

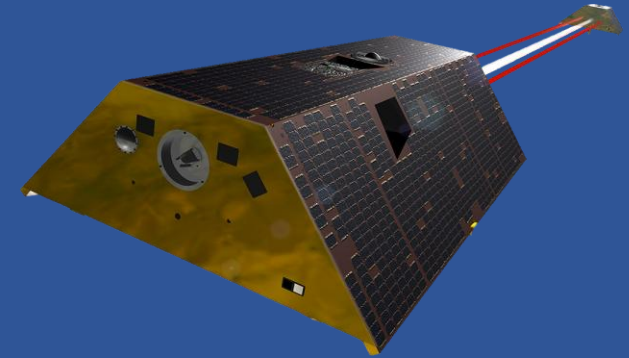


Quantum Frontiers



Institute of Geodesy - LUH

AI-Driven Accelerometer Data Transplantation for Next-Generation GRACE-like Satellite Gravimetry Missions



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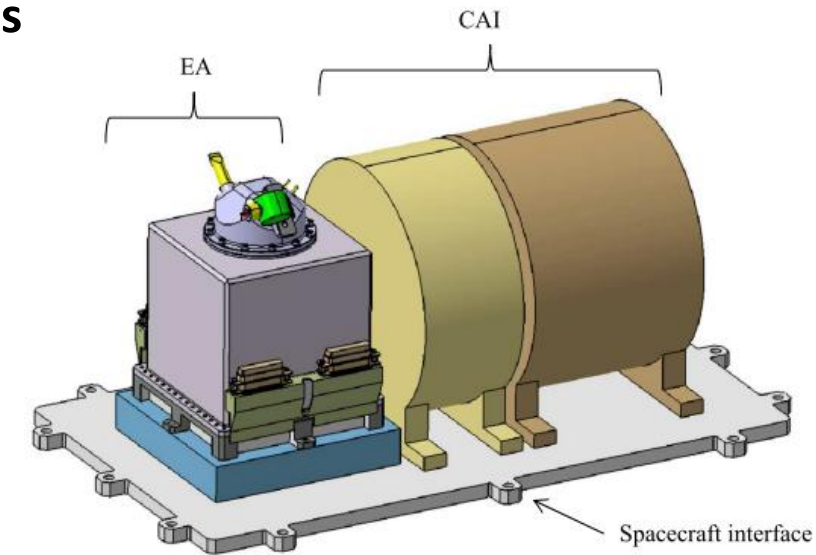
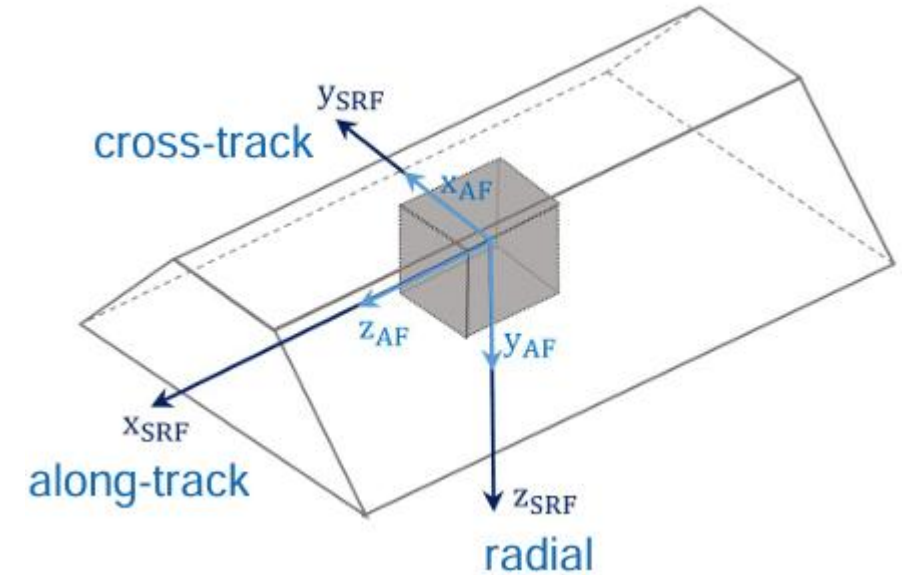
✓ Measurement of non-gravitational accelerations

- Atmospheric drag
- Solar radiation pressure
- Earth radiation pressure
- Thruster firings

