Comparing Calculated and Measured Losses in a Satellite-Earth Quantum Channel

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Abstract—**Long distance distribution of quantum states is necessary for quantum communication and large scale quantum experiments. Currently this distance is limited by channel loss. Previous theoretical analysis [1] and proof of concept experiments [2] showed that satellite quantum communication may have lower losses than optical cable based counterparts. Recently the QuESS experiment [3] realized the first satellite-Earth quantum channel. In this paper we compare theoretical predictions of different mathematical models with experimental results regarding channel loss. We examine the HV-5/7 model, HV-Night model and Greenwood model of optical turbulences, the geometric [4] and diffraction [5][6] models of beam wander and beam widening. Furthermore we take into account the effect of atmospheric gases and aerosols as well as the effect of pointing error. We find that theoretical predictions are largely in the same order of magnitude as experimental results. The exception is the diffraction model of beam spreading where our calculations yielded only one tenth of the measured value. Given the ever changing nature of weather conditions and the changing composition of atmospheric aerosols we conclude that calculated and measured losses are in good agreement.**

Keywords—satellite; quantum communication; channel loss; downlink;

I. INTRODUCTION

Quantum communication is the emerging field of sending and receiving messages using extremely weak signals. These signals could be single photons, coherent laser pulses or pairs of entangled photons. The signals are governed by quantum mechanics and thus behave fundamentally differently than classical counterparts.

One example of this unusual behavior is that unknown quantum bits cannot be observed or copied without running the risk of irreversibly changing them. These changes can later be detected revealing any eavesdropping attempt, which is extremely useful for cryptography. Another interesting property of quantum bits is that they can be entangled, meaning that their otherwise random behavior during measurement remains correlated even if they are separated by large distances.

These unusual behaviors allow for applications, which would not be possible otherwise. The most famous of these applications is quantum cryptography (cryptography with mathematically proven security [7][8][9][10][11]). Since quantum channels cannot be wiretapped without alerting the communicating parties, it is possible to distribute cryptographic keys on a quantum channel and check if there was an eavesdropping attempt. If the keys were compromised they are discarded. Otherwise they can be used to encrypt secret massages.

Other possible uses of quantum channels include sending two bits of data at the cost of sending a single quantum bit in a full duplex quantum channel (a method called superdense or quantum dense coding [14][15]). Other large scale experiments have also been proposed that require entangled photon pairs (such as experiments testing theories about quantum gravity [12][13]).

A good and detailed theoretical introduction to quantum information can be found in [14] while a more practical and communication centric introduction can be found in [15].

However, quantum communication requires long distance distribution of quantum bits. The distance at which quantum bits can be transmitted is currently limited by channel loss─either the loss of an optical cable or losses in free space. Experiments and theoretical works show that out of these two possibilities free space communication has lower losses. This motivated the race toward satellite-based quantum communication [16][17] which is currently unfolding even in the economic world of CubeSats [18][19].

The QuESS (Quantum Experiment at Space Scale) experiment realized the first satellite-Earth quantum channel. The satellite produced entangled photon pairs and transmitted them to two ground stations at Lijiang and Delingha China via two downlinks. The transmitters onboard the satellite produced photons in the near infrared range. This means that the equipment and communication resembles optical downlinks and not radio frequency transmissions.

In this paper, we compare theoretical predictions for channel loss with measured values. This is necessary because theoretical predictions of quantum communication are based on mathematical models describing classical light beams. This approach requires the assumption that properties of the atmosphere are either completely or at the very least largely independent of light intensity and that individual photons behave in a way that is consistent with an infinitesimal part of a classical light beam.

II. SOURCES OF LOSS IN SATELLITE-EATRH QUANTUM CHANNELS

Free space losses can be induced by multiple causes. In the following section we detail the sources of loss that we have taken into account in our calculations.

A. Pointing Error

Errors in targeting may result in the photon missing the detector and thus contribute to the free space channel loss. In our calculations we used the reported [3] value of the targeting error measured in the QuESS experiment and assumed that the targeting error had a Gaussian profile as reported [3].

