



Correction: Estimating the link budget of satellite-based Quantum Key Distribution (QKD) for uplink transmission through the atmosphere

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The article provides a detailed link budget calculation for various Indian locations, which is highly dependent on the input parameters like the choice of wavelength and beam divergence. Due to algebraic corrections and typographical revisions, the link loss values presented in Tables 1, 3 and 4 have been revised. This leads to changes in keyrate and QBER values reported in Tables 5, 6 and 7 in the main article.

Table 1 gives the modified link budget calculation for the signal beam at 810 nm with a chosen 20 μ rad divergence. This leads to a smaller footprint of the signal at the receiver located 500 km away in a LEO satellite. This is required for optimal signal transmittance. Also, we add the loss due to beam wander in row number 6, which was earlier missing in the table. The changes in Table 1 are listed below.

Table 1 Link budget calculation for the IAO Hanle observatory. Rows 1, 2, and 3 represent parameters for the transmitter telescope. Rows 4, 5 and 6 represent propagation loss. Rows 7, 8, and 9 represent parameters for the receiver telescope (the rows that are not mentioned in this table remain same as the Table 1 in the article)

No	Parameter	unit	signal
1	Tx gain (G_t)	dB	109.03
2	Tx Beam divergence ($2\Theta_B$)	μ rad	20
4	Path loss (L_r)	dB	-257.79
5	Atmospheric attenuation (η_{atm})=0.651	dB	-1.84
6	Beam Wander loss (L_{BW})	dB	-0.40
7	Rx gain (G_r)	dB	121.32
9	Rx pointing loss	dB	-1.83
10	Total loss	dB	35.91

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Modified η_{atm} includes η_{tur} , which was calculated based on discussions provided in Sharma et al. [4].

With similar corrections to Table 3, we present the revised loss calculation for the uplink 532 nm, and for the downlink 1550 nm beacons with their beam divergence fixed at 500 μ rad. This high divergence leads to optimal footprints of the beacon lasers for the best possible tracking at the receiving ends. The changes in the table are listed below.

Table 3 Link budget for uplink 532 nm and downlink 1550 nm beam with only the rows that have changed values from Table 3 in the article

No	Parameter	unit	Uplink	Downlink
1	Tx power (P_t)	W	1.0	1.0
5	Tx gain (G_t)	dB	81.07	81.07
8	Path loss (L_r)	dB	−261.48	−252.16
9	Atmospheric transmittance (η_{atm}) = 0.73/0.81	dB	−1.36	−0.9
10	Turbulence (η_{tur}) = 0.64/0.96	dB	−1.88	−0.18
12	Rx gain (G_r)	dB	124.97	109.66
14	Total loss	dB	63.08	66.91

Table 4 is revised as the total loss for all three ground station locations has been revised.

Table 4 Link budget analysis for 3 different locations in India for uplink beacon, downlink beacon and signal beam of wavelength 532 nm, 1550 nm and 810 nm, respectively

Location	Uplink beacon loss in dB	Downlink beacon loss in dB	Signal loss in dB
IAO Hanle	63.08	66.91	35.91
ARIES Nainital	67.22	67.54	37.78
Mount-Abu	66.26	66.93	37.19

Estimated QBER and keyrate for 3 different locations in India, considering WCP source-based decoy state QKD protocol and entanglement-based BBM92 protocol. The key rate is calculated for the asymptotic limit as given in Bourgoïn et al. [1]. The changes we report here contribute to Table 5, 6 and 7 in the main article.

