Optical Link Simulator Dashboard

User Manual

February 24, 2026

1 Purpose of the Optical Link Simulator Dashboard

The purpose of this dashboard is to simulate and analyze the performance of optical links across current optical data relay constellations. It provides an intuitive interface to configure ground stations and satellite networks, calculate routing paths, and evaluate complex performance parameters for optical communications.

1.1 Engineering Relevance

These parameters allow engineers to:

- Compare constellation relay performance.
- Trade aperture size vs transmit power.
- Evaluate divergence sensitivity.
- Assess network latency.
- Estimate required pointing precision.

2 Simplifications and Assumptions

To ensure the simulation runs efficiently while providing highly accurate estimates, the following assumptions are made:

1. **Uniform Optical Routing:** Optical signals are used for the entire communication link. This includes both the Direct-to-Earth (DTE) links (ground stations to satellites) and Inter-Satellite Links (ISL).
2. **Instantaneous Positional Snapshots:** The simulation evaluates all satellite positions at the exact initial link time. It does not account for the slight orbital movement of the satellites during the fractional seconds it takes for light to propagate to the target.
3. **Standardized ATP Times:** Acquisition, Tracking, and Pointing (ATP) times are considered as one consistent, user-defined value added to every single hop. In reality, this time can fluctuate depending on whether the satellite is targeting an in-plane neighbor or a cross-plane target.

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Prerequisites

- You must have **MATLAB 2025** (or newer) and the **Satellite Communication Toolbox** installed.
- You need an active **Space-Track.org** account to pull live satellite data. You must input your login credentials directly into lines 17 and 18 of the `FXN_download_tles_request.m` script before running the application.

Standard Setup Steps

1. **Select Satellite Groups:** Choose one or multiple satellite constellations from the list box to include in your simulation. *Warning: Selecting a larger number of satellites will significantly increase the computation time.*
2. **Define Locations:** Select your start and end cities from the dropdown menus. Alternatively, you can input custom coordinates in the standard format: `[latitude, longitude, altitude]`.

3. **Set the Initial Link Time:** Choose the starting time for the simulation. It is set to 'NOW' (UTC) by default, but you can uncheck this to input a custom historical or future date.

4. **Define Distance and Elevation Constraints:** Set the maximum allowable link distance (in kilometers) for both ground station connections and inter-satellite links. You must also define the minimum elevation angle (in degrees) above the horizon required for ground station links to establish a connection.

5. **Set ATP Time:** Define the Acquisition, Tracking, and Pointing time in milliseconds. This delay will be applied to every hop in the sequence.

Optional Advanced Settings

6. **Configure Advanced Parameters:** Click "Advanced settings..." to open a secondary configuration menu where you can define:

   - *Simulation Settings:* Sample time intervals, maximum routing attempts, and the 2D map's visual basemap.
   - *Technological Specifications:* Core optical hardware parameters, including Wavelength (nm), Data rate (Gbps), Transmit Power (W), Aperture Diameters (mm), Divergence Angles (μrad), Pointing Errors (μrad), Bits per symbol, and Packet bits.
   - *Atmospheric Model:* The atmospheric attenuation coefficient and the tropospheric height for signal degradation modeling.

7. **Save Configuration:** Click "Save" to apply your advanced settings and return to the main dashboard.

8. **Execute:** Click "Run simulation" to begin the calculation. The results will populate in the log, readouts, and visual globes once complete.

4 Window Description

- **Top-Left: Inputs**
  - The user can set link definitions and technological specifications.
  - A Status Log window returns simulation status updates, errors, and progress reports in real-time.

- **Bottom-Left: Data & Link Parameters**
  - **Left (TLE file used window)**: Prints out all Two-Line Element (TLE) text data loaded into the simulation for the chosen satellites.
  - **Middle (Link Summary)**: Displays overall performance values for the complete end-to-end link calculated after the simulation finishes.
  - **Right (Hop Sequence Data)**: Prints out a detailed table of the performance analysis values calculated for each individual hop in the routing path.

- **Top-Right: 2D World Map**
  - Shows the satellite nodes used and the optical link connections made, mapped onto a flat Mercator projection.

- **Bottom-Right: 3D Globe**
  - Displays a spherical globe with the used ground stations, satellite nodes, and physical links rendered in three dimensions.

