

To the Graduate Council:

I am submitting herewith a dissertation written by Alexander Miloshevsky entitled “The Impact of a Nuclear Disturbance on a Space-Based Quantum Network.” I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Mechanical Engineering.

Zhili Zhang, Major Professor

We have read this dissertation
and recommend its acceptance:

Nicholas A. Peters

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Accepted for the Council:

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(Original signatures are on file with official student records.)

The Impact of a Nuclear Disturbance on a Space-Based Quantum Network

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Alexander Miloshevsky

December 2022

To my wife, my family, and friends.

Abstract

Quantum communications tap into the potential of quantum mechanics to go beyond the limitations of classical communications. Currently, the greatest challenge facing quantum networks is the limited transmission range of encoded quantum information. Space-based quantum networks offer a means to overcome this limitation, however the performance of such a network operating in harsh conditions is unknown. This dissertation analyzes the capabilities of a space-based quantum network operating in a nuclear disturbed environment. First, performance during normal operating conditions is presented using Gaussian beam modeling and atmospheric modeling to establish a baseline to compare against a perturbed environment. Then, the DEfense Land Fallout Interpretive Code software and computational fluid dynamics study the effect of a nuclear explosion on the surrounding environment. Finally, these sources of noise are combined to estimate the degradation of quantum states being transmitted through a nuclear disturbed environment. It is found that the effects of a nuclear environment on a quantum network is a function of the height of blast, the explosive yield, and the network design. Debris lofted into the atmosphere during a surface blast dissipate after a couple of hours, yet the concentration is initially high and results in heavy signal loss. The nuclear fireball produced additional background light interference that scatters into the receiver's detector from tens of seconds to a couple of minutes, causing excessive noise in the detector. All these effects are likely to impede a quantum network's ability to distribute quantum information between a ground station and low Earth orbit satellite for approximately one transmission

period. Afterwards, by the next satellite pass, normal operation is expected to resume. These results provide the operational capabilities of space-based optical quantum networks following a nuclear explosion. The model can be expanded to model satellite-based quantum networks in other harsh atmospheric environments.

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Chapter 1

Introduction

Quantum communications and networking offers the potential for information processing to go beyond classical limitations. The potential of unconditionally secure communication [9], distributed computation [10], and quantum supremacy [11] from technologies based on the governing laws of quantum mechanics is driving a demand for the development of reliable long distance entanglement distribution. To facilitate these technologies, researches have set their eyes on the development of a “quantum internet” [12, 13, 14], yet the challenge transmitting quantum information on the Continental scale remains. In the long term, an ongoing effort is underway to develop quantum repeater [15], a device that would be the quantum analog to a classical repeater and solve the heavy loss problem of transmitting “quantum bits”, or “qubits”, over long distances in optical fiber and free-space [16]. Quantum repeaters promise to break up the desired transmission range into shorter and manageable segments, then using quantum teleportation [17] the smaller segments are entangled, eventually entangling the end users [18]. Progress in developing this technology has been slow due to classical amplification techniques not being applicable for quantum signals, requiring a different approaches. Attempting to amplify quantum signals would result in the uncontrollable loss of photon characteristics such as the entanglement and encoded information. Additionally, creating perfect copies of

unknown quantum states is impossible due to the no-cloning theorem [19], which states that high fidelity perfectly copied of unknown quantum states cannot be created. This theorem both enables quantum cryptography [20] but also presents the greatest challenge for any ambitions of long distance application that this technology requires for widespread adoption.

Until quantum repeaters are realized, a near-term solution for any prototype quantum internet is of a mix of short-range optical fiber, satellites, and ground stations acting as trusted nodes [21]. Optical fiber can provide the means to distribute entanglement in cities with research looking into using existing fiber infrastructure and dark fiber for transmitting quantum information alongside classical signals [22, 23]. Meanwhile, long range distribution on a continental scale can be achieved with a large number of satellites to theoretically span the globe each acting as trusted nodes [24] and act as the backbone of a near-term quantum internet. Recent high-profile demonstrations have shown the promise of a satellite-based approach in advancing the operational range of quantum communications [25, 26, 27] with more experiments and demonstrations under development. There are several ongoing international efforts in satellite quantum communications including China [25, 26], Canada [28, 29], Japan [30, 31, 32], US [33, 34], Singapore [35], and Europe [36, 37, 38, 39].

This dissertation investigates the feasibility of quantum networks in less than ideal conditions where a severe disturbance is present in the environment. It is vital to understand the operational limitations of space-based quantum networks in less favorable operating conditions for this technology to mature for everyday use. The atmospheric disturbance of choice is a nuclear disturbed environment. The purpose of the proposed project is to investigate the viability and operational limitations of a quantum network in a nuclear disturbed environment. These results can guide the development and operation of a space-based quantum internet in the event of a detonation of a nuclear device. The formalism can also be expanded to analyze other hostile operating conditions such as wildfire smoke, increased aerosol concentration,

volcanic ash lofted into the atmosphere, increased light pollution, etc.. The analysis is performed through three key tasks.

The first task involves modeling of a laser-based free-space optical (FSO) link propagating through the vacuum of space (inter-satellite links) and through the Earth’s atmosphere (links between ground stations and satellites). Modeling the propagation of a single photonic qubit adheres to many of the same principles as a laser beam, therefore modeling a propagating laser beam provides a good estimate of the transmission likelihood of a quantum signal through free-space. This problem has been extensively studied and we rely on previously established models and literature for guidance. Assessing the performance of a laser-based FSO channel also serves to compare against perturbations caused by a nuclear disturbance. The laser beam is assumed to behave as a Gaussian beam and is governed by diffraction theory. This provides a baseline to understand operational limitations of links between low-Earth orbit (LEO) and geosynchronous orbit (GEO) satellites. To simulate the atmospheric turbulence, we model the index of refraction structure constant as a function of altitude. This leads to the calculation of a quantity known as the Fried parameter [40], which quantifies the “seeing distance” and captures the effect of turbulence on a beam propagating through the atmosphere. A wavelength dependent scalar quantity is included to account for the absorption and scattering loss by the various aerosols in the atmosphere. Combining these models should result in a good approximation of the different costs incurred by propagating through the vacuum of space and through the Earth’s atmosphere for uplink and downlink satellite and ground station configurations.

The second task uses a combination of computational fluid dynamics (CFD) and Oak Ridge National Laboratory (ORNL) developed software DEfense Land Fallout Interpretative Code [41, 42] (DELFI) to model the effects of a nuclear explosion on the surrounding environment. The effects of a nuclear explosion can be broken up into 4 categories, the blast/shockwave, the thermal radiation, the initial nuclear radiation, and the long-term nuclear radiation [43]. For the

purpose of this dissertation, we do not calculate the evolution of the shockwave and assume all the necessary infrastructure remains intact. The nuclear radiation effects from a high altitude nuclear explosion are considered here [6], but is not within the scope of this dissertation. DELFIC can model the nuclear cloud rise and estimate its dimensions with time. The ORNL-built Airborne Planning Tool [44, 45] (APTTool) combines DELFIC and a complementary software called Hybrid Single-Particle Lagrangian Integrated Trajectory [46] (HYSPLIT) to estimate the nuclear debris concentration in the surrounding atmosphere from the cloud rise calculations. With the debris concentration in the atmosphere known, by applying Mie scattering [4], the transmission probability of a photonic qubit through the debris present in the quantum optical channel is determined. The CFD open source software OpenFOAM [47, 48] and COMSOL [49] are used to characterize the temporal evolution of the temperature of the nuclear fireball. Using the temperature profile, Planck’s radiation law [50] is applied to determine the number of additional photons that the detector receives. These additional photons increase the noise count of a quantum detector and degrade the network performance.

The final task adopts the signal transmission probability (atmosphere and nuclear debris) and the detector noise (background light, dark count, and nuclear fireball interference light) to estimate the quantum state and analyze the degradation of entanglement in the entangled pair case. A variety of entanglement measures and metrics are considered for assessing the performance of quantum communication protocols, however the focus is state fidelity. At first, the single photon case is presented. One photon is transmitted a FSO channel with a disturbed environment and the other photon of the entangled pair is measured at the transmitter. Then, the number of quantum networks is increased to two and entanglement metrics like fidelity, concurrence, and entanglement of formation are calculated to measure the degradation of the entanglement. Finally, the means for expanding the formalism to three or more entangled qubits is introduced.

This dissertation is the first to attempt to the knowledge of the author in documenting the performance and capabilities of a space-based quantum network operating in a nuclear disturbed environment. The research is a unique multidisciplinary project that pulls on theory from optics, quantum information science, and nuclear physics. The research topic combines Gaussian beam propagation, atmospheric turbulence, computational fluid dynamics, and quantum state estimation to advance the understanding of free-space and satellite-based quantum networking in a nuclear disturbed environment and can be applied for modeling other hazardous environments.

The dissertation is organized as follows: Chapter 2 covers the necessary background information for this dissertation. Topics such as Gaussian beam propagation, atmospheric effects, nuclear weapon effects, and quantum state estimation are discussed. Chapter 3 covers effects on the signal transmittance due the atmosphere from scattering, absorption, and turbulence. Then the atmosphere is perturbed by a nuclear device detonates near the surface lofting debris into the environment and starting fires nearby releasing smoke into the atmosphere. Chapter 4 focuses on detector side noise due sky radiance and increased light interference from a nuclear fireball. Chapter 5 combines the results from the previous two chapters to estimation the degradation of the quantum state in a nuclear disturbed environment for single-photon and multi-photon networks. Finally, chapter 6 summarizes the key results and draws conclusions from the dissertation.

Chapter 2

Background

The nature of the problem requires a discussion of electromagnetic radiation propagation through free-space, effects from propagating through the atmosphere, nuclear weapon effects and their interaction with the surrounding environment, and the quantum mechanics. The following sections are dedicated to introducing each topic.

2.1 Propagation of an Electromagnetic Wave

Free space optical (FSO) communications use light as the means of transporting information through free-space. Since the desired distance for exchanging information can span kilometers, the best carrier for the encoded information is a photon. An immediate problem when attempting long distance communications terrestrially is obstructions in the propagating path and the curvature of the Earth. To overcome this limitation, quantum networks propose to use optical fiber and satellite-based networks. An advantage of using satellite-based technology is the lower attenuation due to the decreasing density of the atmosphere at higher altitudes as opposite to the exponential loss for optical fiber [25].

The propagation of a photon from a single photon source used in quantum communications is susceptible to the same effects as a beam from a laser. Therefore, it

is convenient to model the propagation of a laser-based FSO communications link and apply the results to a quantum network operating in the same conditions. Laser communications have been previously modeled using the transverse electromagnetic mode (TEM) model for Gaussian beams [51, 52, 53]. This model uses Gaussian functions to describe the electromagnetic field patterns perpendicular to the propagating direction of a photon. For our application, we use the TEM_{00} mode, which is the fundamental transverse mode and lowest order Gaussian beam wave [54]. This should paint a sufficient picture of the optical wave propagation, though using higher-order modes may be more suitable for different lasers [54]. The limitation on the communication range is the diffraction rate of the beam [55].

We consider the near-infrared (IR) (800 nm – 2000 nm) wavelength region for the classical and quantum optical communications links. We specifically focus on the 800 – 850 nm and 1550 nm range due to pre-existing satellite telecommunication technology operating at these wavelengths, the favorable transmission through the atmosphere, detector efficiency for these wavelengths, and previous experiments and literature focusing on operations at these wavelengths.

The propagation of a laser beam from any ground station to a plane or satellite involves passing through the Earth’s atmosphere. Several effects complicate any attempt to communicate optically through the atmosphere. The atmosphere is composed of various gases, molecules, atoms, and water vapor that are trapped by gravity and can absorb or scatter photons leading to a reduction in the beam brightness (beam scattering). Absorption results in the loss of the photon, scattering can change the propagating path of the photon resulting a loss event, weather conditions such as rain, fog, and clouds can adversely affect the transmittance of the beam. Any model describing the propagation of a beam through the atmosphere needs to consider absorption, scattering, weather, and atmospheric turbulence. The absorption and transmittance spectrum of the atmosphere is a well-researched topic [56]. Software has been developed to model the atmospheric transmission spectrum like Low Resolution Transmission [57] (LOWTRAN) and

MODerate Resolution Atmospheric TRANsmission [58, 59] (MODTRAN). Software like MODTRAN provide the transmittance for wavelengths ranging from 200 nm to 100,000 nm.

The atmosphere becomes less dense with an increase in altitude, this creates a temperature and density gradient. The small inhomogeneities in atmospheric conditions lead to fluctuations in the atmosphere's refractive index. The variation in the refractive index create the necessary conditions for optical atmospheric turbulence. To determine the beam distortion due to the atmosphere requires an understanding of the refractive index profile for the atmosphere with respect to altitude. This is done by calculating the atmospheric structure constant, C_n^2 , to determine the strength of turbulence [54]. The Hufnagel model [60, 61] is a statistical model based on data obtained from balloon flights in 1972 [62] that measured the temperature of the atmosphere and inferred the value of C_{n^2} from Kolmogorov turbulence theory. This model estimated the structure constant from 3 km above sea-level to an altitude of 24 km. The Hufnagel model was later improved by Ulrich [54, 61, 63] and Valley [64] to become the Hufnagel-Valley model which now included an exponential term that estimated the ground turbulence from ground level to 3 km. The most commonly used version of this model is the Hufnagel-Valley 5/7 model. In this model, the independent parameters are chosen such that the structure constant has a coherence length of 5 cm and the isoplanatic angle is $7 \mu\text{rad}$ at 500 nm. Propagating uplink through the atmosphere is a greater challenge than downlink. In the uplink scenario, the beam encounters the turbulent atmosphere at the start of propagation. This leads to greater divergence of the beam because the divergence of the beam has a longer time to manifest. In the downlink case, the beam only encounters the atmosphere towards the end of propagation and the beam does not experience a substantial amount of divergence [65]. The Fried parameter [40] was introduced in 1966 and it estimates the statistical strength of the atmospheric turbulence from the structure constant. This parameter is used to quantify the perturbation of the wavefront as it propagates through the atmosphere. It is typically

given in units of cm. Using the structure constant, the Fried parameter, and a scalar quantity for scattering and absorption provides a good approximation of the increased attenuation caused by light propagating through the atmosphere.

2.2 Nuclear Weapon Effects

The aftermath of a nuclear explosion is a complex environment that is dependent on a plethora of factors. A nuclear explosion is defined as the high release of energy due to a nuclear reaction where transformations occur to the nuclei of the interacting atoms [43]. The effects can be divided into four primary categories, blast effects, thermal effects, short-term radiation effects, and long-term radiation effects. In greater detail, the effects from a nuclear device can include ground cratering, high-pressure shockwave, electromagnetic pulse, ionizing radiation, increase in the atmospheric ion density, ejected soil, nuclear fallout, thermal radiation, and a high temperature fireball. The interdependence of these effects has a profound and lasting effects on the surrounding environment. The height of blast (HOB) from the surface of the Earth determines how the released energy of the blast is distributed into the previously mentioned effects. There are four distinct types of nuclear explosions, each depending on the HOB: a subsurface burst, a surface burst, an air burst, and a high-altitude burst. Subsurface bursts are classified as those occurring underwater or underground and are not in the scope of this dissertation. In a surface burst, the detonation point is slightly above or at the surface of the Earth. In this scenario, the nuclear fireball expands along the surface of the Earth. Due to the high density of the atmosphere at the surface, the nuclear weapon effects are more localized. Air bursts are explosions that occur at an altitude below 30 km ($\sim 100,000$ ft). The difference between a surface and air burst is that the fireball in an air burst never interacts with the ground. High-altitude burst occur above 30 km ($\sim 100,000$ ft) and differ from the other types as the density of the atmosphere is significantly lower than in the other cases. High-altitude nuclear explosions are more likely to lead to changes

in the ionosphere as a result of an increase in charged particle concentration. This can result in radio blackout where the increase in the charge concentration prevents communication systems that depend on longer wavelengths (i.e. radio and microwave) from operating, however the effects are negligible in the near-IR optical range. The cut-offs for each scenario are arbitrary and not to be taken as strict definitions.

During a nuclear explosion, the release of an enormous amount of energy causes the surrounding mass to heat up leading to an increase in temperature and pressure of the surrounding air. Initial radiation is released in the form of prompt neutrons and gamma rays as the fission/fusion reaction occurs. Milliseconds following the explosion, there is an intense flash of light and the nuclear fireball expands to its maximum size, continuing to release an enormous amount of thermal radiation. Any nearby interacting material becomes a source of residual radiation. An electromagnetic pulse (EMP) can fry nearby electrical circuitry leading to power outages. Seconds following the explosion, thermal pulses can cause fires within a couple of miles of the detonation site, which can produce smoke that can obstruct optical transmission. At this point, the blast wave has rapidly traveled outward past the detonation point. Tens of seconds following the explosion, the nuclear fireball begins to rise bringing dirt and debris with it that is sucked up in the updraft. The dirt and debris is mixed with radioactive material in the fireball creating fallout particles. Minutes later, the cloud rises rapidly and the debris particles begin to fall to the ground. Hours later, winds carry fallout downwind, fires continue, and the radiation levels begin to drop due to radioactive decay.

The detonation of a nuclear weapon in the atmosphere can create adverse conditions for free space optical and quantum communications. In a nuclear disturbed environment, two effects can degrade a classical or quantum optical communications link, the increased transmission loss of the optical signal and the additional background noise in the detector due to the fireball. The degradation of the optical link in a nuclear disturbed environment is caused by the weapon debris, soil, smoke, and haze injected in the atmosphere. The dominant source

of the loss is the absorption and scattering (Mie scattering [66]) from the various aerosols and extra debris present in the atmosphere. Though the fireball only last a few minutes before substantially cooling of, it can oversaturate and damage any onlooking detector. Additionally, operating on a single photon level makes quantum networks sensitive to any increase in background noise which decreases the signal-to-noise ratio of the channel, negatively affecting the performance of the network. For this reason, space-based network experiments occur at nighttime as daytime operation remains prohibitive due to the high sky radiance and remains an active area of research [67, 68, 69, 70].

For the purpose of this project, we assume that the critical infrastructure suffers no damage from the electromagnetic pulse (EMP), thermal pulse or the pressure shockwave. The widespread destruction of infrastructure and equipment due to the high-pressure blast wave is likely to impede communications on the ground. The EMP causes rapidly varying electromagnetic fields that can damage any circuitry within range of the burst, particularly satellites. Therefore, these effects are acknowledge as valid concerns, not included considered in this dissertation, and left as future work.

2.3 Quantum Mechanics

First, an brief explanation of the necessary linear algebra is presented. Then a discussion of some quantum mechanical phenomenon of interest to this dissertation are discussed.

2.3.1 Bra-ket Notation

Quantum physicist use the bra-ket notation [71, 72, 73] (Dirac Notation), introduced by Paul Dirac in 1939 [74], to represent the linear algebra and mathematics that describes quantum states and observables. A state vector represent a quantum state that that is a possible outcome to a measurement made on the system denoted by a

ket vector. For an N -dimensional vector space, with an orthonormal basis $|e_n\rangle$, the state vector is depicted by the ket,

$$|\psi\rangle = \sum_{n=1}^N \alpha_n |e_n\rangle. \quad (2.1)$$

where $|e_n\rangle$ are the states accessible to the system that have some probability amplitude associated with each state α_n . In matrix notation, for an N dimensional space, the ket is denoted by,

$$|\phi\rangle = \vec{\phi} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_N \end{pmatrix}. \quad (2.2)$$

The bra is a vector in bra space, which is "dual" (anti-linear) to the ket vector space,

$$\langle\psi| = (|\psi\rangle)^\dagger = \sum_{n=1}^N \langle e_n| \alpha_n^*. \quad (2.3)$$

A Hilbert space is a infinite dimension, complete, complex vector space with a defined inner product, though the term is sometimes applied to finite dimension vector space. The inner product of two vectors yielding a complex number,

$$\langle\psi|\phi\rangle = \sum_{n,m} \alpha_n^* \beta_m \langle e_n|e_m\rangle = \sum_{n,m} \alpha_n^* \beta_m \delta_{n,m} = \sum_n \alpha_n^* \beta_n \quad (2.4)$$

where $\delta_{n,m}$ is the Kronecker delta. This is equivalent to the dot product for 3-dimensions. Another operation that is useful is the multiplication of a ket to a bra, which is known as the outer product,

$$|\psi\rangle\langle\phi| = \begin{pmatrix} \alpha_1\beta_1^* & \alpha_1\beta_2^* & \dots & \alpha_1\beta_N^* \\ \alpha_2\beta_1^* & \alpha_2\beta_2^* & \dots & \alpha_2\beta_N^* \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_N\beta_1^* & \alpha_N\beta_2^* & \dots & \alpha_N\beta_N^* \end{pmatrix}. \quad (2.5)$$

The result of the outer product is a matrix, which differs from the inner product which is a scalar. Sometimes it is necessary to deal with a composite system, which is a bigger space that spans some combination of subspaces. The subspaces are combined using the tensor product. For example, in the case of a two qubits with states 0 and 1,

$$|\psi\phi\rangle = |\psi\rangle \otimes |\phi\rangle = (\alpha|0\rangle + \beta|1\rangle) \otimes (\gamma|0\rangle + \delta|1\rangle) \quad (2.6)$$

$$= \alpha\gamma|00\rangle + \alpha\delta|01\rangle + \beta\gamma|10\rangle + \beta\delta|11\rangle. \quad (2.7)$$

Wave functions are not capable of describing every quantum systems. A density operators/matrix provides a quantitative description of the quantum system and contains any significant physical information about the system, typically denoted as ρ . The density matrix is calculated from the state vectors as follows,

$$\rho = \sum_{n=1}^N p_n |\psi_n\rangle\langle\psi_n|. \quad (2.8)$$

where, p_n is the probability distribution for state n . The trace of an operator is,

$$\text{Tr } A = \sum_{n=1}^N \langle e_n | A | e_n \rangle. \quad (2.9)$$

2.3.2 Quantum Phenomena

Uniquely quantum phenomena such as superposition, no-cloning, and entanglement (nonlocal correlation) are not available to classically designed and are key features that enable quantum protocols. Throughout this dissertation, a quantum network

is defined as any tool that helps facilitate the transmission of quantum information from one party to another. Quantum communications is defined as the processing and application of the transmitted quantum information for communications purposes.

Taking an isolated particle, quantum superposition [75] allows the particle to exist in a quantum state that is a linear combination of all accessible quantum states to the system. As an example, take an electron with the quantized property spin up or spin down. In the absence of a measurement, say by an observer or some interaction by a particle in the environment, the electron can be in either spin up or spin down, but also it can exist in a state that is a combination of the two available states, spin up and spin down. Measurements or interactions on the isolated particle yield one of the possible states by “collapsing” the superposition into any one of the available states given by some probability associated with each state being observed. The qubit can be described by the ket,

$$|\psi\rangle = a|0\rangle + b|1\rangle. \quad (2.10)$$

Here we are using Dirac (bra-ket) notation [74] discussed in the previous section to express the quantum state. The ket notation $|\psi\rangle$ represents a column vector that is a linear combination of all possible states a quantum system has access to. These states are pure quantum states that are characterized by a single ket vector and cannot be written as a mixture of other quantum states. The ket $|0\rangle$ represents the quantum state “0” (or say spin up in the electron example) and $|1\rangle$ represents a quantum state “1” (spin down). The complex numbers a and b are the probability amplitudes associated with their respective quantum state. The probability the system collapses to one state or the other is found by taking the modulus square of the probability amplitude. For the ket vector in Equation 2.10, the probability of measuring state $|0\rangle$ is $|a|^2$ and $|1\rangle$ is $|b|^2$ and since the system must exist in one state or the other, their probabilities must sum to 1 and the normalizing condition $|a|^2 + |b|^2 = 1$ is required. A measurement always yields 0 or 1, yet different probabilities are associated with obtaining each state. Quantum bits are best described by a state vectors; however,

it is easier to use the Bloch sphere (unit sphere) representation for visualization (Figure 2.1).

The no-cloning theorem [19] states that it is impossible to make a high-fidelity copy of any unknown quantum state. This has great applications for the field of quantum cryptography because any adversary cannot create a copy of an incoming encoded quantum bit, measure the copy gaining information and send the original to the intended receiver. With the no-cloning theorem, an adversary can only measure the intercepted qubit. This would introduce a noticeable error for the users and alert them to the presence of an adversary intercepting the quantum channel. This in essence is the goal of quantum-key distribution (QKD). However, this theory also presents challenge in fields like quantum computing, where creating copies of information using classical techniques is impossible.

Entanglement [76, 77] is the final phenomenon of interest that only appears on the quantum scale and has no classical equivalent. Entanglement is a special case of superposition. A common technique for producing entangled pairs is a nonlinear optical process spontaneous parametric down-conversion [78]. The entangled particles are intertwined even when they are spatially separated over large distances [76]. To date, researches have been able to successfully entangle up to 14 photons [79]. The information is shared between the particles nonlocally, so that measurement of one particles effects the other particles instantaneously. Measurements of one of the particles has an effect on the pair and the pair “collapses” to a single state and the entanglement is forever lost. This means that extensive care needs to be taken to isolate qubits from the environment to prevent noise from interacting with a qubit in a process known as decoherence [80].

