Constellation Optical Link

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ABSTRACT

A constellation optical link enables high-bandwidth, low-latency communication between multiple small satellites in low Earth orbit. This project models and prototypes an optical inter-satellite link using Gaussian beam propagation while accounting for alignment jitter, thermal effects, and free-space attenuation. Analytical models are validated through MATLAB simulations to assess link margin, beam divergence, and telescope performance. The goal is to develop a reliable, power-efficient optical communication architecture for scalable satellite constellations.

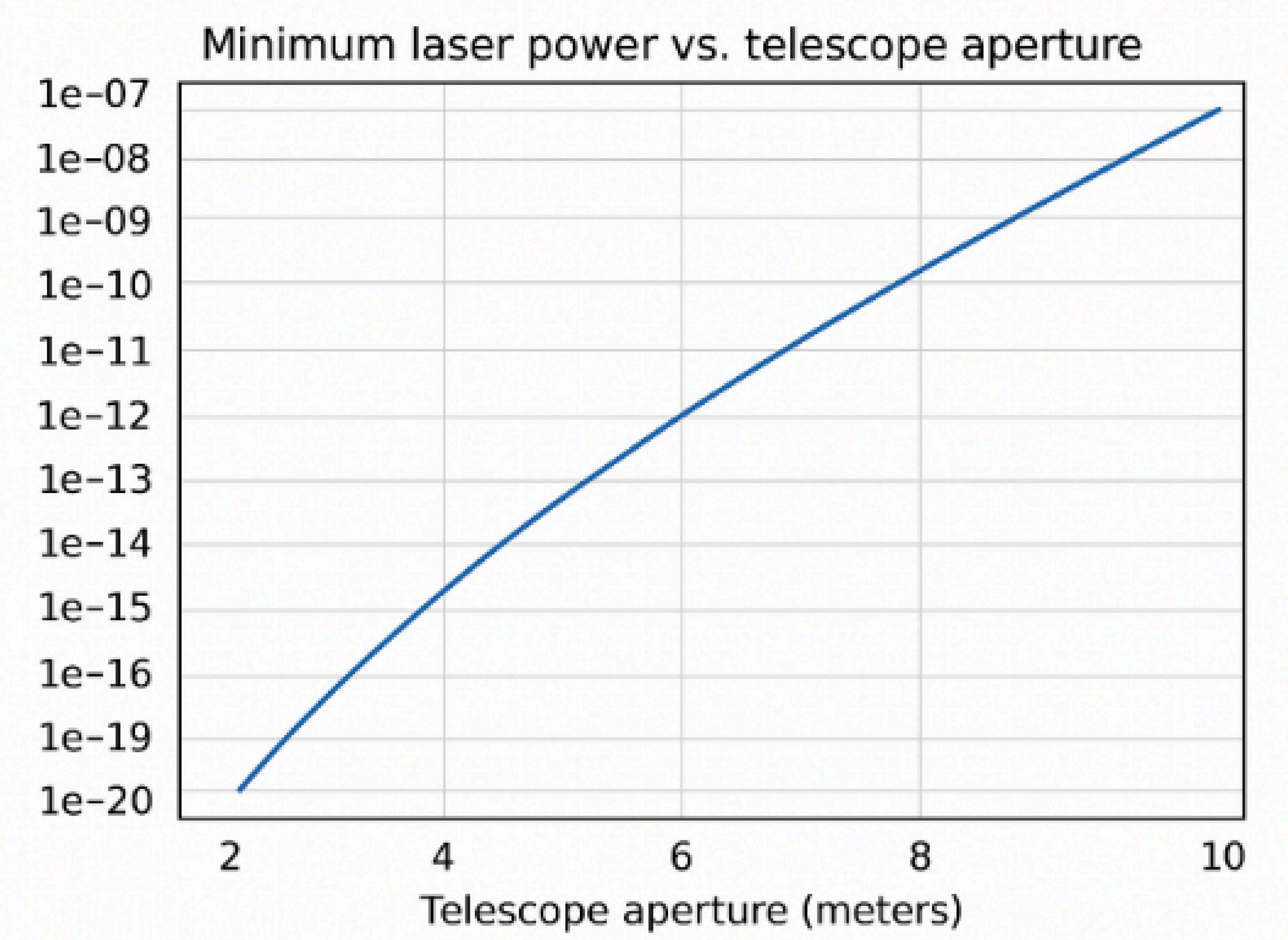
OBJECTIVE

- Develop an analytical model for inter-satellite optical links incorporating Gaussian beam propagation, thermal effects, and alignment jitter.
- Simulate link performance in MATLAB to evaluate beam divergence, spot size, received power, and link margin across varying orbital separations.
- Optimize telescope parameters and pointing accuracy while assessing the feasibility of modular optical terminals for scalable multi-satellite constellations.
- Propose a preliminary hardware concept for future CubeSat optical communication terminals.