5 Physics Explanation

The dashboard calculates the viability and performance of each hop using a series of optical physics and link budget equations. Here is a breakdown of how the performance parameters in the output table are derived:

5.1 Optical Frequency and Wavelength

The fundamental optical frequency (ν) is calculated from the speed of light (c) and the user-defined wavelength (λ):

$$\nu = \frac{c}{\lambda} \tag{1}$$

5.2 Transmitter and Receiver Gains

$$G_t = \left(\frac{\pi D_t}{\lambda}\right)^2 \tag{2}$$

$$G_r = \left(\frac{\pi D_r}{\lambda}\right)^2 \tag{3}$$

5.3 Free-Space Path Loss (FSPL) and Atmospheric Loss

This represents the natural loss of signal strength as the optical beam spreads out through empty space over a given range (R). It is calculated in decibels (dB):

$$FSPL_{dB} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) \tag{4}$$

$$L_{atm} = e^{-\alpha L} \tag{5}$$

5.4 Beam Divergence and Aperture

The physical spread of the laser beam radius (w) at the receiver is dictated by the transmitter's divergence angle (θ_{div}) and the range:

$$w(R) = \theta_{div} R \tag{6}$$

The receiver's aperture area (A_{rx}) dictates how much of this spread beam can be captured, based on the receiver diameter (D_{rx}):

$$A_{rx} = \pi\left(\frac{D_{rx}}{2}\right)^2 \tag{7}$$

5.5 Geometric Coupling and Pointing Loss

Geometric coupling efficiency (η_{geo}) estimates how much of the beam actually hits the receiver aperture, capped at 100% (1.0):

$$\eta_{geo} = \min\left(1, \frac{A_{rx}}{\pi w^2}\right) \tag{8}$$

Pointing loss (L_{point}) accounts for transmitter jitter and targeting errors (θ_{err}), modeled as a Gaussian loss profile:

$$L_{point} = \exp\left(-\left(\frac{\theta_{err}}{\theta_{div}}\right)^2\right) \tag{9}$$

5.6 Received Power (P_r)

This is the core link budget equation. It calculates the raw optical power hitting the receiver in Watts, factoring in the transmit power (P_t), hardware efficiencies (η_{tx}, η_{rx}), pointing losses, geometric coupling, and any atmospheric attenuation (L_{atm}) for ground-to-space links:

$$P_r = P_t \cdot \eta_{tx} \cdot \eta_{rx} \cdot \eta_{geo} \cdot L_{point} \cdot 10^{-L_{atm}/10} \tag{10}$$

5.7 Photon Rate and SNR Proxy

To evaluate the signal quality, the received power is converted into a photon count. First, the energy of a single photon (E_{ph}) is found using Planck's constant (h):

$$E_{ph} = h\nu \tag{11}$$

The received photon rate (R_{ph}) in photons per second is:

$$R_{ph} = \frac{P_r}{E_{ph}} \tag{12}$$

The dashboard calculates a "Photons per bit" metric ($N_{ph/bit}$) as a proxy for the Signal-to-Noise Ratio (SNR), dividing the photon rate by the data rate (R_b). The $SNR_{ph,dB}$ is then represented in decibels:

$$SNR_{ph,dB} = 10\log_{10}(N_{ph/bit}) \tag{13}$$

5.8 Doppler Shift

For fast-moving satellites, the relative radial velocity (v_{rad}) causes a shift in the perceived optical frequency (f_d), calculated as:

$$f_d = \left(\frac{v_{rad}}{c}\right) f_0 \tag{14}$$

5.9 Timing and Latency

The total time for a single hop (t_{hop}) is the sum of three factors: the physical light propagation time (t_{prop}), the hardware transmission time for the packet (t_{tx}), and the mechanical/software pointing time (t_{point}):

$$t_{hop} = \left(\frac{R}{c}\right) + \left(\frac{\text{Packet Bits}}{R_b}\right) + t_{point} \tag{15}$$

5.10 Bit Error Rate

For OOK:

$$BER = Q\left(\sqrt{2 \cdot SNR}\right) \tag{16}$$

6 Interpretation of Results

Each hop includes:

- Link type (DTE / ISL)
- Distance (km)
- Elevation angle (deg)
- Received power (dBm)
- SNR (dB)

- Photon rate
- BER
- Propagation delay
- ATP delay
- Total latency

Total system latency:

$$t_{total} = \sum t_{hop} \tag{17}$$