Qubits [81] are the simplest quantum mechanical system possible and are a two-state quantum system. As an example, throughout this dissertation the physical realization of a qubit is the encoding of information in the polarization of a photon. Other examples include the magnetic field of an electron, or in the internal state of an atom or molecule. Photonic qubits are a convenient choice due their transmission

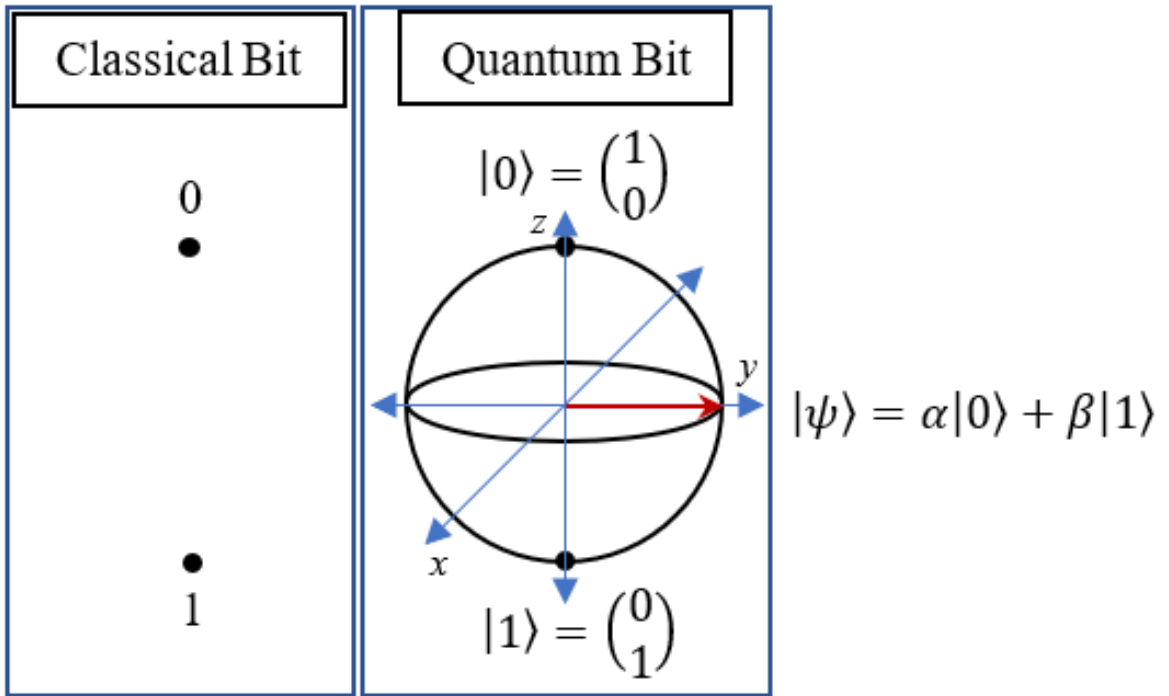


Figure 2.1: The possible states of a classical bit compared to the possible states of a quantum bit (qubit). The qubit is represented in the Bloch sphere and is in some state described by the wave vector $|\psi\rangle$

speed, lower loss and less noise than other carriers, and the ease of high precision manipulation. Photonic qubits can encode quantum state on the photon through polarization, momentum, frequency, energy, etc. as the chosen degrees of freedom. Higher level (three or more) systems are called “quantum dits” or “qudits”. For the two-photon case, we are interested in analyzing the performance of the maximally entangled states that are given by the four Bell states [71],

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B) \quad (2.11)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |0\rangle_B - |1\rangle_A \otimes |1\rangle_B) \quad (2.12)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B) \quad (2.13)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B) \quad (2.14)$$

One of the greatest achievements of the 1980s and 1990s was the development of theoretical ideas that utilize quantum entanglement as the key piece to potentially revolutionize communication and computation beyond classical limitations. These ideas manifested into quantum key distribution [82], quantum teleportation [17], quantum secret sharing [83], superdense coding [84], quantum computation, and distributed quantum computing [10]. The advantage of using qubits over classical bits lies in the entangled properties of a qubit pairs and how a qubit can simultaneously exist in a superposition of both states at once.

Distributing entangled photons over long distance is an ongoing challenge for quantum networks. The theoretical device known as a quantum repeaters [15] promises to resolve this issue by breaking up long distance into smaller, more manageable sections. The practical realization of the technology however, has proven difficult. In the meantime, trusted nodes connected by optical fiber and free-space satellites are a promising alternative for continental scale entanglement distribution. The loss in optical fiber scales exponentially [25], resulting in the transmission range being limited to a couple hundred kilometers. This makes satellites an attractive alternative in the near-term for any global quantum internet due to the lower loss

when compared to fiber. The quantum particle interacts with a lot of different things on its way to the detector and in the detector. Decoherence can occur from heat, radiation, cosmic rays, other particles. Quantum decoherence is a process of the environment interacts with the qubit, changing the quantum states in an unpredictable way resulting in the loss of the encoded information. This can lead to the loss of quantum properties such as superposition and entanglement, therefore extensive care needs to be taken to protect the propagating qubit.

Quantum key distribution [82, 85, 86, 87] (QKD) is a quantum cryptography protocol to produce and distribute a random encryption key between two remote parties that can be used for encrypting or decrypting encoded messages. Unlike classical communication, the laws of quantum physics are used to guarantee the security of the encrypted key, regardless of the computational power of the adversary. Observations of quantum states has a noticeable effect on the state. Therefore, any eavesdropping attempts can be detected and the protocol can be aborted, unlike in classical communication schemes where an eavesdropping adversary is undetectable. Strides have been made to demonstrate the feasibility of this technology in recent years. Downlink QKD using decoy-state Bennett-Brassard 1984 (BB84) protocol has been demonstrated from a LEO satellite to a ground-based station separated by a distance up to $\sim 1,200$ km with a channel loss of 55 dB [25]. Quantum teleportation at distances up to $\sim 1,400$ km with a loss of 52 dB has been demonstrated between an observatory and a LEO satellite [26]. These demonstration shows the boost to link efficiency and transmission range satellite-based networks provide. Numerical models and simulations are being developed to understand network performance and means of improving them [5, 55, 88, 89], particularly achieving QKD operation during daytime [69]. Ongoing research is also attempting to address and compensate for issues arising due to the Doppler shift effect [90]. These models and experiments are promising stepping stones to the development of a worldwide quantum network. The objective of quantum information sciences is not to replace classical technology, but to create devices that utilize both classical and quantum technology harmoniously

to provide an enhanced end user experience, going beyond what is classically possible. This means that quantum protocols, such as QKD as an example, are alongside classical communications protocols to provide secure communications, yet the quantum protocol on its own is meaningless and does not provide a feasible means of relaying information without its classical counterpart.

Chapter 3

Surface Blast Effects on Optical Channels

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3.1 Introduction

The detonation of a nuclear weapon in the atmosphere can create adverse conditions for free space optical communications, including quantum communications. A nuclear detonation has three main outputs: blast, thermal and ionizing radiation [43]. These

effects occur over the span of seconds, but the resulting environment, i.e., the nuclear disturbed environment, can persist for hours to days afterwards. In a nuclear disturbed environment, two major effects can degrade an optical communications link: increased transmission loss of the optical signal and the addition of more background noise in the detector. The degradation of the optical link in a nuclear disturbed environment is caused by absorption/scattering of the optical signal due to nuclear cloud formation, weapon debris/soil lofting and elevated levels of particulate matter in the air (haze/smoke), for example, from a nearby burning city. Ionospheric effects from high altitude nuclear detonations can have significant effects (polarization, reflection, decoherence, phase effects, etc. [43]) on a radio-frequency communications link due to the increased electron density in the upper atmosphere, but it has negligible effects in the near-IR optical range. In this paper, we consider near-IR wavelengths for the classical and quantum communications links. In this regime, the dominant loss mechanism will occur from absorption/scattering, and more specifically, Mie scattering due to the various aerosols and particulate matter injected into the atmosphere from the nuclear detonation. To keep the scope manageable, we consider detector noise effects elsewhere.

As a nuclear fireball rises and cools, it forms a cloud filled with water vapor droplets, weapon debris and entrained material (soil, concrete, etc.) that was in the vicinity of the fireball. This cloud will cause significant scattering and absorption to the wavelengths we are investigating for the optical link. Additionally, the material lofted by the cloud will remain airborne for hours to days afterwards, depending on the particle size distribution of the material. The high thermal output of a weapon detonation can cause secondary fires to start in an urban or rural area. The subject of burning cities and ‘nuclear winter’ has been studied in detail by many research groups over the past couple of decades [91, 92] but is outside the research scope of this study. Instead, we investigate blast-generated particulate matter in the air and its resulting effect on an optical communications link. The radiative output of the debris is substantial in the first hours, but the density of the lower atmosphere

(generally around the tropopause and below for surface-level detonations) allows for charge recombination, minimizing the effect of ionization on beam transmission. We therefore assume this term is minor relative to the attenuation of the debris itself and neglect it. In this way, we provide a scoping study of the additional loss that arises from various nuclear blast scenarios on an earth to satellite optical (conventional and quantum) communications link.

Typical free-space conventional communications build in generous power margins by launching bright signals with millions or more of photons to account for signal losses. However, quantum communications generally operate at the single-photon level. Thus, while we compute the impact of loss generally, we expect the nuclear disturbed environment to present greater challenges for quantum communications. However, there are compelling capabilities not available without quantum signal transmission, namely information theoretic security through quantum key distribution (QKD) protocols [82, 85, 86, 93], where security remains independent of computational capability. In addition, by distributing entanglement, one can teleport quantum information over large distances provided one also has classical communications [17]. As it is required for teleportation, entanglement is considered a key resource for quantum communications and networking. Limitations on the range over which entanglement can be shared due to channel loss restrict the scale of global quantum networks [94]. Without quantum repeaters [15], a channel using commercial optical fiber can transmit quantum signals roughly only a couple of hundred kilometers [95]. A terrestrial free-space optical (FSO) channel can suffer from obstacles in the field of view, atmosphere related effects, and the curvature of the earth that limit transmission range [96]. Satellite-based networks are a potential solution for long-range entanglement distribution on a global scale. Satellite-based architecture offers longer communication range than optical fiber due to lower attenuation scaling. Proof-of-concept demonstrations have been performed or are in conceptual phases for satellite quantum communications in China [25, 26], the United States [33, 34], the European Union [36, 37], Japan [30, 31], and Canada [28, 29]. In addition, there has

been much theoretical work analyzing the effect of the atmosphere and turbulence on satellite quantum communications [55, 88, 97, 98, 99]. A feasibility analysis of satellite constellations to realize a global quantum network has been performed [24].

The main contribution of this manuscript is to estimate the additive nuclear disturbed penalty for earth-space communications links. That is, we calculate the loss penalty to an optical signal attempting to pass through (a) the stabilized nuclear cloud, (b) later-time transported airborne debris, and (c) ash and smoke from secondary fires initiated by the detonation. We assume that these loss terms are fully separable from the normal transmission losses in the atmosphere due to air, ambient airborne particulates, turbulence, etc., and that these loss terms (in dB) may be added to the atmospheric losses for the full transmitter-to-receiver attenuation estimate. We also assume that any photon interaction with the nuclear cloud or debris results in extinction of the photon (that is, no photon interacts weakly yet still survives to the receiver). Therefore, the loss terms are direction-independent and apply equally to both ground-to-satellite and satellite-to-ground transmission. All direction- and distance-dependent losses would be attributable to the atmospheric attenuation term.

3.2 Background

Before analyzing the performance of a quantum channel in a disturbed environment, it is necessary to determine what is possible during more favorable operating conditions. A concept of operations schematic for a future space-based communications network is shown in Fig. 3.1. The figure provides a summary of the optical channels that can be considered and for concreteness, we specifically consider heralded two-qubit entanglement distribution between ground stations and satellites. In heralding, one photon of the entangled pair is measured at the transmitter while the other is sent over the free-space optical channel. In the ideal limit, this is analogous to having an ideal deterministic single photon source, and could also represent a directly encoded photon, as typically used in QKD.

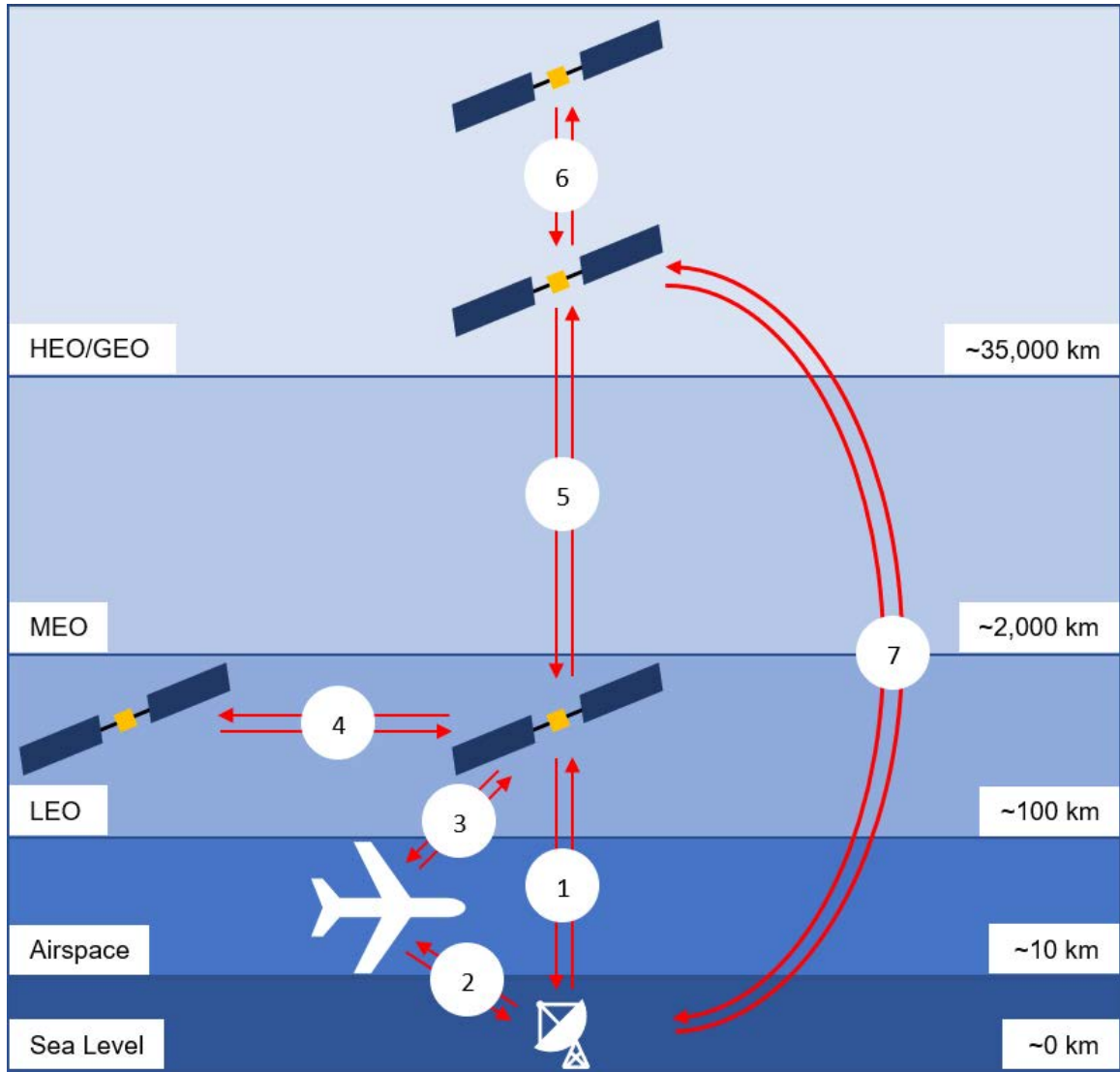


Figure 3.1: A schematic of the principle of operation for different link scenarios in a hypothetical space-based quantum and/or classical communications network: 1) Ground-to-low Earth orbit (LEO) 2) Ground-to-aircraft 3) LEO-to-aircraft 4) LEO-to-LEO 5) LEO-to-geosynchronous orbit (GEO) 6) GEO-to-GEO 7) Ground-to-GEO. All types of links can be bidirectional.

An encoded quantum photon propagating through a free space optical (FSO) channel displays similar behavior as a classical pulse of light with otherwise similar characteristics (e.g., wavelength, spatial mode, pulse duration, etc.) transmitted in the same conditions. Modeling the optical loss of a laser-based FSO link therefore has become a standard way to gain insight into the performance of a quantum link. More specifically, Gaussian beam propagation is applied to analyze the performance of an optical channel to infer the limitations of a quantum link due to diffraction and the atmospheric turbulence [55]. This section introduces the Gaussian beam propagation methodology and the atmospheric model that analyze the optical channel of a quantum link between ground stations and satellites.

3.2.1 Atmospheric Model

A Gaussian beam is a focused or collimated beam of light where the irradiance and transverse electromagnetic field are defined by a Gaussian function. The Gaussian beam approximation is suitable for small divergence angles where the paraxial approximation is applicable. We assume that our laser beam is perfectly collimated and of a Gaussian form described by the fundamental transverse electromagnetic mode (TEM₀₀). The complex amplitude of the electric field for a Gaussian beam at a distance z from the waist is given in [51] as

$$U(\mathbf{r}) = U_0 \frac{\omega_0}{\omega(z)} \exp\left\{\left(-\frac{r^2}{\omega^2(z)}\right)\right\} \exp\left\{\left(-ikz - ik\frac{r^2}{2R(z)} + i\zeta(z)\right)\right\}, \quad (3.1)$$

where U_0 is the maximum value of the amplitude, ω_0 is minimum beam radius at the waist ($z = 0$), $R(z)$ is the radius of curvature, r is the radius at a distance z , i is the imaginary unit, k is the wavenumber $k = 2\pi/\lambda$. The evolution of the real part of the Gaussian beam in the propagating direction z can be calculated from the beam waist [100]

$$\omega(z) = \sqrt{\omega_0^2 + z^2\theta_d^2}, \quad (3.2)$$

where the beam divergence θ_d is given by

$$\theta_d = \frac{\lambda}{\pi\omega_0} , \quad (3.3)$$

and λ is the channel wavelength. We assume the beam is transmitted either from a satellite or a ground station and the spot size spreads as it propagates to the receiver at another satellite or ground station.

The irradiance of the beam is obtained from the modulus squared of the electric field as

$$I(r, z) = I_0 \frac{\omega_0^2}{\omega^2(z)} \exp\left\{\left(-\frac{2r^2}{\omega^2(z)}\right)\right\} . \quad (3.4)$$

By integrating the irradiance an expression for the power passing through a circular receiver of radius r_0 is

$$P(z) = \int_0^{2\pi} \int_0^{r_0} I(r, z) r dr d\theta . \quad (3.5)$$

By solving Equation 3.5, the transmission power ratio for an unfocused beam is

$$\frac{P_R}{P_T} = 1 - \exp\left(-\frac{2r^2}{\omega^2(z)}\right) . \quad (3.6)$$

The link efficiency ratio for an channel is the power passing through a receiver aperture of diameter D_R from a transmitting device of diameter D_T that is separated by a link distance of L and is calculated as

$$\frac{P_R}{P_T} = 1 - \exp\left(-\frac{2D_R^2}{D_T^2 + 4L^2\theta_d^2}\right) . \quad (3.7)$$

Here, the minimum beam waist is treated as half of the diameter of the transmitting aperture $\omega_0 = D_T/2$ and the collection radius is half of the diameter of the receiving aperture $r = D_R/2$. The optical link attenuation is the inverse of the link efficiency:

$$\frac{P_T}{P_R} = \left(1 - \exp\left(-\frac{2D_R^2}{D_T^2 + 4L^2\theta_d^2}\right)\right)^{-1} . \quad (3.8)$$

Equation 3.8 is sufficient to understand the propagation of a beam that is purely diffraction limited and gives a lower bound of the channel attenuation. Given the typically high loss over the scenarios considered, the attenuation A is more conveniently expressed in dB by converting the attenuation ratio as follows:

$$A = 10 \times \log_{10} \left(\frac{P_T}{P_R} \right). \quad (3.9)$$

Several obstacles complicate any attempt to transmit an optical signal through the atmosphere including scattering, absorption, and variations in the atmospheric refractive index [97]. The atmosphere consists of various gases, atoms, water vapor, and molecules trapped by the gravity of the earth. The various molecules present in the atmosphere can absorb or scatter a photon leading to a reduction in signal power. Meanwhile, changes to the temperature, density, pressure, and humidity of the air cause variations in the refractive index of the atmosphere [54]. The propagation of a beam through the atmosphere causes a distortion of the beam shape due to the constant variation of the index of refraction. These effects manifest as twinkling, beam wandering, image distortion, etc. [101]. Various mathematical models have been proposed that attempt to characterize the index of refraction structure constant [102].

We model the index of refraction structure constant, C_n^2 , as a function of altitude, h , using the Hufnagel-Valley (HV) model [54]. The HV model was proposed by Hufnagel based on balloon-borne measurements of the temperature of the troposphere made by Bufton et al. [60, 62, 103]. The model was improved later by Valley with the inclusion of a ground-level turbulence term [64] that increases the scope of the different conditions on the surface [104]. The HV model is chosen due to the flexibility offered by the parameters to model the turbulence in different geographical locations. The atmospheric structure constant according to the HV model is:

$$C_n^2(h) = 5.94 \times 10^{-53} \left(\frac{v}{27} \right)^2 h^{10} e^{-\frac{h}{1000}} + 2.7 \times 10^{-16} e^{-\frac{h}{1500}} + C_n^2(0) e^{-\frac{h}{100}}. \quad (3.10)$$

Here, the atmospheric structure constant is a function of the following: increasing height from the surface, h , the root mean squared wind speed, v , and the ground level turbulence, $C_n^2(0)$. We chose the typical values of $v = 21$ m/s for the wind speed velocity and a ground-level turbulence of $C_n^2(0) = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ to obtain an approximation of the atmospheric turbulence where the isoplanatic angle is $7 \mu\text{rad}$ and the atmospheric coherent length is 0.05 m at $\lambda = 500$ nm.

Using this form of the structure constant, the effect of the atmospheric turbulence on a propagating beam is determined from the atmospheric coherence length or the Fried parameter r_0 . The Fried parameter is defined as [40],

$$r_0 = \left(0.423 k^2 \sec \zeta \int_{h_0}^L C_n^2(z') dz' \right)^{-\frac{3}{5}}. \quad (3.11)$$

where ζ is the zenith angle, k is the wave number $k = 2\pi/\lambda$, and h_0 is the ground level altitude. The divergence angle as a result of atmospheric turbulence is

$$\theta_{atm} = \frac{\lambda}{r_0}. \quad (3.12)$$

We assume that the divergence due to the atmosphere is squared and additive to the diffraction divergence [55] due to the divergences being dependent on different sources. The attenuation for an optical link through the atmosphere is given in [55] as

$$\frac{P_T}{P_R} = 10^{\frac{A_{air}}{10}} \left(1 - \exp \left(- \frac{2D_R^2}{D_T^2 + 4L^2(\theta_d^2 + \theta_{atm}^2)} \right) \right)^{-1}, \quad (3.13)$$

where A_{air} (dB) is the attenuation of the atmosphere due to scattering and absorption. (Note that [55] expressed air attenuation as A_{atm} ; we changed this to A_{air} and instead use A_{atm} to refer to attenuation due to air molecules, turbulence, and thermal diffraction within the atmosphere.)

We are only interested in the fundamentals of the problem and therefore, we do not consider pointing loss, transmitting factors for the telescopes, or detector inefficiency. These are scaling factors and applications of these parameters to the equations can

be found here [55, 98]. Calculations using Equations 3.8 and 3.13 were verified by comparing to previously published results of Aspelmeyer et. al [55].

The optical channel is assumed to operate at a wavelength of 1550 nm, which has an atmospheric attenuation $A_{air} = 1$ dB from [55] for scattering and absorption by air molecules between ground and space. The 1550 nm wavelength is assumed due to existing satellite technology operating in that wavelength range and eye safety concerns of using shorter wavelengths. A link distance of $L = 400$ km is assumed between the ground station (at sea-level, $h_0 = 0$ km) and orbiting satellite. The space aperture has an assumed diameter of 0.1 m (D_T for downlink, and D_R for uplink) and the ground station aperture has an assumed diameter of 1 m (D_R for downlink, and D_T for uplink). The angular divergence is $\theta_d = 9.87 \times 10^{-7}$ for the uplink scenario and $\theta_d = 9.87 \times 10^{-6}$ for the downlink case. In the uplink case, the Fried parameter is $r_0 = 0.193$ m and the atmospheric divergence is $\theta_{atm} = 8.04 \times 10^{-5}$. Using Eq. 3.13, the downlink and uplink clear air attenuation for this configuration are 16.0 dB and 34.0 dB, respectively. This gives us a reference optical link scenario, which we will later consider in the context of how a heralded entangled link degrades with the addition of the nuclear disturbed attenuation.

For debris particles, all scattering and absorption interactions are assumed to remove a photon from the optical beam, so the extinction attenuation (the sum of the scattering and absorption attenuations) $Q_{ext} = Q_a + Q_s$ is taken as the metric for beam loss due to debris interference. Because the larger particle sizes fall out of the atmosphere relatively quickly, Mie scattering is assumed for all airborne particles at 1 hour or later. The PyMieScatt Python package [4] is used to calculate Q_{ext} [66] between the transmitter and receiver due to all particle sizes at all atmospheric levels using the equation

$$Q_{ext} = \frac{2}{x^2} \sum_{n=1}^{n_{max}} (2n+1) \text{Re}(a_n + b_n) , \quad (3.14)$$

where a_n and b_n are coefficients that are functions of the complex refractive index m and the size parameter

$$x = \pi d_p / \lambda , \quad (3.15)$$

where d_p is the particle diameter and λ is the wavelength. Note that this does not yet include attenuation from the atmosphere. Attenuations are calculated for 800 nm and 1550 nm wavelengths. By evaluating Eq. 3.14 for all particle sizes, the per-particle extinction attenuation is found for all particles.

The total attenuation (in dB) of an optical transmission between a ground station and a satellite is calculated as the integral of the attenuation of all particles between the transmitting and receiving stations. The discretization of the atmosphere within the transport calculations renders the integral as a sum over the vertical layers. The total attenuation is therefore given as

$$A_{total} = \sum_{l=1}^{l_{max}} \sum_{d=1}^{100} \left[10 * \log_{10}(e^{n_{d,l} * \pi * r_d^2 * Q_{ext,d} * V_l}) \right] , \quad (3.16)$$

where l is the vertical layer, d is the particle size class, $n_{d,l}$ is the vertical particle number density (particles per meter), r_d is the particle radius, $Q_{ext,d}$ is the single-particle extinction attenuation, and V_l is the layer thickness.

For this simulation, the attenuation is independent of the direction of the signal transmission (i.e., ground-to-satellite versus satellite-to-ground). This independence is the result of two simplifying assumptions. First, *only* non-interacting photons pass through the debris. Any interaction at all results in photon extinction. This renders the problem tractable, as solutions do not need to be considered for the rare cases of photons that may weakly interact yet still reach the receiver with some altered angle and wavelength. Second (and partly a result of the first assumption), the signal attenuation is separable between the debris and the atmosphere. The attenuation effects of atmospheric diffusion (A_{atm}), signal direction (A_{dir}), and aperture sizes ($A_{aperture}$) are also assumed to be additive to the attenuation of the cloud (A_{cloud}),

debris (A_{nuc}), or smoke (A_{smoke}) in the attenuation calculations that follow using Equation 3.17. This should hold true because the signal is weak and operating on a single photon level so that nonlinear effects do not need to be considered.

$$A_{total} = 10 \log_{10} \left(10^{\frac{A_{atm}}{10}} + 10^{\frac{A_{nuc}}{10}} + 10^{\frac{A_{dir}}{10}} + \dots \right). \quad (3.17)$$

Further, the attenuation dependence on transmitter/receiver distance as well as the direction of transmission (i.e., satellite-to-ground or ground-to-satellite) are contained entirely within A_{atm} , A_{dir} , and $A_{aperture}$ [55]. Since the nuclear disturbance terms A_{nuc} , A_{cloud} , and A_{smoke} are assumed to be extinction-only attenuation effects, their resulting losses are the same whether the material is close to the transmitter, close to the receiver, or anywhere in between. Therefore, the nuclear-disturbed attenuation losses apply equally to ground-to-satellite communications and satellite-to-ground communications, regardless of the altitude of the satellite. These terms also apply equally to ground-to-aircraft and aircraft-to-ground communications if the debris is assumed to be entirely within the line of sight (i.e., the aircraft is flying above the debris, not through or below it).

