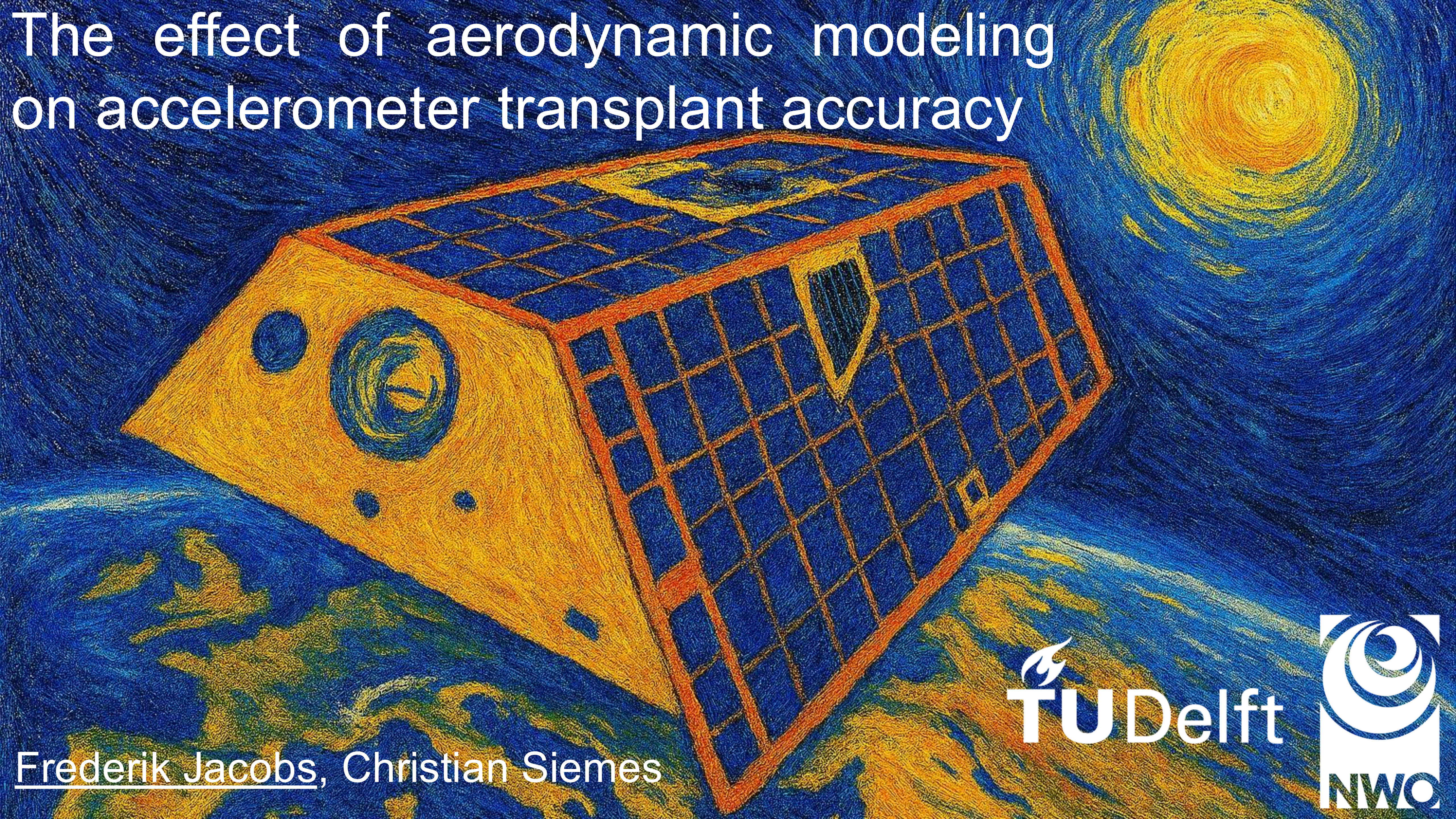
The effect of aerodynamic modeling on accelerometer transplant accuracy



Frederik Jacobs, Christian Siemes

Accelerometer issues of GRACE/-FO

- Accelerometers measure the non-gravitational accelerations, so that the effect can be removed from the ranging measurements

- Accelerometer issues
  - **GRACE-B:** Turned off in 2016 to save power
  - **GRACE-D:** Noise levels increased a few weeks after launch
- With one accelerometer malfunctioning or being turned off, time-variable gravity field models are (much) less accurate

→ Solution? Transplant!

