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Vacuum Beam Guide for Quantum Communication

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Vacuum Beam Guide

- Long, cylindrical tube designed to maintain a vacuum inside, typically at a pressure of 1 Pascal.
- Lenses are mounted inside the tube to direct the beam along a specific path.
- The system comprises several small sections of straight pipes connected and mirrors at the joints to guide the beam in the required direction.
- I have majorly worked on finding out the best possible set of parameters (Focal Length of the lens, Lens Separation, and initial beam parameter.) for minimum photon loss along the array.

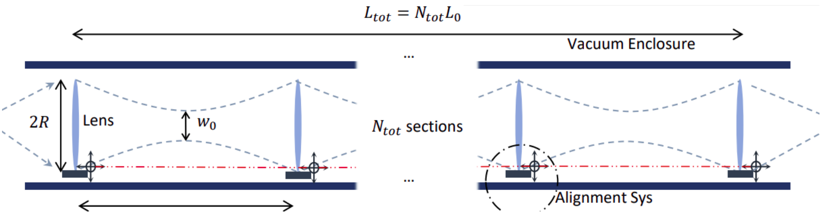


Figure: This is an illustrative picture of VBG, showing the confocal solution for focal length and lens separation. [Huang et al., 2023]

VBG and other Methods of quantum communication

- **VBG:** Photon loss can be as low as 10^{-4}dB/Km due to the vacuum environment, minimizing scattering and absorption. [Huang et al., 2023].
- **Optical Fiber:** Typically experiences a photon loss of about 10^{-1} dB/km, which translates to significant losses over long distances.[Sangouard et al., 2011]
- **Satellite-based Communication:** Photon loss varies based on atmospheric conditions but can be $\sim 10^{-3}$dB/km, provided that each satellite, in the low earth orbit, separated by 120 km, maintains other losses below 2% and employs 60-cm diameter telescopes to eliminate diffraction loss [Goswami and Dhara, 2023].

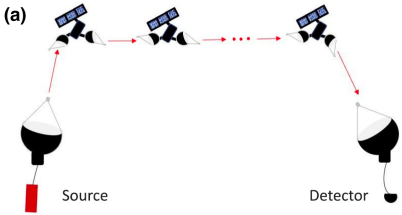


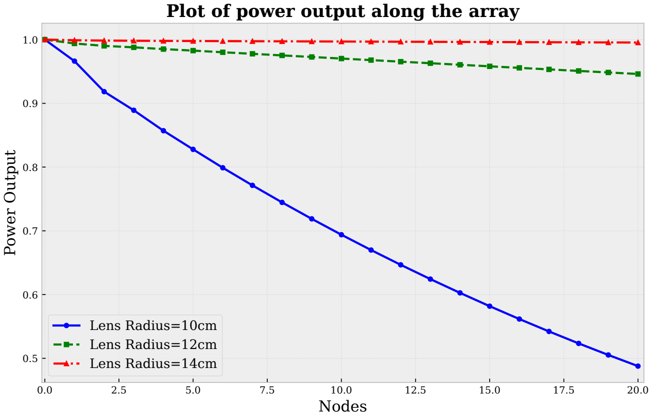
Figure: It is an illustrative picture of the satellite network discussed above. [Goswami and Dhara, 2023].

Importance of Facilitating Quantum Communication Over Extensive Distances

- **Quantum Key Distribution (QKD):** Enables the secure exchange of encryption keys over large distances, crucial for protecting sensitive data in finance, government, and military applications.
- **Long-Distance Entanglement:** Facilitates the distribution of entangled particles over thousands of kilometers, which is essential for advanced quantum technologies and experiments.
- **Quantum Networks:** Lays the foundation for a global quantum internet, enabling instant and secure communication across continents, enhancing collaboration and information exchange.
- **Enhanced Telescope Baselines:** Extends the baseline of telescopes using VBG, improving the resolution and sensitivity of astronomical observations.

Lens Radius

In the initial literature [Huang et al., 2023], possible considerations were made for lens sizes of 10 cm, 12 cm, and 14 cm. Based on the reassessment of these options, by trying out the confocal solution, we chose 12 cm for our primary investigation.



Optimization to Get the Best Parameters

I utilized two methods during this internship to determine the optimal parameters for minimizing photon loss in the array. We employed the SciPy library for differential evolution optimization, and for MCMC, we used the emcee library. It should also be noted that, for my investigation, I assumed that there is no tilt in the lenses and that the lenses are perfectly aligned, with no translational errors in their positions.