3.2.2 Quantum State Estimation (QSE)

To understand how a quantum link will degrade, we must consider how the reduced transmission impacts our ability to estimate the quality of a transmitted quantum state. Our quantum state estimation technique utilizes statistical inference via application of Bayes rule,

$$P(\tau|\mathcal{D}) = \frac{P(\mathcal{D}|\tau)P(\tau)}{P(\mathcal{D})}, \quad (3.18)$$

which allows expression of the probability of parameter set τ given dataset $\mathcal{D}$, $P(\tau|\mathcal{D})$, based on specific events and prior knowledge. In this case, our events are photon counts measured from a photon detector. Our parameter space describes the quantum

state as well as experimental aspects such as photon attenuation. We previously applied this technique to two-qubit states in some simple scenarios [105].

Our specific concept of operations involves an entangled photon pair source operated as a heralded single-photon source, a single loss transmission channel, and a perfect measurement apparatus. The primary parameter affecting the state estimation is the attenuation of the channel.

The application of Bayes's rule to a single state channel includes complete enumeration of the possible experimental outcomes given our initial state, a single pair of entangled photons. For the heralded single-photon source, we assume perfect detection of the sender's herald photon, imperfect transmission of the signal photon sent to the receiver, and perfect measurement and detection by receiver's apparatus. Fig. 3.2 illustrates the potential outcomes for our photonic qubits in any given measurement basis in which both sender and receiver measure a binary result, 0 or 1, with a transmission channel efficiency α , $1 - \alpha$ is then the attenuation.

We can use this probability tree to build the single-basis likelihood. In this scenario, the single-basis likelihood is,

$$\begin{aligned}
P_{kl}(\mathcal{D}|p_{ij}, \alpha) &= \alpha^C (1 - \alpha)^{A_0 + A_1 - C} \\
&\times p_{00}^{c_{00}} p_{01}^{c_{01}} p_{10}^{c_{10}} p_{11}^{c_{11}} \\
&\times (p_{00} + p_{01})^{A_0 - c_{00} - c_{01}} \\
&\times (p_{10} + p_{11})^{A_1 - c_{10} - c_{11}},
\end{aligned} \tag{3.19}$$

where $k, l \in I, X, Y$, to denote measurements in the rectilinear, diagonal, and circular bases, respectively, $\mathcal{D} = \{A_0, A_1, c_{00}, c_{01}, c_{10}, c_{11}\}$, $\mathcal{C} = c_{00} + c_{01} + c_{10} + c_{11}$, and $A_0 + A_1 = N$ being the total number of photon pairs shared between sender and receiver. A_0 and A_1 are sender's single-photon counts and c_{00} , c_{01} , c_{10} , and c_{11} are the sender's and receiver's coincidence counts. As can be seen in Eq. 3.19, the attenuation is the same for all bases and measurement channels which leads to the reduced representation in which the attenuation is not intertwined with the

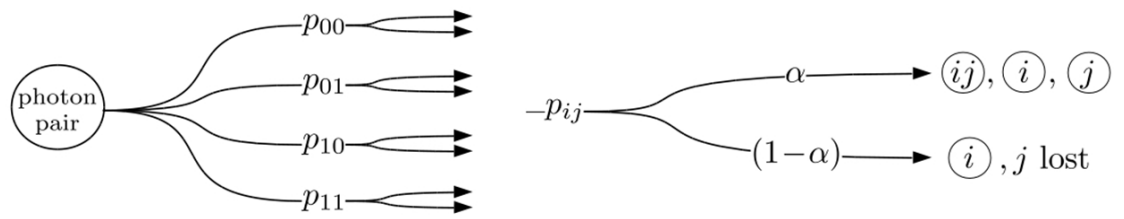


Figure 3.2: Potential measurement and loss outcomes for sender and receiver's shared photon pair.

individual measurement outcomes. Thus, the attenuation's effect on the quantum state estimation, in this case, amounts to an increased uncertainty due to fewer measurements results. Understanding this uncertainty is important as one is often required to do parameter estimation to carry out a desired protocol, for example, to do quantum key distribution. The complete likelihood can then be written as a product of the individual basis likelihoods,

$$P(\tau, \alpha | \mathcal{D}) = \prod_{k,l} P_{k,l}(\tau, \alpha | \mathcal{D}) , \quad (3.20)$$

where we have adjusted the parameterization ($p_{ij} \rightarrow \tau$), see Appendix 6.1, such that the density matrix (ρ) associated with these probabilities fulfills all quantum criteria:

$$\begin{aligned} \text{Tr}(\rho) &= 1 && \text{Probabilities sum to 1,} \\ \langle \psi | \rho | \psi \rangle &\geq 0 && \text{Positive semi-definite,} \\ \rho &= \rho^\dagger && \text{Hermitian.} \end{aligned}$$

With the complete parameterized likelihood, we can apply Bayes's rule to obtain the normalized probability distribution. With this we simply integrate to estimate any mean or related standard deviation of any parameter or function of parameters $\mathcal{F}(\tau, \alpha)$ as

$$\bar{\mathcal{F}} = \int \int d\tau d\alpha P(\tau, \alpha | \mathcal{D}) \mathcal{F}(\tau, \alpha) . \quad (3.21)$$

The complexity of the integral typically requires a numerical approach to evaluate it. We use a Markov chain Monte Carlo algorithm known as slice sampling [106] to evaluate the integrals. Thus, calculation of any integral of the form given in Eq. 3.21 is approximated numerically as

$$\bar{\mathcal{F}} = \lim_{R \rightarrow \infty} \frac{1}{R} \sum_{i=1}^R \mathcal{F}^{(r)} , \quad (3.22)$$

where $\mathcal{F}^{(r)}$ is a single value $\mathcal{F}(\tau^{(r)}, \alpha^{(r)})$ at specific sample points $\tau^{(r)}$ and $\alpha^{(r)}$. This approximation converges on the correct value for large R . In our approach,

independent samplers are run in parallel. The statistics from each sampler are then compared with each other. Once, all samplers agree, defined by their estimation overlap, the numerical approximation is accepted [105]. The quantity central to our entanglement analysis is the density matrix for which the mean estimate is

$$\bar{\rho} = \int \int d\tau d\alpha P(\tau, \alpha | \mathcal{D}) \rho(\tau) . \quad (3.23)$$

We note that the density matrix as defined in Appendix 6.1 is connected to the probability distribution $P(\tau, \alpha | \mathcal{D})$ through the parameters τ .

There are a variety of entanglement measures and metrics used within the research community. Some of these have specific relevance to a certain application or perhaps an especially simple evaluation. We have chosen to use the Entanglement of Formation (EOF) as our entanglement measure which is based on another quantity called the *concurrence* $\mathcal{C}$ [107]. For two qubits, the concurrence is expressible as

$$\mathcal{C} = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\} , \quad (3.24)$$

where the λ 's are the decreasing ($\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4$) eigenvalues of the matrix $\rho \cdot \tilde{\rho}$ with

$$\tilde{\rho} = (\sigma_y \otimes \sigma_y) \rho^* (\sigma_y \otimes \sigma_y) \text{ with } \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} . \quad (3.25)$$

The EOF is then determined using the formula

$$E(\rho) = h\left(\frac{1 + \sqrt{1 - \mathcal{C}(\rho)^2}}{2}\right) , \quad (3.26)$$

with

$$h(x) = -x \log_2(x) - (1 - x) \log_2(1 - x) , \quad (3.27)$$

where $h(x)$ is known as the binary entropy.

3.2.3 Nuclear Debris Model

The Defense Land Fallout Interpretive Code (DELFIIC) is used to calculate the nuclear cloud dimensions as a function of time. DELFIIC models nuclear cloud rise and formation by solving eight differential equations related to the detonation and the surrounding atmosphere [41, 42]. The cloud rise model begins when the fireball reaches pressure equilibrium with the atmosphere and is essentially a rising hot gas bubble within a cooler medium. At this time, the shock wave has separated from the fireball, leaving temperatures of the gas phase and condensed phase, mass of debris and entrained air, internal kinetic energy (of the vorticity of the toroidal core), and the fireball rise rate, radius, and volume. Ballistic ejecta, which are typically very large particles (perhaps >1 cm in diameter), fall to the ground within a few seconds and are ignored. The remaining lofted debris is modeled as the DELFIIC default lognormal particle size distribution for U.S. continental soil, which ranges from about 3 microns to 450 microns in diameter [41]. The conservation equations are solved iteratively in time until the cloud stabilizes at its final altitude, at which point it has lost its internal vorticity. During this time, the advection of the cloud due to ambient winds is accounted for, and the gravitational settling of particles is computed, allowing some of the larger particles may fall to the ground prior to the end of cloud rise. These calculations result in a description of all lofted particle sizes at cloud stabilization time and whether they remain in the cloud volume, have landed on the ground, or are at some intermediate altitude.

Once DELFIIC has calculated the particle locations at cloud stabilization, these data are passed to the National Oceanic and Atmospheric Administration’s (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) code for atmospheric transport [46]. HYSPLIT’s particle representation (as opposed to a puff representation) of the debris is transported using atmospheric and wind data from the North American Mesoscale Forecast System (NAM) at 12 km resolution [108]. The HYSPLIT’s “concentration” calculations are used to predict the volumetric

concentrations of all debris particle sizes in the atmosphere as a function of time after detonation, altitude, and latitude/longitude.

The DELFIC cloud rise model and the HYSPLIT atmospheric transport code are integrated using the ORNL-built Airborne Planning Tool (APTool) [44, 45]. A surface-level nuclear detonation is simulated every 4 hours from January 1 through December 31, 2019, resulting in over 2,000 simulations per yield scenario. The detonation simulations are independent of each other (i.e., not cumulative over time). The debris location as a function of latitude, longitude, and altitude is calculated at one-hour intervals from 1 to 6 hours at a latitude/longitude resolution of 0.05 degrees (very roughly 5 km) and eight to thirteen vertical layers, depending on the yield. The simulation ensemble is performed for yields of 10 kt, 100 kt, and 1 Mt (1,000 kt). Concentrations are calculated using 10 minute averages to reduce instantaneous spikes or depressions in concentration. The resulting concentration outputs are then inspected using APTool post-processing utilities to find the peak attenuation due to debris between a ground transmitter and a vertically-overhead receiver. As discussed in Section 3.2.1, these results apply equally to satellite-to-ground transmission. Signal losses (in dB) are assumed to be additive to normal atmospheric losses, so a zero loss condition would be expressed as 0 dB.

3.3 Results

3.3.1 Nuclear Link Loss - Stabilized Cloud

For the first effect in a nuclear disturbed environment, nuclear cloud formation and stabilization are calculated for yields of 10 kt, 100 kt and 1 Mt at a height of burst of 1 m. The cloud was represented as a homogeneous mixture of water vapor (the liquid water content of the cloud is 1 g/m³), soil and weapon debris. The particle size distribution for the soil and weapon debris is assumed to be the default DELFIC lognormal distribution with a median particle diameter around 130 μm [41] and the

water vapor droplets are assumed to have a uniform diameter of $12\text{ }\mu\text{m}$. The cloud data is inputted into the MIE scattering equations [66] to determine the amount of attenuation the optical link experienced during propagation through the nuclear cloud. The optical link is assumed to pass through the center of the nuclear cloud. The added attenuation through the stabilized cloud is given in Fig. 3.3. While the actual stabilization time and size of the stabilized cloud will vary with atmospheric conditions for a given shot scenario (e.g., humidity, temperature, wind conditions, air pressure, etc.), very rough conceptual sizes and times for the stabilized clouds may be considered as follows: 3 km cloud diameter at 5 min for a 10 kt yield, 10 km cloud diameter at 10 min for 100 kt, and 30 km cloud diameter at 15 min for a 1 Mt yield. Even for a 1 Mt detonation, direct transmission through a stabilized cloud is unlikely, and even then only for a small window of time.

3.3.2 Nuclear Link Loss - Transported Debris

During the initial cloud rise, the vorticity within the cloud causes it to retain shape, minimizing atmospheric diffusion. Additionally, the debris falling from the cloud is directly under the cloud itself and can result in very large attenuations, albeit for relatively small footprints. Eventually, as the vorticity weakens and the cloud cools, the cloud rise ceases and the debris begins to move in the atmosphere according to the winds, turbulent diffusion, and other meteorological effects. For a 1 Mt explosion, cloud rise typically ends about 15 to 20 minutes after detonation, while cloud rise from 100 kt and 10 kt detonations typically end after about 10 minutes and 5 minutes, respectively. From here, the debris will diffuse in the atmosphere, lowering the peak volumetric concentration and, by extension, the peak attenuation. Diffusion also causes the debris to occupy a larger volume of the atmosphere, increasing the region in which ground/satellite communications may be affected. Since the transport and diffusion is heavily dependent on atmospheric conditions, an ensemble of simulations

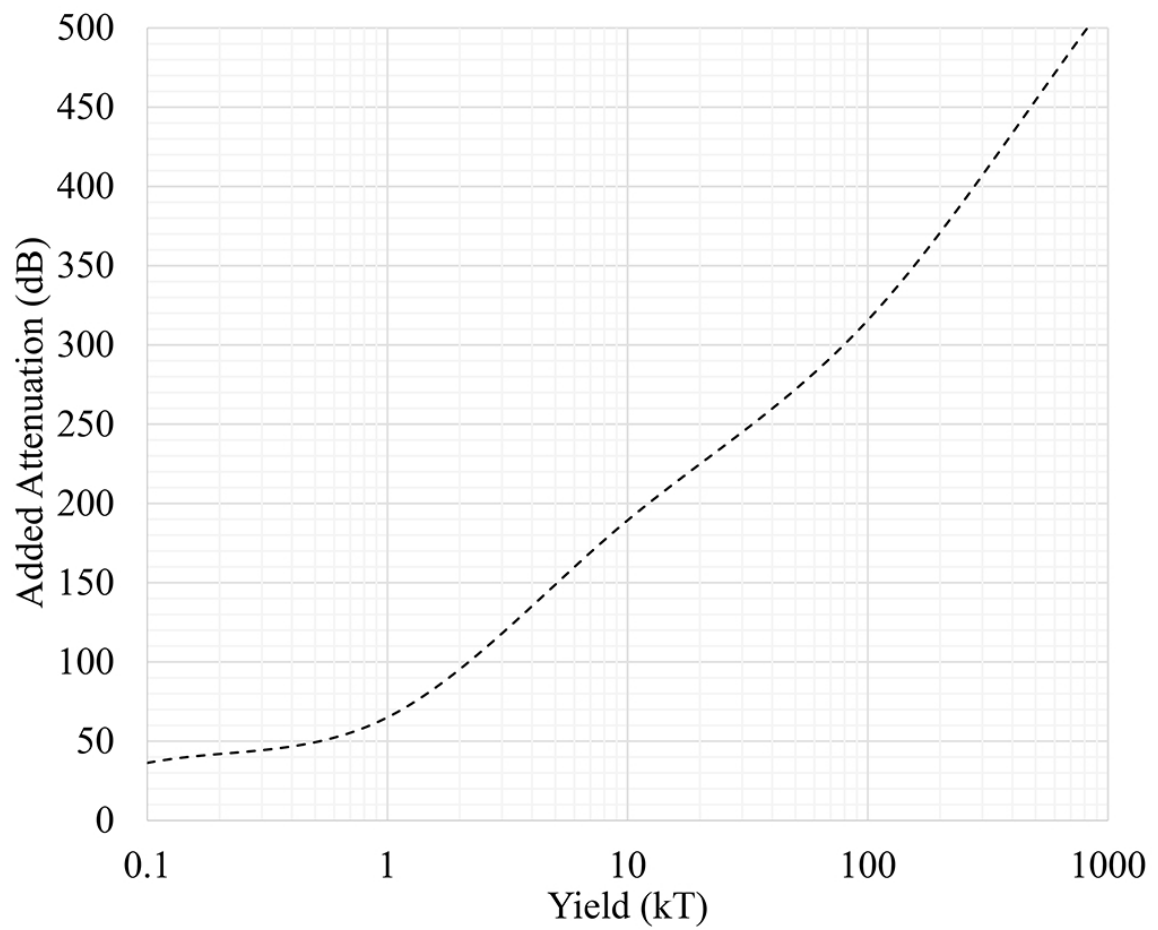
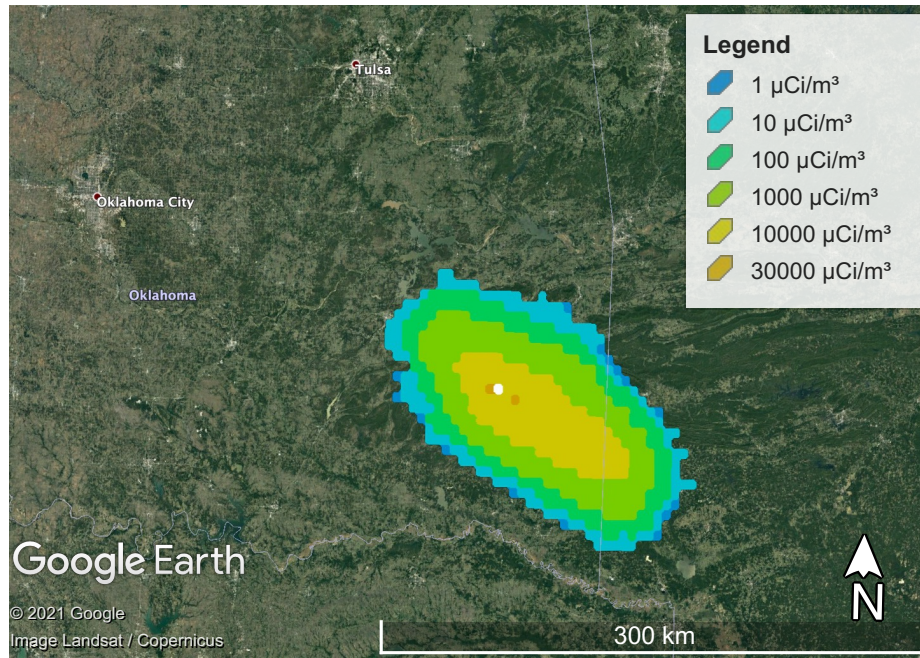


Figure 3.3: 1550 nm optical attenuation through a nuclear cloud as a function of weapon yield.

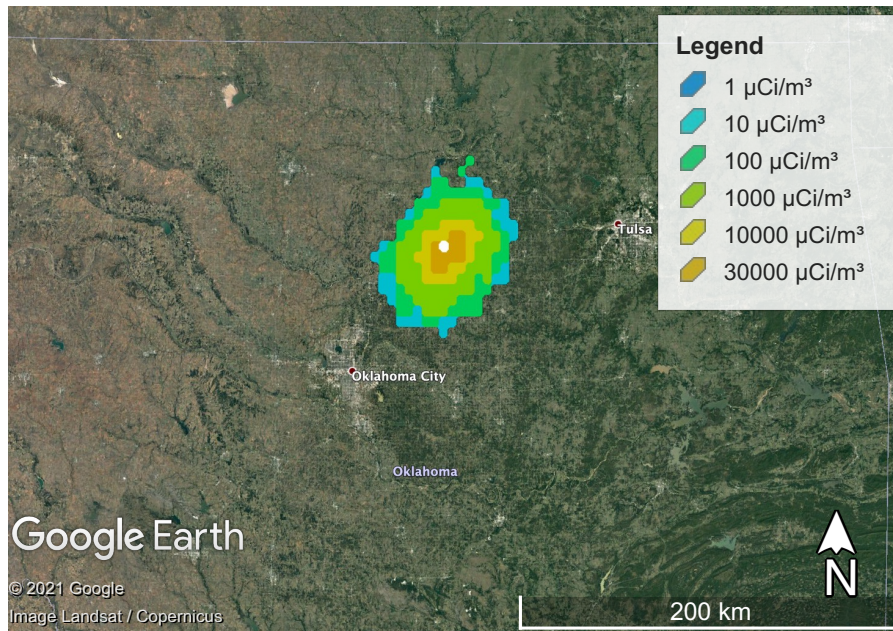
is performed for each explosive yield value to generate a statistical measure of the potential signal attenuation as a function of time.

The ensembles are analyzed in two manners. First, the maximum observed attenuation of each simulation is recorded as a function of time, regardless of downwind position. Fig. 3.4 illustrates the change in location of the attenuation observation for two different detonation times. This represents the maximum possible signal loss that the nuclear debris could cause at a given time after detonation and is therefore an upper bound to potential signal disruption. The maxima are determined for all simulations within an ensemble and collected into a distribution of upper bounds as a function of time. Fig. 3.5 shows the aggregated maximum observed attenuation of each simulation for yields of 1 Mt, 100 kt, and 10 kt. The 1550 nm wavelength is evaluated for all yields, and the 800 nm wavelength is shown for the 1 Mt case as a comparison. For 10 kt yields, no attenuation greater than 3 dB is ever observed. For 100 kt, attenuation is only once observed as high as 14 dB at 1 hour, but 90% of scenarios have a maximum attenuation of 5 dB or less, and 99% have a maximum attenuation of 10 dB or less. At 1 Mt, 96% of all scenarios have a maximum attenuation of 20 dB or less at 1 hour, and all but one scenario have a maximum attenuation of 10 dB by 2 hours. The 800 nm and 1550 nm simulations provide nearly identical results due to the wide range of particle sizes within the transported debris. Because of this, the rest of the results are given for the 1550 nm wavelength and are assumed to be applicable to the 800 nm wavelength.

Since the maximum attenuation values in Fig. 3.5 are independent of the attenuation of the clear air atmospheric channel (A_{atm}), the additional attenuation A_{nuc} for the 1550 nm wavelength of the 1 Mt yield ensemble are plotted in Fig. 3.6. At 3 hours, 95% of the 1 Mt simulations have no location where the debris contribution to attenuation is greater than 3 dB and the median 1 Mt simulation has a maximum attenuation of 0.9 dB.



(a) March 1, noon detonation



(b) October 1, 8 AM detonation

Figure 3.4: Debris activity (in $\mu\text{Ci}/\text{m}^3$) at 10 km above ground at 1 hr after a 1 Mt detonation in Oklahoma City for two different detonation times. The location of maximum attenuation is shown as a white dot.

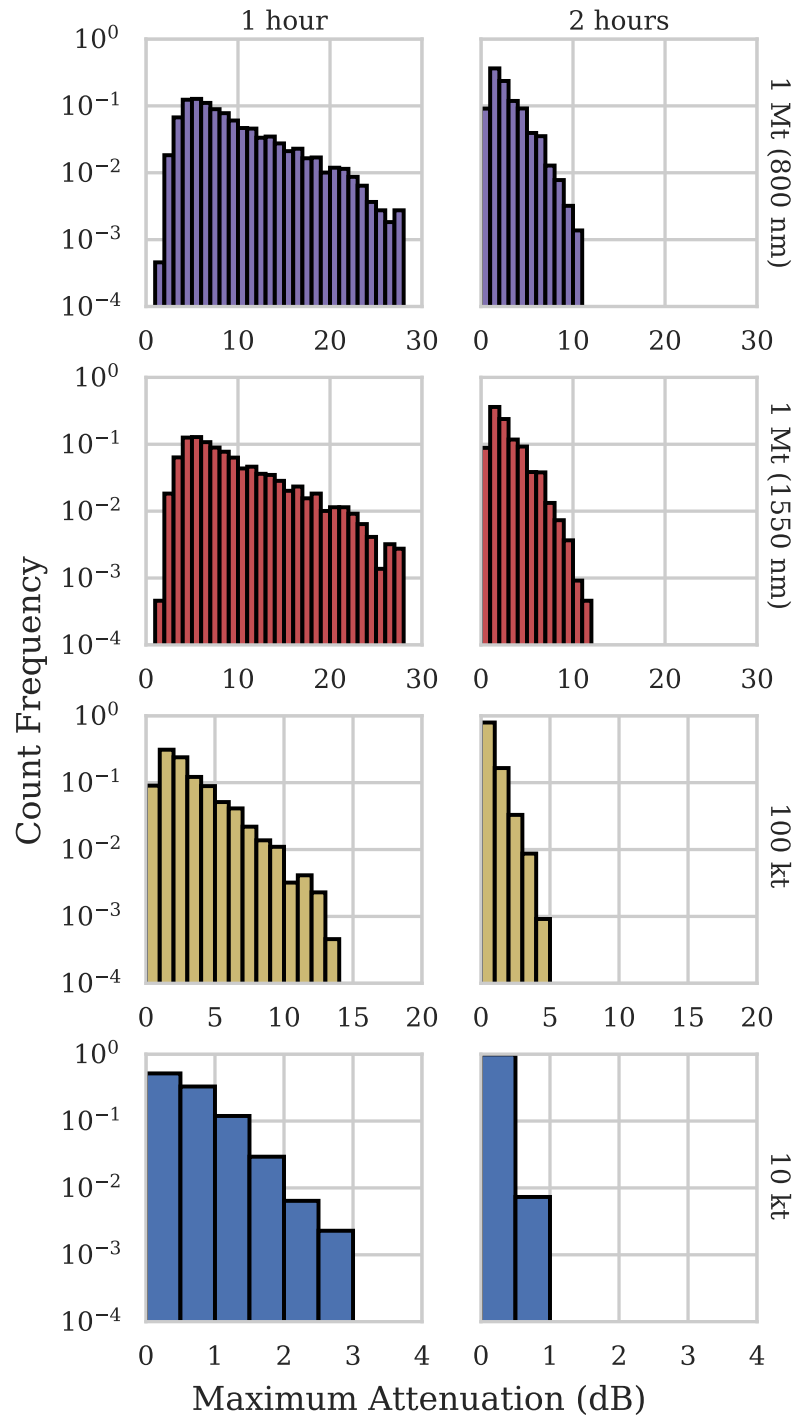


Figure 3.5: Maximum attenuation at 1 and 2 hours after detonation. 1 Mt attenuation is shown for both 800 nm and 1550 nm wavelengths for comparison. All others are 1550 nm.

