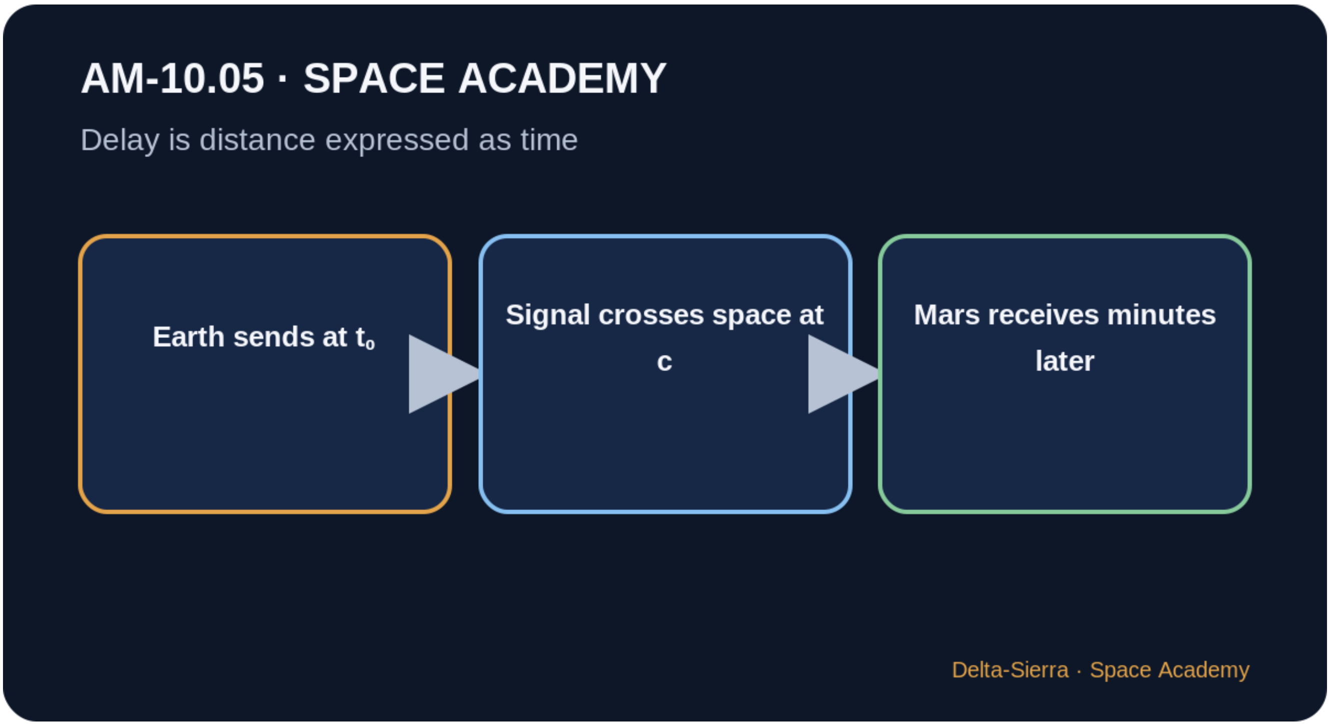
AM-10.05 — Light time, latency and atomic clocks: why Mars can never be controlled in real time

Why can no radio technology remove the minutes of delay between Earth and Mars, and why does a precise clock become a navigation instrument?



No protocol exceeds c; mission design must therefore include autonomy and asynchronous operations.

1 - Understand the scene

An Earth operator sees a rover approaching a dangerous rock. Even if they click 'stop' immediately, the command must cross space; the rover receives it minutes later. Its confirmation then takes minutes to come back. This is not slow Internet: it is the finite speed of light.

The same limitation becomes a tool. Precisely measuring when a signal is sent and returned provides distance information from flight time. A stable clock is therefore both a synchronization device and an indirect geometry sensor.

2 - Essential vocabulary

Latency - Delay between sending information and receiving it or observing its effect.

One-way light time - Time for a signal to cross the distance in one direction.

Round trip - Signal trip to the destination and a return response; often called RTT.

Atomic clock - Clock whose reference frequency is tied to an extremely stable atomic transition.

Ranging - Distance measurement using, among other methods, signal propagation time.

Autonomy - Ability to decide and act without waiting for distant human commands.

3 - Step-by-step mechanism

Geometry imposes delay

NASA’s 2026 Mars Relay Network page gives an Earth-Mars distance range of about 54.6 to 400.2 million km, corresponding to roughly 3 to 22.4 minutes one-way light time. Radio cannot abolish that distance.

