

# Earth–Moon Optical Link via Three-Satellite Constellation

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## INTRODUCTION

Wireless optical (FSO) communication offers significant advantages over RF systems including greater bandwidth, higher data rates, lower power consumption and more compact terminals. Despite atmospheric propagation challenges on Earth, it remains a promising solution for future space missions, particularly for Earth–Moon links in support of NASA's ARTEMIS program, where the absence of an atmosphere makes FSO especially effective [1,2].

The design and performance assessment of a satellite constellation for continuous bi-directional optical communication between Earth and the Moon is presented (Figure 1). The analysis considers two operating wavelengths: 1064 nm and 1550 nm.

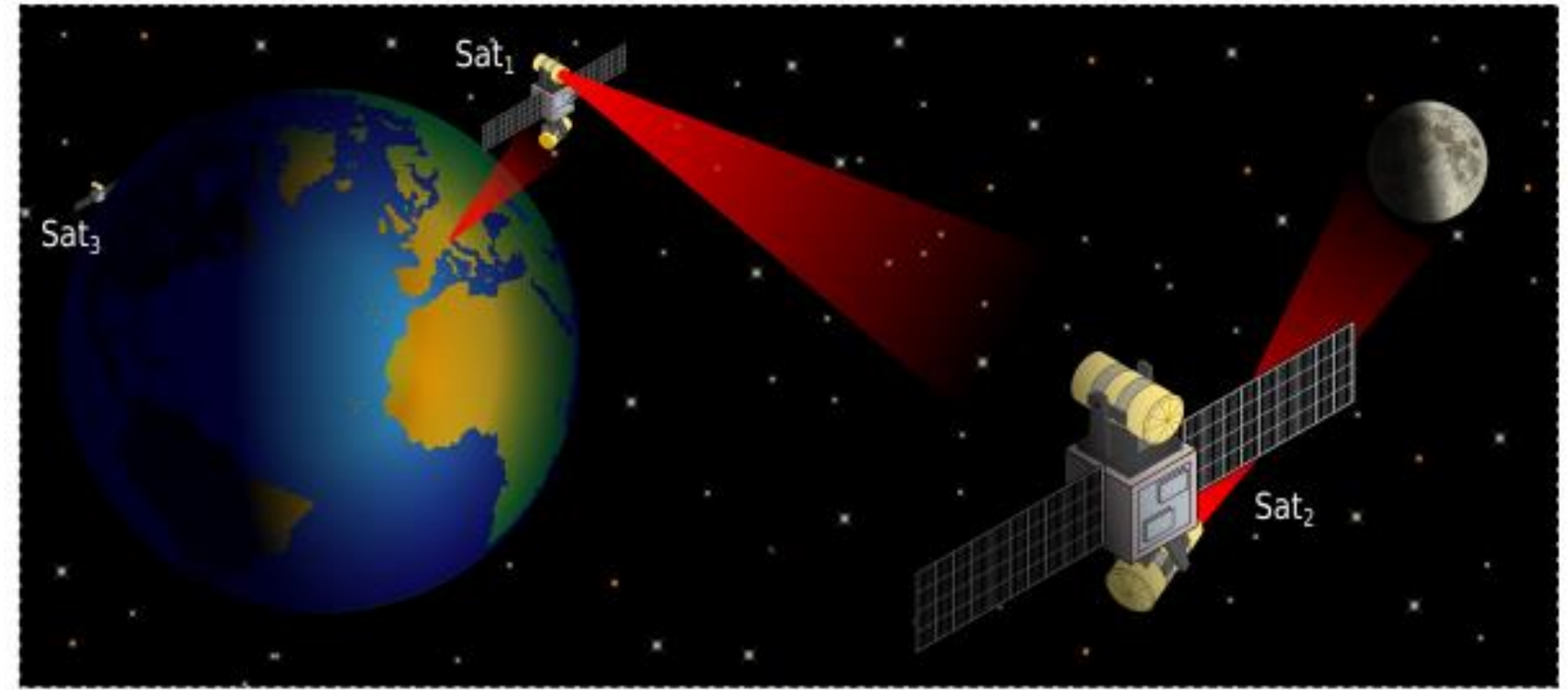


Figure 1: Architecture of the constellation network.