- Modeled accelerometer product to replace the malfunctioning accelerometer
  - Developed since 2006 (Save, 2006)

Transplants

Existing transplants

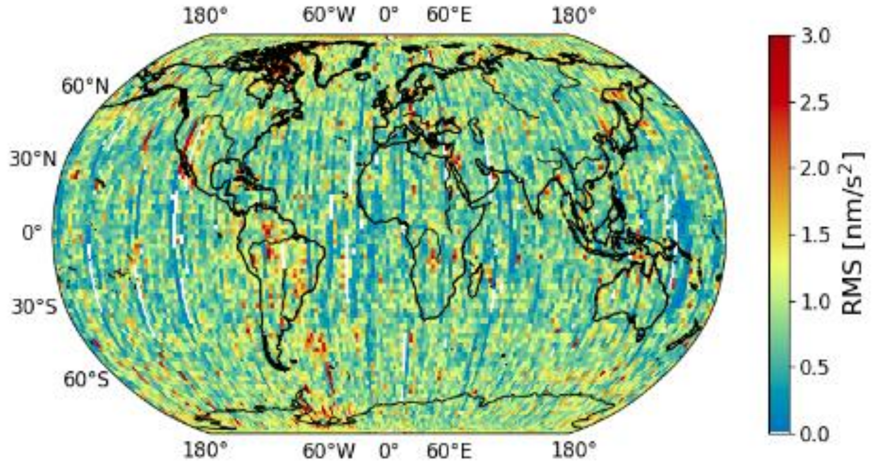
- JPL (Bandikova ,2019; Harvey, 2022; Harvey, 2024)
- ZARM (University of Bremen) (Huckfeldt, 2023)
- TU Graz (Behzadpour, 2019)
- Leibnitz University Hannover (Romeshkani, 2025)

Each transplant has its own methodology and assumptions

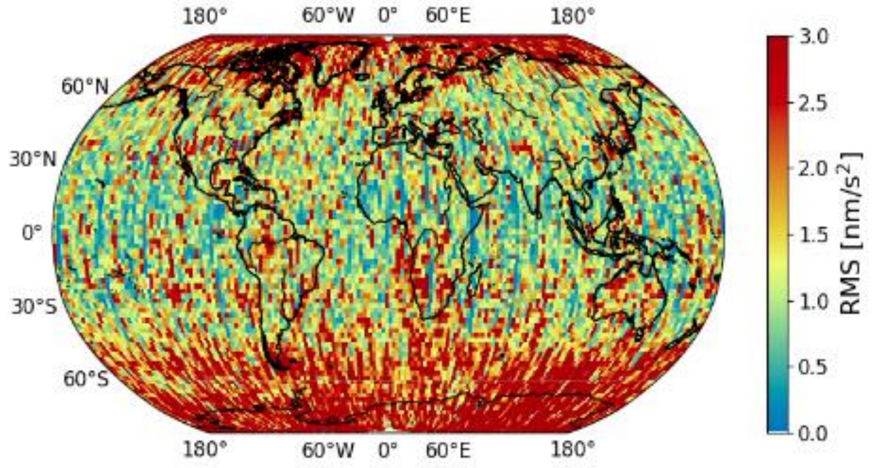
- Attitude correction
- Aerodynamic/radiation/thruster models
- Machine learning