In the QuESS experiment the detector mirror of the telescope was a Cassegrain reflector [3]. We approximated this in our calculation by assuming that the cross section of the

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detector is a perfect circle with radius equal to the radius of the primary mirror and disregarded the blind spot created by the secondary mirror.

B. Beam Spreading and Beam Wander

Since the refraction of air is temperature dependent, fluctuations of air temperature can deflect and distort light signals. This effect depends on atmospheric conditions: the optical turbulence strength (denoted by C_n^2) is a parameter that describes the strength of these fluctuations. Higher C_n^2 values are associated with more beam widening and distortion. The magnitude of C_n^2 depends on wind speed, altitude and several other factors such as geographical features.

Atmospheric effects can also cause the center of a classical beam to wander. Higher C_n^2 values are also associated with more beam wander. It is worth noting that we do not distinguish between beam wander and beam spreading here, since in the long term time average the beam wander can be described as just another source of beam spreading. The beam widening is characterized by the radial beam divergence angle (or beam divergence for short) which is measured in micro-radians.

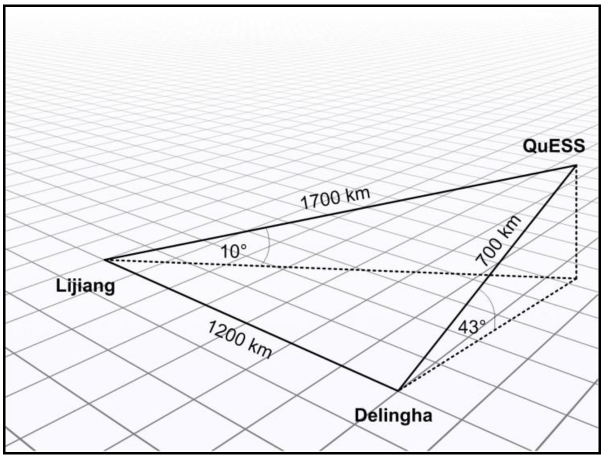

Fig. 1. Longest two-link distance between the satellite and the two ground stations.

C. Atmospheric Attenuation

Atmospheric gases and aerosols (solid particles of dust and liquid droplets) absorb and scatter light thus contributing to the channel loss. In our calculations, we took a semi-empirical approach. Instead of relying on purely theoretical calculations of molecular extinction we used experimentally measured values [20] of atmospheric transmittance.

This method is not only simple and easy to use, but it also gives us a more realistic picture of the aerosol profile as function of altitude than theoretical models. Since aerosol extinction is typically stronger than molecular extinction [20], we can expect a realistic result even with relatively inaccurate data about molecular extinction.

However, in these experiments [20] the wavelength was slightly different than in the QuESS experiment. Since aerosol extinction is mostly independent of wavelength (this statement is supported by both experimental data [20] and the theory of Mie-scattering [21]), we approximated aerosol extinctions by linear interpolation of measured values. In case of molecular extinction, we used the closest available analog which was a measurement performed using GaAs laser.

D. Efficienny of the Detector and the Optical Setup

Losses of the optical setup (due to imperfect detector efficiency, noise and inefficiencies in the photon generation process) are reported in the article [3] detailing the QuESS experiment. We have taken these efficiencies into account in our calculations.

III. Channel Lengths and Elevation Angles in the QuESS Experiment

An important factor in determining the channel loss is the relative position of the ground station and the satellite. The elevation angle as seen from the ground station determines the effective thickness of the atmosphere whereas the distance to the satellite determines the channel length. Therefore both of these parameters are required to estimate the channel loss.

The article describing the results of the QuESS experiment [3] focuses on two geometric arrangements. One is the moment when the communication is established and losses are the highest, and the other is when the overall two-channel length is the shortest and the channel loss is the lowest. In both cases the authors disclose either the channel length or the elevation angle but not both. However one can be calculated from the other.

We used the satellite - ground station - Earth center triangle to calculate the missing parameters. According to our calculations when communication was established (see Figure 1.) the satellite-Lijiang distance was 1700 km and the elevation angle at Lijiang station was 10°. At the same time the satellite-Delingha channel length was 700 km and the elevation angle at Delingha was 43°.

