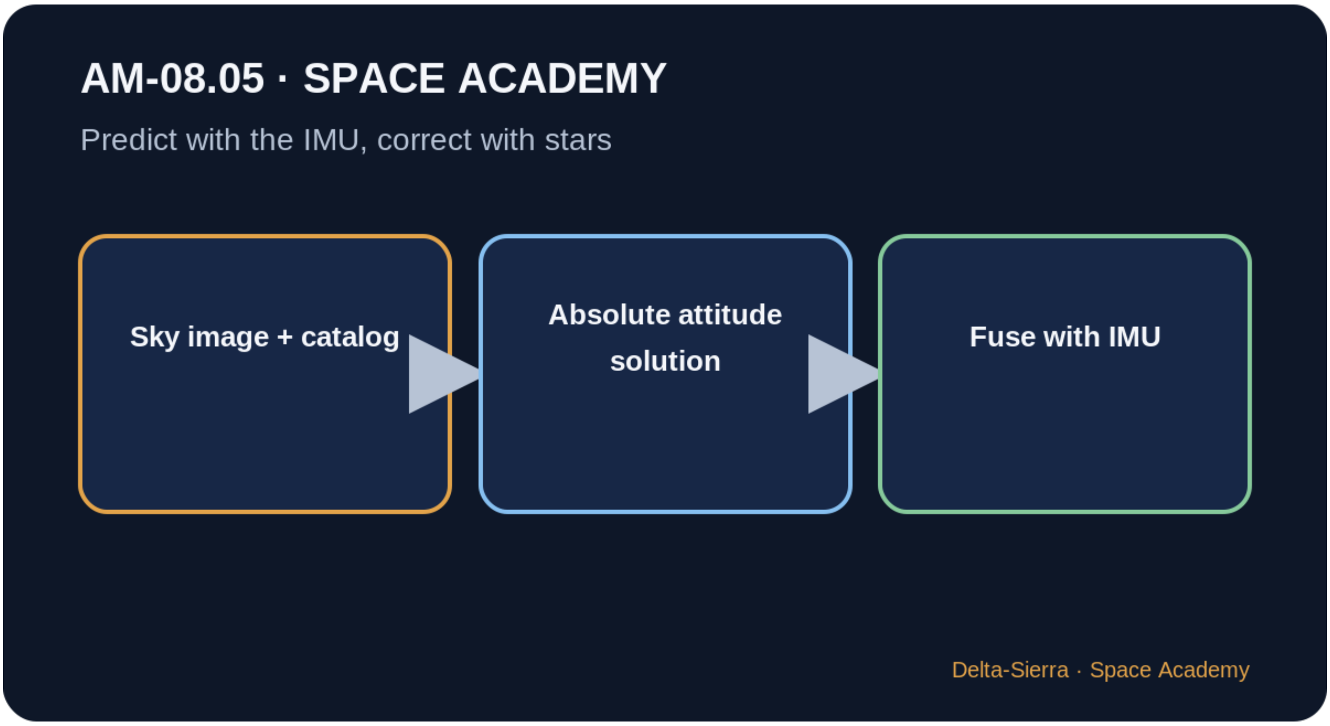
AM-08.05 — Star trackers and sensor fusion: finding attitude from the stars

How can a camera looking at stars tell a spacecraft which way it is pointing?



The star tracker provides an absolute reference; the IMU provides continuity between solutions.

1 - Understand the scene

A spacecraft shuts down its engines and coasts. Its IMU knows how it has rotated over the last few seconds, but a small drift accumulates. A specialized camera images several stars. Software compares their pattern with an onboard catalog and recovers the sensor's absolute attitude: that is the job of a star tracker.

A robust system does not choose between IMU and stars. It combines them: the IMU predicts attitude rapidly between images, while the star tracker periodically corrects drift. This predict-then-correct idea lies at the heart of many navigation estimators.

2 - Essential vocabulary

Star tracker - A specialized camera and processor that identify stars and provide three-axis attitude.

Star catalog - Onboard database containing known directions of reference stars.

Attitude - The spacecraft orientation in space, not its position.

Field of view - The portion of sky visible to the sensor.

Sensor fusion - Consistent combination of measurements with different strengths and weaknesses.

Kalman filter - A family of methods that predict a state, compare the prediction with a measurement, then correct the estimate according to uncertainties.

