Cellular on the Moon: Lunar Rover Communications

Studying when and how different lunar communication links can be used

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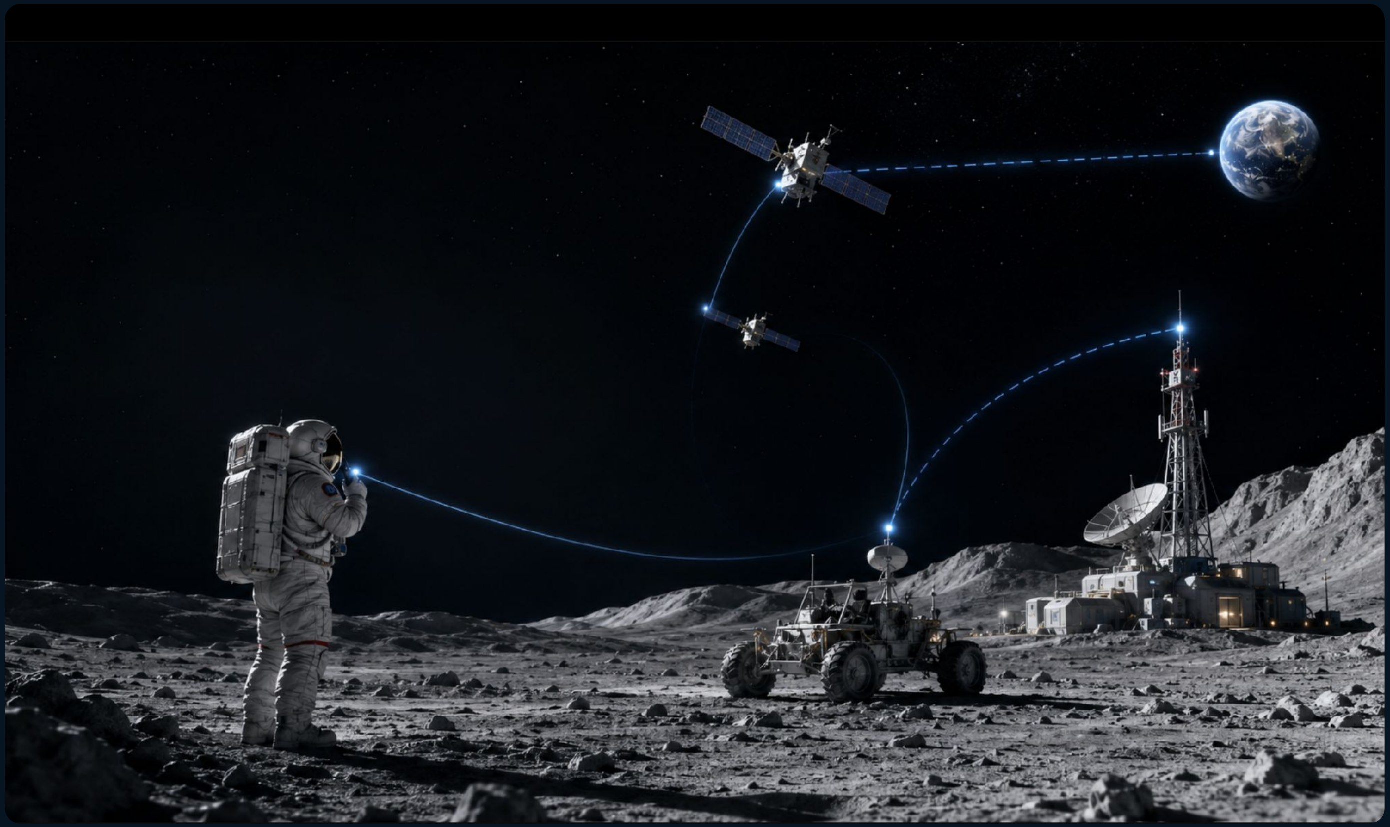
The Moon Creates a Communication Problem



terrain, motion, visibility, and distance all change the link

Why it is difficult

- Craters block radio signals.
- Earth is not always visible.
- Satellites move in and out of view.
- Distance weakens the signal.
- Working links can fail later.

