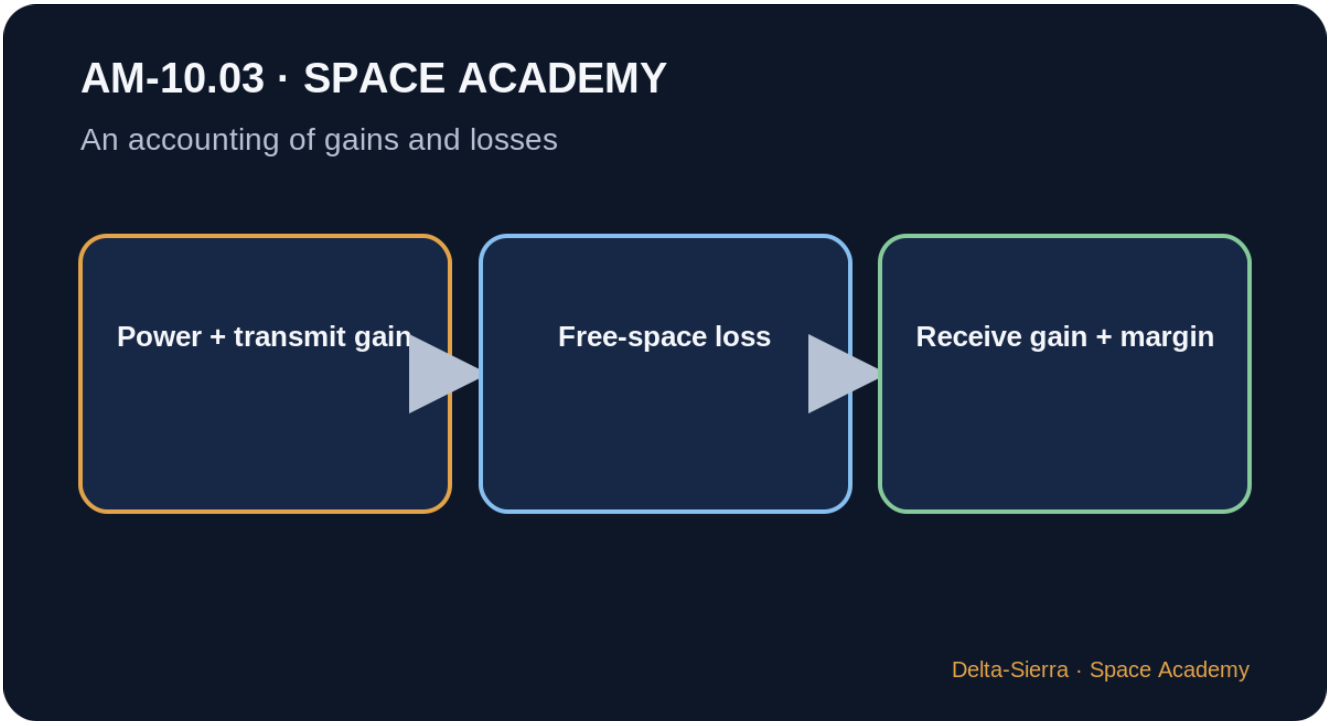
AM-10.03 — Link budget: add gains and losses all the way to the receiver

How can engineers know before flight whether a signal crossing millions of kilometres will still be strong enough to decode?



The signal becomes extremely weak; the budget checks whether the full chain remains usable.

1 - Understand the scene

A Mars radio can transmit correctly yet deliver nothing useful to Earth if the signal arrives below receiver noise. A link budget is an energy accounting exercise: start with transmitted power, add gains, subtract losses, then check what remains at the receiver with margin.

Engineers use decibels because the ratios are enormous. Instead of multiplying and dividing numbers spanning many orders of magnitude, gains and losses become additions and subtractions.

2 - Essential vocabulary

Link budget - Accounting of signal power from transmitter to receiver, including gains, losses, and margin.

Decibel - Logarithmic unit expressing a ratio. For power, dB = 10 log10 of the ratio.

dBW - Power in decibels relative to 1 watt.

dBm - Power in decibels relative to 1 milliwatt.

Free-space path loss - Reduction in power density mainly due to geometric spreading with distance.

Link margin - Difference between available performance and the required minimum.