- **Differential Evolution:** is an optimization algorithm that evolves a population of candidate solutions by using mutation, crossover, and selection to minimize objective functions. [Storn and Price, 1995]
- **Markov chain Monte Carlo:** sampling method that generates samples from a probability distribution using a Markov chain to approximate complex distributions or perform Bayesian inference. [Gilks et al., 1995, Brooks et al., 2011]

Differential Evolution Algorithm

- **Initialization:** Generate initial population within parameter bounds.
- **Mutation:** Create mutant vectors using DE/rand/1 strategy.
- **Crossover:** Combine mutant vectors with target vectors to form trial vectors.
- **Selection:** Determine which vectors advance to the next generation based on fitness.
- **Termination:** Repeat until stopping criteria are met.

$$\mathbf{v}_{i,G} = \mathbf{x}_{r1,G} + F \cdot (\mathbf{x}_{r2,G} - \mathbf{x}_{r3,G}) \tag{1}$$

Results with Differential Evolution

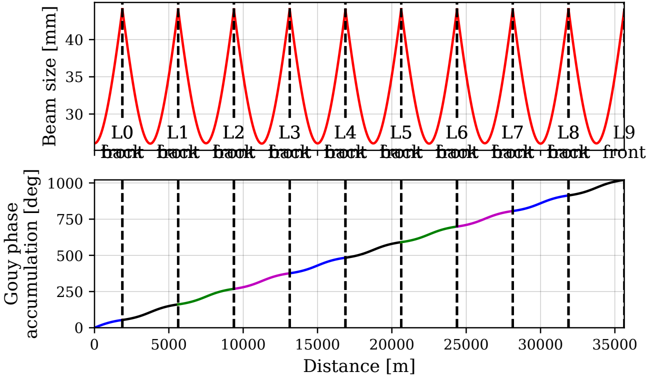
The DE algorithm yielded optimized parameters for lens radii of 12 cm and 14 cm. The results indicate a lower loss for the 14 cm aperture radius.

Run # (Lens radii)	L_Lens (m)	Loss (ppm)	L focal (m)	w0 (mm)	z0 (m)	Pop size	Iters (max)	Pass
Run 1 (12cm)	2061.44	2524	2432.5	33.7	-141.0	4	4.0	N/A
Run 2 (12cm)	3320.24	1465	2291.0	33.1	515.1	4	4.0	Fail
Run 3 (12cm)	3054.50	1302	1313.4	25.5	248.1	2	2.0	Fail
...	...	...	...	...	...	...	...	...
Run 10 (12cm)	3706.92	1087	1421.0	25.8	5.8	16	60.0	Fail
Run 11a (12cm)	3750.64	1086	1441.9	26.1	2.5	16	60.0	Pass
Run 11b (12cm)	4012.25	1628	1337.9	23.9	-6.3	16	80.0	Pass
Run 12 (12cm)	3753.38	1087	1447.4	26.1	-12.0	16	60.0	Fail
Run 13 (12cm)	4698.40	887	1819.6	29.3	9.0	16	60.0	Pass
Run 1 (14cm)	5002.80	796	1914.6	30.0	-12.3	16	60.0	Pass

Table: Optimization results for lens array parameters. The "Run" column indicates the iterations and lens radius for each attempt. The "Pass" column shows the success flag from SciPy's differential evolution, indicating convergence to an optimal or near-optimal solution. It should be noted that Run 11b represents a solution where we used maxtem=10. and for others, it is maxtem =2

Beam Size and Gouy Phase

For visualization of the beam along the array, I produced the plot of beam size and the gouy phase along the array. This is plotted for the for optimized parameters (Run 11a) with a 12 cm radius aperture lens.



Markov-Chain Monte Carlo (MCMC) Method

The MCMC method samples from probability distributions using a Markov chain.

- **Initialization:** Start with an initial guess for the parameter values.
- **Proposal:** Generate new candidate values based on the current state using a proposal distribution.
- **Acceptance:** Decide whether to accept or reject the candidate values based on the acceptance probability.
- **Iteration:** Repeat the proposal and acceptance steps to build a chain of samples.
- **Burn-in and Convergence:** Discard initial samples to remove dependence on the starting point and check for convergence to the target distribution.

MCMC Results

Corner plots created from MCMC for a lens radius of 12 cm show variations in photon loss across different parameter configurations.