❖ allows for a separation of gravitational and non-gravitational forces

✓ Hybrid ACC (EA + CAI) *

- Short-term sensitivity of EA and a long-term stability of CAI
- Time-invariant measurement stability
- Making calibration processes unnecessary

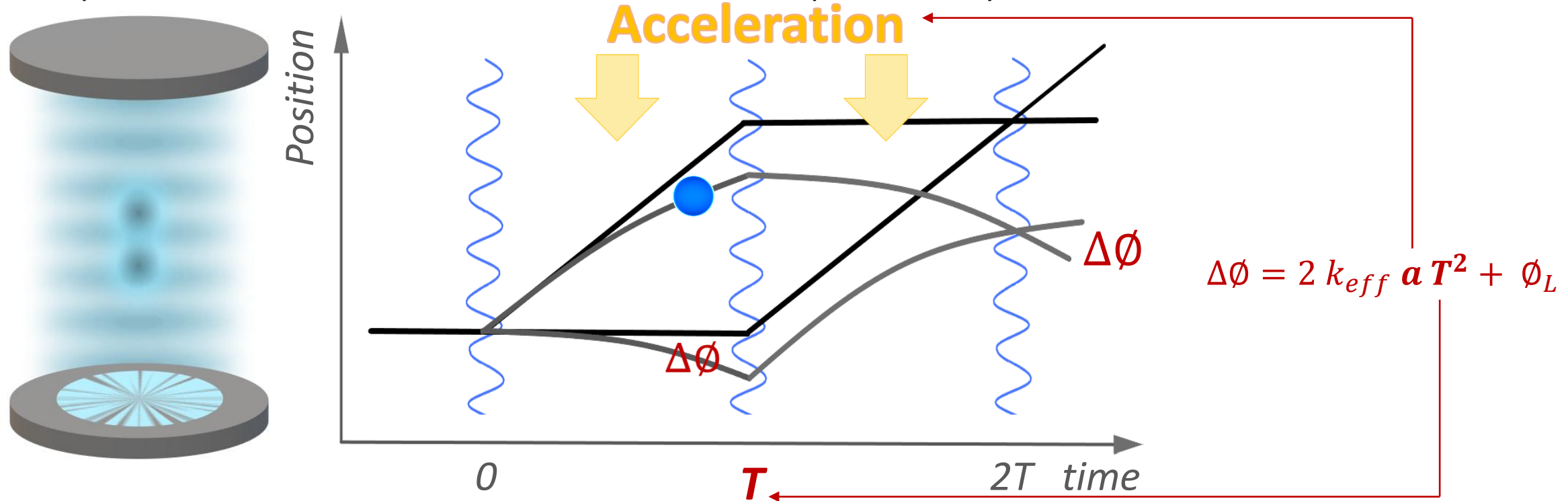


(Zahzam, et al., 2022)

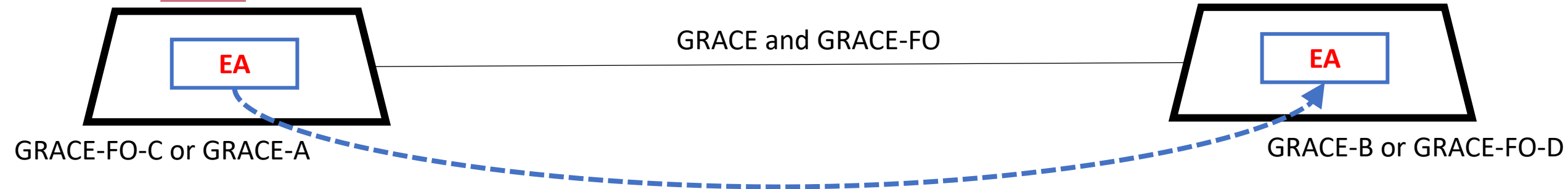
*Electrostatic accelerometer (EA) , Cold Atom Interferometry (CAI) , Hybrid (H)

What is a quantum sensor?

- Quantum interferometer, e.g., accelerometers and gyroscopes
- Based on Cold Atom Interferometry (CAI).
- Second pulse changes their directions and brings the two paths back toward each other.
- Using wave-like nature of atoms
- Third pulse recombines the two paths.
- At the end, we measure the phase difference between the two paths.
- This phase difference tells us about the acceleration experienced by the atoms.