## SATELLITE CONFIGURATION

The constellation must ensure continuous coverage of both an Earth station and the lunar receiver (Figure 2), minimizing communication gaps. Among the equatorial orbits analyzed, GEO emerges as the optimal solution, requiring a single satellite to maintain continuous Earth coverage and two additional satellites to ensure uninterrupted lunar coverage while minimizing beam handovers. Two architectures were investigated: Configuration A (Conf A) uses the first satellite (Sat<sub>1</sub>) as a master to redirect the beam toward one of the other two satellites acting as relays (Sat<sub>2</sub> and Sat<sub>3</sub>). Configuration B (Conf B) instead employs all satellites to redirect the beam toward the Moon. For both configurations, satellite locations were determined by identifying the arrangement that minimizes link interruption and free-space losses between the satellites and the lunar receiver. The optimal satellite longitudinal spacing was found to be  $[-90^\circ, 0^\circ, 90^\circ]$  for Conf A and  $[-120^\circ, 0^\circ, 120^\circ]$  for Conf B (Figure 3).

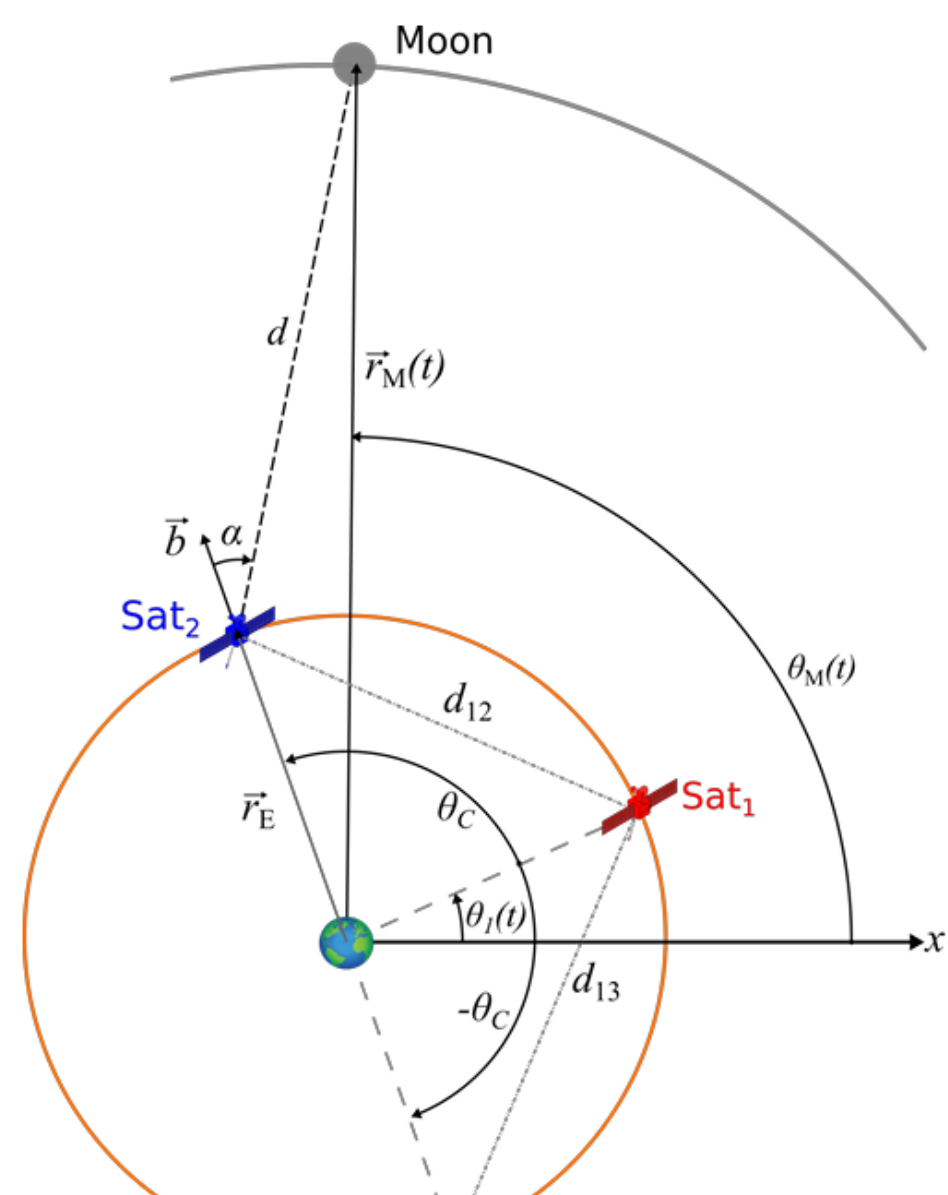


Figure 2: 2D orbital model.