Know which options are available before selecting a link.

Surface Base Station Link

Nearby surface connection

How it works

- The rover talks to a base station on the lunar surface.

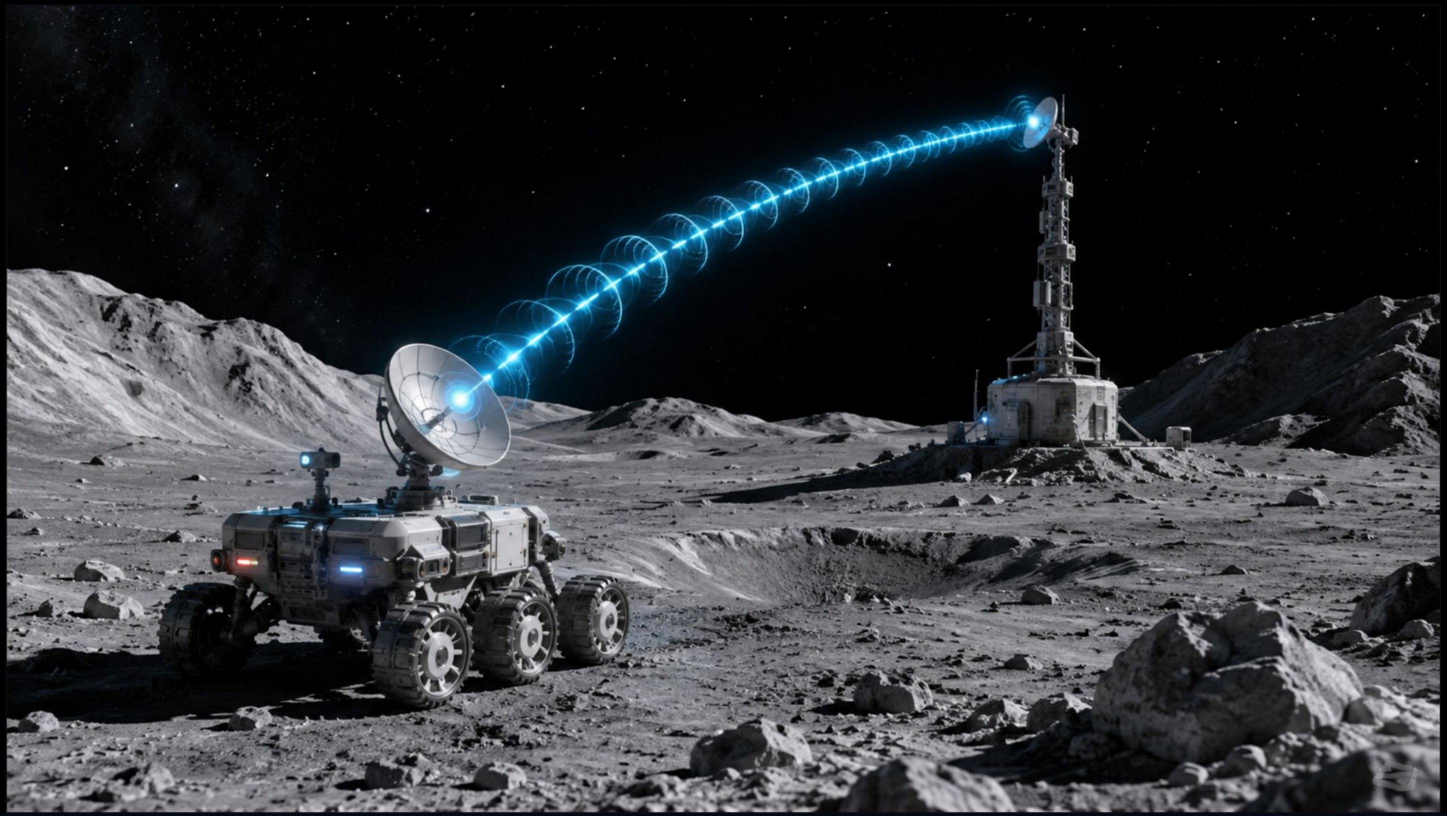
Main advantage

- Strong local link when the rover is nearby.