3 - Step-by-step mechanism

Image a pattern, not a name

The star tracker detects bright points, measures their relative image positions, and searches for a configuration compatible with its catalog. Once several stars are identified, geometry yields sensor attitude.

Lost in space

A capable tracker may have to recover attitude without a reliable initial guess. This “lost in space” acquisition requires enough visible stars and algorithms able to recognize the pattern.

Predict then correct

Between star solutions, the IMU propagates attitude. When a new star image arrives, the estimator compares prediction and observation, then adjusts attitude and often gyro biases.

4 - Formulas and reading

$$\text{innovation} = \text{mesure} - \text{prédiction}$$

“innovation equals measurement minus prediction.” Innovation here means the residual between observation and expectation.

The difference tells the estimator in which direction the predicted state should be corrected. The actual correction also accounts for uncertainties.

$$\text{état corrigé} = \text{état prédit} + K \times \text{innovation}$$

“corrected state equals predicted state plus K times innovation.” K is an estimator correction gain.

A reliable measurement receives more weight; an uncertain one receives less. This is a conceptual form, not a full Kalman derivation.

5 - Units and checks

Attitude can be represented by angles, matrices, or quaternions. Star-tracker accuracy is often expressed in arcseconds: one arcsecond is 1/3600 degree. The key idea is scale: a few arcseconds is a very small angular error.

> Excellent angular precision only helps if the sensor is correctly aligned with the spacecraft. Mechanical alignment calibration is part of the problem.

6 - Three demonstrations

Example 1 — One arcsecond

Convert 18 arcseconds to degrees.

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18 ÷ 3600 = 0.005°
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> Conclusion: The angle is tiny; this gives intuition for star-tracker precision.

Example 2 — Correcting drift

The IMU predicts 20.4° while the star solution gives 20.0°. For a teaching weight K = 0.75:

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innovation = 20.0 − 20.4 = −0.4°
correction = 0.75 × (−0.4) = −0.3°
corrected state = 20.4 − 0.3 = 20.1°
```

> Conclusion: The estimator moves toward the measurement without necessarily copying it exactly.

Example 3 — Temporary loss

The star tracker is blinded for 8 s while the IMU keeps providing angular rates.

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star tracker: no solution
IMU: propagate attitude
stars return: update estimate
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Conclusion: Functional complementarity prevents instantaneous loss of all attitude knowledge.

7 - Deepening

Stray light and the Sun

A star tracker can be disturbed by the Sun, a bright planet, reflections, or thruster plumes. Mounting geometry and exclusion zones are studied before flight.

Update rate is finite

The camera exposes, reads out, and computes a solution. The IMU produces data much faster, which is why the two complement each other.

A filter does not create information

Sensor fusion cannot turn bad measurements into truth. It requires a model, realistic uncertainties, and rejection of outliers.

Redundancy and disagreement

Two star trackers can improve availability, but alignment errors or different optical environments can make them disagree. The system needs fault-detection logic.

8 - Why this matters for Mars

Pointing a high-gain antenna, orienting solar arrays, performing a trajectory correction, or making a scientific observation can require much better attitude knowledge than visual intuition.

Autonomous Mars missions must keep knowing their orientation when Earth cannot correct them in real time. Inertial plus stellar sensing is therefore a core navigation-resilience example.

9 - Common traps

- Thinking a star tracker gives spacecraft position.
- Confusing sensor accuracy with whole-spacecraft accuracy.
- Ignoring glare and field-of-view constraints.
- Treating a Kalman filter as a “magic average”.
- Ignoring timing and alignment between different sensors.

10 - Guided exercises

Question: An error is 36 arcseconds. How many degrees?

Answer: 36 ÷ 3600 = 0.01°.

Question: Why is the IMU useful if the star tracker is more accurate in absolute attitude?

Answer: Because it updates rapidly and continues between star solutions or during temporary loss.

Question: What does an innovation near zero mean?

Answer: Measurement and prediction are close for the compared quantity; that alone does not prove the entire system is correct.

11 - What you should explain

- Explain how a star tracker recognizes a star pattern.
- Distinguish attitude from position.

- Explain the predict-correct principle of sensor fusion.
- Convert arcseconds and degrees.
- Name major causes of star-solution loss or degradation.

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/