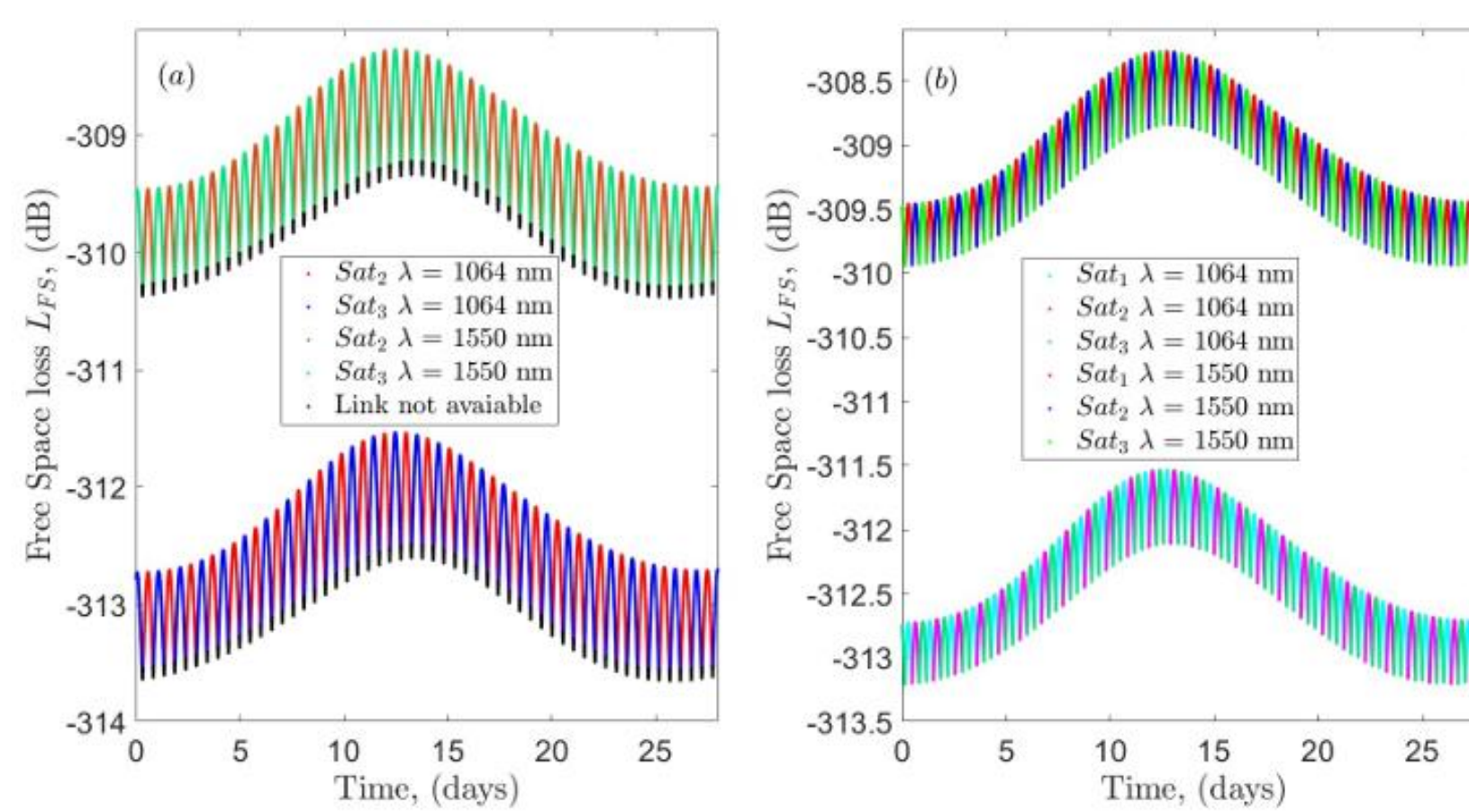


Figure 3: Free space attenuation over a lunar orbital period. (a) refers to Conf A, while (b) refers to Conf B.

## LINK DESIGN

The system performance was evaluated in terms of link margin (LM) and bit error rate (BER) for each segment, in both uplink and downlink, including atmospheric turbulence effects [3,4,5]. The reported BER values are computed without the use of error correction coding. To maximize system efficiency, the transmitter diameter was optimized by