Table 5 Estimated QBER and keyrate for 3 different locations in India, considering WCP source-based decoy state QKD protocol. The key rate calculated for the asymptotic limit as given in [1]

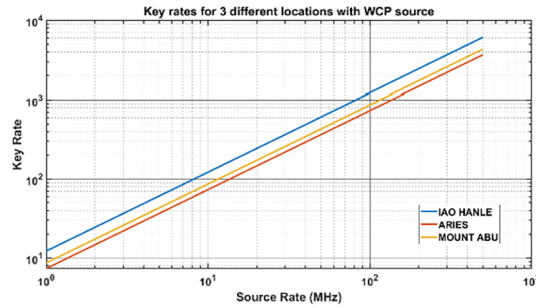
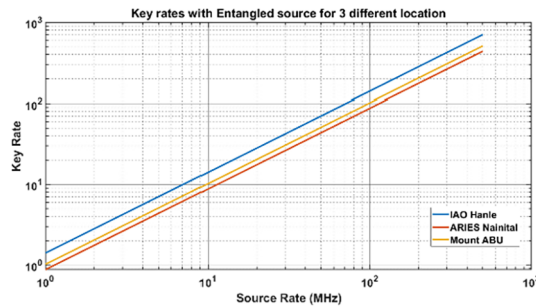
Observatories	Loss (dB)	QBER for WCP in %	Keyrates for WCP in bps
IAO Hanle	35.91	2.29	122.48
ARIES Nainital	37.78	2.96	73.55
Mount-Abu	37.19	2.72	86.63

Table 6 QBER and key rate calculation for 3 different locations in India for Entangled sources

Observatories	Loss (dB)	QBER for Entangled source (%)	Keyrates for Entangled source (bps)
IAO Hanle	35.91	5.62	14.08
ARIES Nainital	37.78	5.78	8.75
Mount-Abu	37.19	5.72	10.2

Table 7 Link budget analysis for 3 different potential locations as ground stations in India

Observatories	Loss (dB)	Keyrates for WCP in bps	Keyrates for Entangled source (bps)
IAO Hanle	35.91	122.48	14.08
ARIES Nainital	37.78	73.55	8.75
Mount-Abu	37.19	86.63	10.2

**Figure 5** Key rate estimation considering Weak Coherent Pulsed source for three observatories**Figure 6** Key rate estimation considering an entanglement-based QKD for the three observatories

Following the above loss calculations, the asymptotic key rates for both WCP and entanglement-based QKD have been revised. Equations 23 and 25 in the article mistakenly refer to the finite key rate formula, whereas we actually use the asymptotic key rate formula as per Bourgoin et al. [1] and Reference 52 in the main article respectively, for our analysis.

Figure 5 and Fig. 6 have been updated with revised final key rate considering both WCP and entangled sources for all 3 observatories.

Typographical error in Table 2 and Table 11 where units of atmospheric parameters H_2O and O_3 are given in g/cm^2 instead of g/cm^3 . Typographical error in Eq. 7 for C_n^2 where $(10 \times h)$ was mentioned instead of $(10 \times h)^{10}$. Typographical error in Eq. 8 for r_0 , as the expression needs to be raised to a power $(-\frac{3}{5})$.

One can also compute r_0 using the ‘seeing parameter’. We have used this method to calculate r_0 for different Indian ground station locations as discussed in Sagar et al. [3].

Figure 9 in the article has been revised to include the cloud model “Cirrus” for consistency, as all loss calculations are given with such considerations.

Other typographical errors in Appendix Eq. A.3 as the $\langle r_c^2 \rangle$ term was missing the square root and Eq. A.4 contains Θ_B instead of Φ_B .

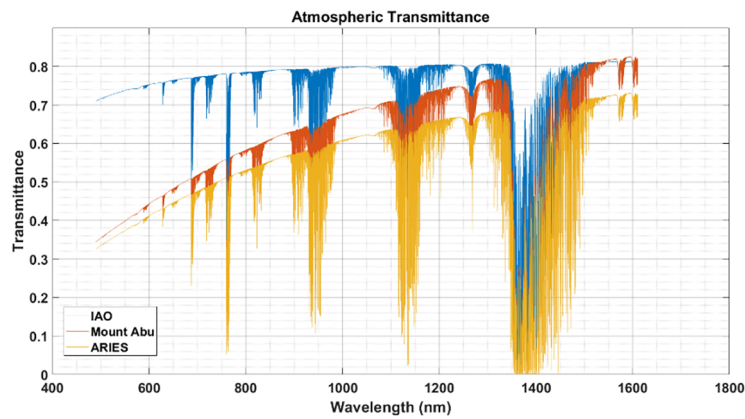


Figure 9 Atmospheric transmittance comparison of three potential observatory locations

