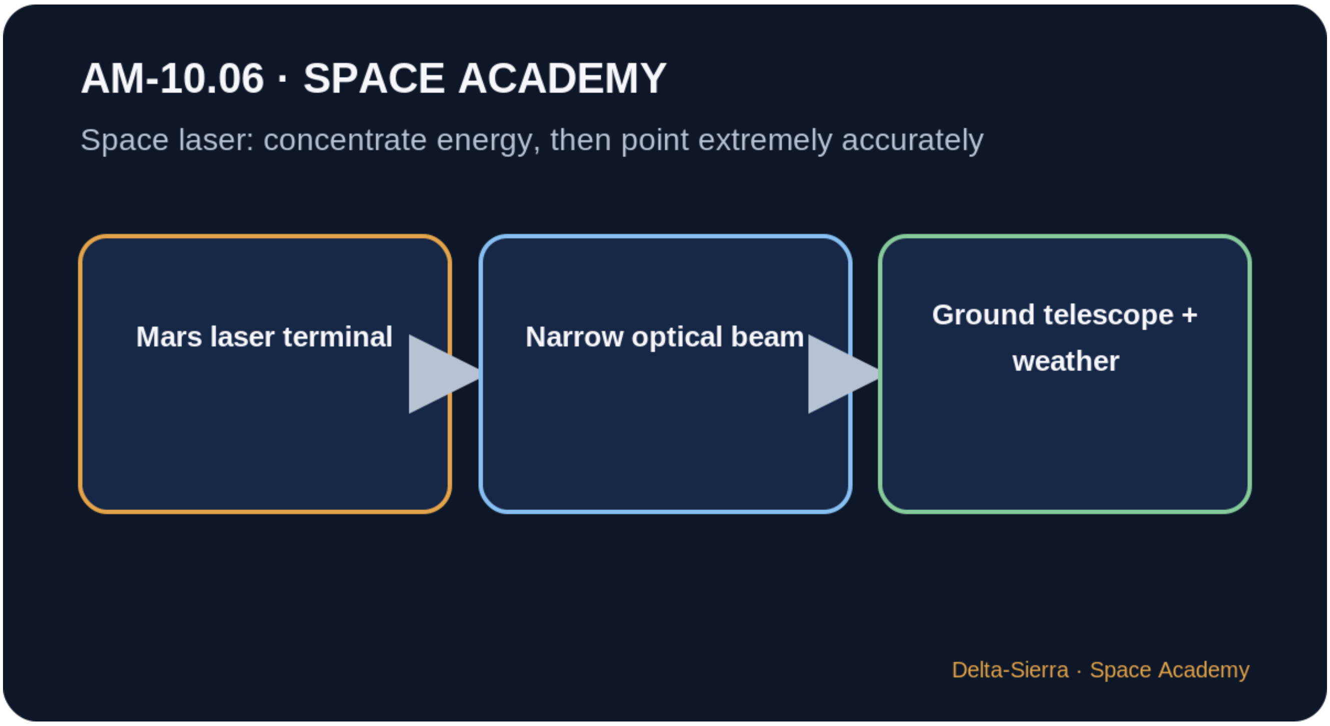
AM-10.06 — Optical communications: sending data with a laser through deep space

Why use a laser when radio already works, and why does pointing become so much more demanding?



Optical communications promise high data return but make pointing, acquisition, and Earth weather major constraints.

1 - Understand the scene

Imagine two lights. One illuminates an entire room; the other concentrates nearly all its energy into a narrow beam. Over enormous distance, concentrating energy is valuable, but it creates a new problem: if the beam misses the target by a tiny angle, the receiver may see nothing. Space laser communications exploit this tradeoff.

NASA demonstrated high-bandwidth deep-space optical communications with DSOC aboard Psyche. That does not make radio obsolete: acquisition, robust command, Earth weather, pointing, and degraded modes make the two technologies complementary.

2 - Essential vocabulary

Photon - A quantum of light; here it can be thought of as an elementary packet of detected light energy.

Laser - A light source capable of producing a highly directional, coherent beam.

Beam - The region of space into which optical energy is concentrated.

Acquisition - The phase in which transmitter and receiver find one another and establish the link.

Pointing - Extremely precise orientation of the terminal toward its target.

Optical ground station - Ground telescope and equipment that transmit or receive the space laser.

Photon counting - Detection of extremely weak optical signals by counting photon events.

3 - Step-by-step mechanism

1 — Concentrate energy

A narrow optical beam sends more transmitted energy toward the target instead of spreading it over a wide angle, supporting very high potential data rate.

2 — Find the target

The tradeoff is precision. The terminal must know the distant station direction, compensate relative motion, and hold the beam despite vibration and attitude error.