considering its gain and the associated losses for each segment (Figure 4). Furthermore, each satellite is equipped with two additional onboard lasers used to forward information to the subsequent target, employing the same optical terminals for both transmission and reception (Figure 5). The LM and BER results obtained indicate the feasibility of the proposed system (Table 1-2).

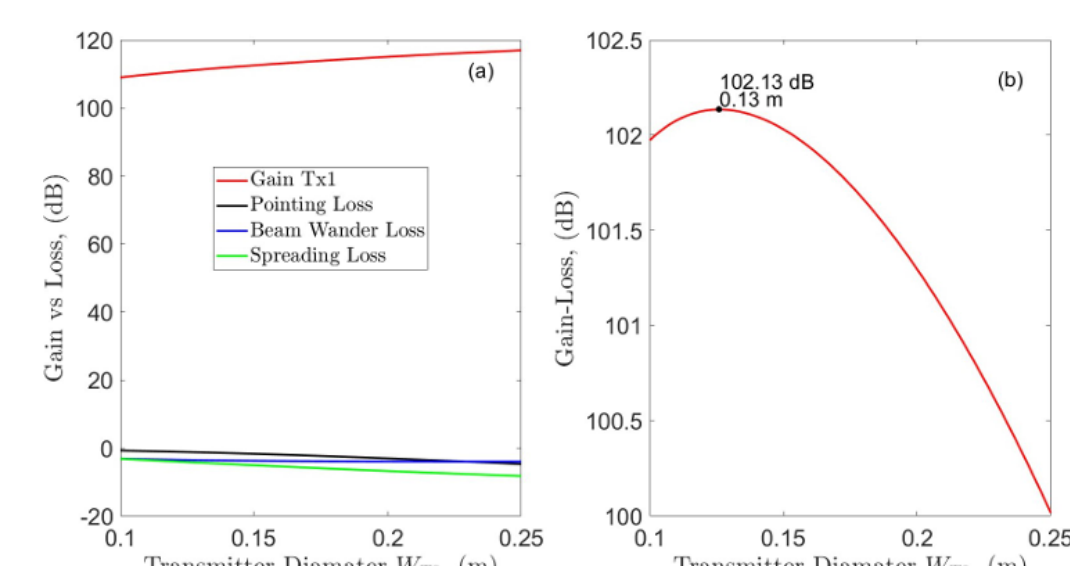


Figure 4: Transmitter diameter (Tx1) optimization for the first segment of the uplink scenario.