Mach-Zehnder Atom Interferometer

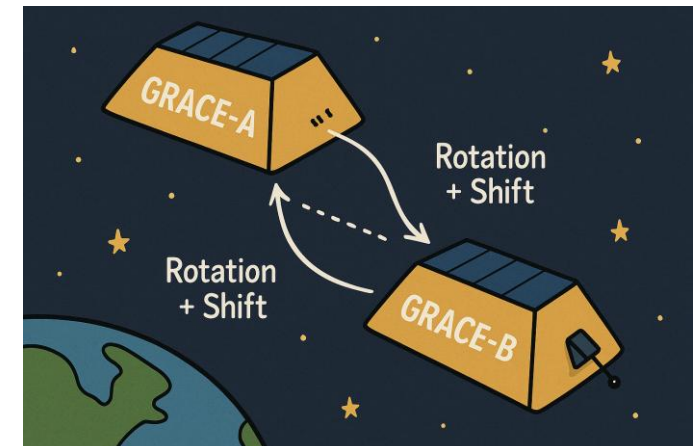


✓ **Why transplant process for GRACE and GRACE-FO?**

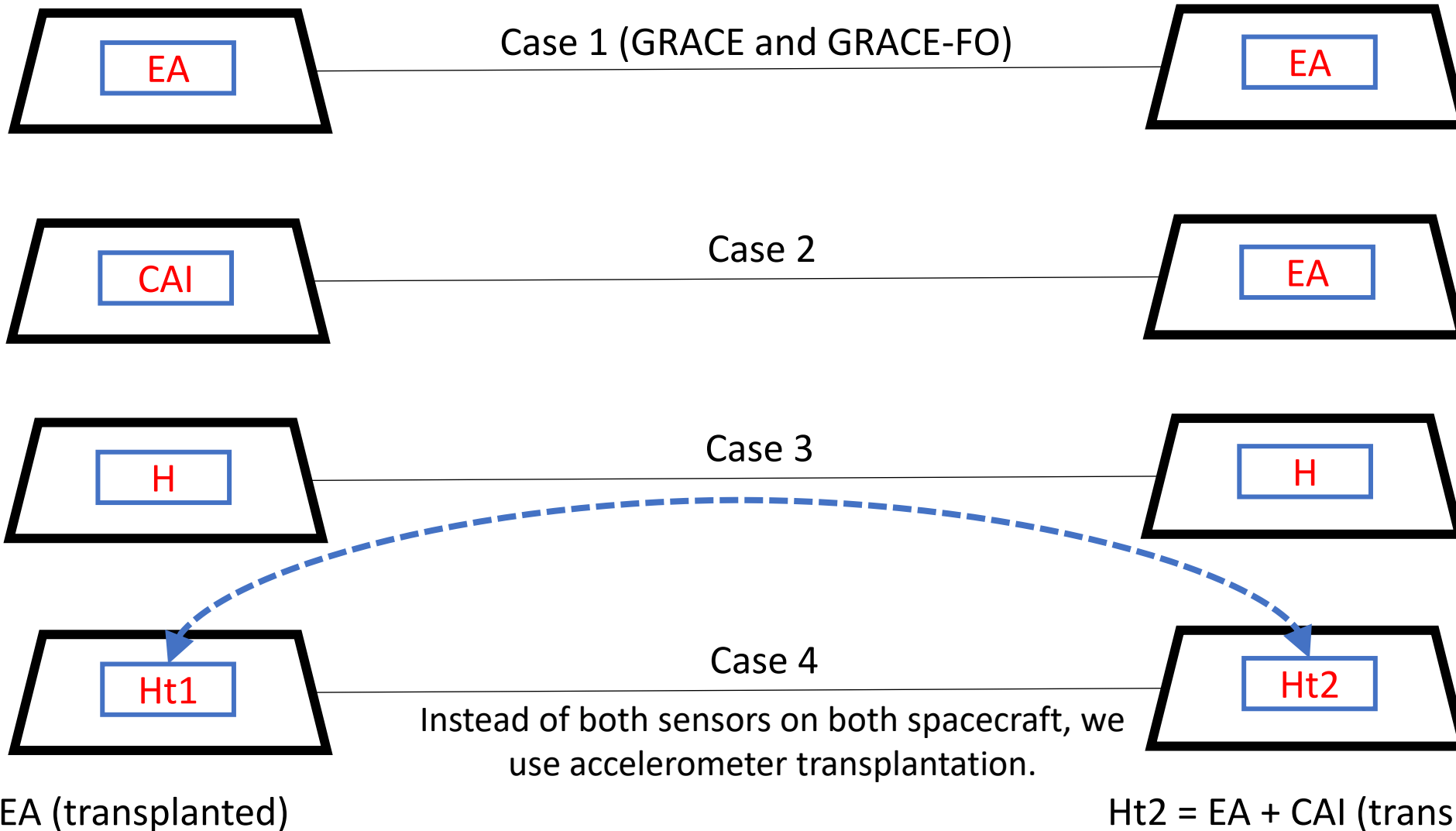
- **GRACE-B accelerometer was switched off** near the end of the mission due to reduced battery capacity.
- **GRACE-D accelerometer data showed elevated noise**, requiring reconstructed or synthetic accelerometer observations.
- The transplant approach assumes the two spacecraft experience similar non-gravitational forces. Measurements from the healthy spacecraft are time-shifted and rotated to approximate the missing observations of the other spacecraft.

