [8] if it encompasses the whole FOV cross sectional area.

As the distance between the fireball and the FOV is increased, the amount of light scattered into the quantum channel is significantly reduced. The irradiance at the FOV decreases as the square of the distance from the fireball, as well as with increased light attenuation from photons traveling through long lengths of
Figure 4. Photon interference from a nuclear detonation for a downlink scenario involving a single-photon detector ground station with a satellite tracking telescope with a FOV of 100 μrad.

Figure 5. Photon interference at 800 nm for a satellite detector (orbiting at 400 km and with a telescope field of view of 100 μrad) from a nuclear detonation at varying distances inside and outside of the field of view of the satellite.

the lower atmosphere. Background photon rates are shown in figure 6 for several distances and aerosol concentration levels.

When the aerosol level in the atmosphere is higher, the scattering coefficient of light increases, which suggests that more light would be scattered into the quantum channel. But the larger scattering coefficient also means that less light reaches the FOV. These competing effects can be seen in figure 6. For the 800 nm wavelength, a high atmospheric aerosol concentration (PM10 level of 50), with a fireball-to-FOV distance of 10 km, the light intensity at a detector is roughly the same as a low atmospheric aerosol concentration (PM10 level of 5) with a fireball-to-FOV distance of 1 km. The increased aerosol level of the atmosphere increases the light interference if the detonation occurs close to the FOV but diminishes the light interference as the distance from the FOV increases. Lastly, the aerosol particle size distribution used in figures 3–6 are that of a remote continental location [21]. However, the particle size distributions (and, by extension, the Mie cross section values) vary with the location of the ground station; different locations and particle size distributions are analyzed further in section 4. Thus far, models for the HOB have been analyzed only up to 50 km. For detonations above 50 km height of burst, the fireball and resulting nuclear cloud physics change dramatically, so a brief discussion of those effects is presented next.
3.2. High-altitude nuclear photon interference

As the HOB of a nuclear weapon increases in altitude, the air density significantly decreases (by roughly a factor of $10^6$ between sea level and 100 km). The low density of the air increases the mean free path for x-ray interaction with the atmosphere, resulting in a significantly larger fireball. Additionally, as the altitude increases, the energy distribution of the blast changes from thermal and blast (0.35 and 0.65 respectively) at sea level to thermal and x-rays (0.6 and 0.2 respectively) at 60 km [14]. Below 50 km, the fireball expands to pressure equilibrium and then rises buoyantly as an under-dense bubble, with vortex flow generating a toroidal cloud (mushroom cloud). Above 50 km HOB, the fireball is over-dense, and the cloud rises ballistically into the atmosphere due to the low-density gradient [25]. As a result, for detonations between 50–100 km, a high-temperature shockwave is formed by the rising nuclear fireball that propagates throughout the upper atmosphere. This phenomenon was seen during one of the historic high-altitude nuclear tests, Hardtack TEAK, which had a HOB at 76.8 km. An image from the TEAK test (taken over 700 miles away in Hawai‘i) can be seen in figure 7. The fireball is the white area in the center of the photograph, whereas the reddish airglow surrounding the fireball is from the air heated by the shockwave propagating through the upper atmosphere. Witnesses of the TEAK shot reported that the ‘fireball turned from light yellow to dark yellow to orange to red. The red spread in a semicircular manner’, (high-atmospheric shockwave) ‘until it seemed to engulf a large part of the horizon’, and ‘remained clearly visible in the southwestern sky for half an hour’ [26]. We simulated the physics of a nuclear detonation at this altitude range (between 50 and 100 km) by creating a COMSOL model of a 100 kT detonation at a 60 km HOB. The simulation results can also be seen in figure 7. Our COMSOL models show a similar result, as the ballistic rise of the fireball creates a high-temperature shockwave that propagates throughout the upper atmosphere. The optical effects from a high-altitude detonation ‘shocked air’ scenario are not well understood. If the shocked air radiates significantly as a black-body emitter, then the methods outlined above should provide good estimates of background photon rates. However, a report by Holland et al [27] claims that the airglow seen in figure 7 is due to the atomic oxygen excitation peak (emitted wavelengths at 650 nm) and would thus not likely cause a significant disturbance at the wavelengths considered here. We leave this question as future work.

For detonations above 100 km, the density is low enough that most of the x-rays escape out to space or are absorbed in the x-ray pancake: x-rays emitted in a downward direction are mostly absorbed at an altitude of around 80 km, forming a cylindrical area or pancake of super heated air [14]. The result is thus a UV fireball from the interaction of the expanding weapon debris with the surrounding ultra-low dense air. The fireball begins to elongate caused by the density gradient and its shape is affected by the Earth’s magnetic field. The fireball and x-ray pancakes are both incandescent and would generate photons that could be scattered into a quantum channel. Historic literature has measured the fireball and incandescent x-ray pancakes to be visible in the sky for approximately 15 to 30 min [27].