The combined two channel length was the shortest when the satellite was 800-800 km from both Lijiang and Delingha stations (see Figure 2.) and could be seen at 36° elevation angle from both ground stations.

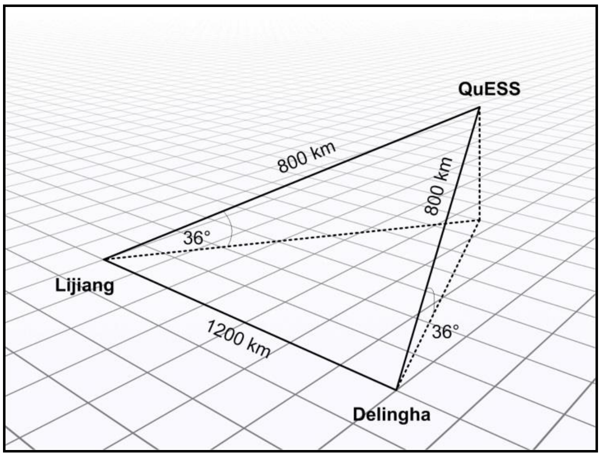

Fig. 2. Shortest two-link distance between the satellite and the ground sations.

It is worth mentioning that Figures 1. and 2. are merely illustrations and the triangles depicted on them are not proportional.

IV. Optical Turblulence

In order to model beam spreading and beam wander in the atmosphere we must know the atmospheric turbulence strength parameter (C_n^2). There are several different turbulence profile models to choose from – these are typically curves fitted onto measured data. Since free space quantum communication is carried out during the night (when the background noise is the lowest) we focused on models applicable to nighttime conditions. In our calculations we used three specific models. These are:

- Hufnagel-Valey 5/7 (or HV 5/7) model [22],
- HV-Night model [22],
- Greenwood model [22].

1) HV 5/7 model: The HV 5/7 is the most widely used model. It is a special case of the more general Hufnagel Valey model. According to the model the optical turbulence strength parameter C_n^2 is given by the following equation:

$$C_n^2 = 0.00594 \cdot \left(\frac{W}{27}\right)^2 \left(h \cdot 10^{-5}\right)^{10} \exp\left(-\frac{h}{1000}\right) + \\ + 2.7 \cdot 10^{-16} \cdot \exp\left(-\frac{h}{1500}\right) + A \cdot \exp\left(-\frac{h}{100}\right), \quad (1)$$

where h is the altitude (measured in km), W is 21 [m/s] and A is $1.7 \cdot 10^{-14}$.

2) HV-Night model: The HV-Night model is another modification of the Hufnagel Valey model. In this model C_n^2 is given by the following equation:

$$C_n^2 = 8.16 \cdot 10^{-54} \cdot h^{10} \exp\left(-\frac{h}{1000}\right) + \\ + 3.02 \cdot 10^{-17} \cdot \exp\left(-\frac{h}{1500}\right) + 1.9 \cdot 10^{-15} \cdot \exp\left(-\frac{h}{100}\right) \quad (2)$$

3) Greenwood model: The Greenwood model was developed for astronomical imaging from mountaintops. It gives C_n^2 as

$$C_n^2 = \left[2.2 \cdot 10^{-13} (h + 10)^{-1,3} + 4.3 \cdot 10^{-17}\right] \cdot \exp\left(-\frac{h}{4000}\right). \quad (3)$$

V. GEOMETRIC BEAM SPREADING MODEL

In this section we compare the calculated beam spreading with the measured values. The far field beam divergence has been reported to be 10 μrad [3].

To calculate the beam wander we used the geometric approximation [4]. This treats optical turbulence as converging or diverging lenses. The radial beam divergence angle can be calculated as [4]:

$$\sigma_\angle = \left(2{,}92 \cdot D^{-1/3} \int_0^H C_n^2(h) \frac{\left(\frac{L_2(h)}{L}\right)^2}{\left|1 - \frac{L - L_2(h)}{F}\right|^{1/3}} dh \right)^{1/2} \quad (4)$$

where L is the total channel length, H is the altitude of the satellite, h is the altitude above ground level in the integration path and L_2 is the beam's slant path length corresponding to a given altitude. F is the focal range and D is the initial beam waist.