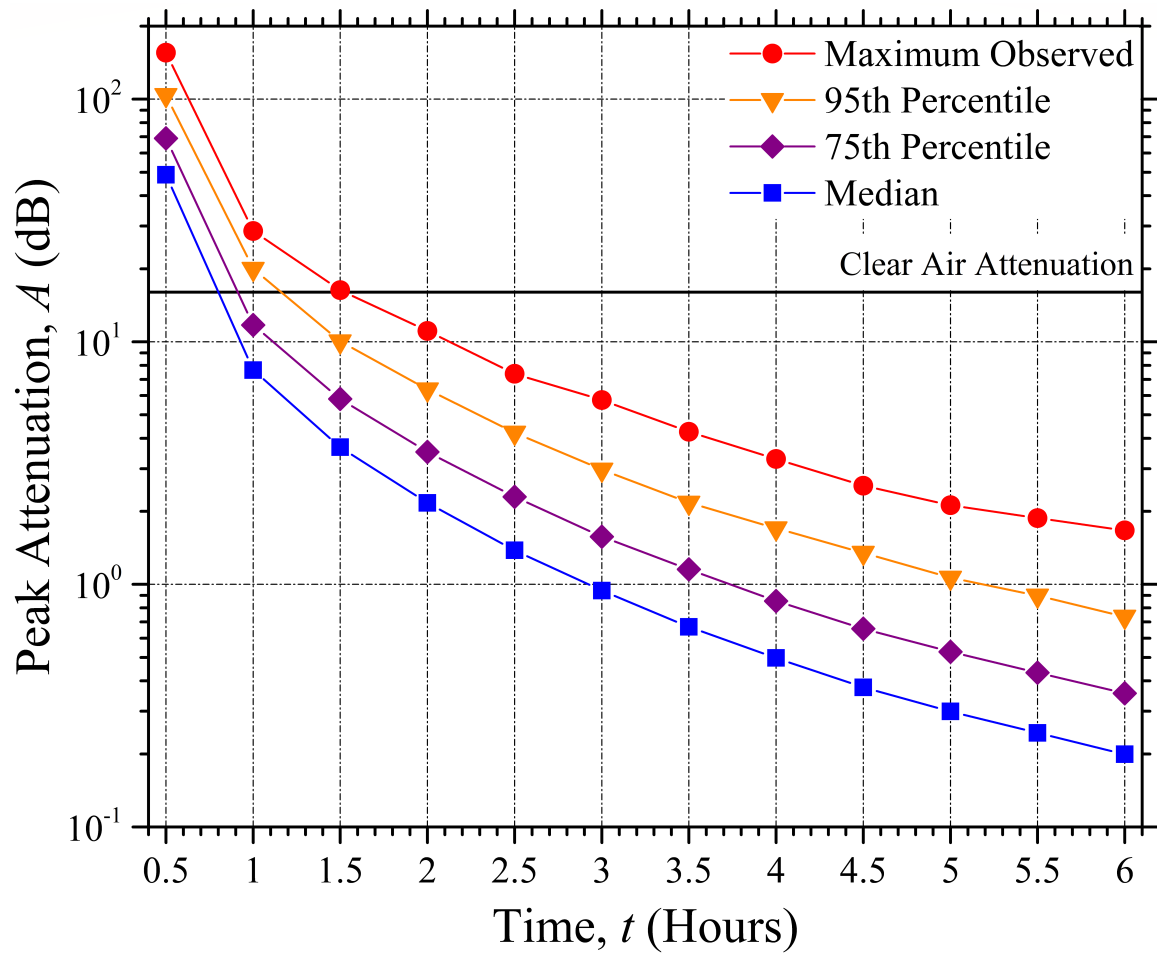


Figure 3.6: Maximum 1550 nm attenuation at 1 Mt.

Where Fig. 3.5 illustrates the maximum observed attenuation in each simulation, Fig. 3.7 shows all observed nonzero attenuation results at all geographic grid locations for each ensemble. (Unlike the maximal histograms, the count frequency is given as a fraction of all observations in semi-log scaling to show the smaller bins. Note the very rapid reduction in count frequency from the first to second bin in all subplots.) In all cases and at all times, nearly all of the geographic grid locations experience less than 1 dB of attenuation due to nuclear debris. For the worst case of a 1 Mt yield and one hour after detonation, there is less than a 1% chance that an affected location would experience added attenuation greater than 10 dB. By two hours, the likelihood of 10 dB attenuation is effectively zero.

3.3.3 Nuclear Link Loss - Secondary Smoke

The last absorption/scattering mechanism that can cause degradation in the optical link is from elevated levels of particulate matter in the air from smoke and haze of a nearby burning city. In this scenario, we assume that a nuclear detonation has occurred in a nearby city, the debris of the nuclear cloud has passed, and that the smoke from the burning city is being blown in the direction of the ground station for the optical link. In smoke, the majority of particles are under 1 μm and so it is common to use the particulate matter 2.5 (PM2.5, typically with units of $\mu\text{g}/\text{m}^3$) equations to determine visibility in the smoke. The amount of smoke and haze from a burning city is difficult to quantify as each city has different parameters (such as fuel loading, city size, average wind speeds, etc.) though some quantification efforts have been performed [91]. A full treatment of smoke is beyond the scope of the present study. As a scoping study, however, a comparison of varying PM2.5 levels are considered for an optical link. The PM2.5 levels, shown in Fig. 3.8 are used to calculate the visibility of the optical link as a function of haze thickness. The equation to relate visibility to PM2.5 levels is taken from [109] and assumes relative humidity levels under 60 percent.

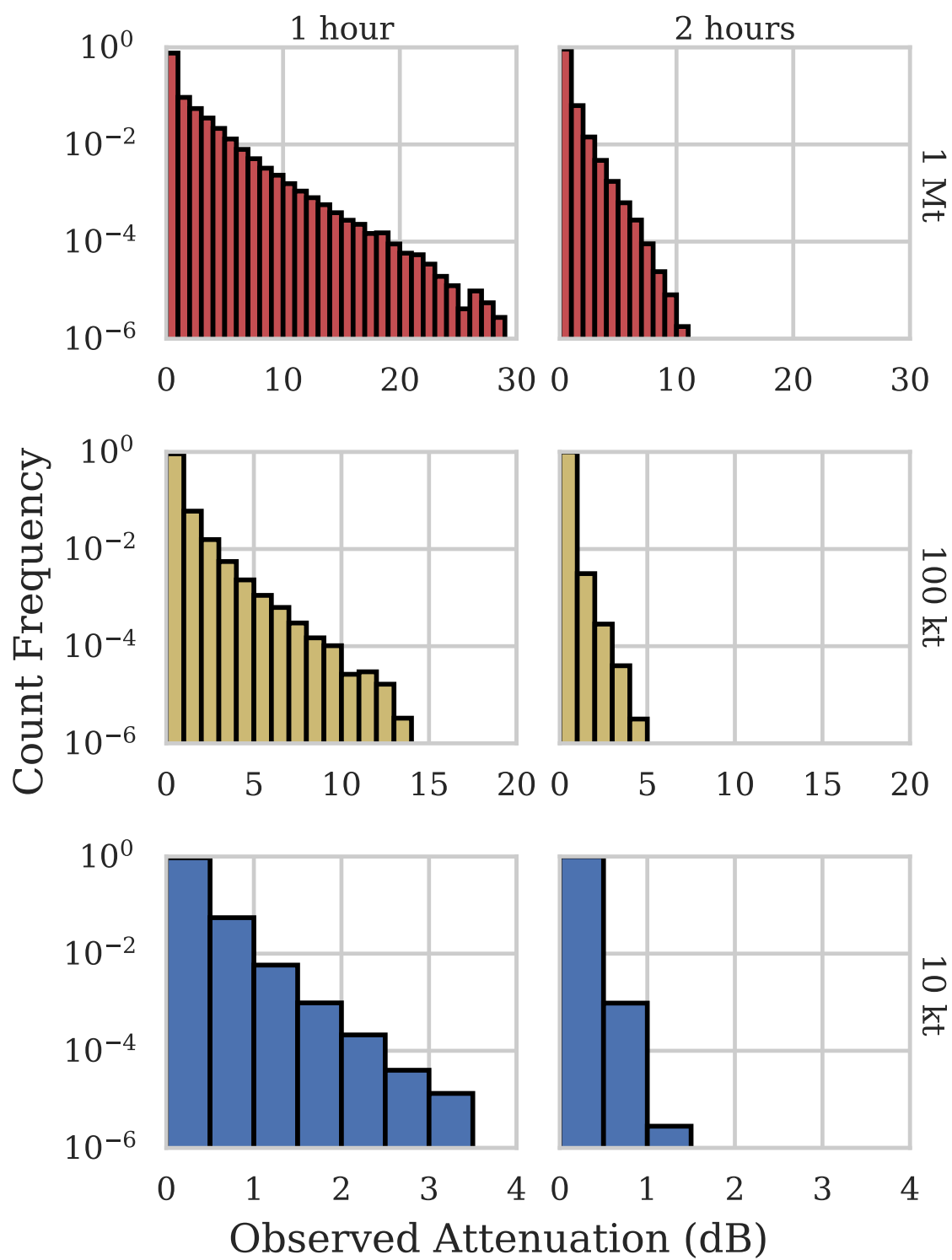


Figure 3.7: Attenuation of the 1550 nm wavelength at all nonzero grid locations for all simulations.

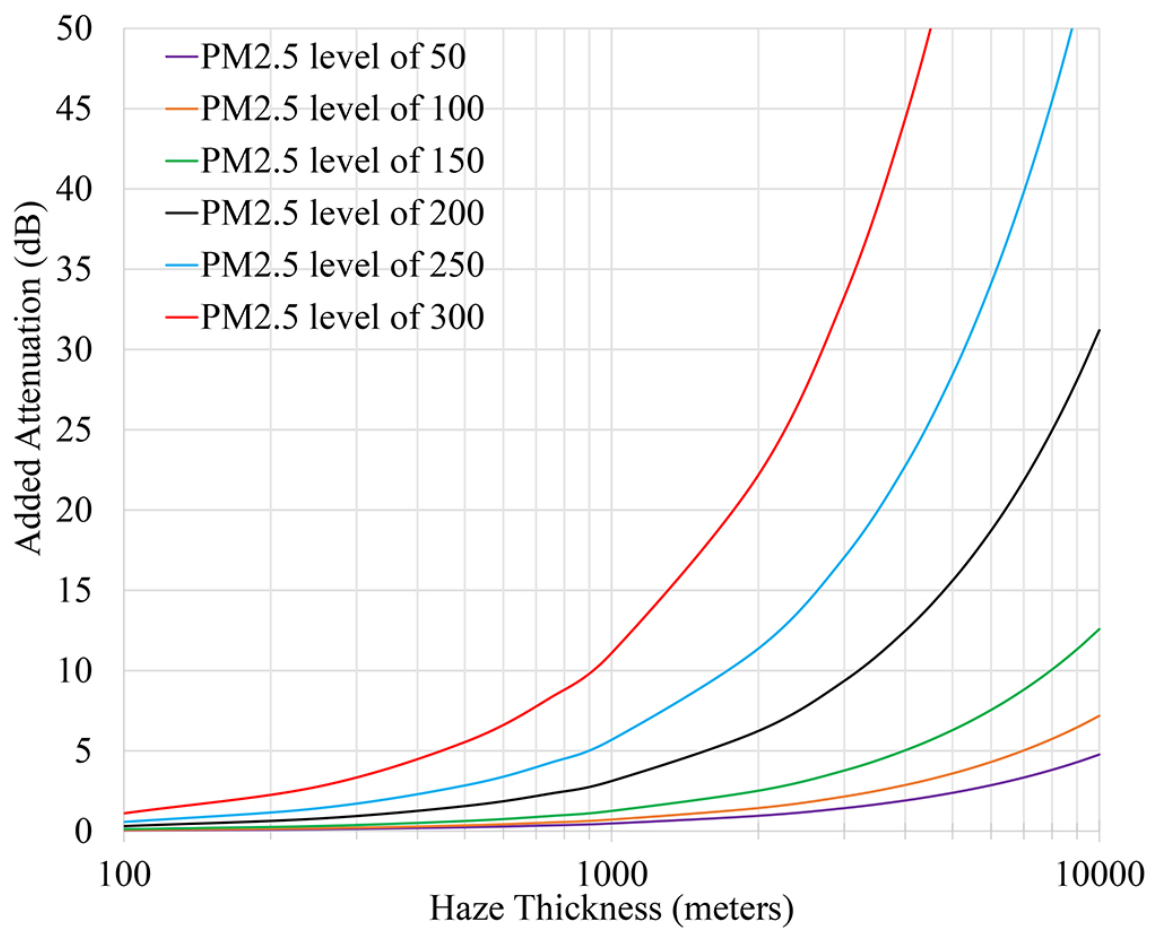


Figure 3.8: Added 1550 nm light attenuation as a function of haze thickness and its PM2.5 level.

The optical link attenuation calculation in Fig. 3.9 assumes a 1550 nm uplink and downlink scenario between a ground station and a satellite; the satellite is assumed to have a 0.1 meter diameter optical aperture while the ground station is assumed to have a 1 meter diameter optical aperture. The amount of haze and smoke is set for a vertical thickness of 3 km for this study and the satellite is assumed to be directly overhead (elevation angle of 90°). Fig. 3.9 is a best case scenario as the attenuation increases when the elevation angle is dropped from 90 degrees (attenuation increases as the inverse of the sine of the elevation angle).

3.3.4 Nuclear Link Loss Summary

Table 3.1 summarizes representative attenuation values for the nuclear cloud and debris terms in comparison to natural sources (clouds, city haze, and atmosphere) as well as the potential secondary effect of post-detonation fire. During the rise of the nuclear cloud up to stabilization, the attenuation of the signal through the cloud is several hundred dB in addition to normal atmospheric losses. However, by an hour after detonation, atmospheric diffusion of the debris reduces the maximum attenuation to a median of 7 dB for a 1 Mt detonation, with 30 dB as the highest attenuation seen at 1 hour in any of the simulations. Attenuation from lower yields are substantially lower at 1 hour as well.

3.3.5 QSE

So far, we have focused on computing the attenuation of an optical channel. Now we will describe how the attenuation translates into the degradation of transmitted heralded entanglement. To do so, we apply the formalism from Section 3.2.2 to simulation data. The simulations assume that 1 million maximally entangled photon pairs are generated by sender for each measurement basis combination, nine million

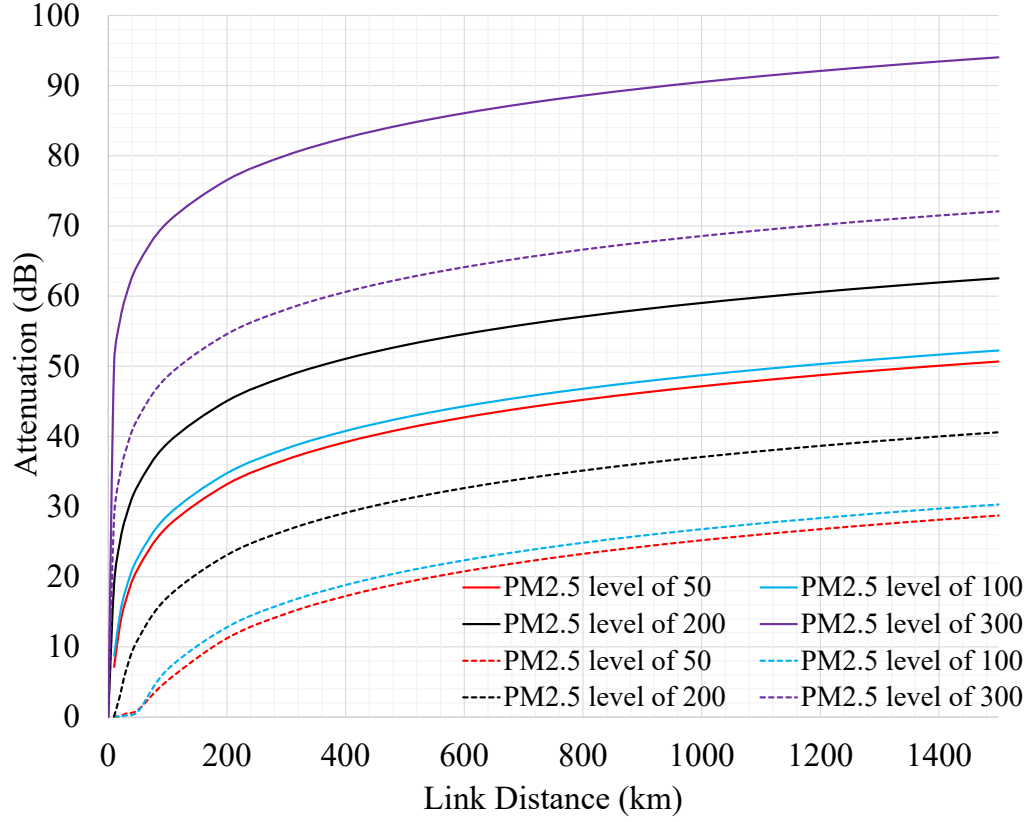


Figure 3.9: Optical link attenuation between a ground station and a satellite for both the uplink (solid line) and downlink (dashed line) scenarios, assuming the link propagates through 3 km of haze at an elevation angle of 90° .

Table 3.1: Summary of Representative Signal Attenuation Terms (in dB).

Nuclear Debris			
Yield	Nuclear Cloud ^a	1 Hour ^b	2 Hours ^b
1 Mt	550	30 (7)	10 (2)
100 kt	350	15 (2)	5 (0.5)
10 kt	250	3 (0.5)	1 (0.1)
Clouds ^c			
Nimbostratus	Cumulus	Stratus	
220	70	25	
PM2.5 Pollutants			
Fire Haze ^d	Foreign City ^e	US City ^e	
30	3	1	
Atmosphere ^f			
Downlink		Uplink	
16.0		34.0	

^a Nuclear Cloud attenuation is calculated at the time of cloud stabilization (i.e., end of cloud rise): approx. 30 min

for 1 Mt, 10 min for 100 kt, and 5 min for 10 kt.

^b Maximum attenuation for all simulations is given. The value in parentheses is the median maximum value across all simulations.

^c Cloud data taken from [110]

^d Fire Haze data taken from [111]

^e Foreign City and US City pollution data taken from [112]

^f $L = 400$ km, $D_S = 0.1$ m, $D_{GS} = 1$ m.

photon pairs total. The photon pair is in the polarization entangled Bell state

$$|\Psi_{-}\rangle = \frac{1}{\sqrt{2}}(|H_A V_B\rangle - |H_B V_A\rangle). \quad (3.28)$$

The sender detects one photon of the pair, heralding a single photon which is sent to the receiver. The transmission channel includes attenuation which has a chance of destroying the single photon. We vary the attenuation from 0 dB to 50 dB. From the collected data we estimate the state, the EOF from Eq. 3.26, and the transmission efficiency estimate $\bar{\alpha}$, the attenuation is $1 - \bar{\alpha}$.

We plot the entanglement and transmission estimates for each attenuation setting in Fig. 3.10, using Eq. 3.17. The numerical data for the combined atmosphere/debris attenuation are given in Table 3.2.

As can be seen in Fig. 3.10, our estimate for the transmission efficiency has almost no uncertainty due to the symmetry of the attenuation and the large dataset. More specifically, the sender gets one count for every photon pair generated. Whether or not the receiver receives a count is directly proportional to the attenuation. Thus, as simulated, this is a very low uncertainty measurement.

We also plot the entanglement of formation versus the loss in Fig. 3.10. From this, one can discern the impact of a change in attenuation from a “normal” operating condition. While our state never changes (it is still maximally entangled), the amount of data we generate decreases with increasing attenuation. Thus, the uncertainty in our entanglement estimates increases due to the finite photon statistics. One could always consider a longer integration time, but this illustrates that there are fundamental limits to how much attenuation is allowable for practical quantum applications. In addition, as satellite platforms may be moving and hence not always aligned, opportunities to collect data may not have a high duty cycle further limiting the data set size.

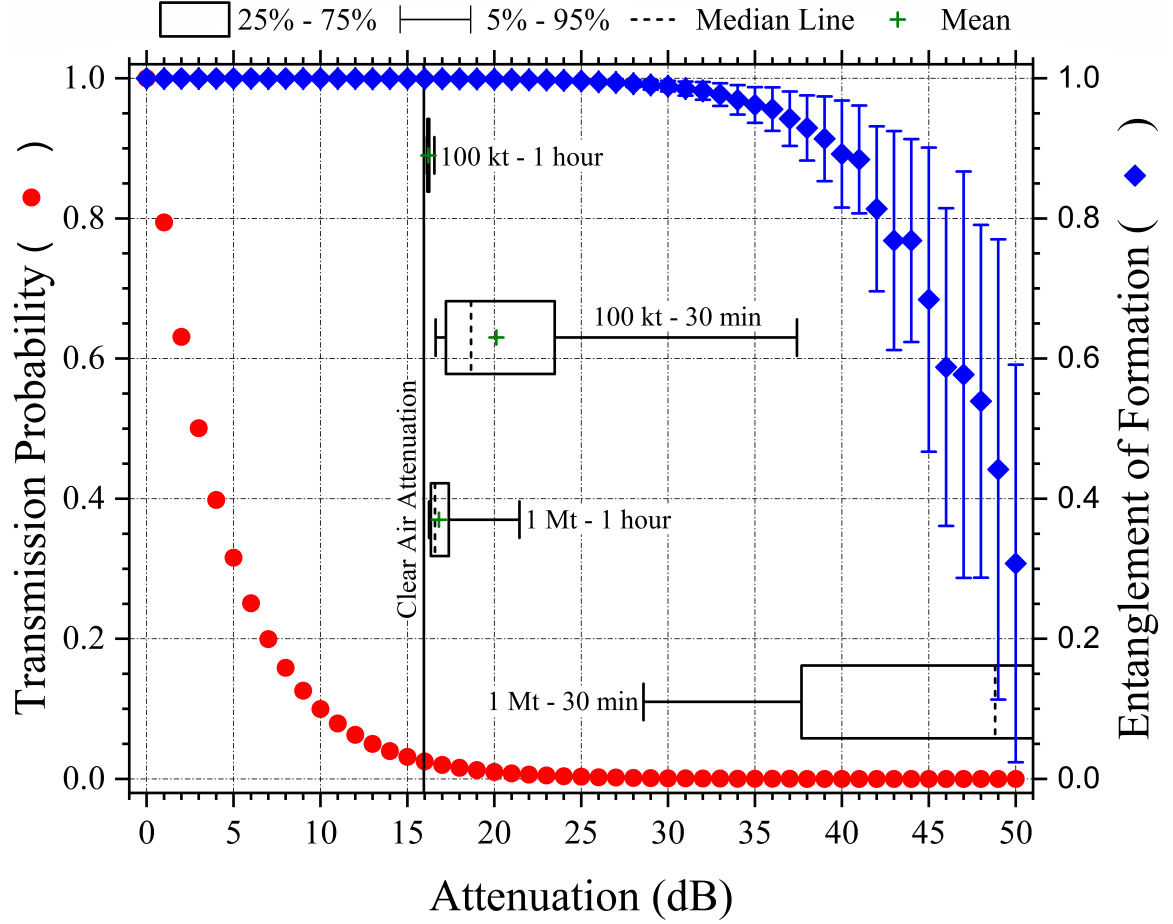


Figure 3.10: The entanglement estimate (with 1 standard deviation) and the transmission probability as a function of the loss in a nuclear disturbed environment after the detonation of a 1 Mt and 100 kt device. The solid black line is the downlink clear air attenuation calculated for a 400 km optical link between a space aperture diameter of 0.1 m and a ground station 1 m in diameter. Box plots are shown for 1 Mt and 100 kt explosions 30 minutes and 1 hour after detonation to show the evolution of the air and nuclear debris attenuation statistics with time. 10 kt data is not shown due to insignificant contribution to attenuation (see Table 3.2).

Table 3.2: Summary of the attenuation due to the nuclear debris and atmosphere for varying yields (kilotons) and times post-detonation (TPD) (hours). The clear air attenuation is assumed to be 16.0 dB for a downlink configuration optical link of 400 km between a 0.1 m diameter space aperture and a ground station with a 1 m aperture size. The mean, standard deviation (SD), median, and 95% confidence intervals (CI) are shown for the nuclear debris attenuations as well as the total mean and median attenuations for the clear air and debris combined.

Yield (kt)	TPD (h)	Nuclear Mean	SD	Total Mean	Nuclear Median (dB)	95% CI	5% CI	Total Median
1000	0.5	55.6	23.9	55.6	48.8	104.	28.3	48.8
	1.0	9.12	5.07	16.8	7.65	20.0	3.58	16.6
	2.0	2.67	1.71	16.2	2.17	6.36	0.841	16.2
100	0.5	18.0	9.16	20.1	15.3	37.4	7.93	18.7
	1.0	2.98	2.08	16.2	2.30	7.30	0.832	16.2
	2.0	0.688	0.589	16.1	0.496	1.87	0.145	16.1
10	0.5	3.98	1.88	16.2	3.51	7.66	1.76	16.2
	1.0	0.598	0.411	16.1	0.481	1.40	0.147	16.1
	2.0	0.120	0.0970	16.1	0.0923	0.310	0.0473	16.1

Application of this approach to a dynamic attenuation is done by analyzing smaller chunks of data from discrete time bins. Analysis of estimates from short time intervals in “real-time” allows tracking channel dynamics.

The spread of attenuation values in Fig. 3.10 are calculated using Eq. 3.17 assuming that $A_{atm} = 16$ dB and A_{nuc} is the nuclear debris values, obtained from the DELFIC simulation and presented in Table 3.2. The spread of values is meant to highlight the degradation of the optical channel as a function of time due to the debris when compared to the normal operating conditions. The mean and the median are provided to show the skew of the distribution. The debris only impairs the optical channel during the first hour, with the severity depending on the explosive yield. Despite the adverse effect on optical channel, only the 1 Mt explosion is able to produce enough attenuation in the first hour where the entanglement severely suffers.

3.4 Conclusions

The research of this paper addresses the potential for airborne nuclear debris to interfere with optical or quantum communications between a ground/satellite transmitter/receiver system. If a nuclear weapon were detonated near the surface of the earth (where a significant amount of ground soil is entrained into the fireball), the rising cloud may contain up to millions of tons of debris. During the cloud rise, much of the debris remains contained in the cloud due to the internal vorticity. If an optical or quantum signal were transmitted through the rising cloud, the signal loss would be in the hundreds of dB, likely rendering successful communication impossible. This condition would last until the cloud reaches its peak altitude, at which point the internal vorticity is completely dissipated and the debris transports in the atmosphere according to wind and gravitational forces. The dissipation of the debris rapidly decreases the peak attenuation of the signal. By the time an hour has passed after the detonation, the maximum simulated attenuation of the signal is bounded within 30 dB for a 1 Mt surface detonation. After two hours, the peak attenuation is reduced

to about 10 to 11 dB for 1 Mt. These peak values, however, are the worst cases in all scenarios, where the signal is being transmitted through the location of greatest loss. For the rising cloud, this is a cross-sectional radius of a few km that is generally found relatively close to the ground zero of the detonation. By one or two hours, the point of peak attenuation may have moved to 100 km or more downwind of ground zero, but the area affected by this attenuation is still relatively small, and the rapid speed of upper air winds will generally ensure that communications at a fixed point are interrupted for only a small window of time.

When looking at the entire region where airborne debris has a measurable attenuation of the signal, it is very unlikely that a ground/satellite system within this region would experience significant attenuation. Even for a 1 Mt explosion at 1 hour, about 90% of all the affected area experience 1 dB or less of attenuation, and 99% of all the area experience less than 1 dB attenuation. If the non-nuclear atmospheric loss is assumed to be about 20 dB, then the additional attenuation burden of the nuclear debris is a very small fraction of the total signal loss. Whether this additional burden is significant will be a function of the transmitter/receiver system.