Figure 6. Photon interference at 800 nm for a satellite detector (orbiting at 400 km and with a telescope FOV of 100 μrad) from a nuclear detonation at varying distances outside the FOV and with different aerosol levels present in the atmosphere.
3.3. Quantum bit error ratio

To relate the increased noise to a quantum communications protocol metric, we consider the quantum bit error ratio (QBER) [29, 30] which is the ratio of erroneous qubit measurements over the total number of measured qubits. The QBER is commonly used as a metric for the performance of quantum key distribution (QKD) protocols. The errors (false detections) can occur from many sources including dark counts in the detector, interference from natural or artificial light sources, or eavesdroppers in the quantum channel. We further consider the specific QBER for a BB84 decoy state QKD protocol, which is given by [31, 32]:

$$\text{QBER} = \frac{e_0 Y_0 + e_{\text{detector}} (1 - e^{-\eta \mu})}{Y_0 e^{-\eta \mu} + 1 - e^{-\eta \mu}}. \quad (8)$$

where $e_0$ is the background error rate, $Y_0$ is the background count rate, $e_{\text{detector}}$ is the probability a photon goes to the wrong detector, $\eta$ is the overall transmission including the channel transmission, detection efficiency, and transmitting optics efficiency, and $\mu$ is the light intensity (mean photon number per transmit pulse). To calculate the QBER for an example uplink scenario in a nuclear disturbed environment, we assume that there is approximately 34 dB of loss in the quantum optical channel [8] due to the turbulence, atmospheric loss (absorption and scattering), and diffraction loss. This translates to a transmission probability of approximately $\eta = 0.04\%$. We do not include any additional loss from pointing and tracking errors or transmitting/receiving optical inefficiencies. The background counting rate $Y_0$ is the detector dark count rate and background counts from light scattering into the detector. We assume that operations are taking place during a full moon clear night and the lunar spectral irradiance $E_{\text{FM}}$ is approximately 3600 W m$^{-2}$ [12] for 800 nm and approximately 1500 W m$^{-2}$ [13] for 1550 nm. The background is random and therefore, $e_0 = 1/2$. We assume the satellite is outfitted with a superconducting nanowire single photon detector (SNSPD) that has a dark count rate of 100 Hz and perfect photon detection efficiency (PDE); though in practice the PDE of SNSPDs can range from $\sim 85\%$–$\sim 98\%$ [33], this is a good approximation since the bulk of inefficiency is due to the channel loss. The probability of the photon going into the wrong detector is $e_{\text{detector}} = 0.01$. Our goal is to bound the QBER with these parameters. All other detector parameters remain as previously mentioned ($\gamma = 100 \mu\text{rad}$, $\Delta \lambda = 1 \text{ nm}$, $\Delta t = 1 \text{ ns}$).

The QBER for a ground-to-space quantum uplink after the detonation of a 100 kT nuclear device at a HOB of 1 km and 50 km is shown in figure 8. The interference of the nuclear disturbed environment compromises the quantum uplink for only a maximum of 90 s. The low altitude fireball (1 km HOB) cools much faster than the high altitude burst (>25 km) and only has an affect for around 20 s on the quantum link.

4. Discussion

The fraction of scattered photons reaching the receiver (regular environment or nuclear disturbed) depends upon the receiver system specifications and the atmospheric and daytime conditions. The receiver system specifications (detection efficiency, timing gate, telescope FOV, and wavelength filter) determine the fraction of background photons that the detector receives. For small variations, decreasing the timing gate and wavelength filter proportionally decrease the background detector noise. The timing gate only makes the detector ‘operational’ when a signal photon is expected to arrive. This timing gate could be implemented in
Figure 8. The QBER post-detonation time series for an uplink configuration satellite-ground quantum network operating during a full Moon with light interference from a 100 kt nuclear device detonating at a HOB of 1 km or 50 km. The full range of the QBER is shown on the left and QBER values below 10% are shown on the right.

Figure 9. Magnitude of the 800 nm photon interference at a detector as a function of telescope FOV for an uplink scenario during a nuclear detonation 10 km away.

several ways—for example, as a bias pulse on an avalanche photo diode (APD), an electro-optic shutter, or by recording the arrival time of all detection events, and removing those that come between the system’s periodic transmission times. Consider a specific APD example: for a 1 ns timing gate and a 10 MHz source, the detector will only be operational (i.e., biased and set to record a photon interaction) for only 10 ms per second. In this case, 99% of the background photons would fall outside the detector window. The wavelength filter has a similar effect; a reduction in the filter bandwidth leads to a proportional reduction in the number of background photons reaching the detector. Although narrower filters are effective at reducing background counts, a filter bandwidth that is too narrow can lead to unwanted effects. As an example, the use of very narrow filters could cause one to miss a signal that is Doppler shifted due to relative motion between the transmitter and receiver without additional compensation (see for instance [34]). Lastly, the FOV of the telescope attached to the detector system will have an important effect on the background photon count rate recorded by the detector. To illustrate the FOV’s relationship to the background photon count, see figure 9, which depicts the background photons for an uplink scenario using different FOV telescopes.