A. HV 5/7 Model

Calculating with the HV 5/7 model, the radial beam divergence comes out to be between 0.019 μrad and 0.02 μrad depending on which transmitting telescope of the QuESS satellite was used.

The lower value of the calculated beam spreading corresponds to the larger telescope (0.3 m diameter) and the higher beam spreading angle corresponds to the smaller telescope (0.18 m diameter).

However, the dependence of beam spreading on channel length seems to be negligible (our calculations yielded approximately the same result for each downlink). The most likely explanation for this independence is that beam spreading is comparably small in vacuum. This means that the spot size at the detectors plane is mostly determined by the part of the optical path that is in the atmosphere.

This path length in the atmosphere is a function of the elevation angle. However a lower elevation angle corresponds to a longer link distance if the altitude of the satellite is fixed. The increase of the spot size seems to be almost perfectly cancelled out by the increase of the channel length and therefore the decrease of the angle corresponding to a given spot size.

Comparing the calculated and reported values we can conclude that these values are small—being several magnitudes smaller than the reported 10 μrad [3] beam divergence.

B. HV Night Model

Using the HV Night model we obtain radial beam divergence angles between 0.009 μrad and 0.01 μrad.

The outcome of the calculation is similar to the previous model: the result is largely unaffected by channel length but depends on transmitter telescope diameter (the smaller beam spreading corresponding to the larger telescope).

Comparing measured and calculated values we conclude that the HV night model gives us results that are also several magnitudes smaller than the 10 μrad radial beam divergence reported in [3].

C. Greenwood Model

Using the Greenwood model we get radial beam divergence angles between 0.16 μrad and 0.17 μrad.

The characteristic is similar to the previous models: the result is largely independent from channel length but depends on transmitter telescope diameter (the smaller beam spreading corresponding to the larger telescope).

Comparing the calculated and measured [3] values we conclude that the Greenwood model yields values roughly one tenth of the reported 10 μrad beam divergence.

D. Comparing the Different Models

Comparing the measured beam spreading with the calculated values we can conclude that none of the optical turbulence models yield the measured result (see Figure 3.). Even the largest result is several magnitudes smaller than the reported value.

Figure 3. shows the calculated values of beam spreading and beam wander, measured in μradians.

As we mentioned before, the QuESS satellite was equipped with two different transmitting telescopes. Black bars in Figure 3 indicate the beam wander/spreading in case of the smaller telescope (corresponding to more beam wander) and white bars indicate the beam wander/spreading in case of the larger transmitting telescope (corresponding to less beam wander). The bars are grouped by model.

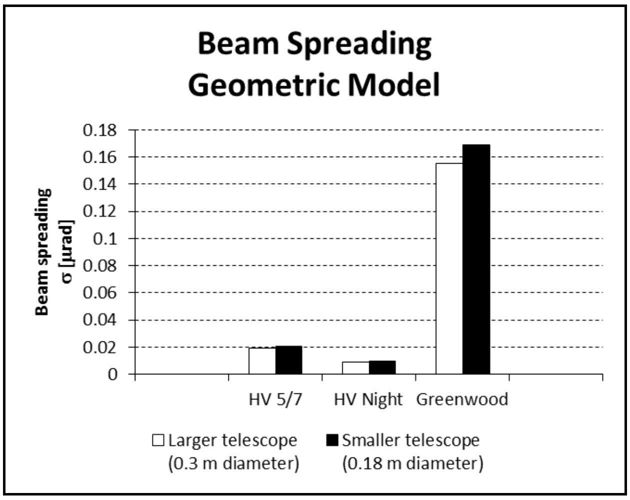

Fig. 3. Calculated values of beam spreading using the geometric model. The measured value was 10 μrad [3], which is significantly higher than the calculted values shown here.