Table 12 Total loss due to turbulence added for different initial beam sizes

D in cm	8 cm	12 cm	14 cm	15 cm	16 cm	20 cm	24 cm
Beam wander loss	2.38	0.87	0.52	0.40	0.30	0.08	0.02
Turbulence loss	0.24	0.52	0.69	0.78	0.89	1.32	1.78
Total loss dependent on D	2.62	1.39	1.22	1.18	1.19	1.4	1.80

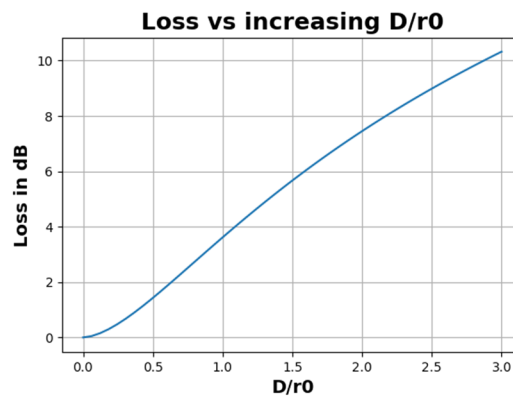


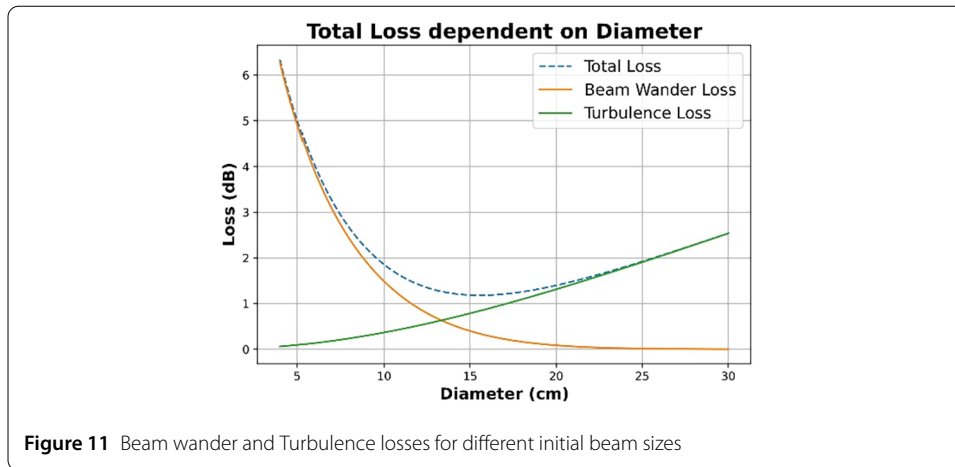
Figure 10 The plot of increasing Strehl ratio loss in dB vs $\frac{D}{r_0}$ value

Further, the angular beam wander was calculated as $\theta_{BW} = \frac{\sqrt{\langle r_c^2 \rangle}}{L}$, using which we calculate the loss due to beam wander in our considered uplink scenario Chen et al. [2]. To calculate attenuation due to turbulence, we use an approximation of the above as given by Sharma et al. [4].

Table 12 is updated with the latest loss values to give us the optimal diameter of the transmitter's aperture during uplink communication, which remains unchanged at ~ 15 cm.

Figures 10 and 11 have been modified. The previous plot depicted Strehl ratio instead of the loss due to Strehl ratio in Fig. 10. The loss dependent on diameter is plotted considering the revised beam wander loss and turbulence loss in Fig. 11.

The final outcomes of the manuscript remain unchanged. The optimal aperture size for the transmitter telescope remains 15 cm in the uplink scenario. The optimal ground



station location among those considered in the Indian territory remains IAO Hanle, with total estimated signal losses of approximately 36 dB, making the observatory the most favorable site.

The original article has been updated.

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