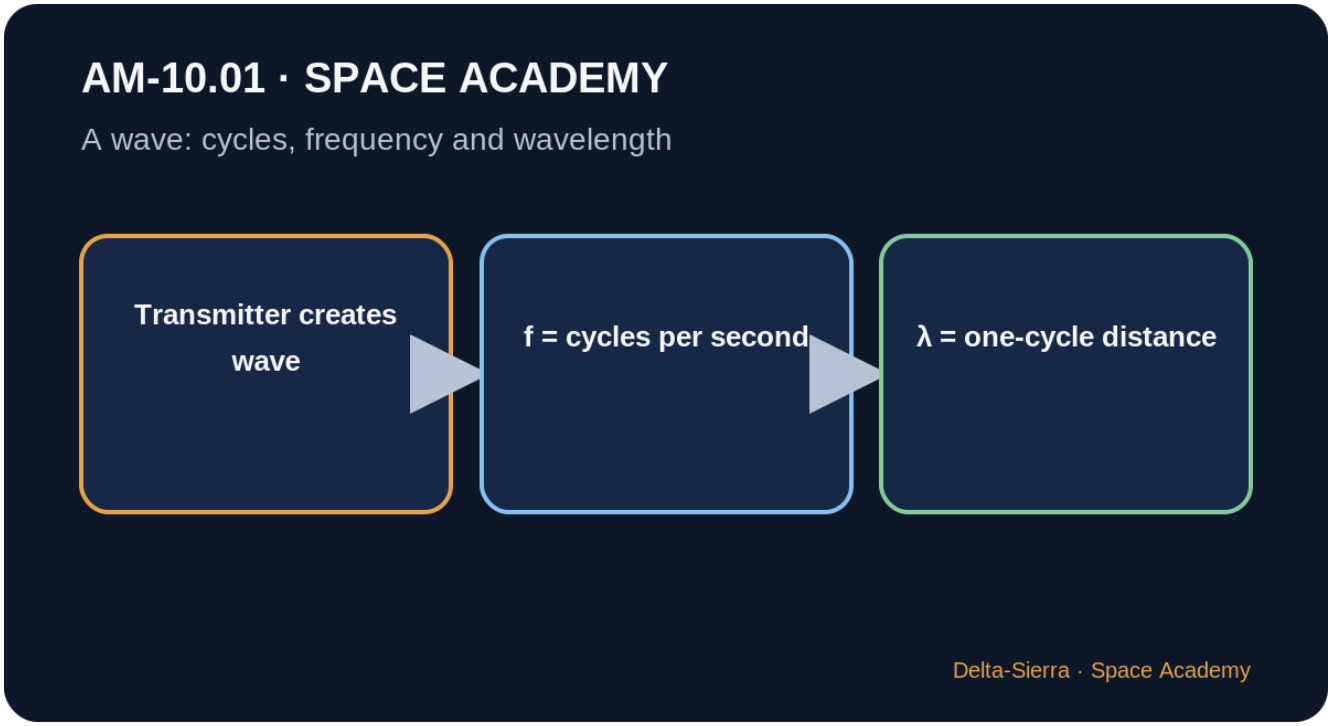
AM-10.01 — Radio waves: frequency, wavelength and why λ = c/f

What actually propagates between a Mars antenna and Earth, and what do Hz, MHz, GHz, and wavelength mean?



Frequency and wavelength describe two aspects of the same pattern propagating at light speed.

1 - Understand the scene

A rover antenna does not throw “bits” as tiny material objects through vacuum. Its transmitter maps information onto controlled variations of an electromagnetic wave. The wave propagates at light speed in vacuum and can be detected by another antenna thousands or millions of kilometres away.

To understand a radio link, first separate three ideas: frequency says how many cycles repeat each second; wavelength is the distance between equivalent points of the wave pattern; propagation speed links the two. This foundation leads to antennas, UHF/X/Ka bands, and link budgets.

2 - Essential vocabulary

Electromagnetic wave - Coupled electric and magnetic field variation that can propagate through vacuum.

Cycle - One complete wave pattern before it repeats.

Frequency - Number of cycles per second. Unit: hertz.

Hertz - One hertz means one cycle per second. MHz is a million hertz; GHz a billion hertz.

Wavelength - Distance traveled by the wave during one cycle. Common symbol: λ, lambda.

Frequency band - A range of frequencies given a name or use, such as UHF or X-band.

3 - Step-by-step mechanism

One phenomenon, two views

If a wave repeats very many cycles per second, each cycle occupies less distance: higher frequency means shorter wavelength because propagation speed is nearly constant in vacuum.