3 — Detect very few photons

After millions of kilometres, the signal is extremely weak. Large telescopes, sensitive detectors, filtering and signal processing distinguish useful photons from noise.

4 — Deal with Earth atmosphere

Clouds can block optical downlinks to a ground station. Real architecture can use geographically diverse sites and retain radio links.

4 - Formulas and reading

$$\theta \approx \lambda / D$$

"theta is approximately lambda divided by D." θ is a beam-angle order of magnitude, λ wavelength, and D aperture diameter.

This simplified relation shows why larger apertures and shorter wavelengths can produce narrower beams. Real terminals use detailed diffraction and optical models.

$$\text{spot} \approx \theta \times \text{distance}$$

"spot size is approximately angle times distance," for a small angle in radians.

A tiny angle becomes a large spot over interplanetary distance; the same geometry means tiny pointing error can move the beam enormously at the target.

5 - Units and checks

Optical wavelength is often expressed in nanometres or micrometres; pointing angles may use microradians; interplanetary range uses kilometres; data rate uses bit/s, Mbit/s, or Gbit/s. For spot ≈ θ×distance, angle must be in radians and distance units must remain consistent.

One microradian is one millionth of a radian. At 100 million kilometres, 1 µrad already corresponds geometrically to about 100 km of transverse displacement.

6 - Three demonstrations

Example 1 — One microradian becomes huge

Take a teaching pointing error θ = 1 µrad over 100 million km.

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1 µrad = 1 × 10^-6 rad
distance = 100,000,000 km
offset ≈ 1 × 10^-6 × 100,000,000 = 100 km
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Conclusion: A tiny angular error can move the beam by tens or hundreds of kilometres at interplanetary range.

Example 2 — Reduce pointing error

If pointing error falls to 0.1 µrad over the same distance.

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0.1 µrad = 1 × 10^-7 rad
offset ≈ 1 × 10^-7 × 100,000,000 km
offset ≈ 10 km
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Conclusion: Ten times less angular error gives ten times less transverse offset in this simple geometry.

Example 3 — Why keep radio

An optical ground station is under thick cloud.

The laser cannot provide a useful path through opaque cloud.
Another optical site may be available elsewhere.
A radio link can preserve essential command and telemetry.

Conclusion: Resilience comes from diverse paths and technologies, not one spectacular link.

7 - Deepening

DSOC as a technology demonstration

NASA/JPL's DSOC experiment aboard Psyche demonstrated broadband optical communications in deep space and concluded after exceeding its technical goals. A technology demonstration does not mean every future Mars link will automatically be optical.

Acquisition before throughput

Before high-rate data transfer, terminals must find one another, establish geometry and lock tracking. Acquisition can use beacons, trajectory predictions and complementary radio channels.

Earth weather diversity

Mars may have clear sky while the intended Earth optical ground station is cloudy. Geographically separated optical sites reduce simultaneous weather outage risk.

Thermal and mechanical stability

A precise laser terminal must reject vibration and thermal deformation. GNC, structure and optical communications therefore become tightly coupled.

8 - Why this matters for Mars

A Mars city will generate far more data than a rover: medical imagery, 3D mapping, tele-science, industrial data, education, and backups. Optical links could become an important high-capacity layer.

Safety still requires fallback paths. Reference architecture should measure service availability and sustained capacity rather than treat a demonstration peak rate as a permanent guarantee.

9 - Common traps

- Thinking a laser can be pointed approximately like a flashlight.
- Quoting high data rate without weather, acquisition, and availability.
- Claiming laser automatically replaces all radio.
- Confusing beam diameter with pointing error.
- Forgetting the Earth ground station is part of the system.

10 - Guided exercises

Question: At 200 million km, what offset comes from 0.5 µrad?

Answer: 0.5 × 10^-6 × 200,000,000 ≈ 100 km.

Question: Why multiple optical ground stations?

Answer: To improve availability despite clouds and local conditions.

Question: Why keep radio?

Answer: For robust command, acquisition, redundancy, and degraded operation when optical links are unavailable.

11 - What you should explain

- Explain the main benefit and main cost of a narrow laser beam.
- Compute a simple angle × distance offset.
- Distinguish radio and optical without falsely opposing them.
- Explain acquisition and pointing.
- Identify Earth weather as an availability constraint.

12 - NASA / JPL sources

NASA - Radio vs Optical Spectrum
https://www.nasa.gov/directorates/somd/space-communications-navigation-program/radio-vs-optical-spectrum/

NASA - Small Spacecraft Communications
https://www.nasa.gov/smallsat-institute/sst-soa/soa-communications/

NASA/JPL - Deep Space Optical Communications (DSOC)
https://www.jpl.nasa.gov/missions/deep-space-optical-communications-dsoc/

NASA - Optical Communications Overview
https://www.nasa.gov/technology/space-comms/optical-communications-overview/