→ But increased post-fit residual RMS

January 2003: before transplant era



January 2017: transplant era

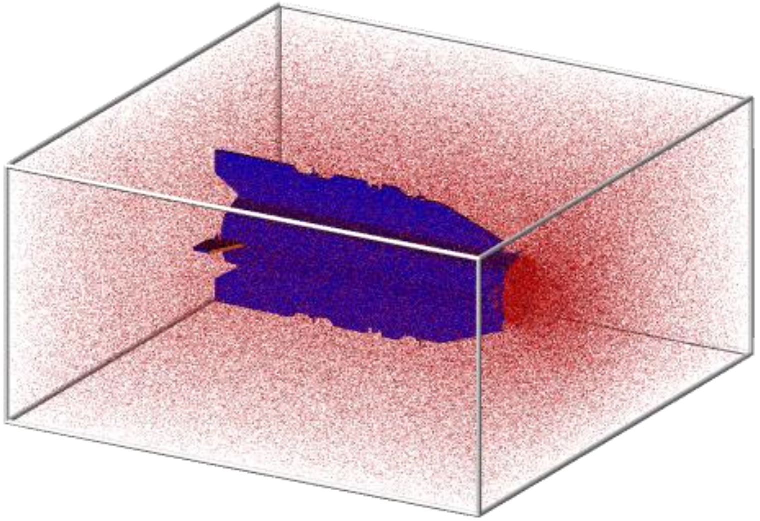


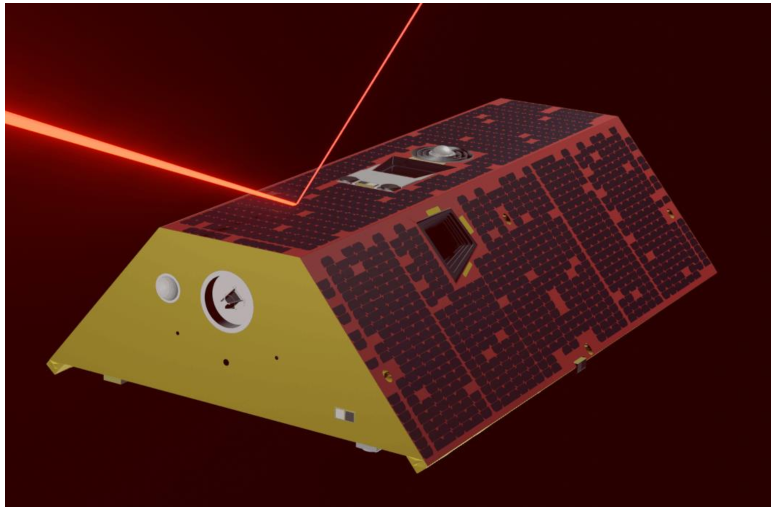
TU Delft

Figure courtesy: Cuadrat-Grzybowski, 2025

Why a TU Delft transplant?

- Expertise in density processing: high-fidelity modeling
- Aerodynamics:
  - DSMC aerodynamic force coefficients (March, 2019)
  - Cross-wind and density retrieval (Doornbos, 2010)
- Radiation pressure (Hładczuk, 2024)
  - Ray-tracing radiation tables
  - Thermal inertia
- Could lift the accuracy of the transplant to a higher level