The volume of air within the FOV scales as the square of the FOV angle. In the uplink scenario of figure 9, when the FOV is reduced by an order of magnitude from 100 μrad to 10 μrad, the background photon count rate drops by two orders of magnitude. In contrast, for a downlink scenario, the FOV effect on the background count becomes minimal. In the downlink scenario, the receiving telescope is on the
Figure 10. Magnitude of the different photon reflection mechanisms for an uplink scenario during a nuclear detonation.

ground, so the narrow portion of the FOV cone (see figure 1) is located in the ‘high scatter’ portion of the atmosphere (0–10 km), where air density and aerosol concentrations are highest. By changing the FOV for the downlink scenario, the narrow portion of the cone does not change much relative to the base; thus, there is a minimal effect on the background photons from light reflection in the atmosphere.

Besides receiver system specifications, the other major influence to the background noise (either natural or nuclear disturbed) are the atmospheric conditions. The diurnal cycle influences the background noise predominantly, but the aerosol and cloud content of the atmosphere—as well as the albedo of the ground around the ground station—all contribute to the background noise. In section 3.1, the photon background count rates for different scatter mechanisms are lumped together into a total. Figure 10 shows an uplink scenario of a deconstruction of the total background photon count rate for all of the different scattering mechanisms.

The aerosol concentration in figure 10 was at a PM10 level of 25 and had a particle size distribution of a remote continental location. The ground scatter is the dominant mechanism for 1550 nm light interference in the uplink scenario when the aerosol concentration is below a PM10 level of 25 (ground albedo was assumed 0.3). When the aerosol level rises above a PM10 level of 25, the dominant scatter mechanism for 1550 nm shifts to Mie scattering in the atmosphere. At 800 nm, Mie scatter is dominant until the PM10 level drops below 10. The ground reflection and Mie scattering are the two main contributors to the background contribution for an uplink scenario; Rayleigh scattering at 800 nm and 1550 nm is several magnitudes lower due to its $1/\lambda^4$ dependence. Minimizing the albedo around a ground station can dramatically reduce the background noise in either a normal or nuclear disturbed environment. Similarly, selecting a location for the ground station that has a natural decreased aerosol concentration and a favorable particle size distribution can help reduce the amount of background interference from Mie scatter. The aerosol particle size distribution for different locations and the Mie cross section versus particle size can be seen in figure 11.

Desert and marine locations have an unfavorable particle size distribution with respect to Mie scattering (large numbers of particles over 1 μm, typically caused by non-anthropogenic sources such as dust and sea spray suspension) that can cause high levels of light scattering and increase noise in the quantum channel. Urban environments usually have a more favorable particle size distribution (larger numbers of particles under 1 μm), though if there is high humidity in the air, the particle size distribution can shift to a larger particle size causing ‘smog’. However, urban environments typically have a much higher total aerosol concentration than that of other locations. The best location for a ground station would have either an extremely low aerosol level, or a favorable particle size distribution and a low aerosol content. High-altitude deserts and remote continental locations both fit that criteria and are ideal locations; conversely, urban locations, ocean fronts, and low altitude deserts are non-ideal locations due to their higher aerosol levels and unfavorable particle size distributions. In conclusion, to reduce background photon noise in a quantum channel for a satellite-to-ground channel, a location with a low ground albedo, low aerosol levels, favorable aerosol particle size distribution, and the most cloudless days should be chosen.
Figure 11. Aerosol particle size distribution for different locations and the Mie cross section as a function of particle size (particle size distributions calculated from Jaenicke [21] and Mie cross sections calculated from Sumlin et al [20]).

5. Conclusions

In this work, a method was developed to calculate the background noise from light scattered in an optical communications channel for uplink and downlink quantum communications. This method was then applied to compute the photon noise one could expect to see in various nuclear-disturbed environment scenarios. The optical noise from a nuclear detonation in a free space quantum communications link will occur for less than 1 min if the altitude of the explosion is below 50 km. Above 50 km, the interference effect can last for several minutes, but more research is needed to accurately model it. Implementing a telescope, timing gate, and wavelength filter in the receiver system can reduce the background noise significantly. The telescope FOV will have the largest impact on reducing the background noise from both natural and nuclear-disturbed environments. In addition, choosing an optimal location for the ground station is crucial in reducing the background photon rates. The best location for a ground station would be a place with minimal cloud cover, low atmospheric aerosols, and low ground albedo. Mie scattering caused by aerosols in the atmosphere is the biggest contributor to noise in a downlink scenario, whereas Mie and ground scatter are the two biggest contributors to the background count rate in an uplink scenario.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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