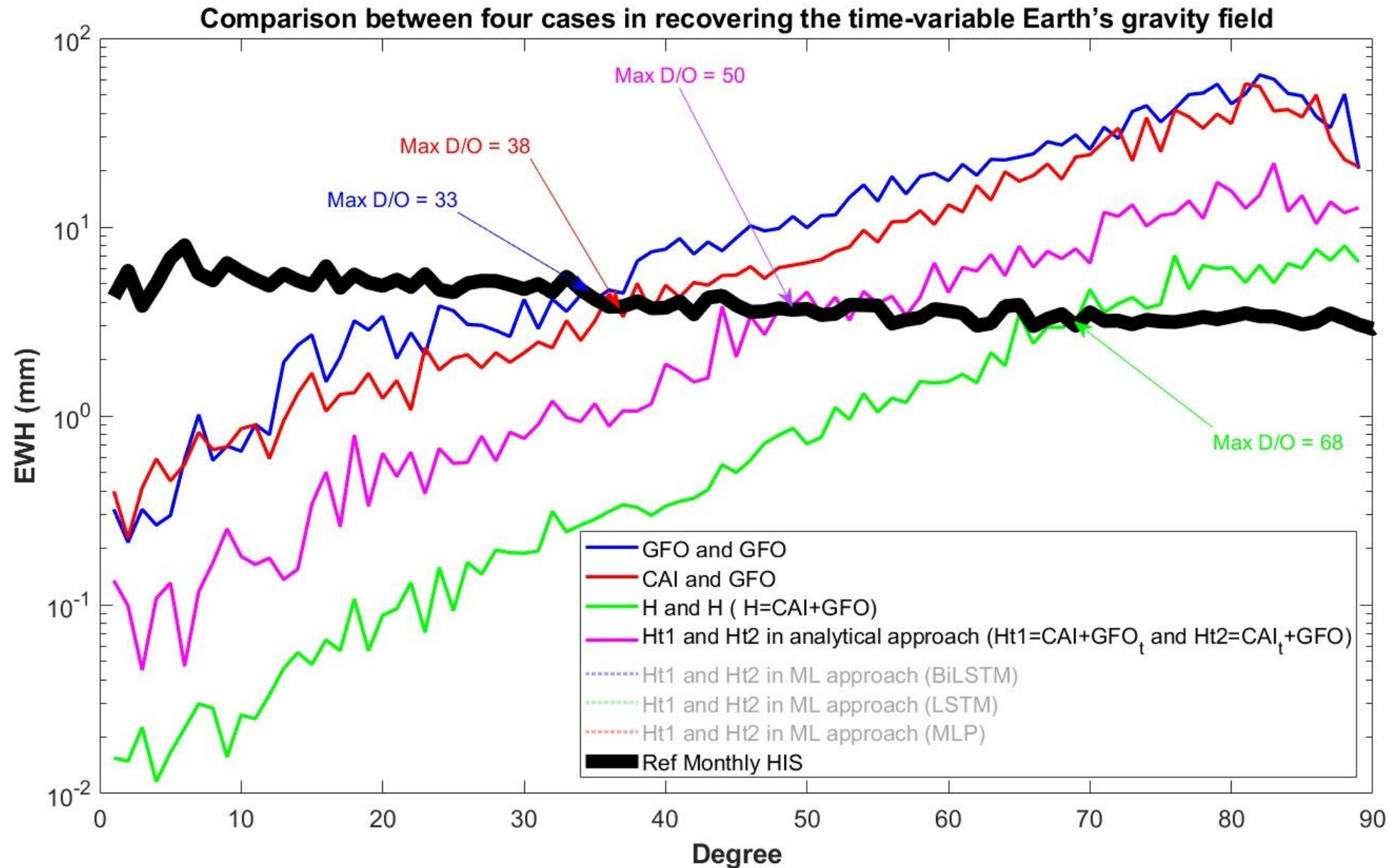
✓ **Transplant product approaches:**

- 1.(JPL, Bandikova et al., 2019; Harvey et al., 2022)
- 2.(TUGRAZ, Behzadpour et al., 2021)
- 3.(JPL, McCullough et al., 2022)
- 4.(LUH, Romeshkani et al., 2025)

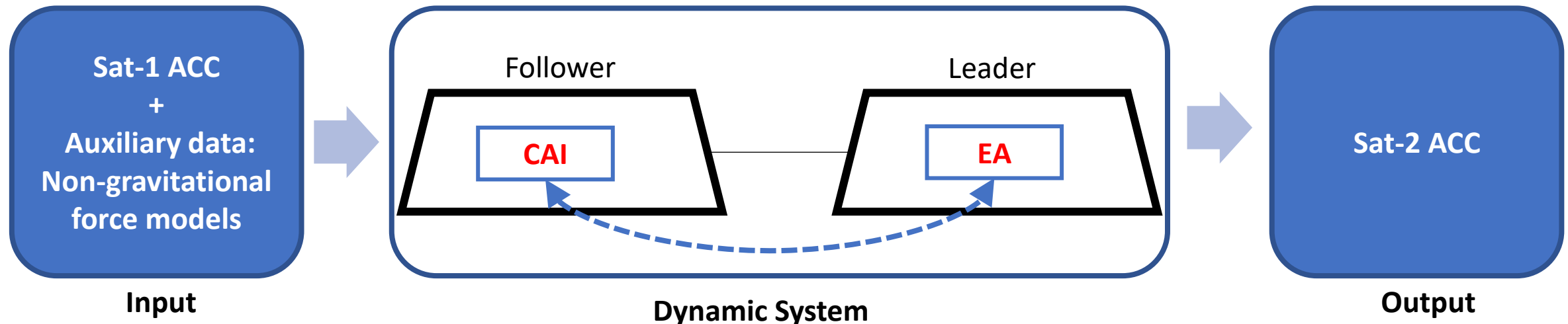


Can we reduce the number of configurations required for comparable gravity field performance while reducing mission complexity and cost?

