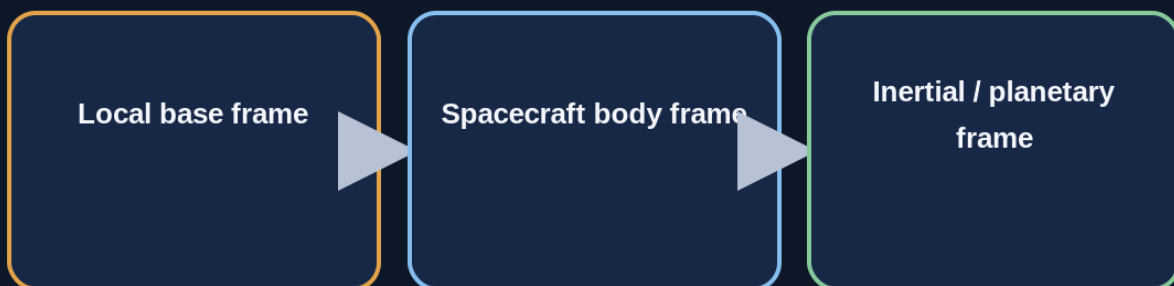


AM-08.03 — Reference frames and time: state where and when before computing a trajectory

Why is a position or velocity meaningless unless we specify the reference frame and the time to which it refers?

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Same reality, multiple frames



Delta-Sierra · Space Academy

A position is never “just three numbers”: it belongs to a frame and a time.

1 - Understand the scene

Imagine a Mars lander whose computer receives the statement 'velocity = 300 m/s'. The number looks precise, but the essential information is missing: 300 m/s relative to what? The Martian ground, the center of Mars, the Sun? And at what time? Numerical components change with the chosen frame even though the physical spacecraft is the same.

Navigation is therefore a discipline of context. Before adding vectors, software must know the origin, axes, orientation, and time attached to each datum. A frame error can be more dangerous than an arithmetic error because a calculation may be perfectly executed on incompatible data.

2 - Essential vocabulary

Reference frame - A system defining an origin and axes so coordinates can be assigned.

Origin - The point assigned zero coordinates.

Axis - An oriented reference direction, such as x, y, or z.

Inertial frame - A frame chosen so the laws of motion are as simple as practical for the problem; it is not rotating with the spacecraft.

Body frame - A frame fixed to the vehicle; its axes rotate with it.

Epoch / reference time - The date and time at which a position, velocity, or attitude is valid.

Light time - The time an electromagnetic signal needs to cross a distance.

3 - Step-by-step mechanism

One point, several numbers

An antenna on Mars can have local coordinates relative to a base, planet-centered coordinates relative to Mars, and a heliocentric position relative to the Sun. These are not three antennas; they are three descriptions of the same object.

Time travels with geometry

Planets, orbiters, and vehicles move. A position valid at 12:00 may be wrong minutes later. Navigation data therefore carry a timestamp or epoch. The time is not decoration; it is part of the datum.

Transforming is not inventing

Changing frame means applying a known mathematical transformation: shift the origin, rotate the axes, and sometimes account for frame motion. The goal is not to change reality but to express the same reality in a compatible language.

4 - Formulas and reading

$$\mathbf{r}_B = \mathbf{R}_{\{BA\}} \cdot \mathbf{r}_A + \mathbf{t}_{\{BA\}}$$

"r in B equals the rotation matrix from A to B times r in A, plus the translation from A to B." It means: rotate the axes, then shift the origin.

This general form expresses the same point in another frame. The beginner does not yet need to compute a full rotation matrix; the priority is understanding what it represents.

$$\Delta t = t_2 - t_1$$

"delta t equals t two minus t one." The Greek letter delta means a difference here.

We subtract the start time from the end time to obtain a duration. An absolute date and a duration are not the same quantity.