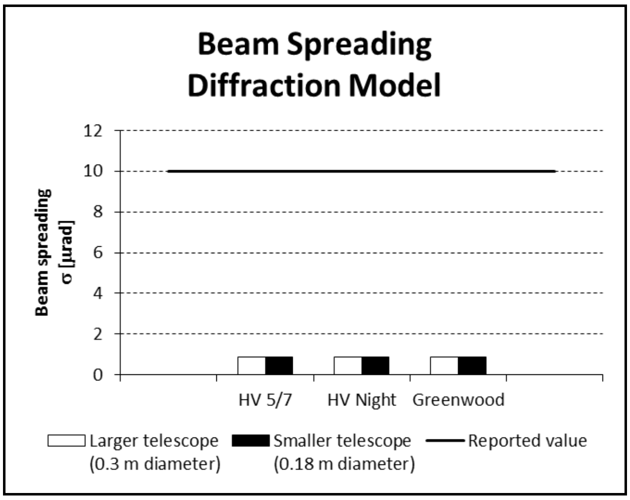

Fig. 4. Comparing measured [3] and calculated beam sreading using the diffraction model. Calculated values are a magnitude smaller than mesured ones.

VI. Diffraction Beam Spreading Model

Another alternative to using the geometric beam wander model is a diffraction based model [5][6]. In this section, we present the results of our calculations using this approximation.

The radial beam divergence angle in the diffraction based model can be calculated as [5][6]:

$$\sigma_{\angle} = arctg\left(\frac{1}{L}\cdot\left[\frac{4L^2}{k^2D^2}+\frac{D^2}{4}\left(1-\frac{L}{F}\right)^2+\frac{4L^2}{k^2\rho_0^{\,2}}\right]^{\frac{1}{2}}\right), \quad (5)$$

where L is the total channel length, F is the focal range, k is the wavenumber and D is the initial beam waist. ρ_0 is the phase coherence, which can be calculated as [5][6]

$$\rho_0 = \left[1{,}46k^2\int_0^H C_n^2(h)\left(\frac{L_2(h)}{L}\right)^{5/3} dh\right]^{-3/5}, \quad (6)$$

where H is the altitude of the satellite, L_2 is the beam's slant path length that corresponds to a given h altitude (assuming a fixed elevation angle).

Since the elevation angle in the QuESS experiment was fairly low, we used Fante's approach to calculate the coherence length [6].

According to our calculations, the beam spreading should be between 0.86-0.87 μrad. This is less than one tenth of the reported 10 μrad [3].

This result holds regardless of the model used for calculating the optical turbulence strength (see Figure 4.). The reason for the discrepancy between the measured and calculated value is currently unknown and warrants further investigation. Possible explanations include higher than expected turbulence or other factors not currently accounted for in our model.

VII. Channel Loss

Using the value of beam spreading measured in the QuESS experiment we can validate our method of calculating the channel loss. In this section we examine the channel loss when the combined two channel length is the longest (maximal loss) and shortest (minimal loss).

The results presented in this section are calculated assuming 50% overall optical efficiencies for the telescopes (while the actual value was reported to be somewhere between 45-55% [3]).

We calculated the channel loss as:

$$QTL = -10\cdot\log_{10}(\tau_1\cdot\tau_2) \quad (7)$$

where τ_1 and τ_2 are the effective transmittances of the two downlink channels (one to Lijiang and the other to Delingha). Each of these effective transmittances can be calculated as:

$$\tau_{1,2} = \tau_{P/S}\cdot\tau_{AE}\cdot\tau_O \quad (8)$$

where $\tau_{P/S}$ is the effective transmittance due to pointing and beam spreading, τ_{AE} is the transmittance due to atmospheric extinction, and τ_O is the effective transmittance due to other effects.

The value of τ_O comes from the reported [3] efficiency of the optical setup, detector efficiency and losses caused by background noise. The other two terms can be calculated using the following equations:

$$\tau_{P/S} = 1-\exp\left(\frac{R^2}{2\cdot\left((L\cdot\tan\sigma_{\angle})^2+(L\cdot\tan\sigma_T)^2\right)}\right), \quad (9)$$

where R is the detector radius at the ground station, L is the total link distance, $\sigma_{\angle}$ is the radial beam divergence angle, and σ_T is the targeting error (as reported in the QuESS experiment [3]).