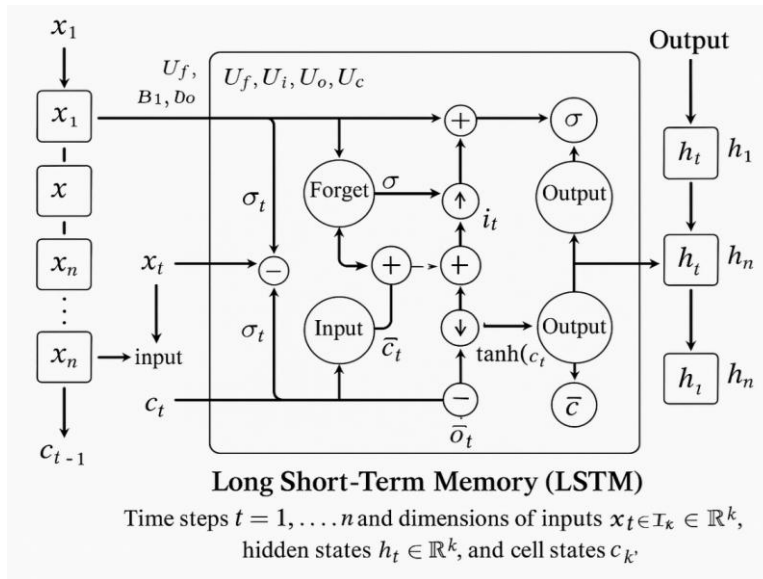




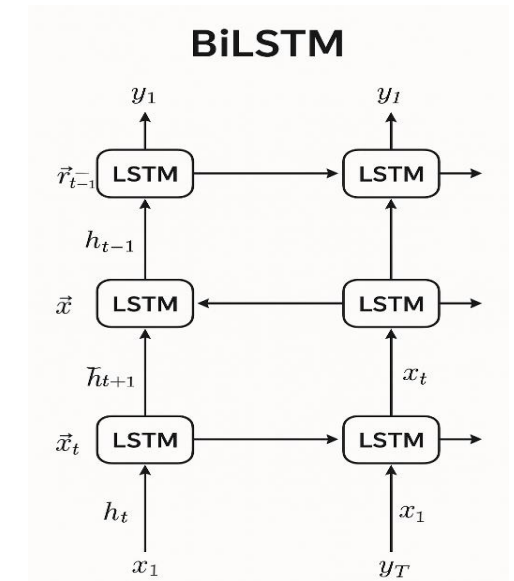
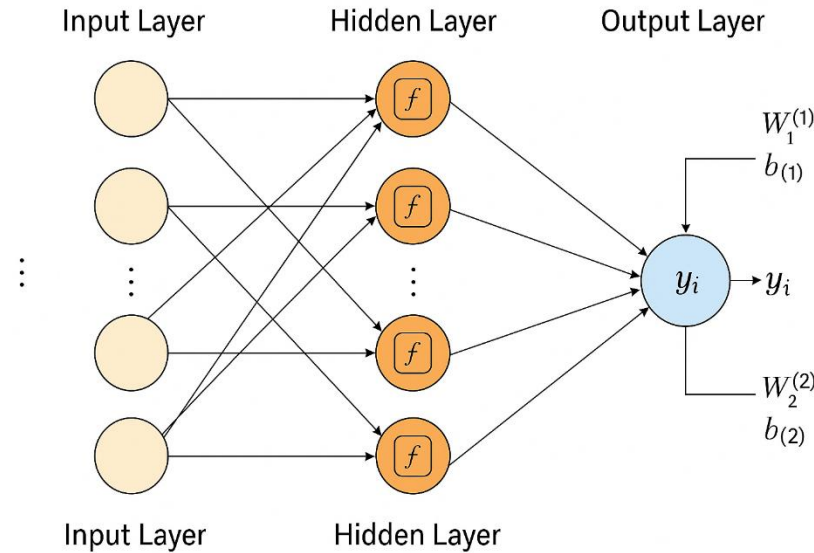
- ✓ **Objective:** Improve the transplant process by
- Assuming a dynamic system with ACC data of one spacecraft as input and other spacecraft's ACC data as output.
 - Using ML algorithms for the recovery of missing data based on available measurements and non-gravitational force models.
 - Learning relationship between the non-gravitational accelerations experienced by the two spacecraft.
 - Capturing **complex relationships** that the conventional analytical transplant method may not fully represent.