5 - Units and checks

Position coordinates may be in metres or kilometres, velocities in metres per second or kilometres per second, angles in degrees or radians, and time as seconds, minutes, or encoded dates. The main danger is not the choice itself but silently mixing incompatible units or time scales.

Habit: mentally attach 'frame + unit + time' to every vector. If one is missing, the datum is not ready to be combined.

6 - Three demonstrations

Example 1 — Local map

A rover is 120 m east and 50 m north of the habitat. In the local frame, the habitat is the origin.

$x = +120 \text{ m}$
 $y = +50 \text{ m}$
 $\text{distance} = \sqrt{(120^2 + 50^2)} = 130 \text{ m}$

Conclusion: The pair (120, 50) is meaningful only because the origin and axes were defined.

Example 2 — Changing origin

An antenna is at $x = 500 \text{ m}$ in a frame whose origin is site A. Site B is at $x = 300 \text{ m}$ in that same frame.

$x_{\text{antenna}/B} = 500 - 300$
 $x_{\text{antenna}/B} = 200 \text{ m}$

Conclusion: Using B as the new origin changes the number, not the antenna.

Example 3 — Time-tagged data

A position estimate was computed at 12:00:00 and the vehicle moves at 20 m/s for 5 s in a straight-line example.

$$\Delta t = 5 \text{ s}$$

$$\Delta x \approx v \times \Delta t$$

$$\Delta x \approx 20 \times 5 = 100 \text{ m}$$

Conclusion: Reusing the old position without accounting for five seconds already creates about 100 m of error in this simplified model.

7 - Deepening

Planetary or local frame?

A planet-centered frame is useful for global mapping; a local frame is more intuitive for rover driving or base construction. Real systems continually transform between them.

Why engineers care about epoch

A trajectory is a function of time. Giving six position-and-velocity numbers without a time is like handing over a photograph without saying when it was taken.

A rotating planet

A point fixed on Mars is stationary in a surface-fixed frame but rotates in a Mars-centered inertial frame. Both descriptions are correct in their own context.

Light time complicates the word “now”

When a ground station receives a measurement, it often describes the spacecraft at the time the signal was emitted, not at reception. Navigation therefore reconstructs time-tagged past events.

8 - Why this matters for Mars

A Mars mission connects solar, planetary, orbital, spacecraft-body, instrument, and landing-site frames. Frame compatibility is a safety requirement.

Future autonomy on Mars will require precise local maps, common frames shared by rovers and habitats, and sufficiently consistent clocks to fuse measurements from different systems.

9 - Common traps

- Confusing altitude with distance from the planet centre.
- Adding vectors expressed in different frames.
- Forgetting that the body frame rotates with the spacecraft.
- Using an old position as if it described the current state.
- Confusing absolute date, elapsed duration, and signal propagation time.

10 - Guided exercises

Question: Why is “ $x = 10 \text{ km}$ ” incomplete?

Answer: Because the origin and direction of the x axis must be known; for dynamic data, time is also required.

Question: Position changes from 200 m to 260 m between 10 s and 13 s. What is the average change rate?

Answer: $\Delta x = 60 \text{ m}$ and $\Delta t = 3 \text{ s}$, so average velocity along that axis is $60 \div 3 = 20 \text{ m/s}$.

Question: Why must a camera and an IMU share coherent time?

Answer: So their measurements describe the vehicle at the same instant; otherwise fusion combines an image with an attitude or acceleration from another moment.

11 - What you should explain

- Define origin, axis, body frame, and inertial frame.
- Explain why position must carry both a frame and a time.
- Distinguish real motion from a coordinate change caused by changing frame.
- Compute a simple Δt and translation.
- Explain why light time requires precise measurement timestamps.

12 - NASA / JPL sources

NASA - State-of-the-Art of Small Spacecraft Technology, Guidance Navigation and Control
<https://www.nasa.gov/smallsat-institute/sst-soa/guidance-navigation-and-control/>

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

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