Finally the atmospheric extinction can be characterized by:

$$\tau_{AE} = \sum_i \exp(-(s_i+k_i)L_i) \quad (10)$$

where L_i is the slant path length in the i^{th} layer of the atmosphere, whose aerosol and molecular extinction is given by s_i and k_i. (These values come from measurements [20]. We used data gathered during the summer, in the middle latitudes, under various weather conditions.)

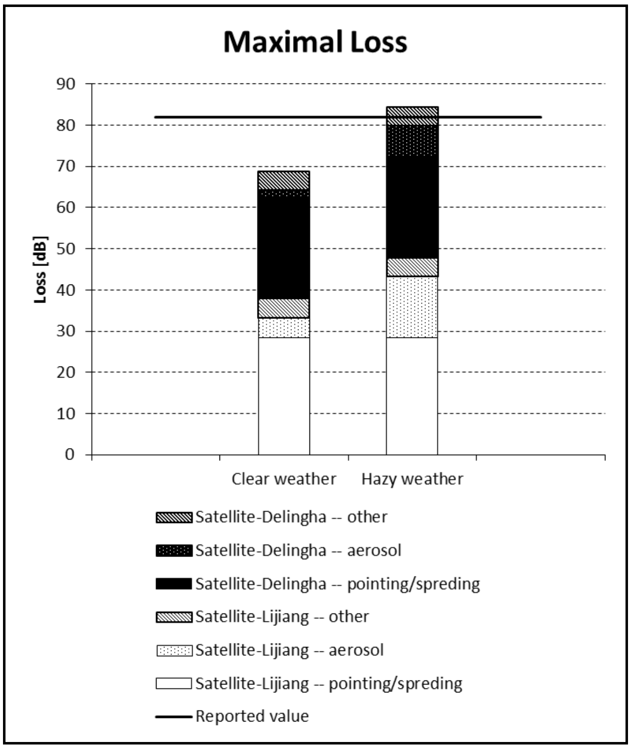

Fig. 5. Calculated and reported losses in case of the longest two-link distance in clear and hazy weather [3].

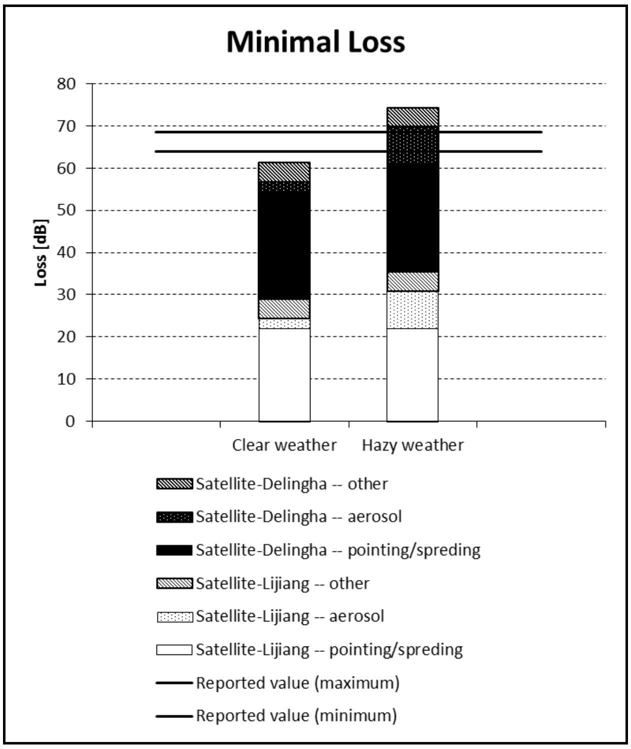

Fig. 6. Calculated and reported losses in case of the shortest two-link distance [3].

A. Maximal Loss

When the communication was established with the satellite (this situation is shown in Figure 1.), the measured two channel loss in the QuESS experiment was reported to be 82 dB [3].