Available when

- The rover is inside coverage and terrain does not block the path.

Best for local coverage near lunar infrastructure.



The base station is useful nearby, but terrain and range limit it.

Lunar Orbiter Link`

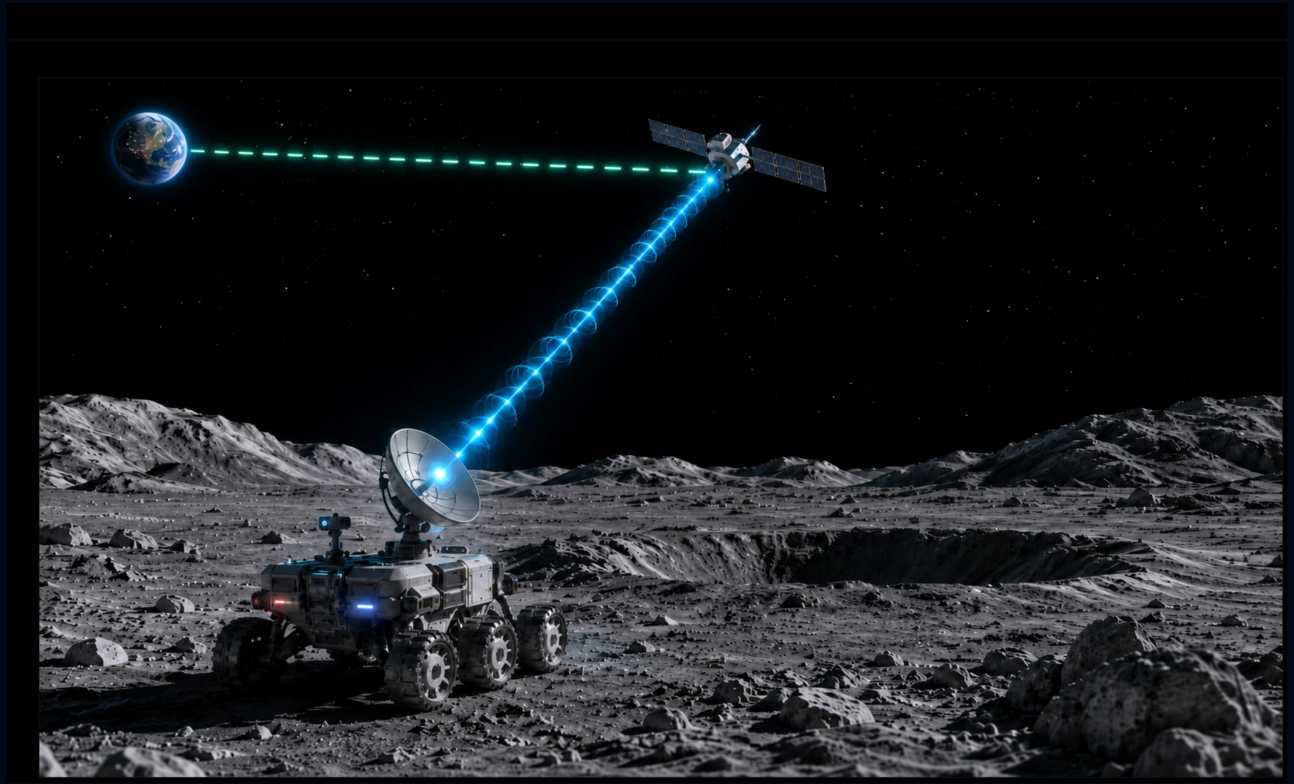
Overhead orbital contact

How it works
- The rover connects while a lunar orbiter passes overhead.