In contrast, the smoke from potential fires caused by a near-surface nuclear detonation may provide a larger, more persistent source of attenuation downwind of the detonation site. The PM2.5 pollutants may cause losses on the order of 30 dB throughout the affected region, and if these fires persist over hours or days, then the attenuation would potentially be present for a much longer time. The general concerns are thus (in chronological order):

1. The rising nuclear cloud, if the transmitter/receiver system is close to, and downwind of, the detonation, but not so close as to be affected by the initial blast or other localized effects.
2. The dispersed nuclear debris, up to an hour after detonation for very large yields, and for less time for smaller yields.

3. Smoke and soot from fires caused by the detonation, which may persist for hours or days after the detonation and become a source of large attenuation for the affected regions. Given that the winds will not be constant, the region of affected transmission may change over time.

Our analyses focused on 1550 nm wavelengths due to their relatively low attenuation through normal atmospheric conditions. A brief inspection of the 800 nm wavelength revealed that the attenuation through debris – whether the rising cloud, the transported debris, or the smoke – was generally insensitive to the difference between these wavelengths due to the broad distribution of particle sizes (typically from 1 to 100 μm).

Lastly, we provide estimates on the impact to entanglement transmission through a nuclear-disturbed optical channel. By adding the effects of the nuclear debris (in dB) to that of the atmosphere, an estimate of the potential degradation of entanglement is found for various yields and times after detonation. In the case of an actual need to transmit a quantum signal through a nuclear disturbed environment, these loss estimates may be applied to the particular transmitter/receiver system, atmospheric conditions, and nuclear-induced disturbance to assist in operational decision-making. By maintaining the assumption of independence of the atmospheric losses and the nuclear losses, the potential attenuation and signal degradation may be rapidly estimated by adding the separate loss terms in dB. As our research is intended to provide upper bound estimates on the potential losses, we minimize the possibility of predicting ‘false positive’ transmission rates using this method.

This research focused on quantifying the severity of potential transmission attenuation due to airborne nuclear debris, in terms of total attenuation and time of significant attenuation. While the analysis is applicable to both conventional and quantum signals, analysis of measures to counteract these effects are beyond the scope of the research, but merit some discussion. As noted, this work assumed communications between a single satellite and a single ground station. Given the

localized effect of nuclear debris attenuation, it is entirely possible that an optical signal or entangled photon may simply be sent to a different receiver, or sent from a different transmitter if such a transmission is time-critical. This decision is best analyzed by the operator of the communications network; in our opinion, however, this course of action is likely to be viable at any time after detonation. Alternatively, changing to a modality (e.g., radio frequency communication, for classical-only communications) that is insensitive to the presence of debris may provide a solution. For solely classical communications, the use of high-intensity lasers to mitigate turbulence [113] or fog [114] may be considered. Similar to a change in wavelength, this obviates the use of single-photon communications, which may or may not be desirable depending on the needs of the user.

Chapter 4

Light Interference from a Nuclear Fireball

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4.1 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 [23] 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 [25, 26, 69, 115]. Recent research on daytime optical link communications has sought to reduce the effects of background light by using enhancements such as adaptive optics [69], a small field of view (FOV) telescope, wavelength filters, or a timing gate [116]. 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 [5]. 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 [7], as well as the increased dark count rate of satellite-based detectors from a high-altitude nuclear detonation [6] will not be addressed.

4.2 Method

4.2.1 Optical Link

The problem considered herein is shown schematically in Fig. 4.1, 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 field of view (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 Fig. 4.1. 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.

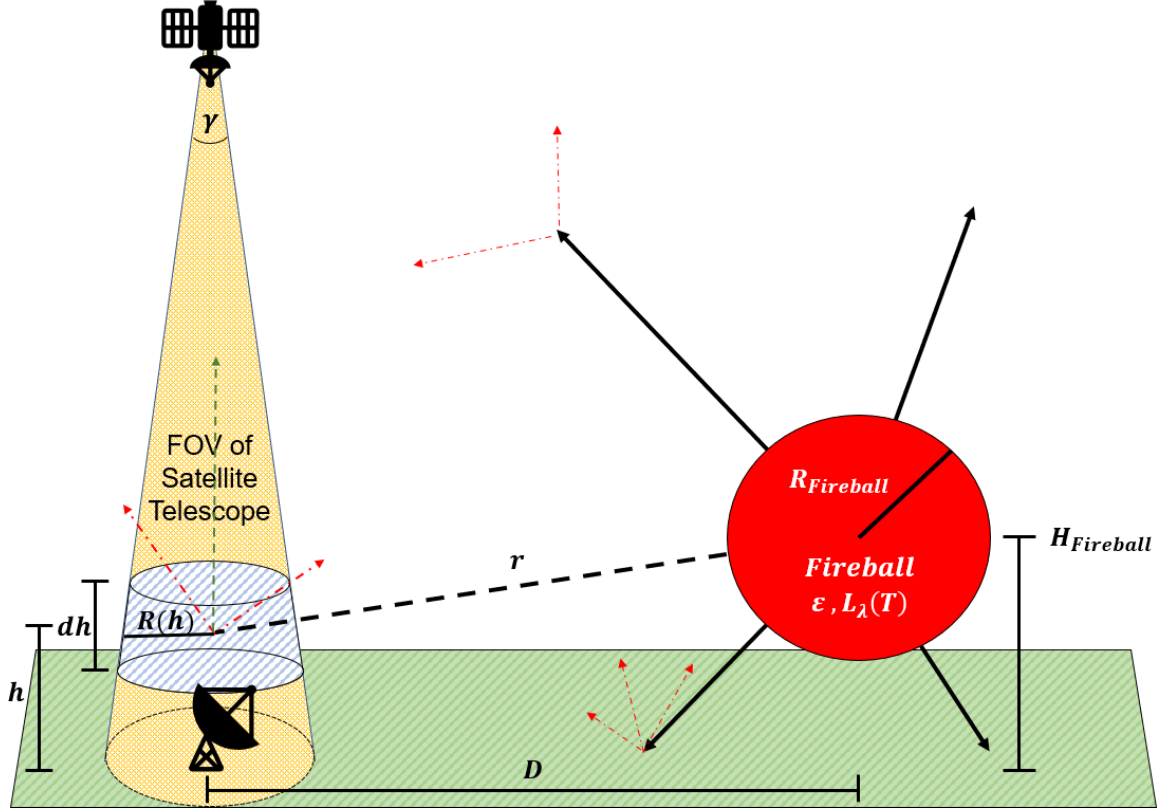


Figure 4.1: Diagram for calculating the scattered light entering a detector on a satellite from a nuclear explosion outside the FOV γ , a distance D away. A nuclear fireball located at a altitude H_{fireball} from the ground with an emissivity of ϵ and a temperature-dependent spectral radiance $L_\lambda(T)$ emits light into the solid angle of the satellite. The solid angle is divided into conic sections of size dh at an altitude of h above the ground with a slant range from the center of the fireball given by r .

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, $E_{\text{H,scatter}}(h)$, at a receiver on a satellite at altitude H is related to the irradiance at the disk, $E(h)$, according to

$$E_{\text{H,scatter}}(h) = [\sigma_R(h)\rho_R(h) + \sigma_M\rho_M(h)] \frac{\tau(h)E(h)}{(H-h)^2} \pi R^2(h) dh, \quad (4.1)$$

where $\tau(h)$ is the transmittance of the portion of the channel from h to the receiver; $\sigma_R(h)$ and σ_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, ϕ_{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 Eq. (4.1) over h :

$$E_{\text{H,scatter}} = \int_0^H [\sigma_R(h)\rho_R(h) + \sigma_M\rho_M(h)] \frac{\tau(h)E(h)}{(H-h)^2} \pi R^2(h) dh. \quad (4.2)$$

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, $E_{\text{H,ground}}$, at the satellite caused by ground scatter is

$$E_{\text{H,ground}} = \alpha_E \frac{\tau(0)E(0)}{H^2} \pi R^2(0), \quad (4.3)$$

where α_E 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, $E_{\text{Total}} = E_{\text{H,scatter}} + E_{\text{H,ground}}$, (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 [5, 88]. Comparison of our method to Bonato's [88] 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 4.1. Both methods assumed a wavelength filter of 1 nm on the detector system, a 100 μrad 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 [117] and the full Moon spectral irradiance is taken from the MT 2009 model for 800 nm [118] and the GEMINI 7 lunar measurements for 1550 nm [119]. The difference in values is from Bonato's [88] assumption that ground scatter dominates

Table 4.1: The amount of background photons reaching a detector ($ph\ s^{-1}$) in an uplink configuration, assuming a satellite orbiting at 400 km, a satellite receiver of 30 cm, and an operating wavelength of 800 nm.

Method	Uplink, 800 nm		Uplink, 1550 nm	
Light Conditions	Daytime	Nighttime, Full Moon	Daytime	Nighttime, Full Moon
Bonato et. al [7]	2.10×10^8	7.60×10^2	1.20×10^8	7.40×10^2
This paper, PM10 level of 5	3.34×10^8	1.21×10^3	1.30×10^8	7.99×10^2
This paper, PM10 level of 25	4.07×10^8	1.47×10^3	1.49×10^8	9.17×10^2
This paper, PM10 level of 50	4.62×10^8	1.67×10^3	1.68×10^8	1.03×10^3

the background photon count rate and that air scatter can be ignored for uplink scenarios. In Section IV, 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.

4.2.2 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 [43]. The change in the electron density of the ionosphere (D, E, and F regions [120]) 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 [43]. 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 [43]. 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 [50]. The spectral

radiance of a black-body at temperature T is given by

$$L_\lambda(\lambda, T) = \frac{4\pi\hbar c^2}{\lambda^5} \frac{1}{\exp\left\{\left(\frac{\hbar c}{\lambda k_B T}\right)\right\} - 1}. \quad (4.4)$$

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

$$E_\lambda(\lambda, T) = \frac{\pi R_{\text{fireball}}^2 L_\lambda(\lambda, T) \tau(r)}{r^2}. \quad (4.5)$$

In order to use this result in Eqs. 4.2 and 4.3, 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 $r = \sqrt{D^2 + (h - H_{\text{fireball}})^2}$. 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

$$E(h) = \frac{\pi R_{\text{fireball}}^2 L_\lambda(\lambda, T) \tau(r) \cos \phi}{D^2 + (h - H_{\text{fireball}})^2}, \quad (4.6)$$

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

$$E(h) = \frac{\pi R_{\text{fireball}}^2 L_\lambda(\lambda, T) \tau(r) (h - H_{\text{fireball}})}{[D^2 + (h - H_{\text{fireball}})^2]^{\frac{3}{2}}}. \quad (4.7)$$

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

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 μm emission typically), fluorescence (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 (CFD) code COMSOL [49] to model the time–temperature profile of the fireball as it rises into the atmosphere (and the resulting photon output).

4.3 Results

4.3.1 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 5,000 K. The radius of the sphere was determined by the ideal gas law and Glasstone’s thermal partition of the yield versus altitude [43]. 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 [121]. 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 Fig. 4.2 for a few time stamps for a 100 kT, 1 km HOB scenario.

The temperature of the fireball was input into Planck’s law (Eq. [4.4]) 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 4.2 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 [122]. For scattering by aerosols, the Mie scattering cross sections were calculated using the *PyMieScatt* Python package [4]. 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 [3]. 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 [3]. 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 $\mu\text{g}/\text{m}^3$). 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 [123]).

Approximate values of the transmittance $\tau_{channel}$ 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

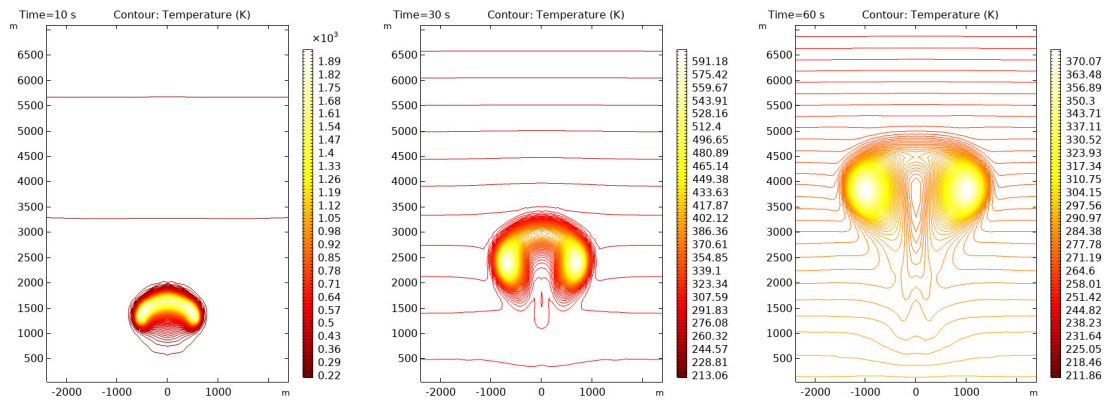


Figure 4.2: COMSOL simulations of the temperature, spatial, and temporal evolution of a nuclear fireball for a 100 kT detonation at a height of burst of 1 km.

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 $\tau_{channel}$ 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 Figs. 4.3 and 4.4 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 [33, 34]. 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 μ 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 1,550 nm, but as

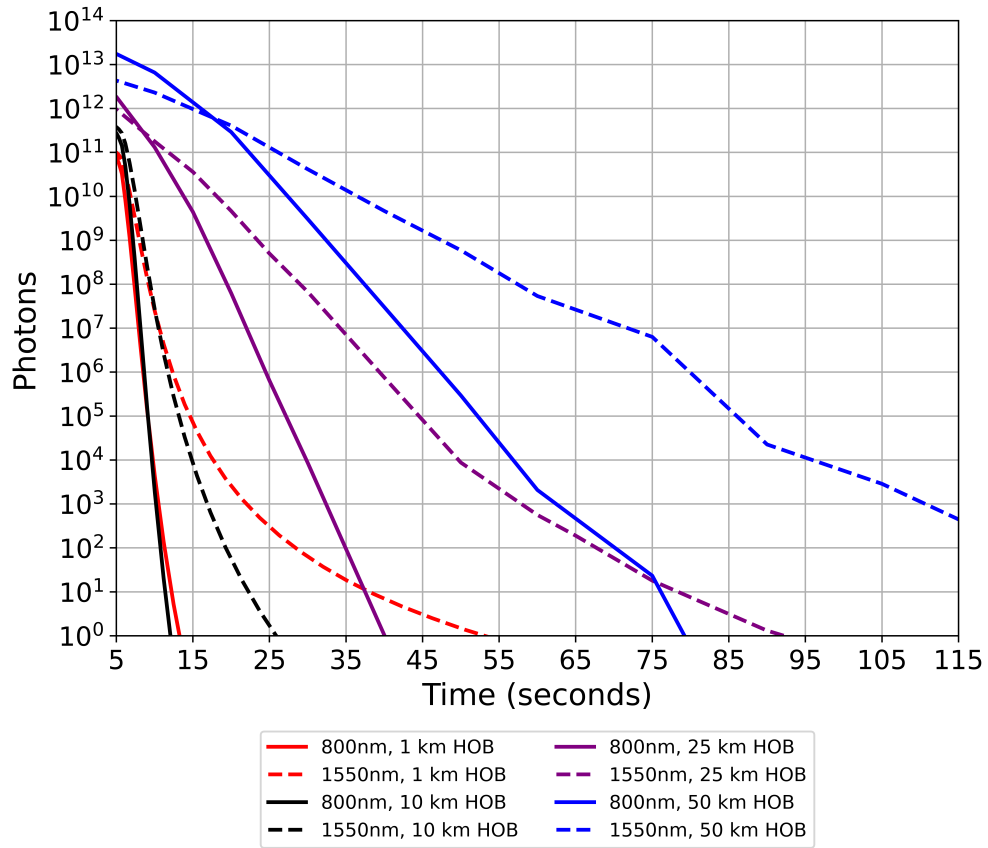


Figure 4.3: Photon interference from a nuclear detonation for an uplink scenario involving a single-photon detector on a satellite orbiting at 400 km with a field of view of 100 μ rad.

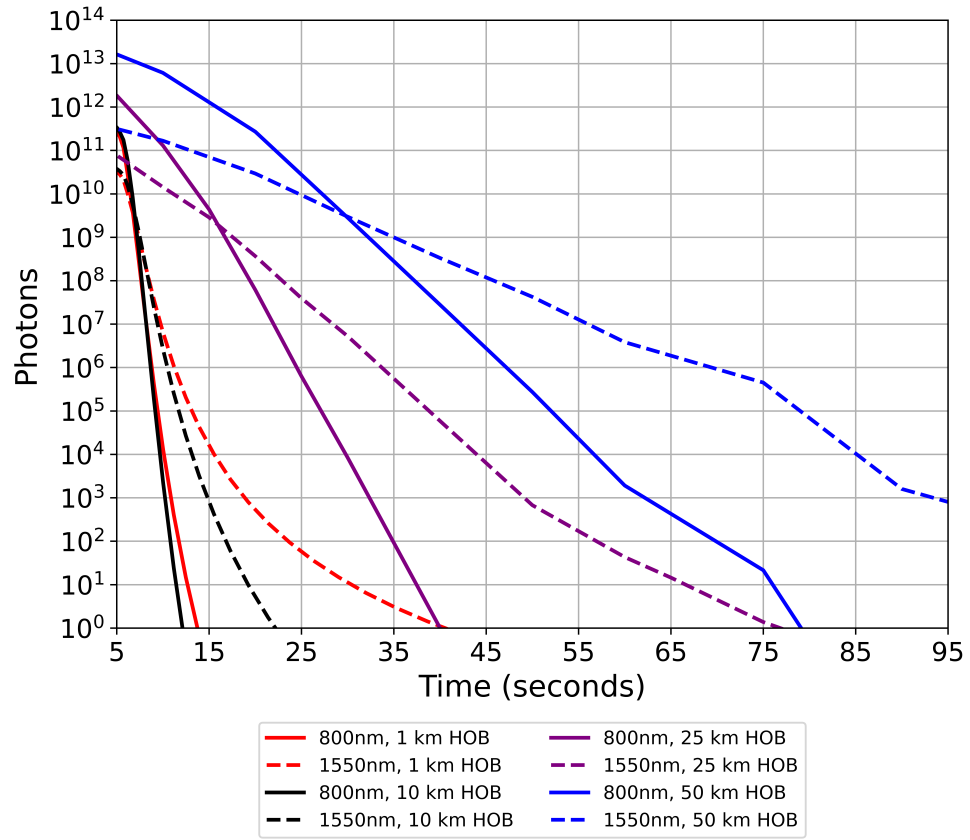


Figure 4.4: Photon interference from a nuclear detonation for a downlink scenario involving a single-photon detector ground station with a satellite tracking telescope with a FOV of $100 \mu\text{rad}$.

the fireball cools, the peak of the black-body spectral distribution shifts to longer wavelengths so that the 1,550 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 Fig. 4.5, 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 [7] 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 the lower atmosphere. Background photon rates are shown in Fig. 4.6 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 Fig. 4.6. 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

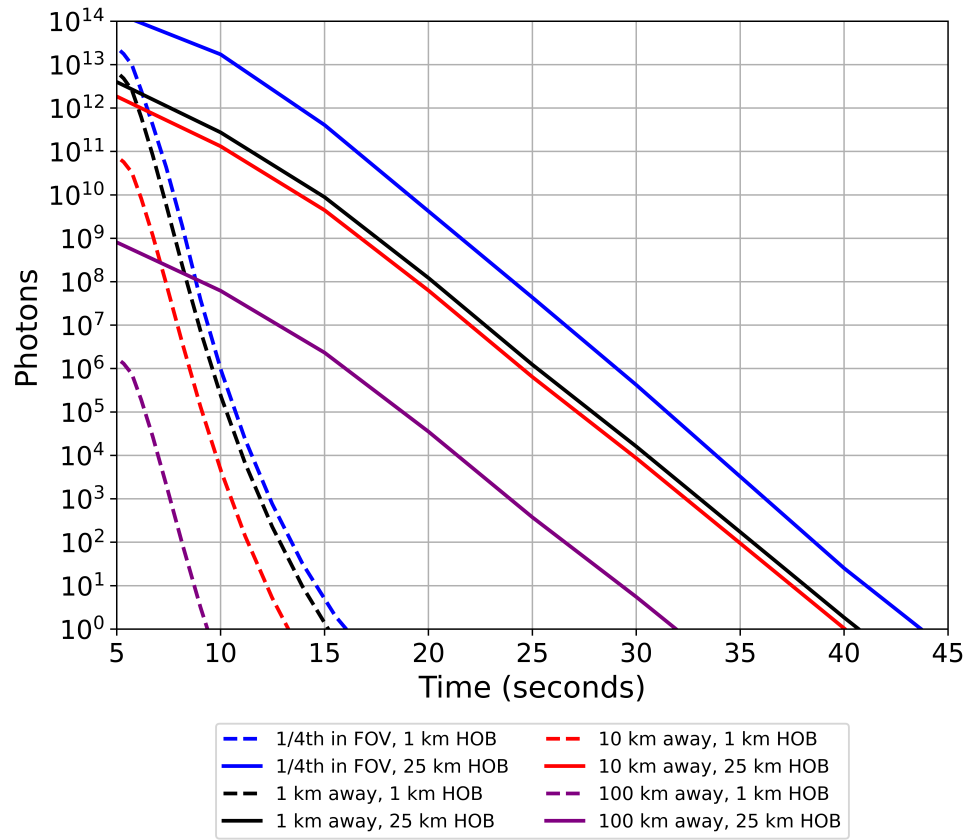


Figure 4.5: Photon interference at 800 nm for a satellite detector (orbiting at 400 km and with a telescope field of view of 100 μ rad) from a nuclear detonation at varying distances inside and outside of the field of view of the satellite.

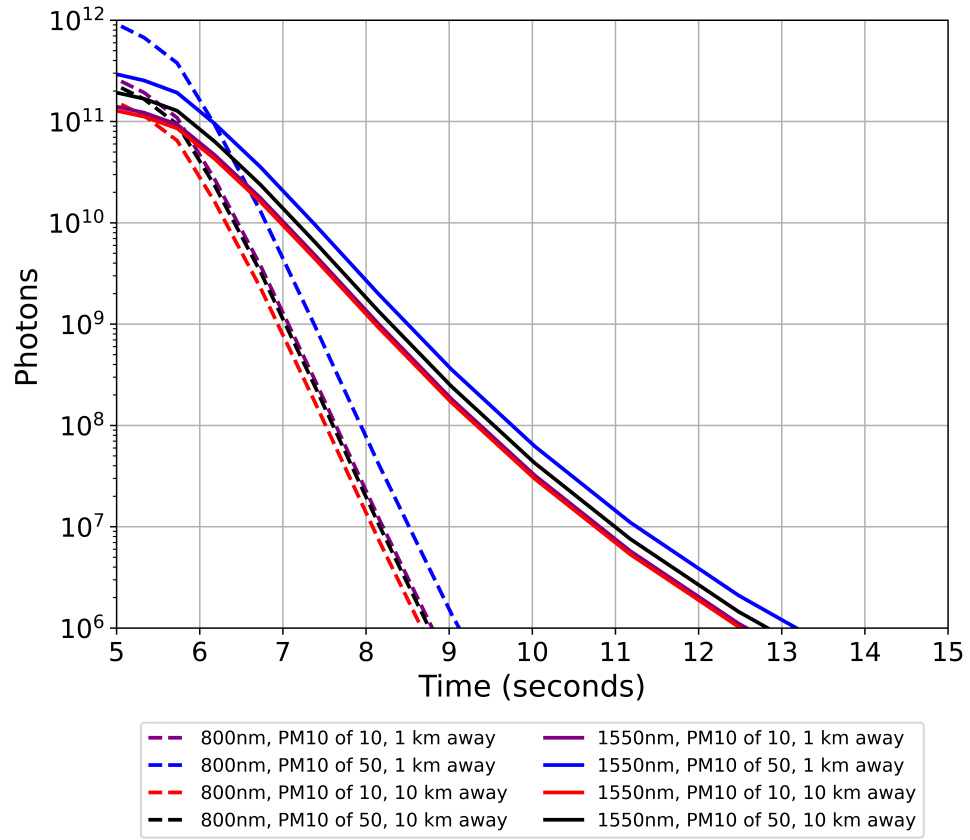


Figure 4.6: Photon interference at 800 nm for a satellite detector (orbiting at 400 km and with a telescope FOV of 100 μ rad) from a nuclear detonation at varying distances outside the FOV and with different aerosol levels present in the atmosphere.

distance from the FOV increases. Lastly, the aerosol particle size distribution used in Figs. 3–6 are that of a remote continental location [3]. 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 4.4. 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.

4.3.2 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 [43]. 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 [124]. 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 Fig. 4.7. 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

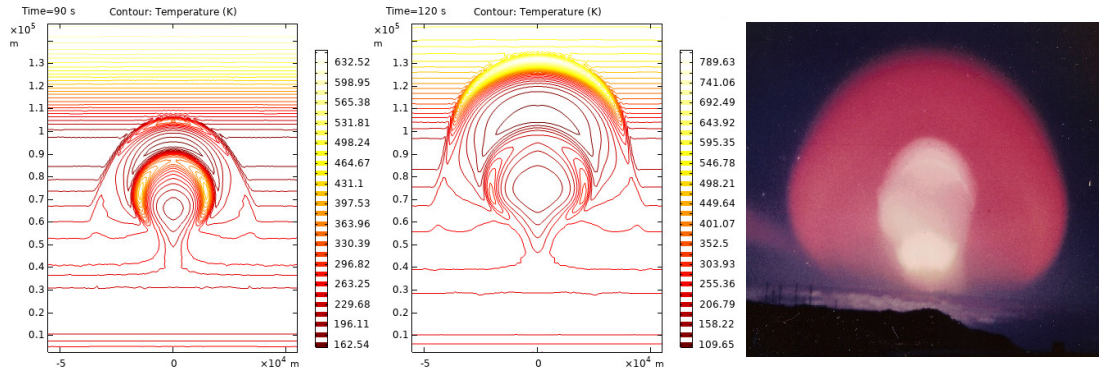


Figure 4.7: (Left, Middle) COMSOL simulations of the temperature, spatial and temporal evolution of a nuclear fireball for a 100 kT detonation at an HOB of 60 km. (Right) Picture taken of the fireball and airglow from the historic nuclear detonation Teak from an observer 700 miles away on Hawai'i (image is from public domain and not subject to copyright issues) [1, 2].

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” [2]. 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 Fig. 4.7. 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. [125] claims that the airglow seen in Fig. 4.7 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 [43]. 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 - 30 minutes [125].

4.3.3 Quantum Bit Error Ratio

To relate the increased noise to a quantum communications protocol metric, we consider the quantum bit error ratio (QBER) [20, 126] 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 [127, 128]:

$$QBER = \frac{e_0 Y_0 + e_{detector}(1 - e^{-\eta\mu})}{Y_0 e^{-\eta\mu} + 1 - e^{-\eta\mu}} \quad (4.8)$$

where e_0 is the background error rate, Y_0 is the background count rate, $e_{detector}$ is the probability a photon goes to the wrong detector, η is the overall transmission including the channel transmission, detection efficiency, and transmitting optics efficiency, and μ 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 [7] 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_{FM} is approximately 3600 W m^{-3} [118] for 800 nm and approximately 1500 W m^{-3} [119] 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 $\sim 85\%$ - $\sim 98\%$ [129], 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 $e_{detector} = 0.01$. 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 4.8. The interference of the nuclear disturbed environment compromises the quantum uplink for only a maximum of 90 seconds. The low altitude fireball (1 km HOB) cools much faster than the high altitude burst ($> 25 \text{ km}$) and only has an affect for around 20 seconds on the quantum link.