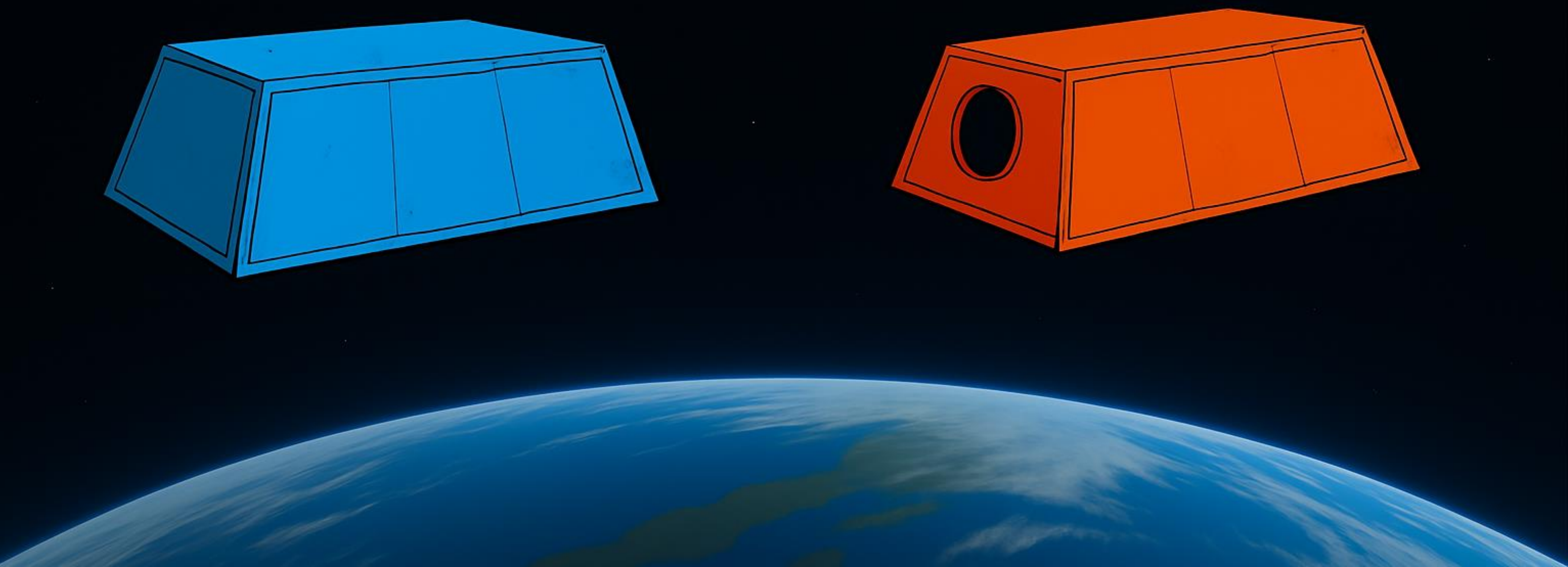




Images from http://thermosphere.tudelft.nl

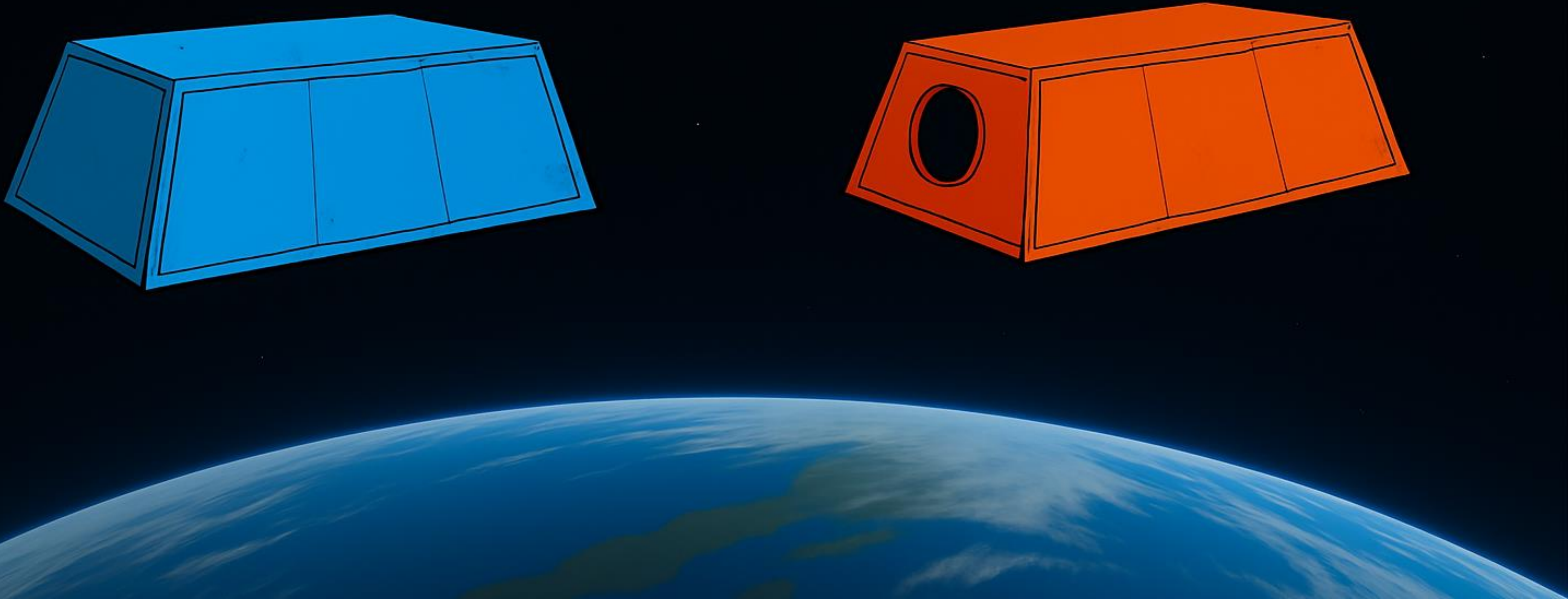
Transplant methodology

Acceleration → Density and wind



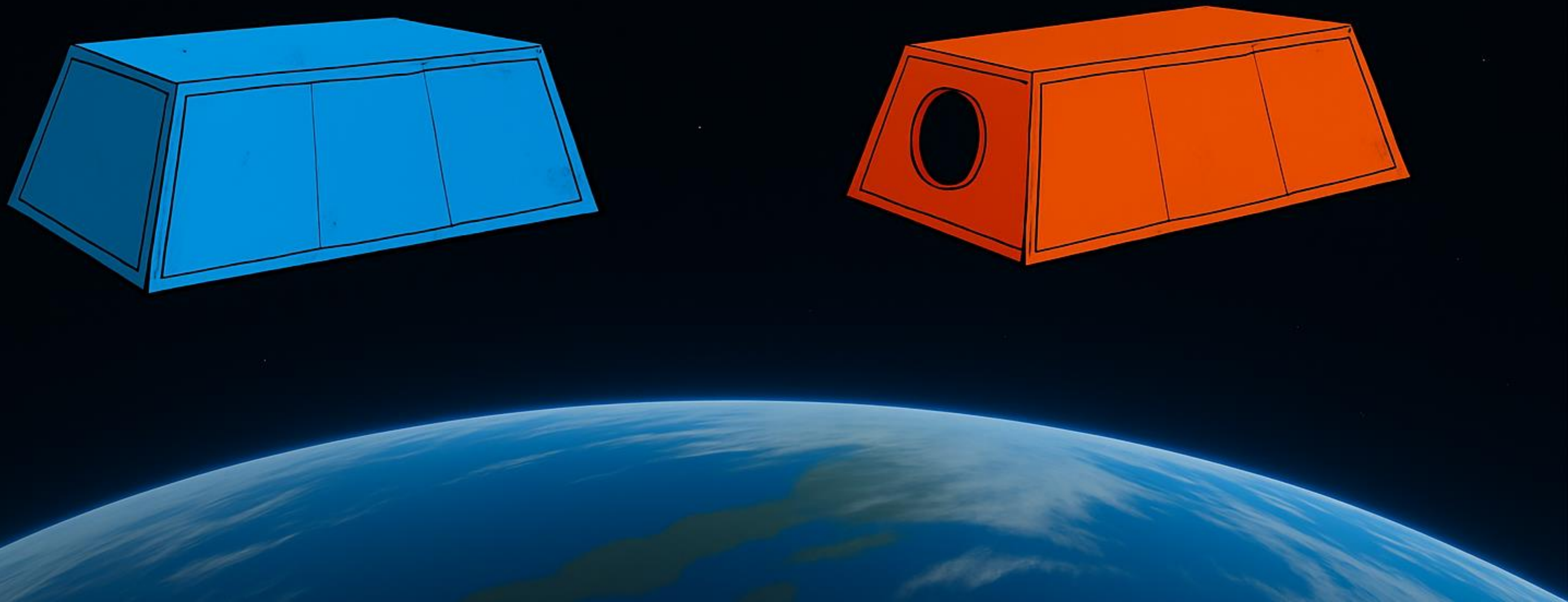
Transplant methodology

Acceleration → Density and wind → Density and wind → Acceleration



Transplant methodology

Density and wind → Acceleration



How can we validate transplants?

Need to know the accuracy of the transplant