Main limitation
- The link appears only during short visibility windows.

Available when
- The orbiter is above the rover's minimum elevation angle.

Available during overhead passes, not continuously.



The orbiter can help beyond local coverage, but only during passes.

Relay Satellite Link

Forward through a relay

How it works

- The rover sends data to a relay satellite, which forwards it to Earth.

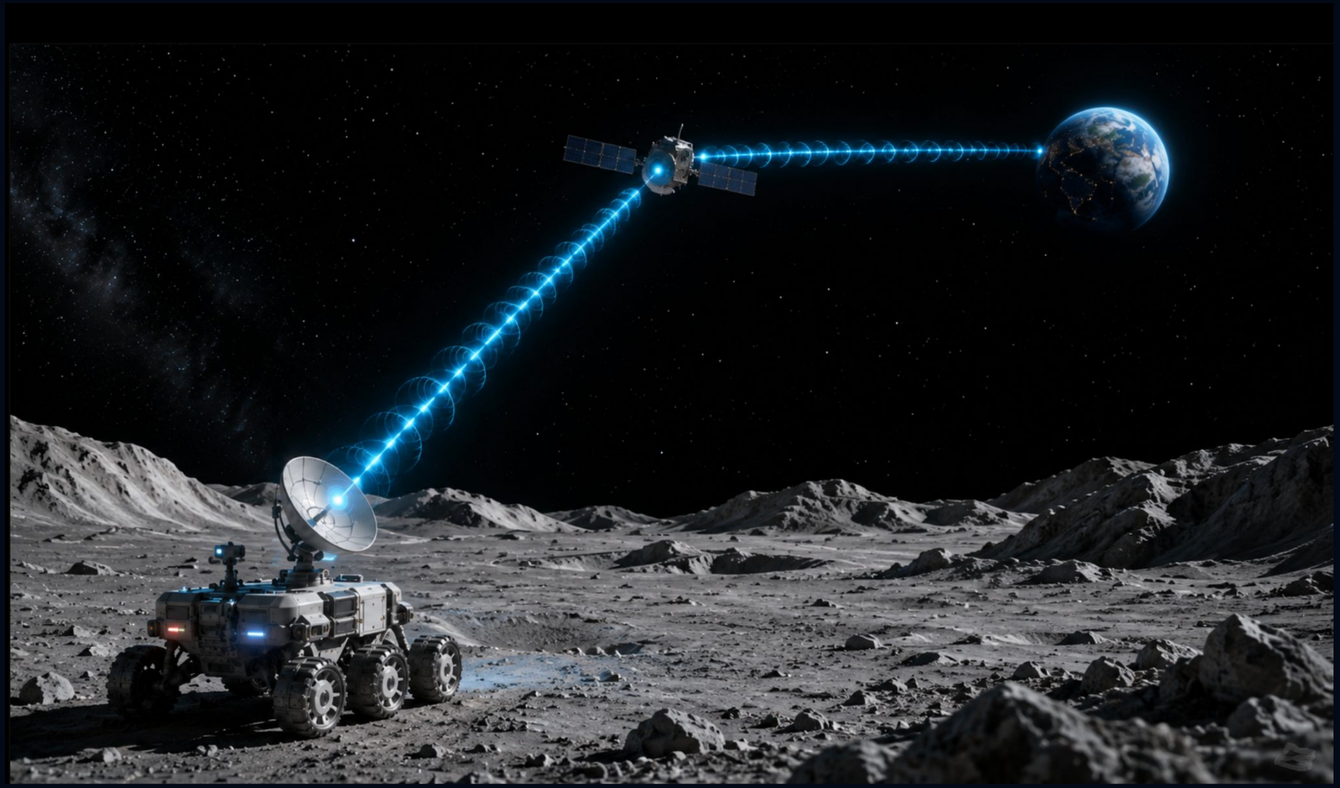
Main advantage

- The relay can bridge the rover and Earth when direct access is poor.

Available when

- The relay has visibility to the rover during its orbit.