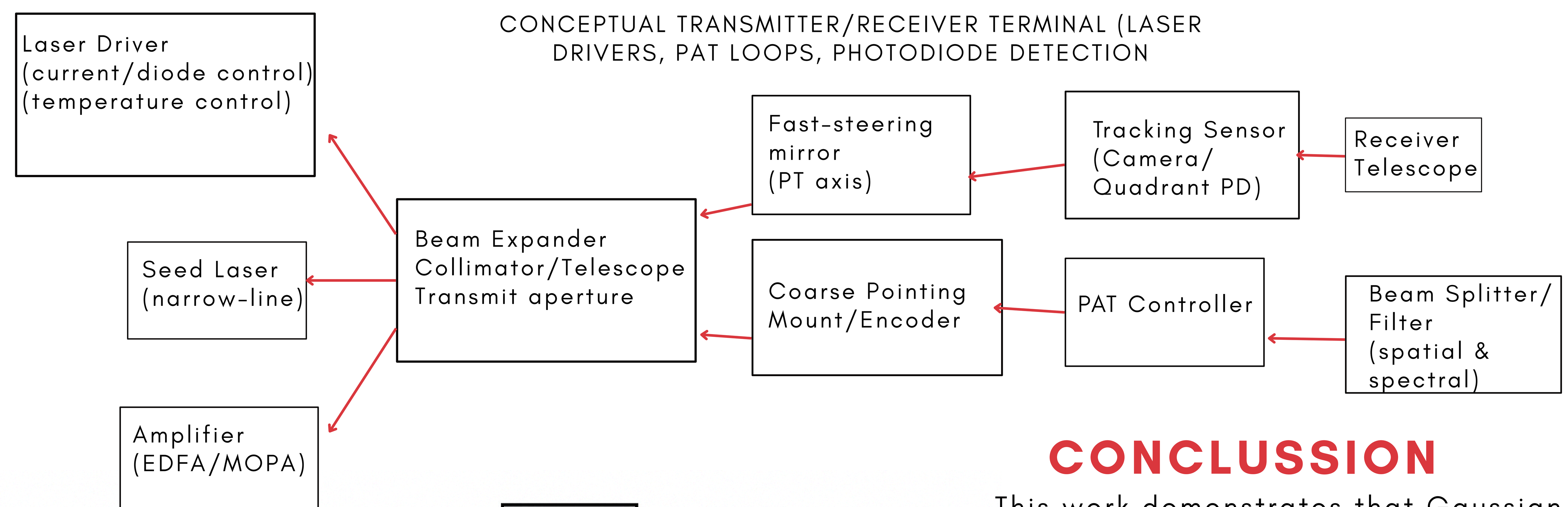
METHODOLOGY

- Modeled Gaussian beam propagation and diffraction to determine spot size, received power, and aperture-dependent link efficiency.
- Applied shot-noise-limited sensing theory to estimate minimum transmit laser power needed for 1 pm–1 nm precision.
- Analyzed pointing jitter and terminal optics (laser, amplifier, beam expander, telescopes) to evaluate realistic performance impacts.
- Combined link budget and noise modeling to generate power-vs-aperture results for CubeSat-scale optical communication links.