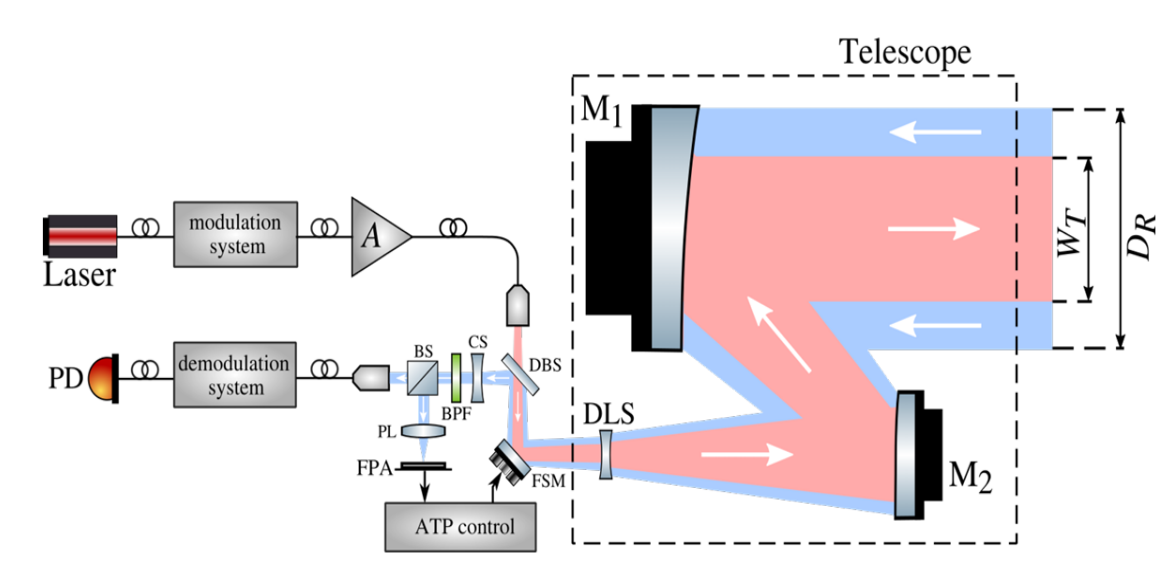


Figure 5: Conceptual optical scheme of a Transmitting and Receiving Unit.

Configuration	Case	Segment	Margin (dB)	
			$\lambda = 1064 \text{ nm}$	$\lambda = 1550 \text{ nm}$
A	Uplink	GS-Sat <sub>1</sub>	6.61	12.12
		Sat <sub>1</sub> -Sat <sub>2,3</sub>	12.06	14.89
	Downlink	Sat <sub>2,3</sub> -Moon	5.97	8.80
		Moon-Sat <sub>2,3</sub>	2.51	5.32
		Sat <sub>1</sub> -GS	12.06	14.89

Table 1: Link margin for both wavelength and for both uplink and downlink.

Configuration	Case	Segment	BER	
			$\lambda = 1064 \text{ nm}$	$\lambda = 1550 \text{ nm}$
A	Uplink	GS-Sat <sub>1</sub>	1e-3	5e-3
		Sat <sub>1</sub> -Sat <sub>2,3</sub>	4e-4	1e-3
	Downlink	Sat <sub>2,3</sub> -Moon	1e-3	2e-3
		Moon-Sat <sub>2,3</sub>	1e-2	2e-3
		Sat <sub>1</sub> -GS	4e-4	1e-3

Table 2: BER for both wavelength and for both uplink and downlink.

## CONCLUSIONS

A three-satellite equatorial GEO constellation enables continuous bi-directional optical communication between Earth and Moon while minimizing system complexity. margin and uncoded BER analyses confirm system feasibility for all segments, with 1550 nm providing superior performance over 1064 nm. The proposed architecture offers a robust and cost-effective alternative to more complex relay systems while maintaining high link availability.

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