Rover -> Relay Satellite -> Earth



The relay path is valuable, but it still depends on orbital visibility.

Direct-to-Earth Link

Long-distance Earth contact

How it works

- The rover communicates directly with Earth when the view is open.

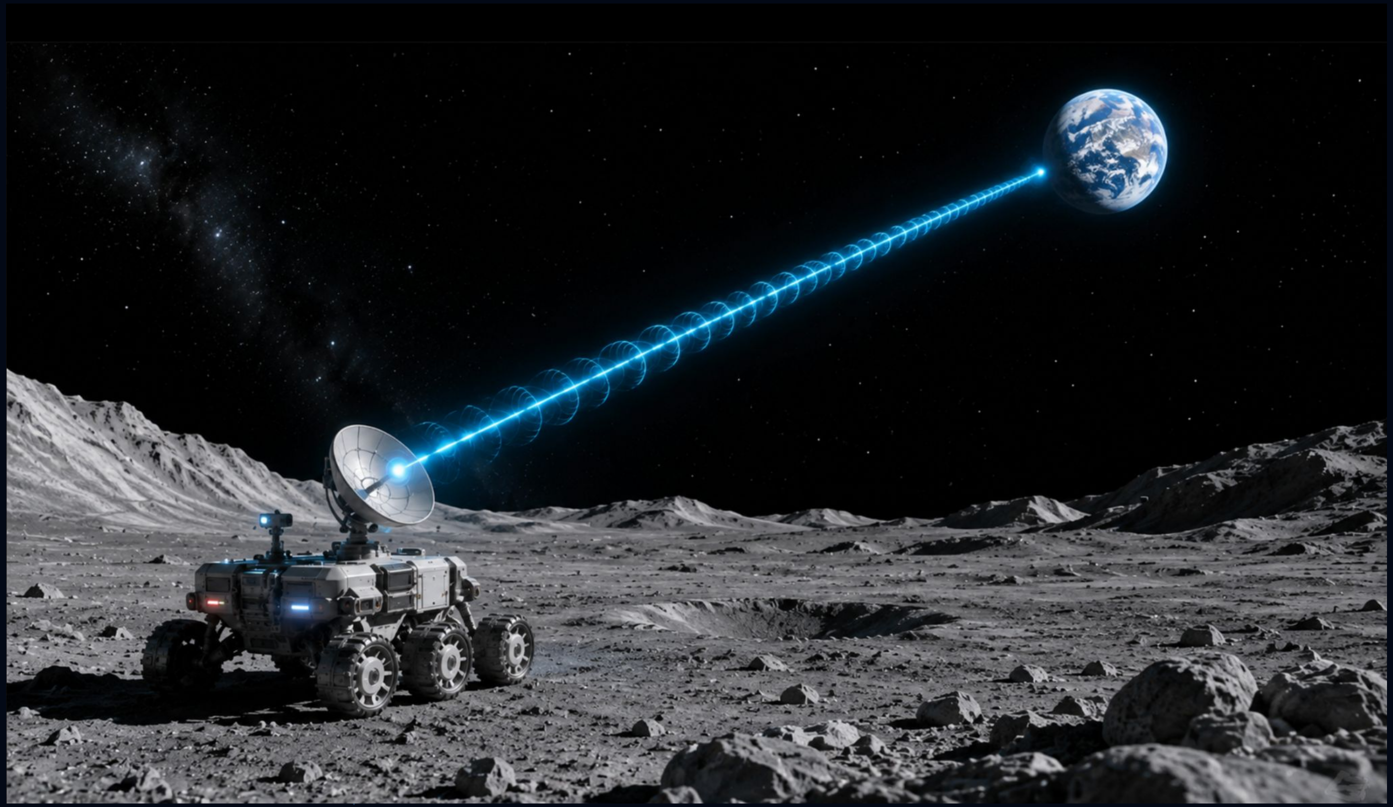
Main limitation

- It needs visibility and requires more power

Available when

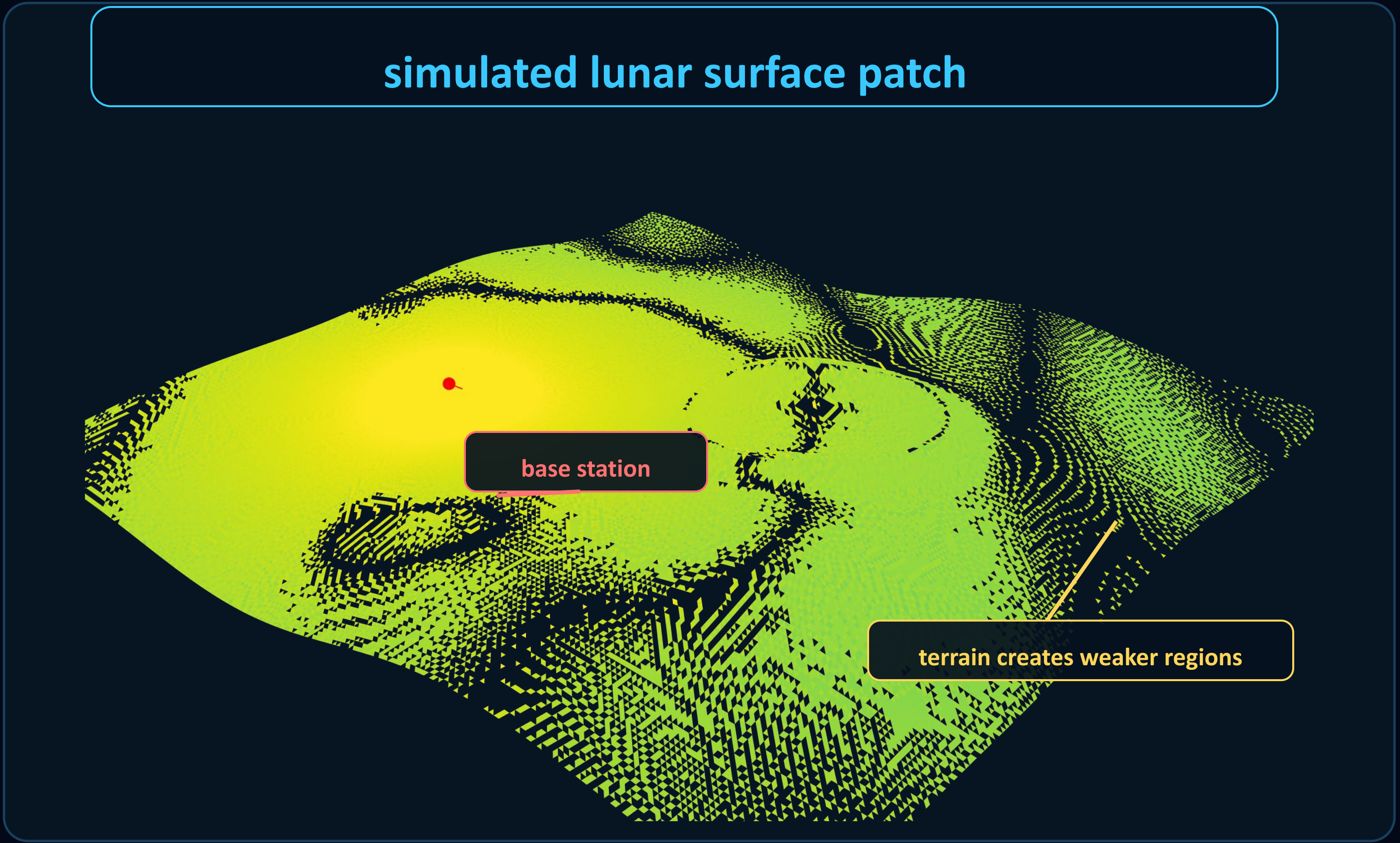
- Duration depends on base-station location and Earth’s rotation

Direct link when Earth is visible.