BLOCK DIAGRAM & RESULTS

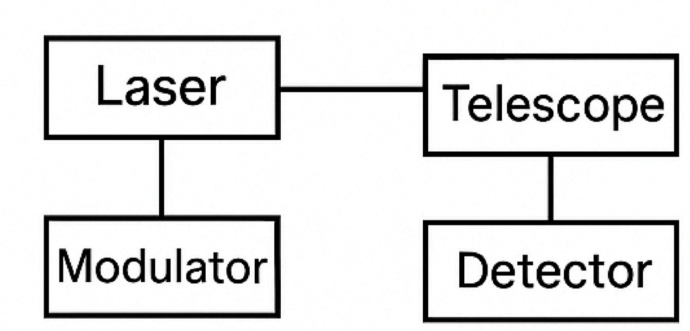


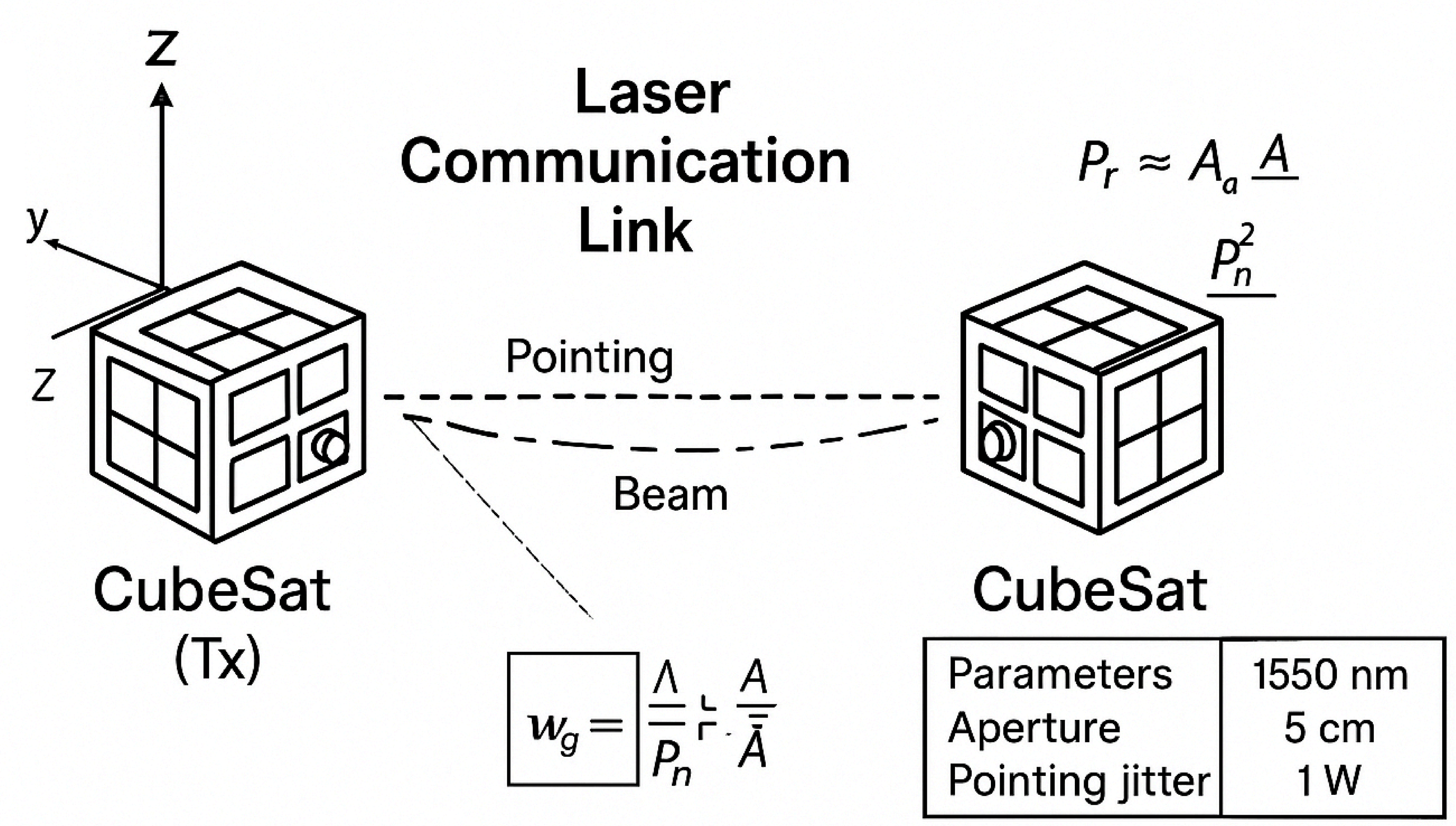
- Shot-noise-limited power estimates for 1 pm–1 nm precision.
- Calculated for a 1550 nm, 1000 km diffraction-limited link.
- Required transmit power decreases rapidly with larger apertures.
- Values shown are optimistic lower bounds (ideal efficiency, no pointing loss).
- Real systems will require higher power due to jitter, coupling loss, and detector noise.
- Larger apertures reduce diffraction loss, decreasing the power required for shot-noise-limited sensing.



Estimated Minimum Laser Power Required for 1 pm–1 nm Precision

Aperture D	P_t for 1 pm	P_t for 10 pm	P_t for 100 pm	P_t for 1 nm
0.05 m (5 cm)	**2.79×10^{-4} W ≈ 0.28 mW**	2.79×10^{-6} W ≈ 2.8 μW	2.79×10^{-8} W ≈ 28 nW	2.79×10^{-10} W ≈ 0.28 nW
0.10 m (10 cm)	**1.74×10^{-5} W ≈ 17 μW**	1.74×10^{-7} W ≈ 0.17 μW	1.74×10^{-9} W ≈ 1.7 nW	1.74×10^{-11} W ≈ 0.017 nW
0.30 m (30 cm)	**2.15×10^{-7} W ≈ 0.22 μW**	2.15×10^{-9} W ≈ 2.2 nW	2.15×10^{-11} W ≈ 21 pW	2.15×10^{-13} W ≈ 0.21 pW
1.00 m (1 m)	**1.74×10^{-9} W ≈ 1.7 nW**	1.74×10^{-11} W ≈ 17 pW	1.74×10^{-13} W ≈ 0.17 pW	1.74×10^{-15} W ≈ 0.0017 pW





CONCLUSION

This work demonstrates that Gaussian beam modeling, sensitivity analysis, and conceptual terminal architecture can effectively characterize the performance of inter-satellite optical links across LEO separations. The results show that diffraction, pointing stability, and thermal effects remain dominant factors in received-power margin and system reliability.

Future Prospects: Continued development will focus on expanded 2-D/3-D propagation simulations, more detailed modeling of thermal-lens dynamics and jitter spectra, and early hardware-in-the-loop validation of transmitter/receiver modules and PAT control loops. These advancements will support the long-term goal of deploying scalable, power-efficient optical terminals for next-generation satellite constellations.

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