ML-based Transplant



LSTM approach



✓ Three different architectures have been investigated in this study

- **Multilayer Perceptron (MLP):**

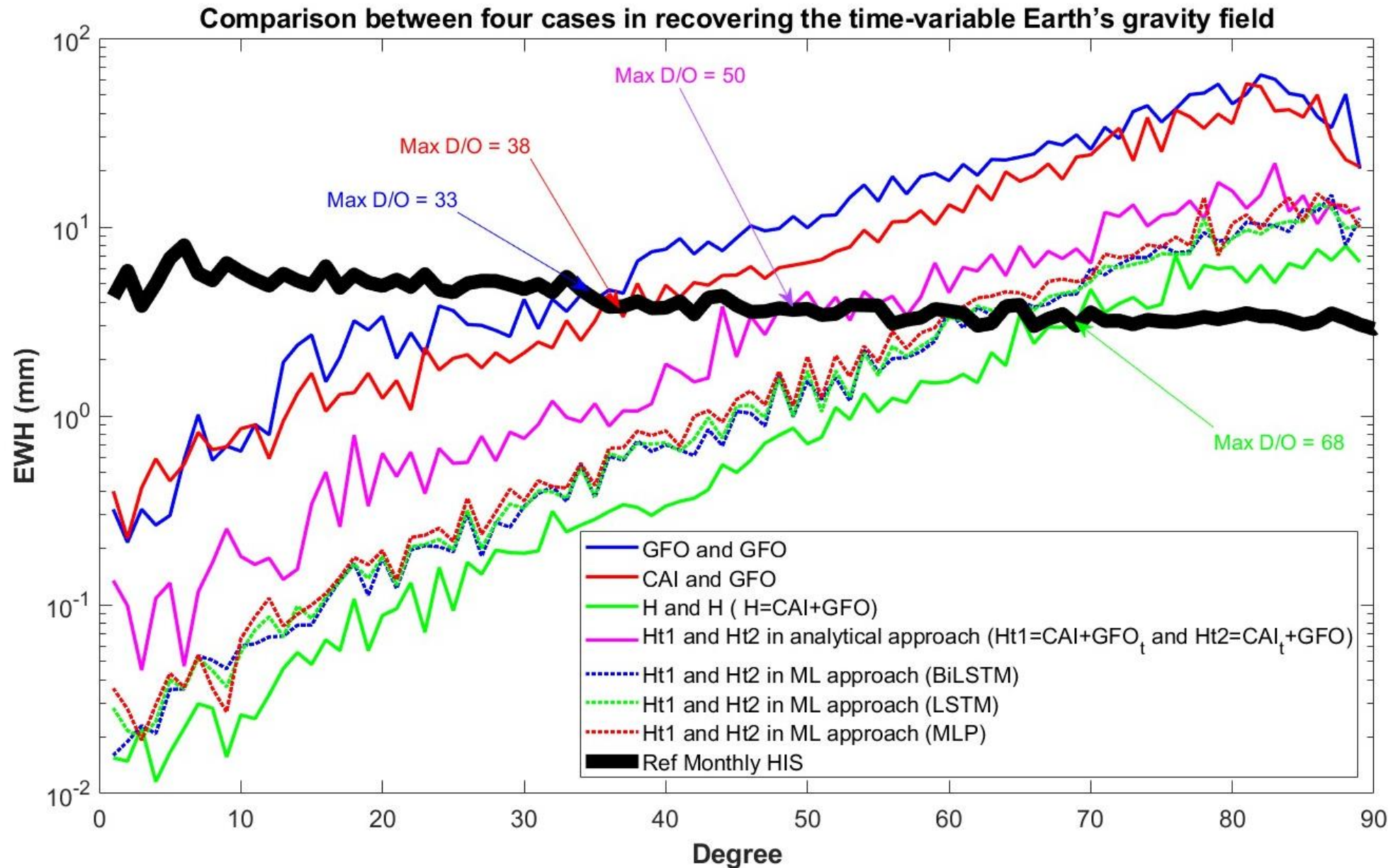
As a baseline model, Capture nonlinear relationships.

- **Long Short-Term Memory (LSTM):**

Designed for sequential data, Learn both short- and long-term temporal dependencies.

- **Bidirectional LSTM (BiLSTM):**

Processes the sequence in both forward and backward directions



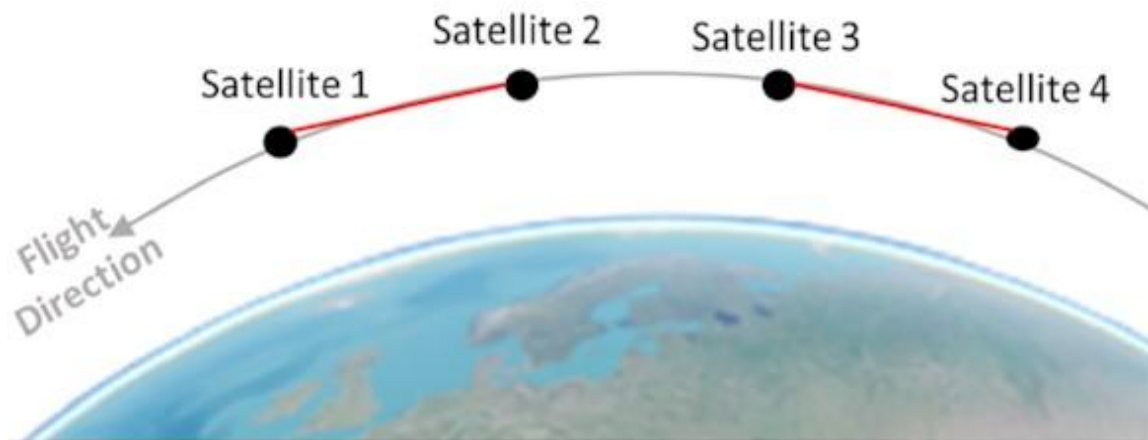
- Hybrid EA–CAI accelerometers offer improved measurement performance for future satellite gravimetry missions.
- Accelerometer transplantation enables reduced-sensor configurations while maintaining useful gravity-field recovery performance.
- Machine-learning-based transplantation significantly improves the recovered gravity field compared with the analytical transplant approach.
- The proposed ML-based configuration approaches the ideal hybrid performance while requiring fewer onboard accelerometers, reducing mission complexity and potentially cost.