Round trip: doubling is only the minimum

If one-way time is 20 min, a basic request-response cannot return in less than about 40 min, before processing, queueing, or protocol delay. Reflex teleoperation from Earth is impossible.

Measure distance with time

A station sends a time-tagged signal, the spacecraft retransmits or responds, and a stable clock measures elapsed time. After known delays are corrected, propagation time provides range information.

4 - Formulas and reading

$$t = d / c$$

“t equals d divided by c.” t is propagation time, d distance, and c light speed.

Time equals distance divided by speed. For one-way free-space radio, c is the propagation speed.

$$d \approx c \times t$$

“d is approximately c times t,” for an isolated one-way propagation time.

The same relation supports ranging: distance is speed times propagation time once relevant delays are separated.

$$RTT \approx 2d / c$$

“round-trip time is approximately two d divided by c.”

In a simplified symmetric model, the signal travels about twice the distance. Real geometry moves during the trip and is modeled more precisely.

5 - Units and checks

Use distance units consistent with c. If c = 299,792 km/s, express d in kilometres to obtain seconds. Real navigation clocks and protocols use much finer timing precision, but teaching examples keep readable numbers.

Better compression cannot remove Mars video-call delay: compression reduces data volume, not the minimum travel time of the first photon across the distance.

6 - Three demonstrations

Example 1 — Favorable distance

Take d = 54.6 million km.

```
t = 54,600,000 ÷ 299,792
t ≈ 182 s
182 s ≈ 3.0 min
```

Conclusion: This matches NASA’s roughly three-minute one-way lower-order figure.

Example 2 — Unfavorable distance

Take d = 400.2 million km.

```
t = 400,200,000 ÷ 299,792
t ≈ 1335 s
1335 s ≈ 22.3 min
```

Conclusion: Minimum round-trip time then approaches 45 minutes.

Example 3 — Teaching range

An isolated one-way time is 600 s.

```
d ≈ 299,792 km/s × 600 s
d ≈ 179,875,200 km
```

Conclusion: Real precision requires correcting electronic delays and moving geometry, but the physical principle is clear.

7 - Deepening

Why a clock is a sensor

If time error becomes range error through $d = c \times t$, timing stability directly affects ranging quality. Clocks are not merely for displaying time.

Deep Space Atomic Clock

NASA demonstrated DSAC in Earth orbit from 2019 to 2021 to test a compact stable mercury-ion clock aimed at greater future deep-space navigation autonomy.

Operational autonomy

Delay forces Mars vehicles to detect obstacles, anomalies, and dangerous conditions locally. Earth provides objectives and plans but cannot close fast control loops.

Network time and science time

Instruments, cameras, IMUs, radios, and computers also need a coherent timeline. Good architecture separates mission time, measurement timestamps, and propagation time.

8 - Why this matters for Mars

Mars settlement cannot copy an Earth mission-control model that decides every action. Local crews and software will need real operational authority.

Interplanetary communication must be designed as asynchronous exchange: messages, packets, delayed synchronization, caches, pre-approved procedures, and systems able to continue through outages.

9 - Common traps

- Treating delay as an Internet ping that can be optimized to zero.
- Confusing one-way and round-trip time.
- Using c in m/s with distance in km.
- Thinking an atomic clock directly gives position without signals and geometry.
- Designing a safety loop that always waits for Earth approval.

10 - Guided exercises

Question: At 150 million km, approximate one-way light time?

Answer: 150,000,000 ÷ 299,792 ≈ 500 s ≈ 8 min 20 s.

Question: If one-way time is 12 min, what is the minimum physical round trip?

Answer: Approximately 24 min before processing.

Question: Why can DSAC support autonomy?

Answer: A stable onboard clock allows more navigation processing from received signals without relying entirely on two-way measurement and ground calculation cycles.

11 - What you should explain

- Compute simple light time with $t = d/c$.
- Distinguish one-way and round-trip time.
- Explain why Mars latency is physical, not merely computational.
- Explain how propagation time can measure distance.
- Relate precise clocks to navigation autonomy.

12 - NASA / JPL sources

NASA Science - Mars Relay Network
https://science.nasa.gov/mars/mars-relay-network/

NASA - Deep Space Atomic Clock
https://www.nasa.gov/mission/deep-space-atomic-clock-dsac/

NASA - What Is an Atomic Clock?
https://www.nasa.gov/missions/tech-demonstration/deep-space-atomic-clock/what-is-an-atomic-clock/