Direct-to-Earth is simple in concept, but visibility controls when it works.

Sionna Shows Where Signals Can Reach



Lunar terrain can create coverage gaps even when a base station is nearby.

What the model shows

What is Sionna?

- A wireless simulation tool for modeling how radio signals travel.

What I created

- Built a simulated lunar surface patch.
- Added uneven terrain and a crater.
- Placed a base station on the surface.
- Generated a coverage map.
- Observed strong and weak signal regions.

Warm or bright = stronger coverage
Cool or dark = weaker coverage

ns-3 Shows When Links Are Available

Availability model

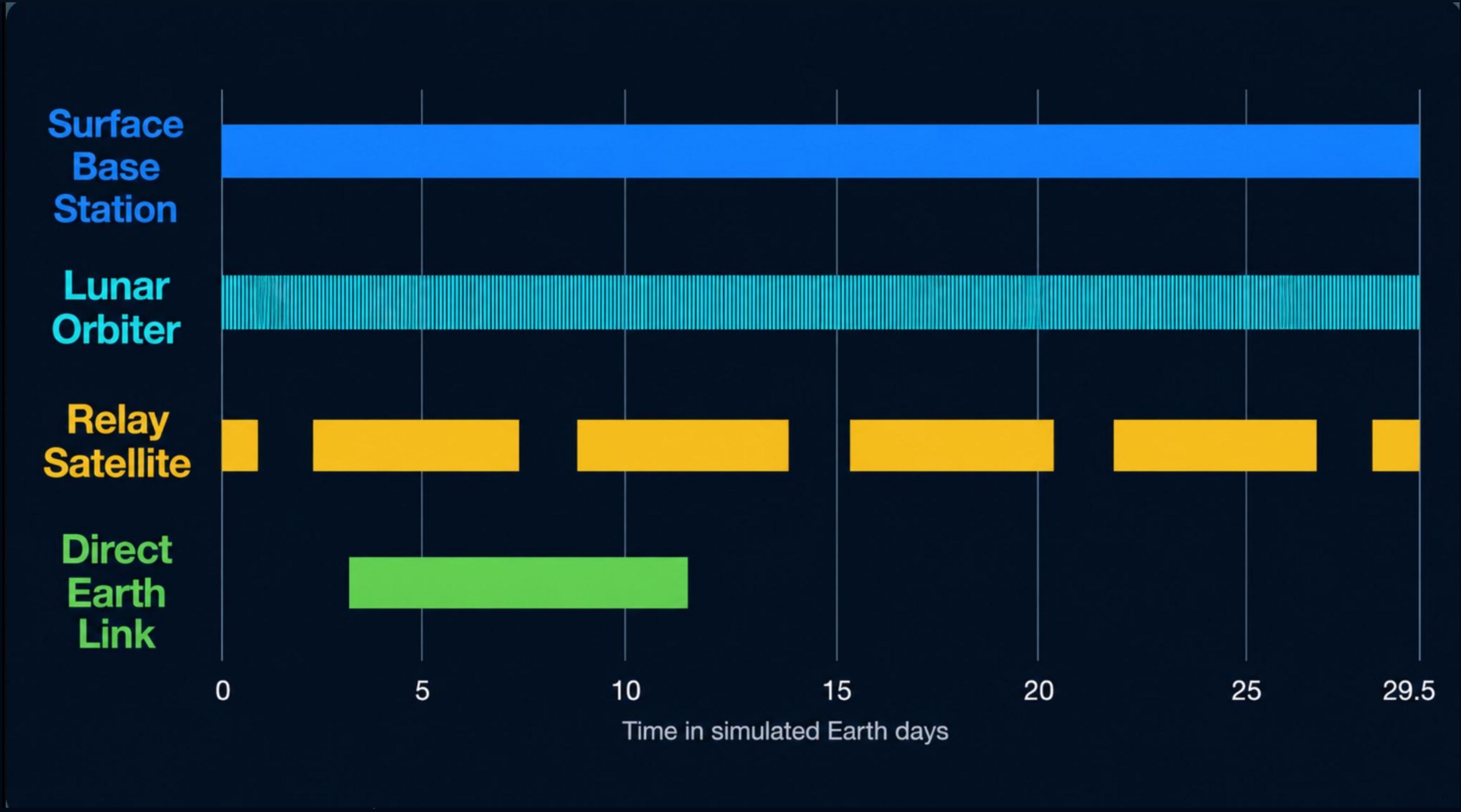
What is ns-3?