4.4 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 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

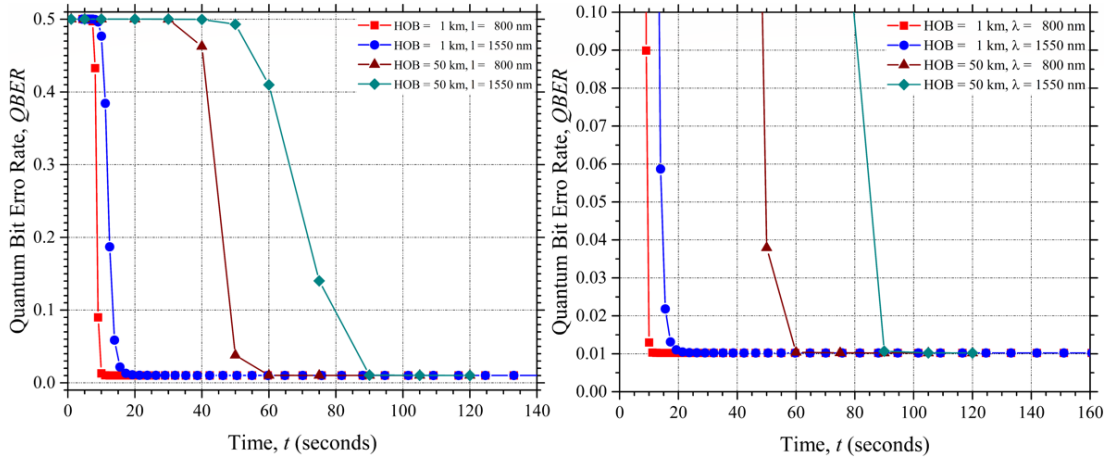


Figure 4.8: The QBER post-detonation time series for an uplink configuration satellite-ground quantum network operating during a full Moon with light interference from a 100 kt nuclear device detonating at a HOB of 1 km or 50 km. The full range of the QBER is shown on the left and QBER values below 10% are shown on the right.

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 [90]). 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 Fig. 4.9, 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 Fig. 4.9, when the FOV is reduced by an order of magnitude from $100\ \mu\text{rad}$ to $10\ \mu\text{rad}$, 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 ground, so the narrow portion of the FOV cone (see Fig. 4.1) 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 4.3.1, the photon background count rates for different scatter mechanisms are lumped together into a total. Fig. 4.10 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 Fig. 4.10 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

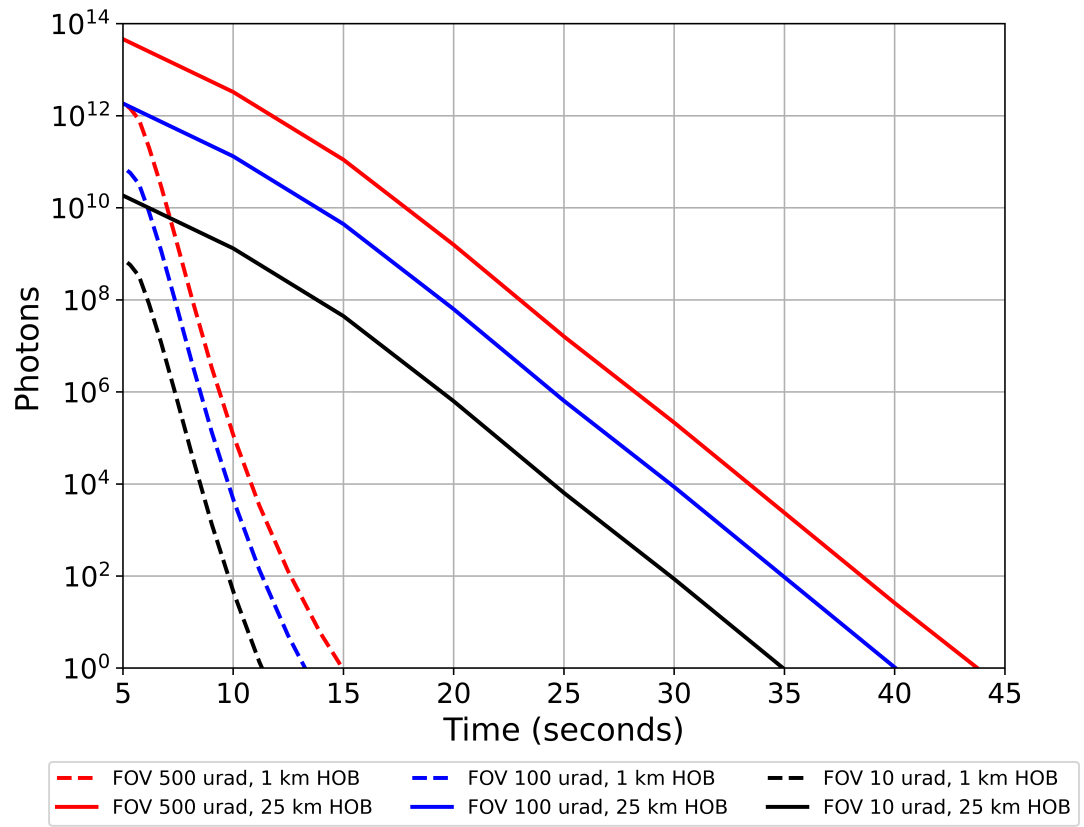


Figure 4.9: Magnitude of the 800 nm photon interference at a detector as a function of telescope FOV for an uplink scenario during a nuclear detonation 10 km away.

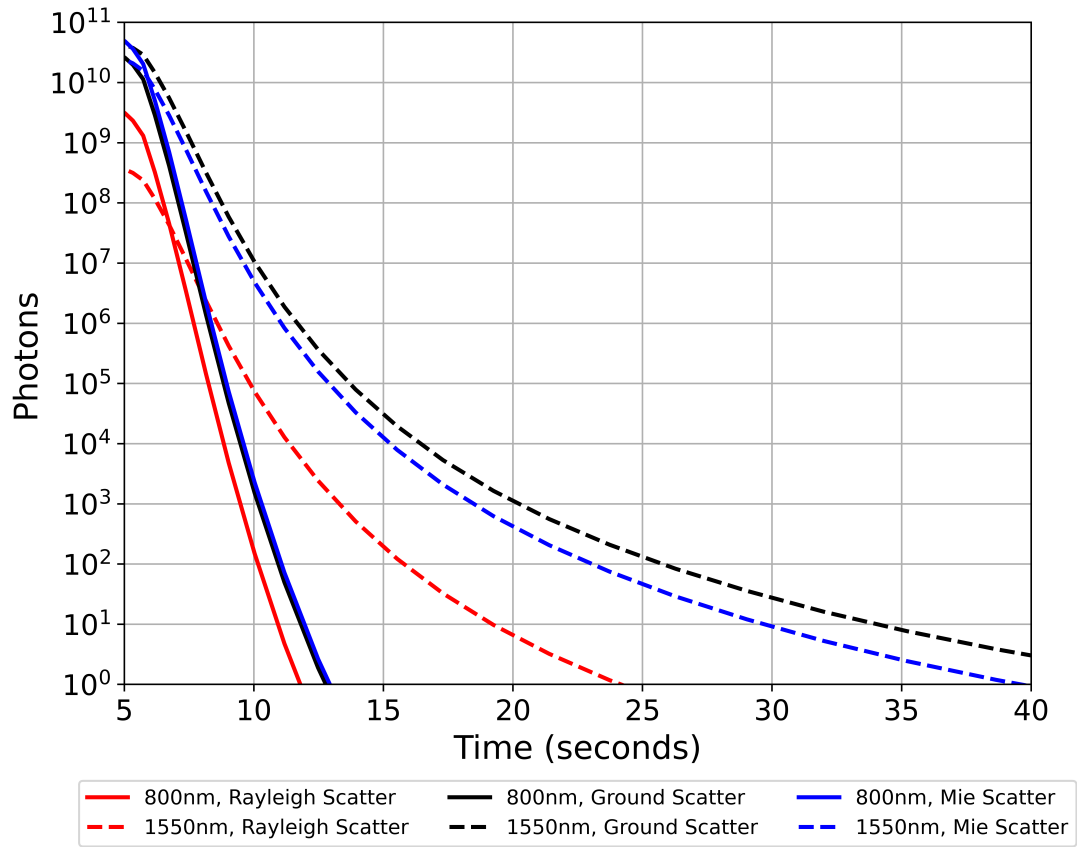


Figure 4.10: Magnitude of the different photon reflection mechanisms for an uplink scenario during a nuclear detonation.

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 Fig. 4.11.

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.

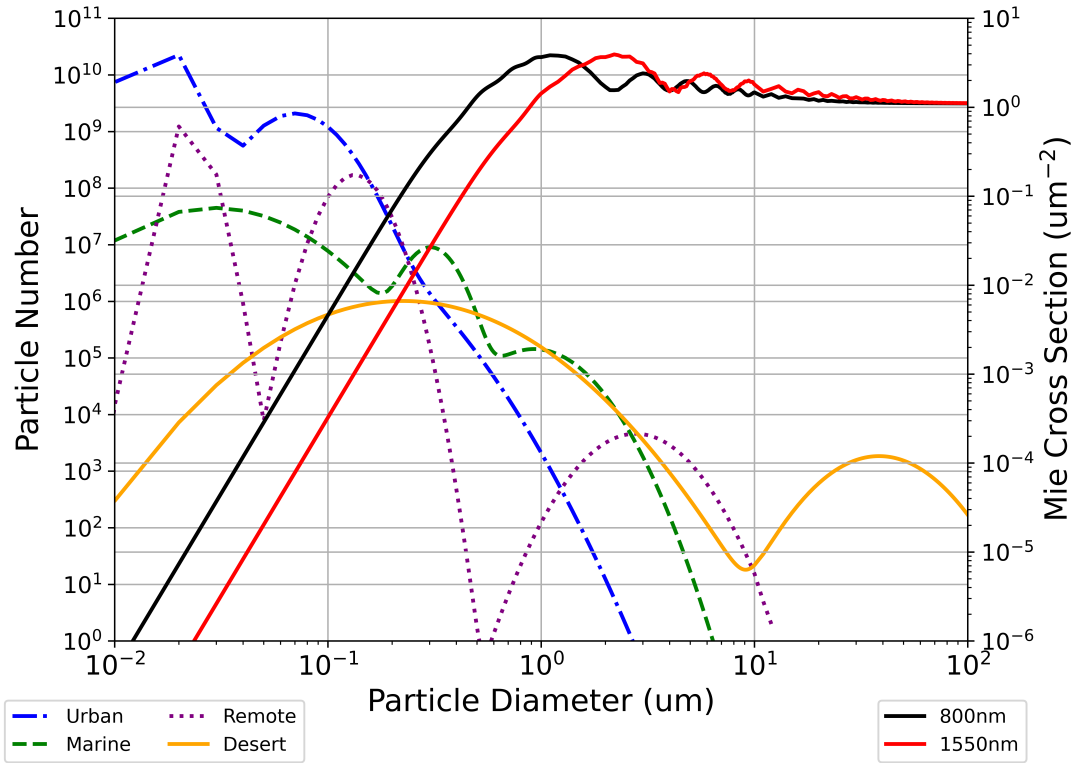


Figure 4.11: Aerosol particle size distribution for different locations and the Mie cross section as a function of particle size (particle size distributions calculated from Jaenicke [3] and Mie cross sections calculated from Sumlin et al. [4])

4.5 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 minute 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.

Chapter 5

Space-Based Quantum Networking in Harsh Atmospheric Conditions

5.1 Introduction

In contrast to present classical cryptography, quantum communications techniques—including quantum key distribution (QKD) [82, 85, 86, 93, 130], quantum digital signatures [131], and quantum secret sharing [83]—promise to enable information theoretic security that is independent of the potential computational resources of an adversary. So far, there has been a major emphasis on QKD networks deployed over fiber and free-space using trusted nodes [132] which include satellites [24, 25] and, more recently, electrical substations [133, 134]. Though QKD has been a major motivating application thus far, more general quantum networks are expected to be based upon entanglement distribution. Ultimately, optical channel loss restricts the scale of a prospective global quantum network [94]. Without quantum repeaters [15], a channel using optical fiber has a limited transmission range roughly on the order of a couple hundred kilometers due to the exponential optical attenuation of light in the fiber as a function of distance [95, 135]. Satellite-based networks are a potential solution for global scale entanglement distribution with today’s technology.

The feasibility of space-based quantum networking has been demonstrated via the Micius satellite for downlink entanglement distribution from a low-Earth orbit (LEO) satellite [115], downlink QKD [25] and quantum teleportation with the successful uplink transmission of a ground-based teleported qubit [26]. When compared to optical fiber, satellite-based technologies can be configured so that they have a lower attenuation per unit distance [25], thus enabling quantum networking on a larger scale. In the near-future, quantum-memory equipped satellites could provide an additional performance boost to entanglement distribution [136]. Operation is currently restricted to night-time missions due to high noise from daytime background photons, however research is on-going to expand to day-time performance [69]. A good deal of theoretical work has been done analyzing the effects of the atmospheric attenuation and turbulence on satellite quantum communications [55, 88, 97, 98, 99, 116]. Analysis of the feasibility of satellite constellations for a global quantum network has been performed [24] as well as applications to QKD [137].

In this manuscript, we extend the state-of-the art by quantifying the operational challenges from additional optical channel loss and detector noise due to harsh atmospheric conditions, with a particular focus on an extreme event such as the atmosphere post-nuclear detonation. We present a model for the quantum state estimation and use it to quantify the fidelity of the quantum information transmission between a satellite and ground station in a downlink configuration. We then analyze the perturbations from ideal operating conditions due to fog, haze, and nuclear weapon effects in the optical channel and additional light interference in the detector.

5.2 Methods

5.2.1 Quantum State Estimation

Figure 5.1 shows the operating assumptions in this paper for the single photon case, the same assumptions apply to the two photon case except the number of parameters

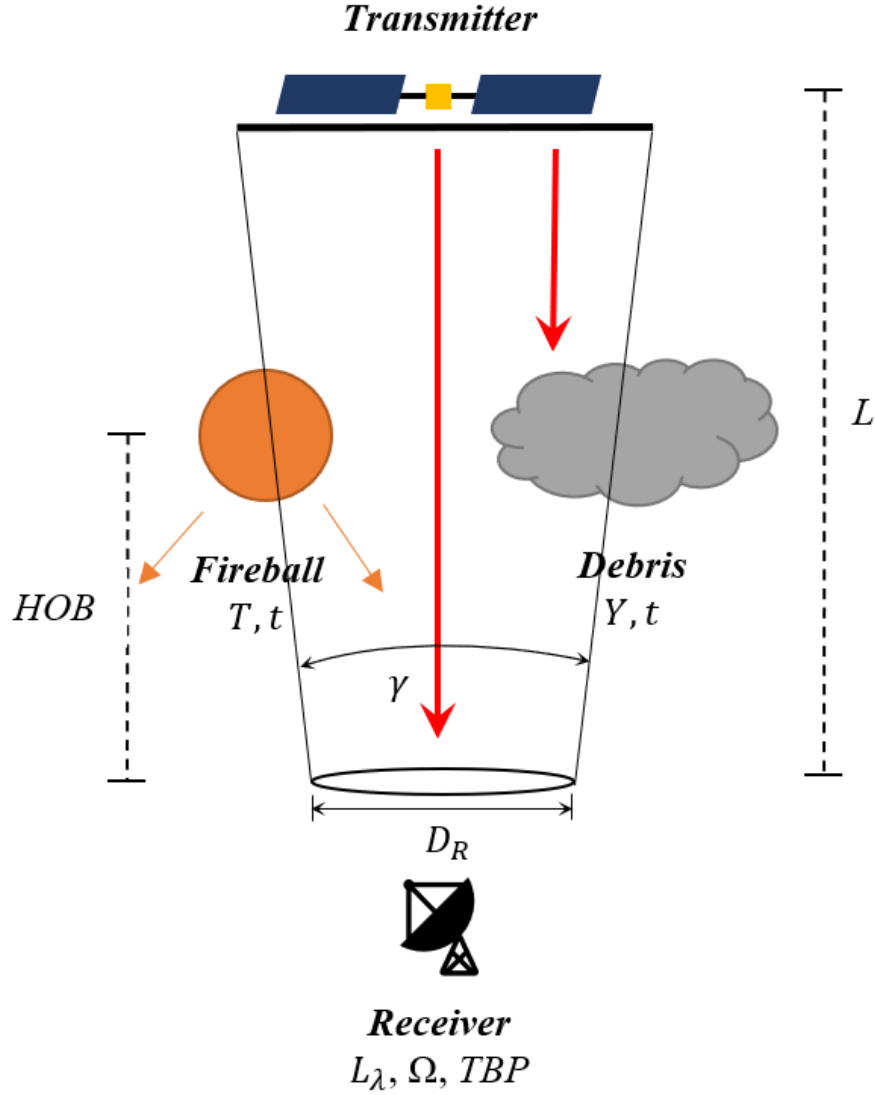


Figure 5.1: Concept of operations. A photon source on a low-earth orbit satellite, orbiting at an altitude L in kilometers directly above a ground station, produces a single (or entangled pair in the two photon case) photon and transmits the photon through the atmosphere to a detector at the ground station. The detector has some angular field of view γ for spatial filtering, a light collecting lens of diameter D_R in meters, and the temporal and spectral filters are set to the time-bandwidth product (TBP) of a transform limited Gaussian pulse. Additional channel noise or increased optical attenuation degrades the distributed entanglement quality and/or throughput. The nuclear disturbance occurs in the line of sight of the detector at some height of blast HOB with an explosive yield Y that creates a nuclear fireball of temperature T as a function of time t . In the case of a surface blast, debris is lofted into the propagation path of the photons increasing the signal attenuation.

is increased appropriately (subscripts A apply to parameters associated with photon A propagating in channel A and subscript B is used for parameters associated with photon B propagating through channel B). We start by deriving the two-photon case and simplifying to the single-photon case. The distribution of an entangled photon pair over two quantum channels to two remote parties, can be described by the following density operator:

$$\rho = \frac{\rho^{AB} + (\rho^{N_A} \otimes \mathbb{1}_2) + (\mathbb{1}_2 \otimes \rho^{N_B})}{\text{Tr}(\rho^{AB} + (\rho^{N_A} \otimes \mathbb{1}_2) + (\mathbb{1}_2 \otimes \rho^{N_B}))}, \quad (5.1)$$

here, ρ^{AB} is the density operator for the maximally entangled photon pair (Bell State), with a photon being transmitted through either channel A or B. ρ^N is noise density operator for the system (detector plus environmental noise) in each respective quantum channel given by a 2-dimensional maximally mixed state ($\epsilon_i \mathbb{1}_2/2$). $\mathbb{1}_2$ is a 2 by 2 identity matrix and ϵ_i is the noise probability. The trace is used to normalize the density operator.

The two-photon density operator can be simplified to analyze the single-photon case for a single quantum channel. We do this by using the heralded single photon argument. One starts with an ideal entangled photon pair, one photon is immediately measured to “herald” the presence of the conjugate photon and to randomly and remotely project it into a pure state [138, 139, 140, 141]. The heralded photon suffers loss during channel transmission (due to diffraction, absorption and scattering during propagation). In this way, the quantum state of an ensemble of identical transmissions is degraded by the probability of photon transmission through the quantum channel t and the system noise ϵ . Assuming that the two photons are polarization entangled and are in the Bell state $1/\sqrt{2}(|HH\rangle + |VV\rangle)$, we set our heralding detector to measure for horizontally polarized light, the two photon density operator simplifies

to the post-selected density operator for the heralded single photon,

$$\rho(\tau, \epsilon) = \frac{t \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \epsilon \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix}}{\text{Tr} \left(t \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + \epsilon \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix} \right)}. \quad (5.2)$$

The transmission channel loss over a free-space link is dependent on a variety of parameters (optical link distance, receiving & transmitting optics, atmospheric conditions, channel wavelength, strength of turbulence, etc.) that affect the probability of successful transmission of a single photon. Extensive discussions on determining the theoretical optical channel loss can be found here [7, 55, 88]. Loss due to the pointing, acquisition, and tracking system, transmitting and receiving optics, and inefficiencies in photon detection are also factors that degrade distributed quantum state quality, but we are interested in the fundamental physics and these sources of loss are not considered here. However, they can be incorporated as scalar factors in the calculation of the transmission probability.

The detector noise from background photons in a free-space channel can be determined using [5, 142],

$$\epsilon = L_\lambda A \Omega \frac{\lambda^2}{c} TBP, \quad (5.3)$$

where L_λ ($\text{ph s}^{-1} \text{m}^{-2} \text{sr}^{-1} \text{m}^{-1}$) is the background light entering the detector at wavelength λ (m), $A = \pi D_R/4$ is the light collecting area of the receiver (m^2), $\Omega = \pi \gamma^2/4$ is the solid angle seen by the detector (sr), γ is the field of view (rad), $TBP = \Delta t \Delta \lambda c / \lambda^2$ is the time-bandwidth product of the pulse (unitless), and c is the speed of light (m s^{-1}). We use the time-bandwidth product instead of a particular time-gate and the spectral filter used in the cited literature as we are interested in the operational limits of the technology. In this work, our optical link setup is modeled after the Modular, Agile, Scalable Optical Terminal (MAScOT) [34] under development by NASA. We assume our detector has a spatial filter of $\gamma = 100 \mu\text{rad}$ and

the spectral filtering and temporal filter are set to the transform-limit of a Gaussian pulse ($TBP = 0.441$). The objective is to screen out as much of the background noise received by the detector as possible. It is assumed the ground station and satellite are designed as follows: the transmitter lens on the satellite has a diameter of $D_T = 0.10$ m, in line with the design specifications of MAScOT for space-based quantum communications research. The ground station telescope lens is $D_R = 1$ m in diameter. The quantum channel wavelength is $\lambda = 1550$ nm as this is a typical wavelength for commercial satellite telecommunications with established free space communications technology. The optical link distance L is 400 km, which is roughly the distance from sea-level to the International Space Station. The total loss due to scattering and absorption from propagating through the atmosphere at 1550 nm is assumed to be 1 dB.

Simplifying the density operator from Equation 5.2 by re-parameterizing the density operator in terms of the signal-to-noise ratio (SNR), where $SNR = t/\epsilon$, yields,

$$\rho(SNR) = \begin{pmatrix} \frac{SNR+1/2}{SNR+1} & 0 \\ 0 & \frac{1/2}{SNR+1} \end{pmatrix}. \quad (5.4)$$

We combine the effects of increased attenuation from the nuclear blast events due to the debris and the increased noise arising from the ensuing nuclear fireball to estimate the quantum state. The effects of loss from transmission through the atmosphere, index of refraction turbulence, and nuclear debris in the quantum optical channel decrease the transmission probability of the propagating photon. Noise in the detector due to the sky radiance, detector dark count rate, and/or light interference from the nuclear fireball emissions increase the probability of an erroneous count and appear in the detector noise parameter.

5.2.2 Fidelity

The fundamental resource that enables quantum communications is entanglement. Often, the primary goal for quantum communications and networking is to share maximal entanglement between remote parties. Therefore, it is important to quantify the quality of the shared quantum state to infer the quality of shared entanglement when separated by some distance, L . Then, one can infer the effects of a hostile environment (such as a nuclear disturbance) by examining how the entanglement or state quality is reduced.

The *fidelity* [143, 144] is a unitless parameter ranging from 0 to 1 that computes the overlap of a measured state with some target state. This is done by measuring the “distance” between the two quantum states. A value of $F = 1$ means the measured state and the target state are identical, if $F = 0$ then the target and measured state are orthogonal. In the case of two-photon entanglement distribution, if the received state has high fidelity with the ideal transmitted state, then the shared entanglement is also of good quality. The state fidelity F is given by,

$$F(\rho, \sigma) = \left(\text{Tr} \sqrt{\sqrt{\rho} \sigma \sqrt{\rho}} \right)^2, \quad (5.5)$$

where, ρ and σ are the density matrices to be compared. The fidelity can provide an estimate of the state error through the quantity known as the infidelity, which is simply $I = 1 - F$. Quantum protocols like BB84 used for QKD have an error tolerance of $\sim 11\%$ depending on the protocol [145]. Therefore, we assume 90% fidelity as a reference for the desirable state fidelity. Using the density operator for the single heralded photon (Equation 5.4), the fidelity as a function of the optical attenuation α (in dB) in the quantum channel is,

$$F(\alpha, \epsilon) = \frac{10^{-\alpha/10} + \epsilon/2}{10^{-\alpha/10} + \epsilon}. \quad (5.6)$$

where the optical attenuation α is related to the transmittance probability through the atmosphere t in Equation 5.2 by $\alpha = 10 \log_{10}(1/t)$.

In the case of two polarized entangled photon pairs being shared in two separate quantum channels, the fidelity is,

$$F(\alpha, \beta, \epsilon_A, \epsilon_B) = \frac{10^{-(\alpha+\beta)/10} + \epsilon_A + \epsilon_B}{10^{-(\alpha+\beta)/10} + 2(\epsilon_A + \epsilon_B)}, \quad (5.7)$$

here the fidelity is a function of the optical channel attenuation α and β in channels A and B, respectively and the noise (ϵ_A and ϵ_B) in channel A and channel B, respectively.

There are a variety of entanglement metrics for bipartite entanglement such as the concurrence ($\mathcal{C}$) and entanglement of formation (EoF) [107]. The *concurrence* $\mathcal{C}$ is a metric for the degree of entanglement. For the concurrence, $\mathcal{C} = 0$ indicates a separable (unentangled) state and $\mathcal{C} = 1$ is maximally entangled. The *entanglement of formation* (EoF) is an entanglement metric that is based on the the concurrence. The analysis can be completed using these entanglement monotones however, we continue to use the fidelity for the ensuing analysis as it is the most convenient metric.