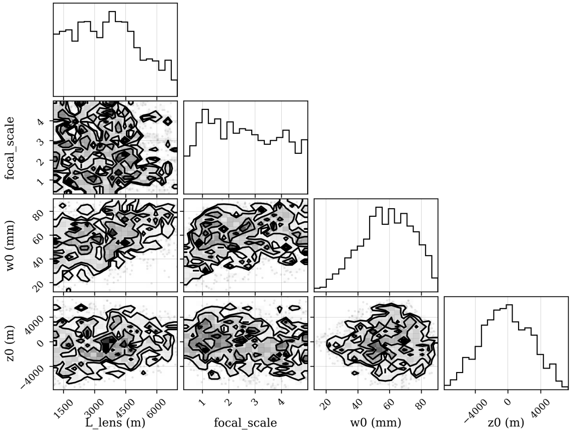
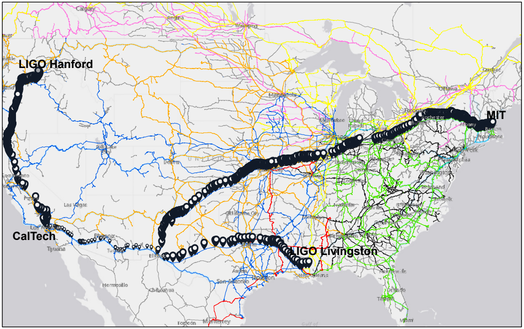


Figure: Corner plots for key parameters: focal length, lens separation, w_0, and z_0.

Potential route of VBG 1.0

- Potential geophysical path for the Vacuum Beam Guide (VBG) connecting: LIGO Hanford, Caltech, LIGO Livingston, and MIT.
- Route primarily follows the Union Pacific Railroad, accommodating Earth's curvature:
  - Maximum horizontal curvature: $7^\circ 30'$ and Minimum turn radius: 764.49 ft [Railroad, nd]
- Segment from Kansas City to Buffalo, connecting to MIT, follows the Norfolk Southern Railway:
  - Maximum horizontal curvature: 10° and Minimum turn radius: 573.69 ft. [Southern, 2023]
- Each point on the map represents potential turning points along the VBG route.

Potential route of Vaccum Beam Guide 1.0



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1:24,041,913

0 160 320 640 mi

0 250 500 1,000 km

Conclusion

- **Optimization Methods:** Differential Evolution needs to be explored for higher values of maxtem, i.e. 10. MCMC (Markov Chain Monte Carlo) provides a more thorough exploration of the parameter space, leading to better visualization of the parameter space.
- **Geophysical Analysis:** Straight VBG construction over long distances is impractical due to Earth's curvature and geographical obstacles. The proposed route utilizes existing infrastructure (Union Pacific Railroad, Norfolk Southern Railway) to accommodate necessary turns and tilts. The route from Kansas City to Buffalo and beyond aligns with practical railway standards.
- **Future Work:** Focus on doing more robust optimization and increasing the complexity and realism in the system. Validate proposed designs through experimental testing and additional simulations.

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References I

Brooks, S., Gelman, A., Jones, G., and Meng, X.-L. (2011).
Handbook of Markov Chain Monte Carlo.
CRC Press.

Gilks, W. R., Richardson, S., and Spiegelhalter, D. (1995).
Markov Chain Monte Carlo in Practice.
CRC Press.

Goswami, S. and Dhara, S. (2023).
Satellite-relayed global quantum communication without quantum memory.
Physical Review Applied, 20(2):024048.

Huang, Y., Adhikari, R. X., Safavi-Naeini, A. H., Jiang, L., et al. (2023).
Vacuum beam guide for large-scale quantum networks.
arXiv preprint arXiv:2312.09372.

Railroad, U. P. (n.d.).
Track construction standards.
https://www.up.com/cs/groups/public/@uprr/@customers/@industrialdevelopment/@operationsspecs/@specifications/documents/up_pdf_nativedocs/pdf_up_ind_ind-trk-const.pdf.

Sangouard, N., Simon, C., Riedmatten, H. D., and Gisin, N. (2011).
Quantum repeaters based on atomic ensembles and linear optics.
Reviews of Modern Physics, 83(1):33.

References II

Southern, N. (2023).
Standards for industry tracks.
https://www.norfolksouthern.com/content/dam/nscorp/pdf/industrial-rail-development/NS-Standards-for-Industry-Tracks-9.28.23.pdf.

Storn, R. and Price, K. (1995).
Differential evolution–a simple and efficient adaptive scheme for global optimization over continuous spaces.
International Computer Science Institute.

Thank You!

Any Questions?