Prefixes avoid huge numbers

400 MHz means 400,000,000 Hz. 8.4 GHz means 8,400,000,000 Hz. Correct prefixes avoid long strings of zeros and reduce errors.

A band does not define the whole link

Saying “X-band” specifies a frequency region, not data rate, power, coding, antenna size, or received quality. Those come in later lessons.

4 - Formulas and reading

$$\lambda = c / f$$

“lambda equals c divided by f.” λ is wavelength, c is the speed of light in vacuum, and f is frequency.

Speed is distance per time. A wave of frequency f completes f cycles per second, so one cycle occupies the one-second travel distance divided by the number of cycles.

$$f = c / \lambda$$

“f equals c divided by lambda.”

It is the same relation rearranged: known wavelength gives frequency.

5 - Units and checks

Frequency uses Hz, kHz, MHz, or GHz. Wavelength uses metres or centimetres. For calculations, convert prefixes first: 400 MHz = 4.00 × 10^8 Hz. Light speed in vacuum is about 2.998 × 10^8 m/s.

Forgetting the factor 1000 between MHz and GHz makes wavelength one thousand times wrong. Write the unit on every line.

6 - Three demonstrations

Example 1 — UHF near 400 MHz

Compute a representative wavelength near UHF rover-to-orbiter links.

```
f = 400 MHz = 4.00 × 10^8 Hz
λ = 2.998 × 10^8 ÷ 4.00 × 10^8
λ ≈ 0.75 m
```

Conclusion: The order of magnitude is three quarters of a metre. Exact mission frequency depends on channel and system.

Example 2 — X-band near 8.4 GHz

Take a teaching frequency of 8.4 GHz.

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f = 8.4 × 10^9 Hz
λ = 2.998 × 10^8 ÷ 8.4 × 10^9
λ ≈ 0.0357 m ≈ 3.57 cm
```

Conclusion: A much higher frequency gives a much shorter wavelength.

Example 3 — Find frequency

A wave has λ = 0.10 m.

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f = c ÷ λ
f ≈ 2.998 × 10^8 ÷ 0.10
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f ≈ 2.998 × 10^9 Hz ≈ 3.0 GHz

Conclusion: A ten-centimetre wavelength corresponds here to about 3 GHz.

7 - Deepening

Why multiple bands

Different frequencies trade antenna size, beamwidth, path loss, electronics, regulation, and propagation. A mission may therefore use several bands for different functions.

Radio and optical

Optical communication also uses electromagnetic waves, but at vastly higher frequencies with lasers and very precise pointing. NASA SCaN treats radio and optical as complementary domains.

Speed in a medium

The simple equation uses c in vacuum. Propagation is slower in cables or material media. For interplanetary free space, using c is appropriate.

Carrying information

A pure carrier does not yet contain a Mars image. The transmitter changes amplitude, phase, frequency, or other properties through modulation and adds coding and synchronization. That deserves a later lesson.

8 - Why this matters for Mars

Mars rovers use UHF links to orbiters and X-band direct links to Earth. Frequency and wavelength help explain why their antennas differ in shape, size, and directivity.

A future Mars settlement would combine local networks, orbital relays, and interplanetary links. Frequency, band, and wavelength appear throughout even though powers and distances differ radically.

9 - Common traps

- Confusing frequency with data rate.
- Thinking higher frequency travels faster in vacuum.
- Forgetting to convert MHz or GHz to Hz.
- Saying radio waves need air to travel.
- Treating physical antenna length as always equal to wavelength.

10 - Guided exercises

Question: Approximate wavelength at 1 GHz?

Answer: λ ≈ 2.998 × 10^8 ÷ 1 × 10^9 ≈ 0.300 m, about 30 cm.

Question: Does 800 MHz have a longer or shorter wavelength than 400 MHz?

Answer: Shorter: doubling frequency halves wavelength.

Question: Why is “X-band = 8.4 GHz” only an example?

Answer: Because X-band covers a range; missions use specific assigned frequencies within it.

11 - What you should explain

- Define cycle, frequency, hertz, and wavelength.
- Read kHz, MHz, and GHz correctly.
- Use λ = c/f with units.

- Explain why higher frequency means shorter wavelength.
- Distinguish frequency band from data rate.

12 - NASA / JPL sources

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

NASA Science - Mars 2020 rover components
https://science.nasa.gov/mission/mars-2020-perseverance/rover-components/

Free educational resource: this lesson explains the principles for beginners. It does not replace operational mission design, flight models, procedures, testing, or agency validation.