5.2.3 Three Channel Quantum Communications

The fidelity for a quantum network consisting of three channels (A,B,C) with optical attenuation α, β, γ , sharing a GHZ state is,

$$F(A, B, C, \epsilon_A, \epsilon_B, \epsilon_C) = \frac{4 \cdot 10^{-(A+B+C)/10} + (\epsilon_A + \epsilon_B + \epsilon_C)}{4 \cdot 10^{-(A+B+C)/10} + 8(\epsilon_A + \epsilon_B + \epsilon_C)}, \quad (5.8)$$

GHZ states can be utilized in protocols such as quantum secret sharing [83]. For example, one could consider a case where a satellite, space station, and incoming space craft are attempting to share three entangled photons. The fidelity for the

GHZ state can be generalized for higher dimensional systems with d levels and M entangled particles by,

$$F(t_A, t_B, t_C, \dots, \epsilon_A, \epsilon_B, \epsilon_C, \dots) = \frac{2d(t_A t_B t_C \dots) + (\epsilon_A + \epsilon_B + \epsilon_C + \dots)}{2d(t_A t_B t_C \dots) + d^M(\epsilon_A + \epsilon_B + \epsilon_C + \dots)}. \quad (5.9)$$

5.2.4 Atmospheric Conditions

The attenuation α_V in units of dB per km is given by [146, 147, 148, 149, 150],

$$\alpha_V(V, \lambda) = \frac{16.99}{V} \left(\frac{\lambda}{550} \right)^{-q(V)} \quad (5.10)$$

here V is the atmospheric visibility and q is a piecewise function of the size distribution coefficient of scattering particles. We assume that the atmospheric visibility is the distance a beam may travel before dropping to 2 percent of the transmitted intensity. There are attempts to estimate the dependence of visibility on the fine particulate matter $PM_{2.5}$ concentration and the relative humidity in various cities [112, 151, 151]. We use the Kim model for determining the value of q , which depends on the visibility as follows [149, 152],

$$q(V) = \begin{cases} 1.6 & V > 50 \text{ km} \\ 1.3 & 6 \text{ km} < V < 50 \text{ km} \\ 0.16V + 0.34 & 1 \text{ km} < V < 6 \text{ km} \\ V - 0.5 & 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & V < 0.5 \text{ km} \end{cases} \quad (5.11)$$

From the attenuation determined by the atmospheric visibility, we are able to quantify the penalty incurred by propagating through various atmospheric hazards

like clouds, haze, pollutants, etc., and add it to any additional sources of loss in the optical channel such as scattering and absorption, diffraction, or turbulence.

5.2.5 Nuclear Disturbed Environment

In a nuclear disturbed environment, there are two main sources for performance degradation of a quantum optical communications link, the heightened optical loss due to scattering and absorption and the extra background noise in the detector. The first source of degradation is caused by the weapon debris, ejected soil, smoke, and haze injected into the atmosphere after a detonation. The extra aerosols and debris introduced into the atmosphere cause increased absorption and scattering (Mie scattering) of the transmitted photons, reducing the likelihood of transmitting quantum information [7]. The second source of degradation arises from high energy x-rays and gamma radiation that consume the surrounding material and create a hot, bright, and roughly spherical nuclear fireball [43]. The hot plasma of the fireball can reach temperatures in the millions of degrees Celsius within the first few microseconds. The emissions and temperature of the nuclear fireball are comparable to that of a mini-sun. Though the fireball only lasts on the order of minutes before substantially cooling, at its peak it can oversaturate and potentially damage any onlooking detector. When operating at a single photon level, large increases in the detector noise cause the signal-to-noise ratio of the channel to plummet, negatively affecting the performance of the quantum network with very few options to mitigate the problem.

In [7], the authors estimated the potential attenuation of a ground/satellite transmission due to the lofted debris generated by a near-surface nuclear detonation. Briefly, for near-surface nuclear yields (Y) of 10 kt, 100 kt, and 1 Mt (1,000 kt), a climatological study was performed using the DEfense Land Fallout Interpretive Code (DELFIIC [41, 42]) to model the nuclear cloud rise and debris morphology. The atmospheric transport was modeled using the National Oceanic and Atmospheric Administration’s (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory

(HYSPLIT [46]) code, and the results were analyzed using post-processing tools within the ORNL Airborne Planning Tool [44, 45] (APTTool) and optical scattering from the PyMieScatt Python package [4]. While [7] evaluated the attenuation likelihood from the debris and atmosphere, here we extend the analysis to the degradation of the quantum state from the increased attenuation in the propagating environment.

The electromagnetic energy emitted by the super-heated plasma can be quantified using Planck’s radiation law by approximating the nuclear fireball as a black body [50]. The spectral radiance of a black body at temperature T is given by,

$$L_{\lambda}(\lambda, T) = \frac{hc^2}{\lambda^5} \frac{1}{e^{(hc/\lambda k_B T)} - 1}, \quad (5.12)$$

where, h (J s) is Planck’s constant, c (m/s) is the speed of light in a vacuum, k_B (J K⁻¹) is Boltzmann’s constant, and T (K) is the temperature of the black body. Therefore, characterizing the temporal evolution of the fireball’s size, location and temperature can help approximate the black body radiation that results in additional noise seen by a single-photon detector [8].

5.2.6 Bayesian Mean Estimation

Using simulated measurements, quantum state estimation can be applied to reconstruct the quantum state. Bayesian mean estimation (BME) is a parameter estimation technique that can be applied to characterize quantum states and offers the ability to include singles counts in the dataset to increase the sampling size. The objective of using BME is to estimate the density operator, the concurrence, and the attenuation associated with the quantum network based on the measurements using a numerical Markov chain Monte Carlo method [153]. One of the advantages of using BME is that it intrinsically yields an error estimate. To consider the impact of loss and finite statistics, our quantum state estimation technique utilizes statistical inference via

application of Bayes' rule [154],

$$P(\tau|\mathcal{D}) = \frac{P(\mathcal{D}|\tau)P(\tau)}{P(\mathcal{D})}, \quad (5.13)$$

which allows expression of the probability ($P(\tau|\mathcal{D})$) of parameter set τ given dataset $\mathcal{D}$. The Bayesian mean estimation methodology is outlined in great detail in [7, 105].

5.3 Results

We begin by analyzing the state fidelity for normal operating conditions in a single quantum channel. This provides a baseline for comparing the additional penalties incurred when operating in harsh atmospheric conditions. Then, we expand the operating principles to the two way case and observe how effects on quantum entanglement degrades from various atmospheric effects as shown in Figure 5.1.

A contour plot for the fidelity in the single photon scenario as a function of the attenuation in the quantum channel, α (in units of dB), and noise at the detector, ϵ , is shown in Figure 5.2. The solid black line is shown as a reference and represents fidelity values of $F = 0.9$. For reliable quantum communications, the channel loss needs to be minimized to improve the signal strength and the noise needs to be suppressed to prevent additional false positive counts. In high attenuation channels, a low-noise detector is critical as it is not possible to amplify arbitrary unknown quantum signals due to the no-cloning theorem [19]. Filtering the background noise is often necessary to keep the fidelity as high as possible. Alternatively, signal strength reduction due to diffraction loss, and scattering could be reduced by a system of trusted nodes (if for QKD applications) to reduce the propagation distance, or adaptive optics to correct for wave distortion [24, 69].

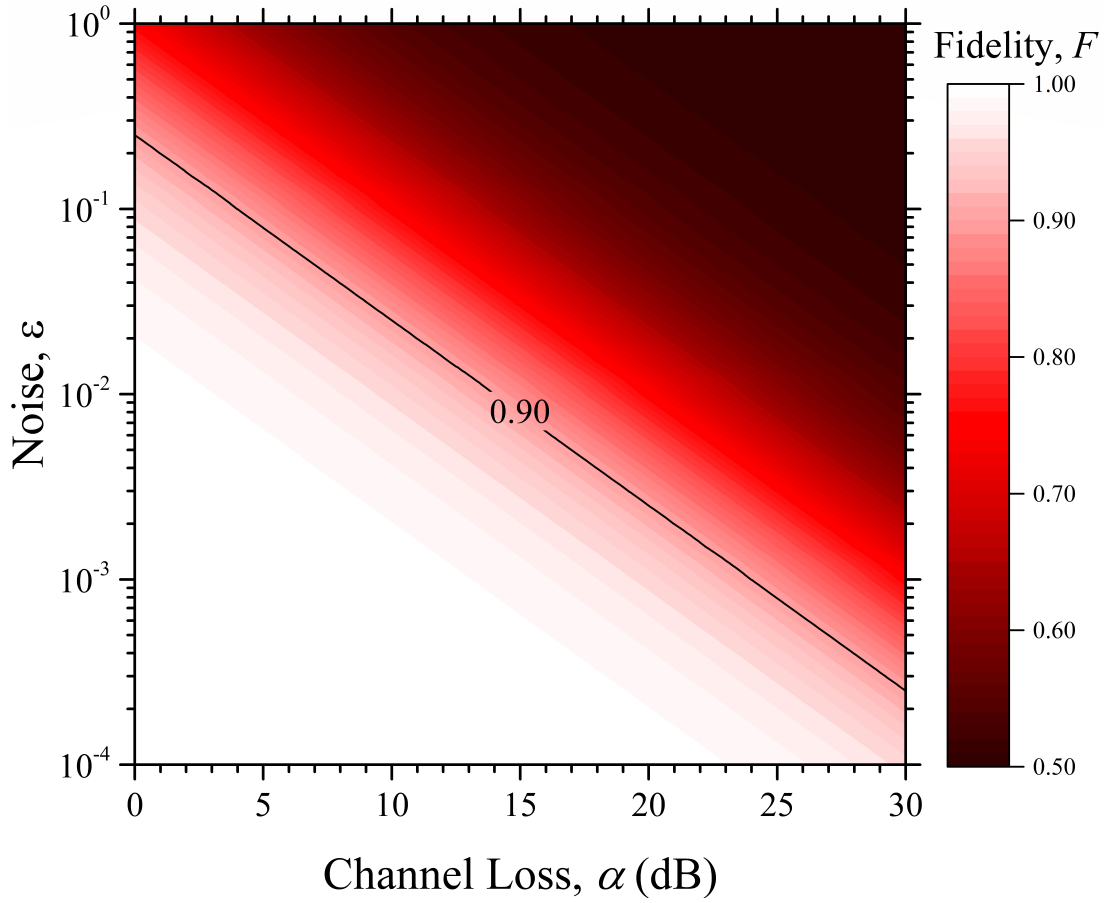


Figure 5.2: The fidelity as a function of the optical channel loss α (in dB) and the noise ϵ in the detector. For reference, a black line is added to represent a fidelity value of 0.9.

5.3.1 Single Photon Case

First, we calculate the fidelity using Equation 5.4 and Equation 5.5 for typical operating conditions without any atmospheric effects (red line in Figure 5.3). In Figure 5.3, the fidelity as a function of the signal-to-noise (SNR) of the single quantum channel is shown. The green squares are for the fidelity values for transform-limited pulses transmitted on a 400-km downlink quantum-optical channel in different sky background conditions. If the detector parameters are set to measure for a transform limited optical pulse, then daytime quantum networking is feasible. In order to achieve a fidelity of 0.9, the SNR of the channel needs to be greater than 4. As expected, when the optical attenuation in the channel is high and/or there is significant background noise in the field of view of the detector, then the state fidelity is poor. The orange diamond, red triangle, and purple triangle plot the SNR and fidelity when there is 1 km of moderate fog, light fog, or haze in the quantum channel. Small atmospheric disturbances reduce the SNR of the quantum channel, however the fidelity remains high. For thick fog conditions ($V = 0.2$), the attenuation becomes too high and the SNR ratio is so low that it is not included in the bounds of Figure 5.3. The impairment in the optical channel due to nuclear debris and aerosols released into the atmosphere from a surface blast is analyzed separately from the increased photon noise probability due to these effects persisting on different time scales. The effects of the nuclear debris released from a surface blast can last on the order of hours [7] while the additional light interference from the nuclear fireball persists on the order of minutes [8]. We show the fidelity for a surface blast of a 1 Mt yield device at different times post-detonation during a clear day (blue dots). We assume that the surface blast lofts debris into the surrounding atmosphere and into the propagating path of the photon [7]. The optical attenuation from the debris ejected in a 1 Mt case is severe and the SNR of the channel has declined by many orders of magnitude and operating conditions are substantially worse than a cloudy day. By 40 minutes post

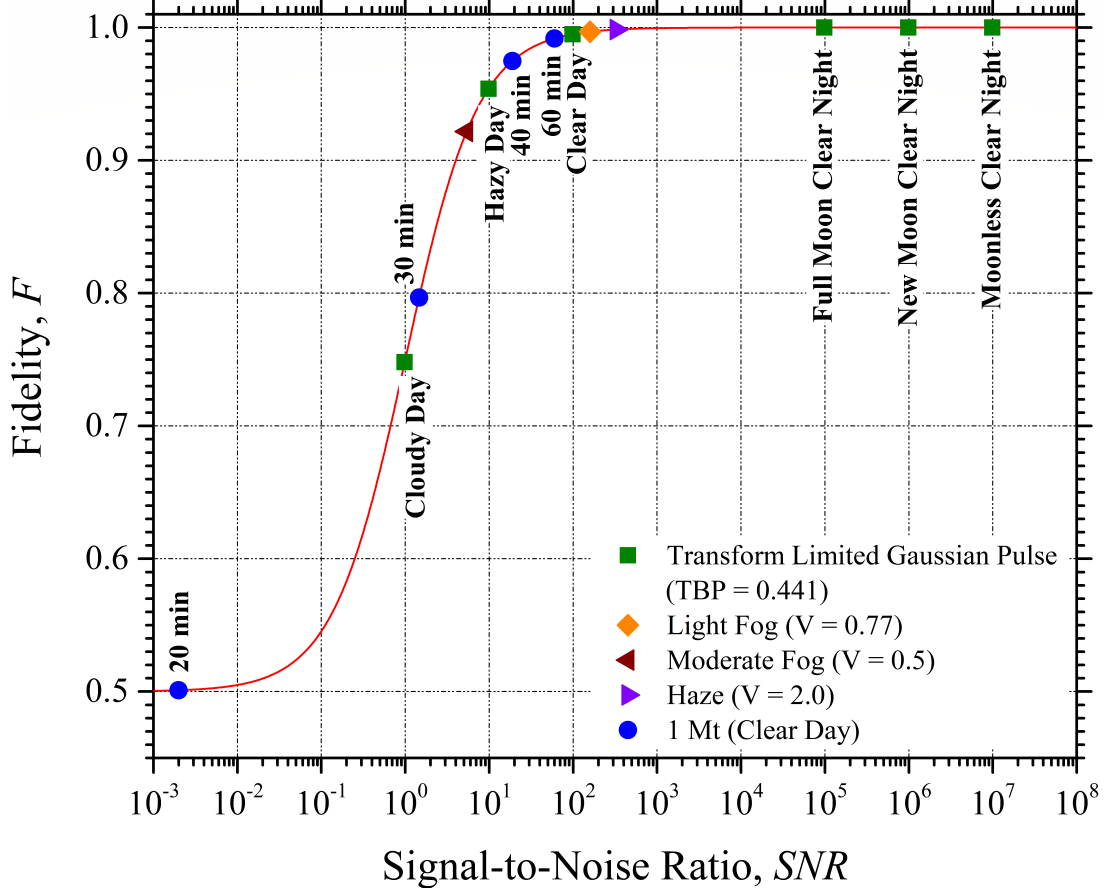


Figure 5.3: The fidelity of a $\lambda = 1550 \text{ nm}$ single quantum optical channel (single-photon case) as a function of the signal-to-noise ratio. The blue circles represent the estimated transmitted entangled state fidelity at different times following the detonation of a $Y = 1 \text{ Mt}$ nuclear device on a clear day. The green squares are for the fidelity of various background conditions when the detector parameters are set to measure a transform limited Gaussian pulse (TBP = 0.441). The sky radiance values are taken from [5]. The orange, red, and purple shapes represent the SNR and fidelity for full moon clear night conditions when 1 km of moderate fog, light fog, or haze is present in the channel.

detonation, the debris has subsided enough that the additional debris only slightly reduces the quality of the transmitted quantum state.

In Figure 5.4, the time series of the fidelity of the single channel impeded by additional debris in the environment from the detonation of a $Y = 1$ Mt nuclear device near the surface is shown for different sky radiance values. For low background noise, the recovery time is very short. This can be seen in the night-time cases where, by 30 minutes, all cases have resumed to normal operation. The recovery is slower for daytime cases where the fidelity does not return to normal levels until after 60 minutes following the blast. The low background noise environment during night-time means the network tolerates the higher signal loss in the optical channel. In higher noise environments as seen during daytime, the recovery takes longer because the detector cannot distinguish between the signal photons and the noise from the elevated sky background.

The effects of the photon emissions from the nuclear fireball on the fidelity are shown as a time series in Figure 5.5. For a device with an explosive yield of 100 kt, the increased noise in the detectors decrease the fidelity for about 10 seconds in the 5 km and 10 km HOB and tens of seconds for the 25 km and 50 km HOB. An important difference from the result in Figure 5.4 is the timescale of the nuclear effects and the duration of the denial of service. The lifetime of the nuclear fireball is dependent on the explosive yield and HOB, but only lasts on the order of minutes while the nuclear debris from the weapon, aerosols, and soil injected into the atmosphere have a lasting effect on the order of hours. The higher the altitude, the lower the density of the atmosphere, which causes the fireball to linger for longer periods of time.

The fidelity as a function of the SNR of the single quantum channel at different times post-detonation of a 100 kt device is shown in Figure 5.6. Considering that a single revolution for a low-earth orbit satellite takes approximately 90 to 120 minutes to complete (depending on the orbiting altitude), and the timescale of each of the

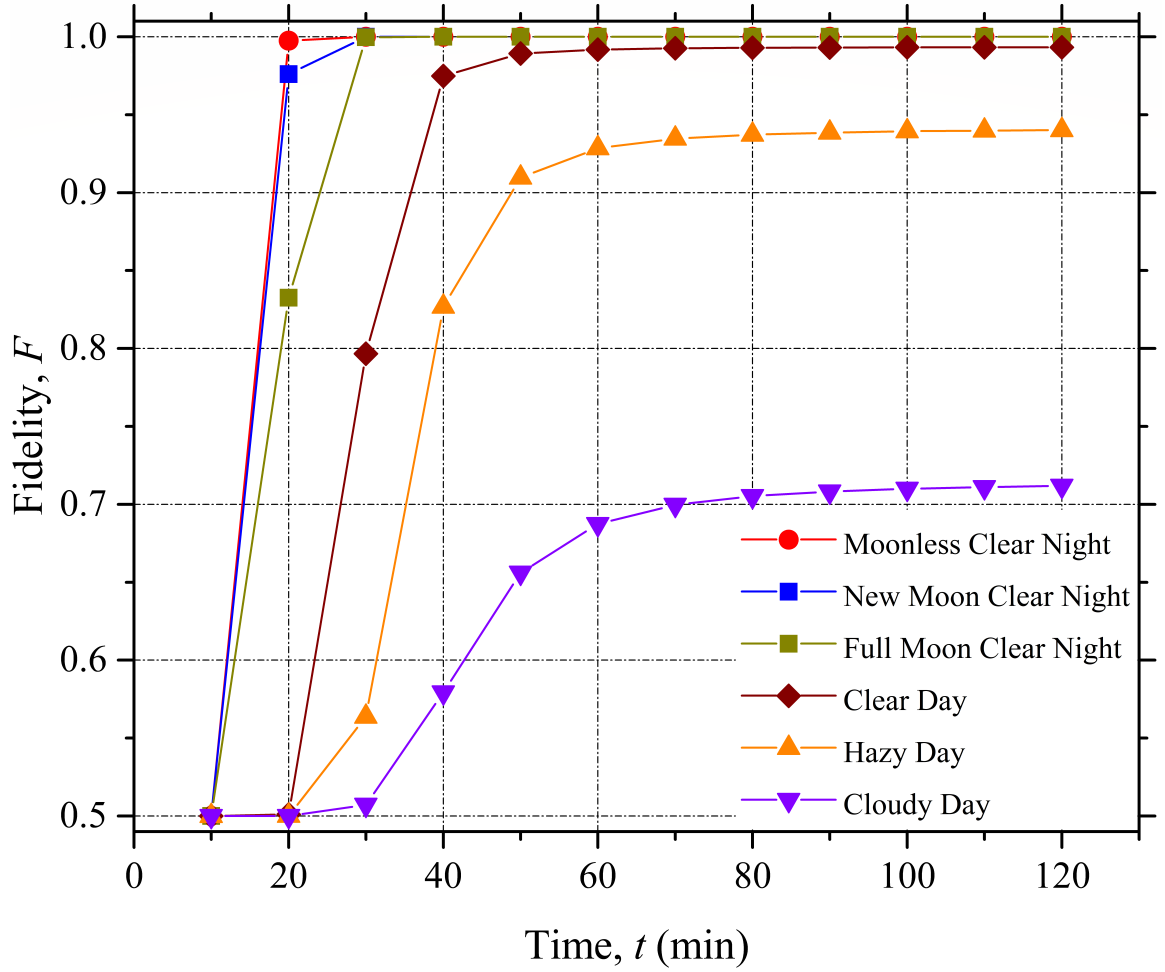


Figure 5.4: The fidelity of a $\lambda = 1550$ nm heralded entangled photon transmission as a function of time following a surface detonation of a 1 Mt nuclear device. The fidelity is calculated for different sky radiance values ranging from moonless clear nights to cloudy days [5].

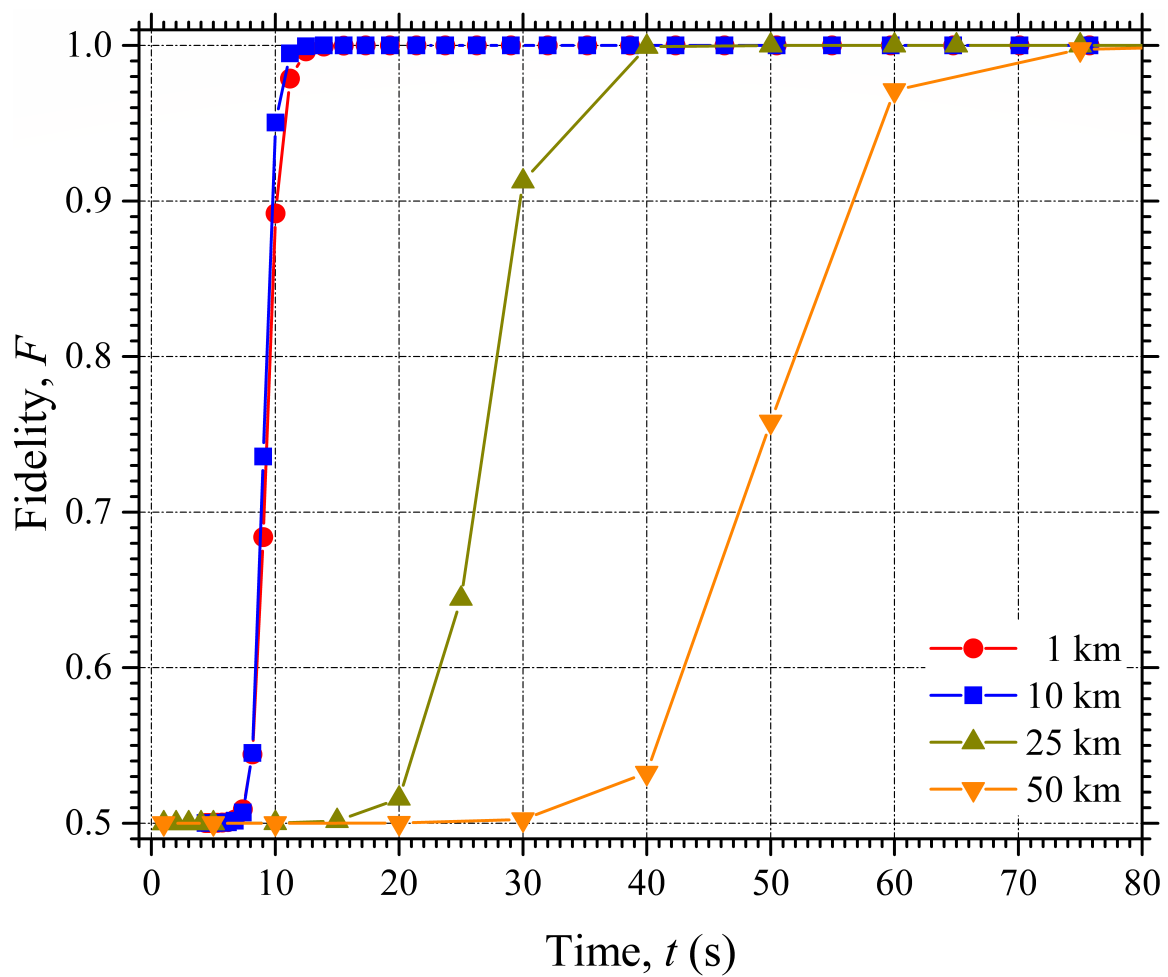


Figure 5.5: The fidelity of a transmitted heralded photon as a function of time following a 100 kt explosion at various height of blast. Only noise from the emissions of the nuclear fireball is considered.

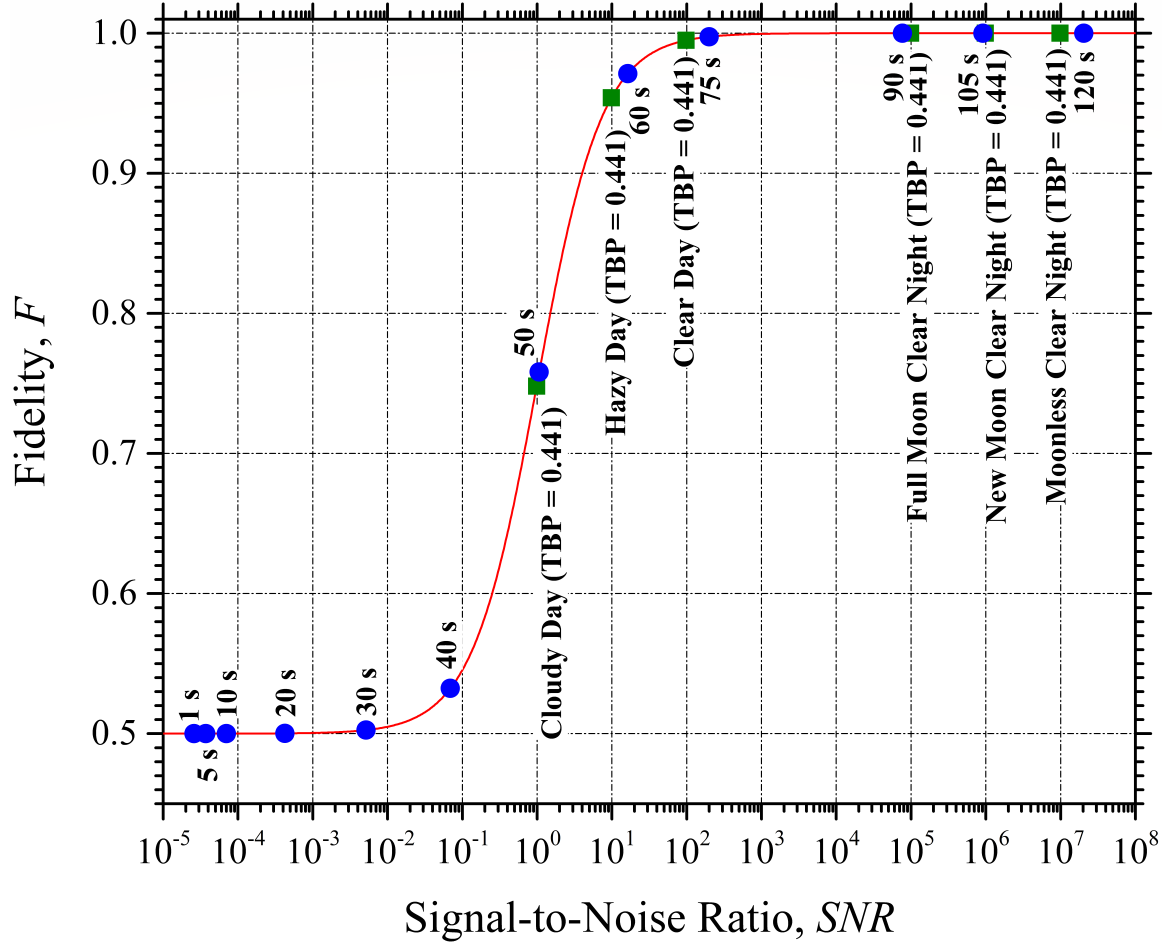


Figure 5.6: The fidelity of a transmitted heralded entangled photon as a function of the signal-to-noise ratio for a downlink network at various times post-detonation of a 100 kt nuclear device at an altitude of 50 km (blue dots) with various sky radiance as a reference (green squares).

nuclear effects, the nuclear disturbance should only deny service for one pass of a low-earth orbit satellite. Subsequent satellite passes may experience mild perturbations due to lingering effects, but operations should largely return to normal. This assumes that neither the satellite nor the infrastructure on the ground are damaged in the initial blast.

