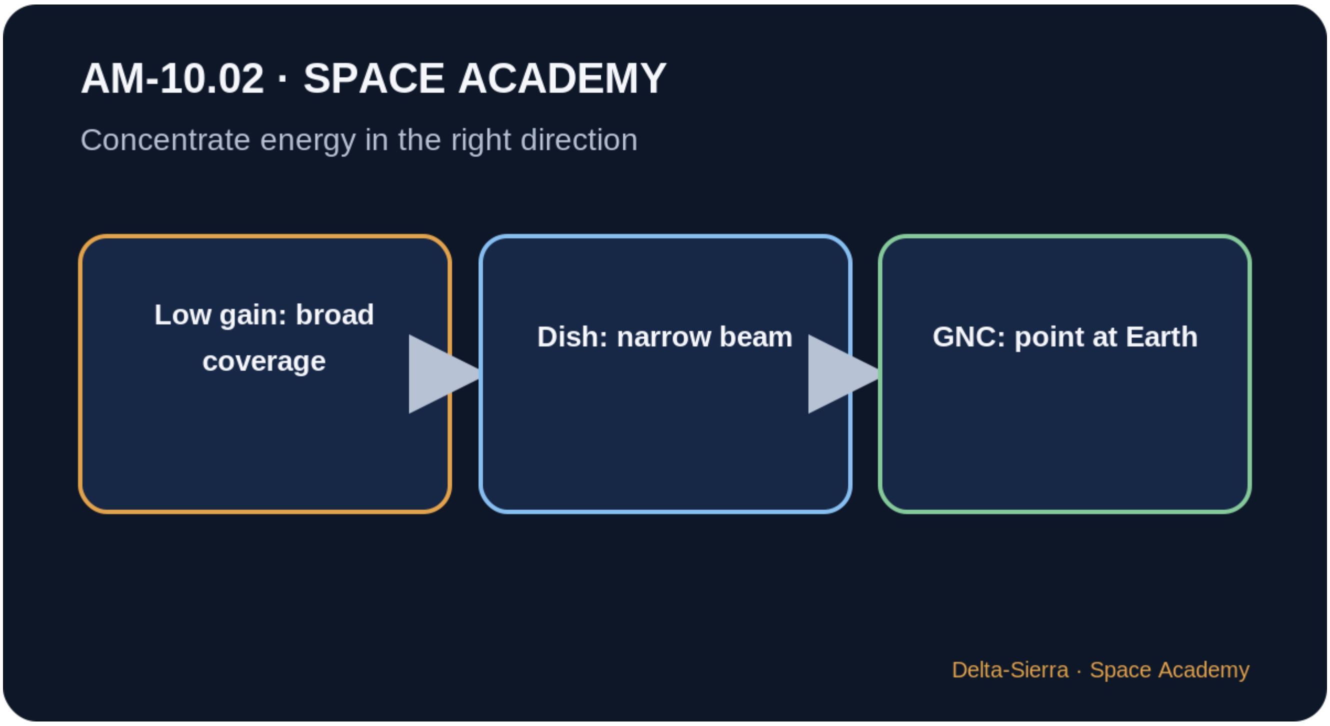
AM-10.02 — Antennas: gain, beamwidth and why a large dish must point accurately

Why can a small antenna communicate broadly while a powerful large dish requires precise pointing?



Gain improves the link by concentrating energy but increases pointing requirements.

1 - Understand the scene

Early in a mission, a spacecraft may use a low-gain antenna because its orientation is not yet well known. The signal is weak but coverage is broad. Later, a high-gain dish concentrates energy into a narrow direction and receives weak signals better—provided it points correctly.

Antenna gain does not mean creating energy. The antenna redistributes available power by direction. More apparent power in the main beam comes at the cost of less elsewhere.

2 - Essential vocabulary

Antenna - A device converting electrical signals into radiated waves, or vice versa in reception.

Directivity - Ability to concentrate radiation in selected directions.

Gain - Measure of directional antenna performance relative to a reference, often expressed in dBi.

dBi - Decibels relative to an ideal isotropic radiator.

Beam - Angular region where an antenna transmits or receives most effectively.

Beamwidth - Angle characterizing the main lobe width; a narrow beam generally requires more precise pointing.