3 - Step-by-step mechanism

Convert watts to decibels

1 W = 0 dBW; 10 W = 10 dBW; 100 W = 20 dBW. The logarithmic scale turns factors of ten into 10 dB steps.

Add the path

A simplified form is received power = transmit power + transmit antenna gain + receive antenna gain − losses, with each term expressed in compatible logarithmic units.

Distance is expensive

In free space, doubling distance increases path loss by about 6 dB because energy density spreads over an area proportional to distance squared. Mars communications are therefore fundamentally different from local links.

4 - Formulas and reading

$$P\_dBW = 10 \log_{10}(P\_W / 1\ W)$$

“power in dBW equals ten times log base ten of power in watts divided by one watt.”

This expresses absolute power on a logarithmic scale referenced to 1 W.

$$L\_fs = 20 \log_{10}(4\pi d / \lambda)$$

“free-space loss equals twenty times log base ten of four pi d divided by lambda.”

This ideal formula captures geometric spreading versus distance d and wavelength λ in consistent units. It does not include all real losses.

$$P\_r = P\_t + G\_t + G\_r - L\_total$$

“P r equals P t plus G t plus G r minus L total,” using compatible decibel units.

Once values are consistently expressed, the accounting becomes addition of gains and subtraction of losses.

5 - Units and checks

Plain dB describes a ratio; dBW and dBm describe absolute power by reference. Antenna gains are often dBi. In a budget line, dBW power can be combined with gain/loss ratios in dB/dBi, but every column must be interpreted correctly.

> Never subtract '200 dB' from '20 watts'. Convert power to a compatible logarithmic reference first.

6 - Three demonstrations

Example 1 — Convert 20 W

Convert a teaching transmitter power.

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P_dBW = 10 log10(20)
log10(20) ≈ 1.301
P ≈ 13.0 dBW
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> Conclusion: 20 W is about 13 dBW.

Example 2 — Simplified budget

Take Pt = 13 dBW, Gt = 20 dBi, Gr = 60 dBi, and total losses = 250 dB.

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Pr = 13 + 20 + 60 − 250
Pr = −157 dBW
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> Conclusion: The result is extremely small, which is normal for deep-space links; it must then be compared with noise, receiver performance, data rate, and coding.

Example 3 — Double distance

Because Lfs contains 20 log10(d), double d.

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ΔL = 20 log10(2)
log10(2) ≈ 0.301
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$\Delta L \approx 6.02$ dB

Conclusion: Doubling distance adds about 6 dB of free-space loss.

7 - Deepening

The budget does not end at received power

Decoding bits also depends on noise, bandwidth, symbol rate, coding, and signal-to-noise ratio. Later lessons should introduce C/N0, Eb/N0, and bit error rate.

Additional losses

Cables, connectors, polarization, pointing, Earth atmosphere, rain at some frequencies, ageing, and implementation margin can add to ideal path loss.

Why lower data rate helps

At the same received power, sending fewer bits per second generally allows more energy per bit and stronger coding redundancy, improving robustness.

Margin as insurance

A link calculated with only 0.1 dB margin may work on paper and fail as real parameters vary. Margin absorbs uncertainty, degradation, and manufacturing spread.

8 - Why this matters for Mars

Earth-Mars distance changes enormously over the planets' orbits; a link must be designed for unfavorable geometry, not just the day the planets are close.

The role of the DSN, large orbiter antennas, and relays becomes clear in the budget: gaining receive aperture, integration time, coding, or antenna gain may be more practical than dramatically increasing rover transmitter power.

9 - Common traps

- Confusing dB, dBW, dBm, and dBi.
- Adding watts and decibels.
- Forgetting that path loss is a positive loss subtracted from the budget.
- Thinking received power alone predicts data rate without noise or coding.
- Using distance in km and wavelength in m without consistent conversion.

10 - Guided exercises

Question: How many dBW is 100 W?

Answer: 10 log10(100) = 20 dBW.

Question: Loss increases by 6 dB. About what power factor is that?

Answer: For power, +3 dB is about ×2 and +6 dB about ×4. A 6 dB loss means roughly four times less received power.

Question: Why can a large receive antenna compensate part of the distance penalty?

Answer: Its receive gain adds dB to the budget and efficiently collects energy from the desired direction.

11 - What you should explain

- Distinguish dB, dBW, dBm, and dBi.
- Convert simple power to dBW.

- Build a Pt + gains − losses budget.
- Explain why doubling distance costs about 6 dB in free space.
- Define link margin and explain why it is needed.

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/