- A network simulation tool for modeling communication links over time.

What I studied

- Communication opportunity windows.
- Link duty cycle.

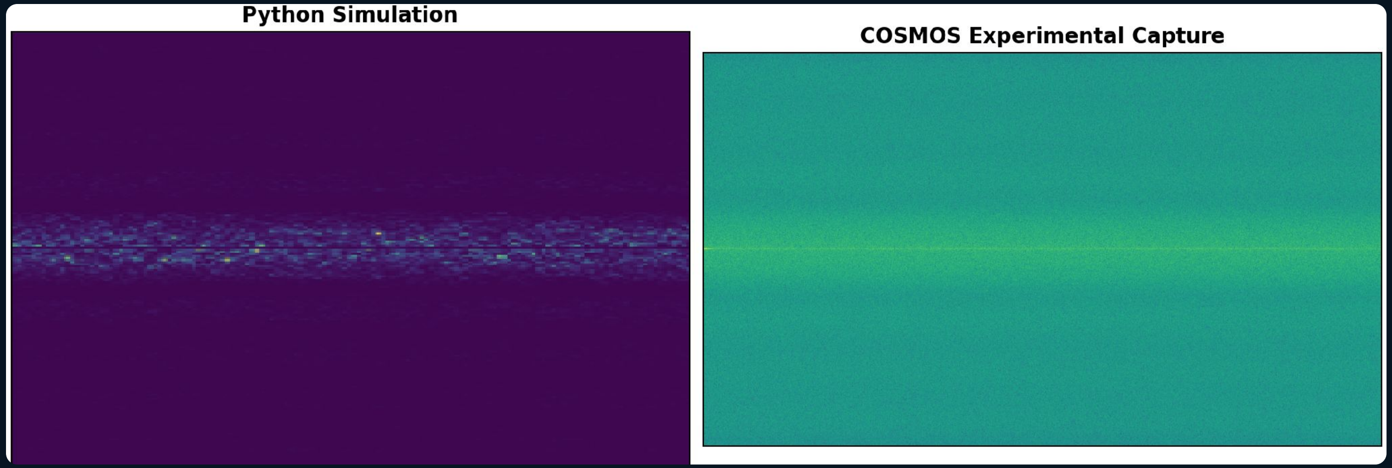
Duty cycle is the percentage of time that a communication link is available.



more filled time = higher duty cycle

Satellite geometry determines when the rover can communicate and how long each contact lasts.

Real Wireless Signals Are Not Perfect



QPSK uses four phases to send two bits per symbol, increasing data rate.

Hardware introduces noise and imperfections that ideal simulations do not show.

SDR and COSMOS testing

- Generated waveforms in Python.
- Used USRP software-defined radios.
- Captured signals on COSMOS.
- Tested QPSK, 16-QAM, BPSK, and OFDM-QPSK.

Observed result

- Python signals appeared cleaner.
- COSMOS showed noise/spreading.
- Captured signals stayed centered.

Understanding the Complete Communication Environment

Sionna

Where can the signal reach?

Terrain and coverage

ns-3

When is the link available?

Visibility and duty cycle

COSMOS

How does the real signal behave?

Noise and hardware effects

Reliable lunar communication requires understanding coverage, timing, and real-world signal behavior together.

Future work

- Improve the ns-3 model.
- Connect simulation results with machine learning

The goal is not only to give the rover more communication options.

The goal is to determine which option can be trusted at each moment.