3 - Step-by-step mechanism

Low gain: pointing tolerance

A weakly directive antenna covers a large part of the sky. It is useful for backup or uncertain attitude but does not concentrate much energy toward Earth.

High gain: concentrated energy

A dish uses its aperture to form a narrow beam. At the same transmitter power, energy density in the useful direction rises, improving the link budget.

Diameter and wavelength

At a given frequency, larger aperture generally means narrower beam. At fixed diameter, shorter wavelength also allows a finer beam. Size, frequency, and pointing accuracy are therefore linked.

4 - Formulas and reading

$$\theta \approx 70 \times \lambda / D$$

“theta is approximately seventy times lambda divided by D.” Here θ is an approximate beamwidth in degrees, λ wavelength, and D dish diameter.

This teaching approximation shows the trade: doubling D roughly halves angular width. Exact coefficient depends on beam definition and aperture illumination.

$$\text{gain\_dB} = 10 \log_{10}(\text{P\_direction} / \text{P\_ref})$$

“gain in decibels equals ten times log base ten of directional power ratio to the reference.”

The decibel compresses large ratios. Antenna dBi compares against an ideal isotropic source.

5 - Units and checks

D and λ are both metres in the beamwidth approximation, so their ratio is dimensionless and the chosen coefficient yields degrees. Gain is often in dBi. A common error is adding dBi directly to linear watts without converting power to decibels.

More gain usually means less pointing tolerance. Always ask: 'how much gain, with what beamwidth and what attitude accuracy?'

6 - Three demonstrations

Example 1 — Teaching beamwidth

Dish D = 3 m, λ = 0.036 m.

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θ ≈ 70 × 0.036 ÷ 3
θ ≈ 0.84°
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Conclusion: A sub-degree beam already requires careful pointing.

Example 2 — Large ground antenna

D = 34 m, same λ = 0.036 m.

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θ ≈ 70 × 0.036 ÷ 34
θ ≈ 0.074°
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Conclusion: The large aperture forms a much narrower beam; these are teaching orders of magnitude, not a DSN performance specification.

Example 3 — Power ratio

One direction has 100 times the power density of the chosen reference.

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gain = 10 log10(100)
log10(100) = 2
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gain = 20 dB

Conclusion: The logarithm converts a factor of 100 into +20 dB.

7 - Deepening

Gain in transmit and receive

The same directional antenna generally helps both directions: it concentrates transmitted power and efficiently collects waves arriving from the aimed direction.

Pointing and GNC

A high-gain antenna turns communication into an attitude-guidance-and-control problem. Link engineering and GNC cannot be designed independently.

Low-gain antenna as insurance

Missions often retain tolerant antennas that can recover basic communications after an attitude anomaly even though their data rate is low.

Frequency, aperture, and mechanics

Higher frequency can yield narrow beams from smaller antennas but tightens pointing, surface accuracy, electronics, and sometimes ground-atmosphere constraints.

8 - Why this matters for Mars

Earth-Mars communication operates with limited spacecraft power over enormous distances. Antenna gain is often a more efficient way to gain link margin than simply increasing transmitter power.

Mars relay orbiters have more power and more capable antennas than rovers, which helps explain their role as intermediaries for science data returning to Earth.

9 - Common traps

- Saying antenna gain creates energy.
- Confusing gain with transmitter power.
- Ignoring pointing cost of a narrow beam.
- Adding dBi and watts without conversion.
- Treating $\theta \approx 70\lambda/D$ as an exact universal law.

10 - Guided exercises

Question: If D doubles at constant λ, what happens approximately to θ?

Answer: It halves.

Question: Why is a low-gain antenna useful after an anomaly?

Answer: Its broad beam tolerates poor pointing and can maintain a minimal link.

Question: A power ratio of 10 corresponds to how many dB?

Answer: 10 log10(10) = 10 dB.

11 - What you should explain

- Define directivity, gain, dBi, beam, and beamwidth.
- Explain why a dish does not create energy.
- Relate diameter, wavelength, and beamwidth qualitatively.

• Compute an approximate $\theta \approx 70\lambda/D$.

• Explain the gain-versus-pointing tradeoff.

12 - NASA / JPL sources

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

NASA - What is the Deep Space Network?
https://www.nasa.gov/directorates/somd/space-communications-navigation-program/what-is-the-deep-space-network/