Thank you for your attention.

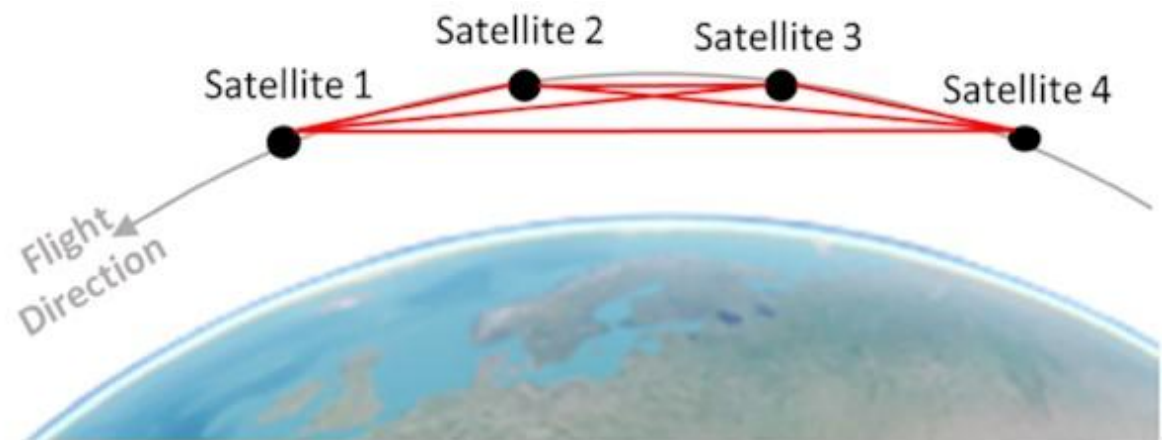
Backup Slides

✓ Advantages of Small Satellite Constellations

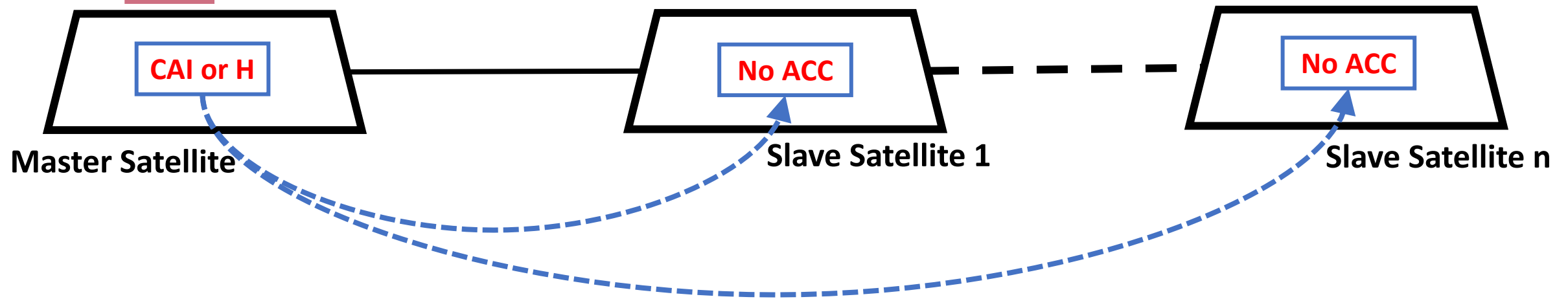
- Reduced temporal aliasing (main limiting factor in satellite gravimetry missions)
- Higher spatio-temporal resolution
- Sub-daily gravity field recovery
- Lower mission cost through miniaturization and scalable constellations



✓ **Pair-wise formation with single inter-satellite link**



✓ **Pearl-string formation with multi inter-satellite link**



✓ Why Accelerometer Transplantation?

- High-precision, complex sensors are not required on all satellites
- Reduction of mission cost and technical complexity

✓ Advantages

- Provides virtual high-quality accelerometer data in Slave satellites
- Scalable for large constellations
- Supports quantum sensor integration (CAI) efficiently
- Improves feasibility of (cheaper) next-generation gravimetry missions