According to our calculations, the loss due to pointing error, beam wander and beam spreading in the satellite-Lijiang channel was 28.54 dB while in the satellite-Delingha channel it was 24.36 dB. The combined two channel loss due to beam spreading and pointing error was 52.9 dB. These values are denoted by white and black bars in Figure 5.

(Note that the values of beam spreading are unaffected by weather conditions; these bars are equally high regardless of whether the weather is clear or hazy.)

According to our calculations, the channel loss due to molecular and aerosol extinction had to be between 4.85 dB and 14.72 dB in the satellite-Lijiang channel (depending on weather conditions). In the satellite-Delingha channel, the loss had to be between 2.05 dB and 7.68 dB. (See the dotted bars in Figure 5. Note that these losses can significantly differ based on weather conditions.)

Taking into account all factors (including optical and detector inefficiencies) the total combined two channel loss had to be between 68.92 dB (assuming clear weather) and 84.43 dB (assuming hazy weather). These calculated values are in good agreement with the reported 82 dB loss [3] (which is shown as a horizontal line in Figure 5.).

B. Minimal Loss

Losses were the lowest when the satellite was closest to the two ground stations (see Figure 2.). The measured two channel loss in this position is reported to be between 64 dB and 68.5 dB [3].

According to our calculations the loss due to pointing error, beam spreading and beam wander had to be 22 dB in the satellite-Lijiang channel and 25.52 dB in the satellite-Delingha channel. These losses are shown as black and white bars in Figure 6.

(Note that these losses do not depend on weather conditions. However they do depend on the ground station, or to be more precise the detector mirror size at the ground station which differed in this case.)

The combined two channel loss caused by beam spreading comes out to be 47.53 dB.

According to our calculations, the channel loss due to molecular and aerosol extinction had to be between 2.38 dB (assuming clear weather) and 8.91 dB (assuming hazy weather) in both channels.

(Note that aerosol extinction is not affected by the detector. This type of loss depends only on the elevation angles—which happened to be equal in this case—and the weather conditions.)

Taking into account all errors, losses and inefficiencies the combined total two channel loss had to be between 61.41 dB and 74.47 dB. These calculated values are in the same order of magnitude as the measured 64 to 68.5 dB reported in the literature [3]. (These values are represented as solid horizontal lines in Figure 6.)

VIII. CONCLUSIONS

In this article, we compared the measured beam spreading and channel loss of the QuESS satellite experiment [3] with calculated values.

We found that our calculations yield significantly lower beam spreading than the reported value [3]. However calculating with the reported value of beam spreading, we obtained losses that agreed with measured losses.

The exact result of beam spreading in our calculations depends on the model of optical turbulence strength being used. We examined the HV 5/7 [22], HV Night [22] and Greenwood [22] models of optical turbulence.

We also examined the geometric optics model [4] and diffraction model [5][6] of beam spreading. Our calculations yielded results that are several magnitudes smaller than that of the reported values [3]. This relationship holds true for all models of optical turbulence strength and all models of beam spreading.

The reason for this discrepancy is currently unknown and warrants further investigation. Possible explanations include stronger than expected turbulence or other unexpected factors not currently present in our model.

Furthermore, we compared reported and calculated losses. The reported losses of a quantum channel in the QuESS experiment were roughly between 60 dB and 85 dB [3]. According to the literature [22], these losses are in the same order of magnitude as the total link loss of a classical satellite-to-ground laser communication channel.

However for quantum channels, other authors [23] estimated the channel loss to be significantly lower than the value reported in the QuESS experiment [3].

To perform our calculations, we used the measured value of beam spreading as reported in [3] instead of our calculated beam spreading. The results we obtained this way were in good agreement with the reported data.

We performed these calculations in two particular cases: the first was when communication was established with the satellite, and the combined two-channel length was the longest (see Figure 1.), and the second was when the satellite was closest to the two ground stations and the two-link distance was the longest (see Figure 2.). In both of these cases we examined clear and hazy weather. Our results show that the reported loss was between the calculated values obtained simulating clear and hazy weather (these correspond to lowest and highest loss respectively). This means that given the correct beam spreading the rest of the model is likely accurate. This accuracy can be further tested by comparing more calculations with more experimental data.

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