5.3.2 Two Photon Case

This section focuses on the transmission of an entangled pair produced on a satellite downlink to two remote parties. To simplify the problem, we assume that the loss due to absorption and scattering remains at 1 dB. In reality, this is highly unlikely as the satellite will be located at some angle from the horizon instead of directly overhead when transmitting the entangled pair to two remote parties. This increases the propagating path of the photon, which further elevates the loss from absorption and scattering. The added complexity of the problem means that we are unable to focus on the SNR of each individual channel, and the time resolution is not as fine. The state fidelity for a two channel network operating during a clear day with nuclear debris present in the propagating path of qubit A from a surface blast of a $Y = 1000$ kt device is shown 30-minutes and 60-minutes post-detonation in Figure 5.7. The nuclear debris is only present in the quantum optical channel A while channel B remains undisturbed. The higher optical channel loss caused by the additional debris in quantum channel A creates an asymmetrical state fidelity with respect to the link distance of channel A and B. With high attenuation in channel A, entanglement distribution is limited by the transmission range of qubit A. After 60 minutes, the debris has begun to settle and operational capabilities are returning to normal conditions.

Finally, we consider the transmission of each entangled photon through an independent loss channel where the attenuation in each channel can destroy the single photon. We vary the loss in each channel from 0 dB up to 50 dB. From the data, we

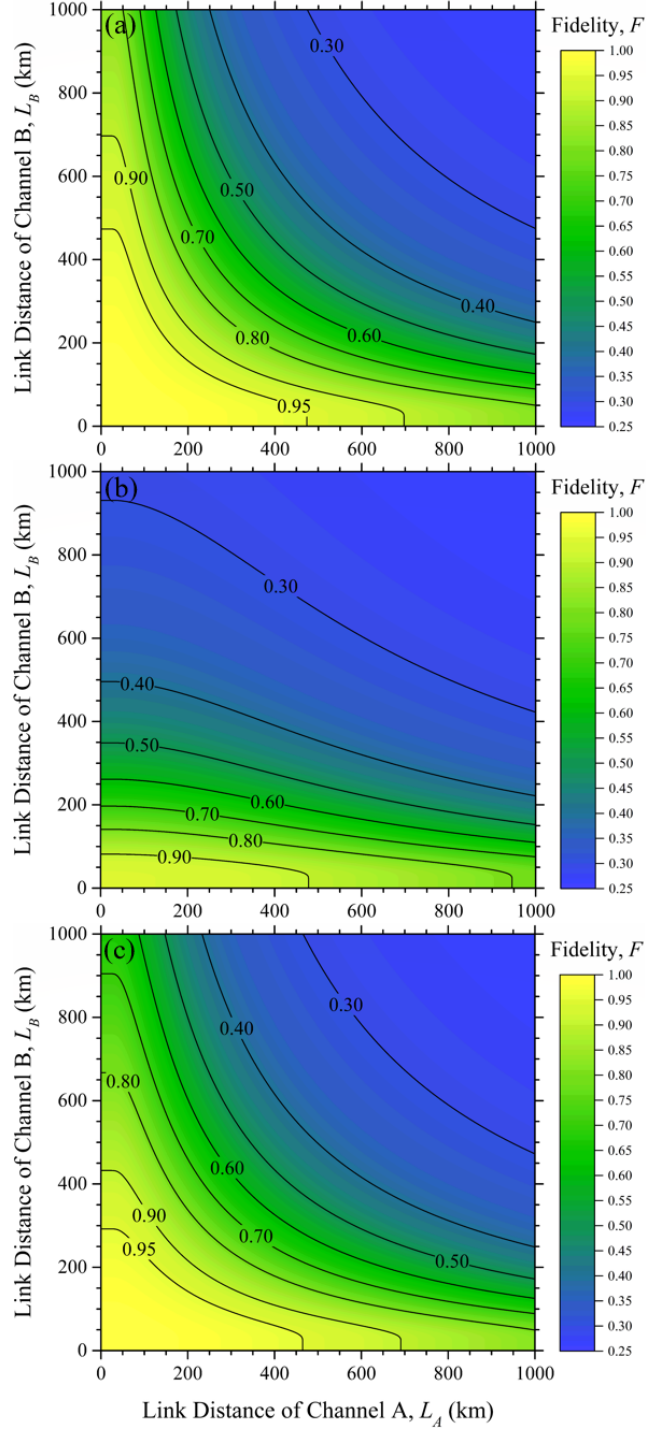


Figure 5.7: The state fidelity for two-photon entangled state distribution at $\lambda = 1550$ nm. There is nuclear debris present in channel A degrading the optical channel. (a) clear day fidelity profile, (b) fidelity profile 30 minutes post-detonation of a $Y = 1$ Mt nuclear device near the surface, (c) fidelity profile 60 minutes post-detonation.

estimate the state and the entanglement of formation. The entanglement of formation (EoF) for the two quantum channel case as a function of the losses in each channel is shown in Figure 5.8. We assume that we have a perfect source that is able to generate 1 million pairs each second. Each transmission channel includes attenuation which has a chance of removing the single photon. We vary the attenuation of each channel from 0 dB to 50 dB. From the simulated data we estimate the state, and from that, the entanglement of formation. Bayesian mean estimation intrinsically allows estimation of the error bars. As we can see, the error increases with the increase in loss. The high channel losses mean that fewer photons make it through which increases the statistical uncertainty.

The combined attenuation of the two channels is what is important since this impacts the two-photon coincidence rate. This is apparent from the stratification seen in the plot giving similar EoF estimates for the same amount of total loss (dashed horizontal lines). The channels should be able to tolerate 40 dB of combined attenuation (for example, 10 dB in Alice’s channel and 30 dB in Bob’s). This is important as the attenuation dynamically varies as a satellite passes overhead and the loss to two intended receivers may change independently. For our assumptions, there is insufficient simulation data to draw any conclusions when the total attenuation goes above 50 dB as the finite statistics results in very large uncertainty (only shown for the case of 25 dB of loss in channel B, for clarity). When insufficient data is available, the Bayesian mean estimation software averages over all two-photon states (entangled and unentangled) giving a non-zero EoF, but with very large uncertainty.

5.3.3 GHZ State

In the case of distribution of a GHZ state to three or four remote parties, the fidelity as a function of the equidistant optical link distance is shown in Figure 5.9. The focus of the figure is not to make one-to-one comparisons of three-photon versus four-photon GHZ entanglement, but to show the added complexity of the problem when going to

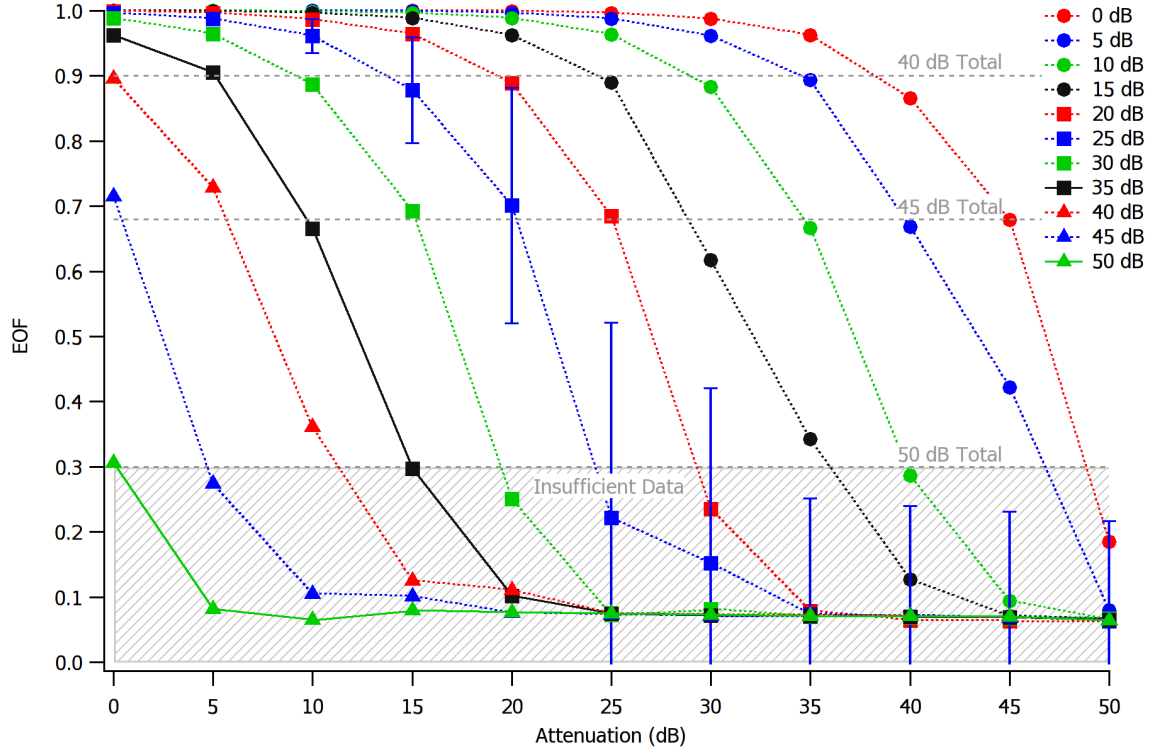


Figure 5.8: The entanglement of formation for a distributed a two-photon entangled state as a function of various optical attenuation values in channel A (horizontal axis) and channel B (legend) of the two quantum channels obtained from the Bayesian mean estimation.

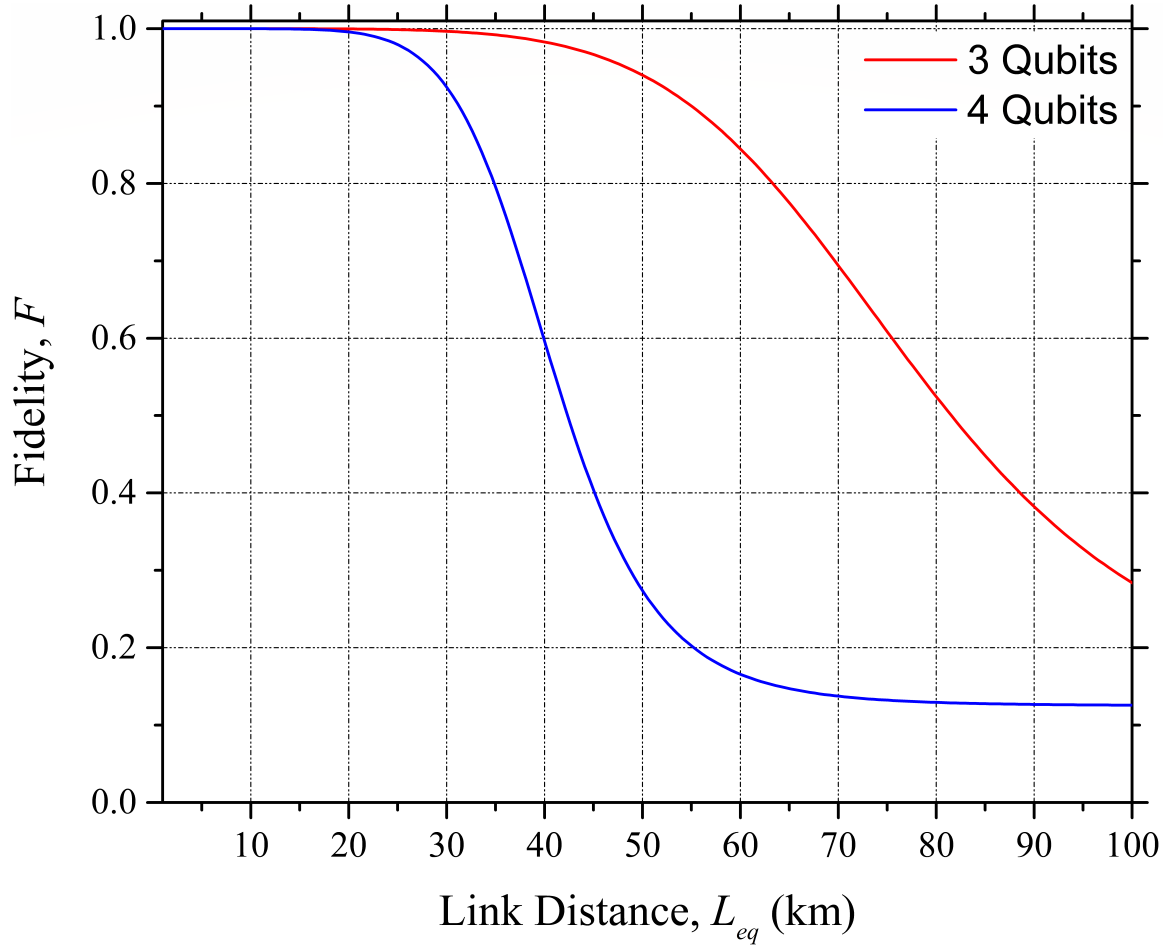


Figure 5.9: The fidelity for entanglement sharing of a GHZ state as a function of the equidistant distance between remote parties. The fidelity for different multi-photon states should not be directly compared due to the different dimensions of the Hilbert spaces.

higher dimensions. When considering only the diffraction loss due to Gaussian beam propagation and detector dark counts, the distribution range is limited to roughly a couple hundred kilometers for the three qubit GHZ state and tens of kilometers in the four qubit GHZ state. Past a couple hundred kilometers, the fidelity has decreased significantly and there is no guarantee that sufficient entanglement can be exchanged. The distance is significantly lower than the distribution range seen in the single or two channel case due to the multiplicative scaling of the total transmittance for each qubit and here we assume each party uses a 10-cm aperture telescope. Therefore, for each photon that is added to the entangled state, there is an increased chance that one of the qubits is lost. In addition, increasing the number of detectors increases the chances of a false count.

5.4 Conclusion

We present a model for analyzing the performance of single photon and entangled photon communications in adverse atmospheric conditions. We analyze the effects of high optical attenuation from haze, smoke, and nuclear disturbed environment and examine the performance impact on a quantum downlink. We find that the impact from the nuclear disturbed environment is strongly a function on the blast scenario and the time after the blast. Shortly after and within close proximity of a blast, the additional attenuation would result in a denial of service. The detector needs to be shielded for a couple of minutes before the increased background noise subsides. The wait time is close to an hour for a 1 Mt blast before the debris in the optical channel settles enough for reliable transmission of the quantum signal. The nuclear disturbed environment quickly dissipates, and as it does, the penalties for quantum communications subside.

Chapter 6

Conclusions

In Chapter 1, the motivation behind the dissertation was introduced. In Chapter 2, background information regarding Gaussian beam propagation, atmospheric effects on Gaussian beams, nuclear weapon effects, and quantum state estimation were discussed to help the understanding of the later chapters. Chapter 3 analyzed the effects of a surface blast of varying explosive yields on the signal transmission likelihood for space-based classical and quantum optical communications networks. Here we saw that for low yield blasts, the debris subsided quickly with the 10 kt explosion yielding minor denial of service when compared to the 1000 kt (1 Mt) nuclear blasts which lofted enough debris into the surrounding environment to deny service for approximately an hour due to the high attenuation. Chapter 4 dealt with the calculation of background noise scattering into a detector with a focus on the effects of the additional light interference by the nuclear fireball. Chapter 5 combined the various nuclear effects with quantum state estimation to determine the effect of a nuclear disturbed atmosphere on the transmission capabilities of quantum states.

A final figure summarizing the duration of impairment by various nuclear weapon effects on a space-based quantum optical network is shown as Figure 6.1. A nuclear blast creates ionizing radiation that increases the free electron concentration of the surrounding atmosphere. This causes a well-known effect called “blackout” that

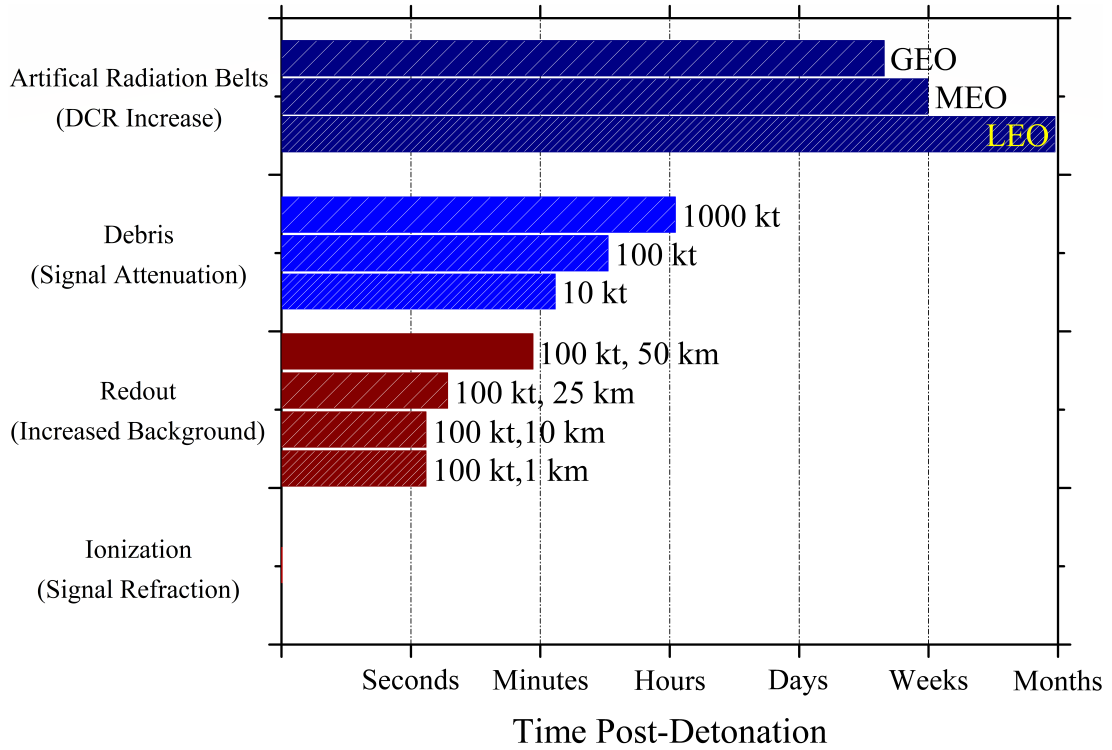


Figure 6.1: The duration of impairment on a quantum network by various nuclear weapon effects. The effects under consideration are the artificial radiation belts [6] from a high-altitude nuclear explosion, signal attenuation due to airborne debris lofted into the atmosphere from a surface blast [7] (Chapter 3), increased light interference from the nuclear fireball [8] (Chapter 4), and ionization of the atmosphere.

can disrupted propagating electromagnetic radiation as observed for radio based communications in multiple nuclear tests. Since quantum networks operate in the near-infrared spectrum, there is a negligible effect on quantum signals. The next effect considered is the redout or increased background count due to the additional photons scattering into the detector from a nuclear fireball [8]. For explosions occurring at a height of blast below 50 km, the additional interference from the fireball lasts less than one minute. Blasts with a height of blast higher than 50 km, the light interference can last for several minutes. The light interference from a nuclear fireball may impede some of the transmission time available between an observatory and a low Earth orbit satellite passing overhead, since the low Earth orbit satellite is only seen for around 7-9 minutes depending on the orbiting altitude. The third effect of concern is the increased signal attenuation due to additional airborne nuclear debris from a surface blast [7]. Thirty minutes following a 10 kt nuclear explosion, the attenuation due to the debris is insignificant when compared to the attenuation due to the atmospheric effects such as absorption, scattering, and turbulence. For a 100 kt nuclear explosion, there is enough debris present to increase the loss thirty minutes following the blast. By the one hour mark, the debris has settled enough where the atmosphere becomes the greatest source of loss. In the 1 Mt case, the nuclear debris concentration significantly attenuates the optical signal and persists almost to the one hour mark. Finally, the last effect occurs during a high-altitude nuclear explosion where the blast can create artificial van Allen belts and releases prompt neutron and gamma radiation [6]. These effects can lead to permanent increases in the dark count rate of the detector and render the detector unfit for quantum communications. The prompt radiation and artificial radiation belts are more potent for low Earth orbit satellite than the higher orbits. Low Earth orbit satellites are more susceptible to the prompt radiation of the explosion due to being closer in proximity. Medium Earth orbit and high Earth orbit satellites normally operate in the outer belt of the van Allen belts, therefore there are better equipped to deal with radiation environments. Also, prompt radiation has to travel farther to reach these satellites

and is more likely to get attenuated. Overall, the best strategy for dealing with a nuclear disturbed environment is waiting for the effects to subside.

6.1 Contributions

Alexander Miloshevsky performed the signal propagation modeling, the background noise modeling, and the quantum state estimation modeling in normal operating conditions and the nuclear disturbed environment. These efforts are the focus of this dissertation and represent a novel contribution to the field of quantum communications. This work would not have been possible without the contributions and assistance of the research collaborators. Brandon Wilson performed the CFD modeling, and the background noise modeling. David Hooper performed the DELFIC calculations and debris analysis. Brian Williams performed the Bayesian Mean Estimation and analysis. Warren Grice provided feedback on the quantum state estimation and background noise theoretical approach and aided in the structure of the papers. Nicholas Peters led the overall project, set the technical goals, discussed the research results, and contributed to the manuscripts.

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Appendix

Parameterizing the two-qubit density matrix

We briefly describe the parametrization of the two-qubit density matrix here, for a complete description of this topic see [105]. For a 4-dimensional Hilbert space, the density matrix is formed using the Cholesky decomposition, requiring $\rho = L(\tau)L(\tau)^\dagger$ with

$$L(\tau) = \begin{pmatrix} L_{11}(\tau) & 0 & 0 & 0 \\ L_{21}(\tau) & L_{22}(\tau) & 0 & 0 \\ L_{31}(\tau) & L_{32}(\tau) & L_{33}(\tau) & 0 \\ L_{41}(\tau) & L_{42}(\tau) & L_{43}(\tau) & L_{44}(\tau) \end{pmatrix}, \quad (\text{A.1})$$

which is a lower triangular matrix with positive real diagonal elements. The parameter set τ includes 15 parameters which describe a unique density matrix.

The elements L_{ij} may be written as

$$\begin{aligned} L_{ij}(\tau) &= U_i V_{ij} & (j \leq i) , \text{ and} \\ L_{ij}(\tau) &= 0 & (j > i) , \end{aligned} \quad (\text{A.2})$$

where

$$\begin{aligned}
U_1 &= \cos(u_1), \\
U_k &= \cos(u_k) \prod_{j=1}^{k-1} \sin(u_j) \quad (1 < k < n), \\
U_n &= \sin(u_n), \\
V_{ii} &= 1, \\
V_{i1} &= \cos(\theta_{i1}) e^{i\phi_{i1}} \quad (i > 1), \text{ and} \\
V_{ik} &= \cos(\theta_{ik}) e^{i\phi_{ik}} \prod_{j=1}^{k-1} \sin(\theta_{ij}) \quad (1 < k < i).
\end{aligned} \tag{A.3}$$

Our simulation has dimension $n=4$, and the parameterized matrix elements of $L(\tau)$ are

$$\begin{aligned}
L_{11}(\tau) &= \cos(u_1), \\
L_{21}(\tau) &= \sin(u_1) \cos(u_2) \cos(\theta_{21}) e^{i\phi_{21}}, \\
L_{22}(\tau) &= \sin(u_1) \cos(u_2) \sin(\theta_{21}), \\
L_{31}(\tau) &= \sin(u_1) \sin(u_2) \cos(u_3) \cos(\theta_{31}) e^{i\phi_{31}}, \\
L_{32}(\tau) &= \sin(u_1) \sin(u_2) \cos(u_3) \sin(\theta_{31}) \cos(\theta_{32}) e^{i\phi_{32}}, \\
L_{33}(\tau) &= \sin(u_1) \sin(u_2) \cos(u_3) \sin(\theta_{31}) \sin(\theta_{32}), \\
L_{41}(\tau) &= \sin(u_1) \sin(u_2) \sin(u_3) \cos(\theta_{41}) e^{i\phi_{41}}, \\
L_{42}(\tau) &= \sin(u_1) \sin(u_2) \sin(u_3) \sin(\theta_{41}) \cos(\theta_{42}) e^{i\phi_{42}}, \\
L_{43}(\tau) &= \sin(u_1) \sin(u_2) \sin(u_3) \sin(\theta_{41}) \sin(\theta_{42}) \cos(\theta_{43}) e^{i\phi_{43}}, \text{ and} \\
L_{44}(\tau) &= \sin(u_1) \sin(u_2) \sin(u_3) \sin(\theta_{41}) \sin(\theta_{42}) \sin(\theta_{43})
\end{aligned} \tag{A.4}$$

with $u_i \in [0, \frac{\pi}{2}]$, $\theta_{ij} \in [0, \frac{\pi}{2}]$, and $\phi_{ij} \in [0, 2\pi]$. The parameter set is then explicitly

$$\tau = \{u_1, u_2, u_3, \theta_{21}, \theta_{31}, \theta_{32}, \theta_{41}, \theta_{42}, \theta_{43}, \phi_{21}, \phi_{31}, \phi_{32}, \phi_{41}, \phi_{42}, \phi_{43}\}. \tag{A.5}$$

Vita

Alexander Miloshevsky was born in Minsk, Belarus. He attended Purdue University and graduated with a Bachelors of Science in Physics in 2016. During his time at Purdue, he participated in the Science Undergraduate Laboratory Internships at Pacific Northwest National Laboratory where he developed an interest for scientific research. He started his Ph.D. at University of Tennessee in 2018, and conducted research under the supervision of Nicholas Peters and Zhili Zhang.