Typically, transplants are only **produced when one accelerometer is down**

→ It cannot be compared to the other accelerometer

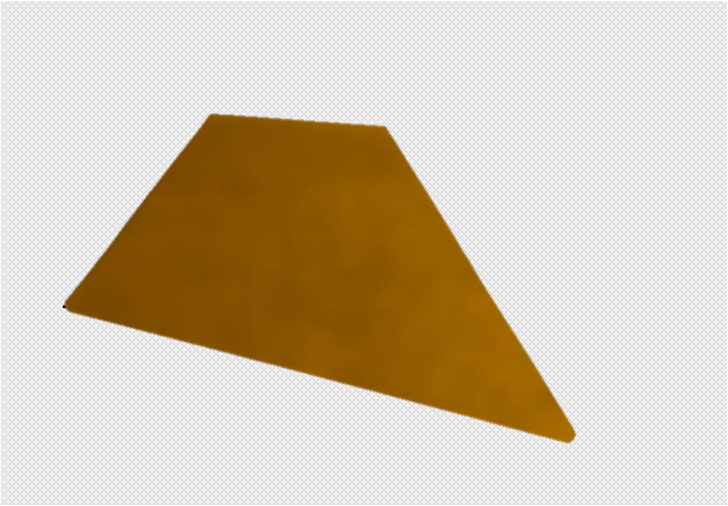
Select two reference years for GRACE for which both accelerometers were operational

- 2003: high solar activity; aerodynamically dominated
- 2009: low solar activity; radiation pressure dominated

Compare the transplant (from GRACE-A to GRACE-B) to the accelerometer (GRACE-B)

This presentation focuses on aerodynamic modeling → 2003

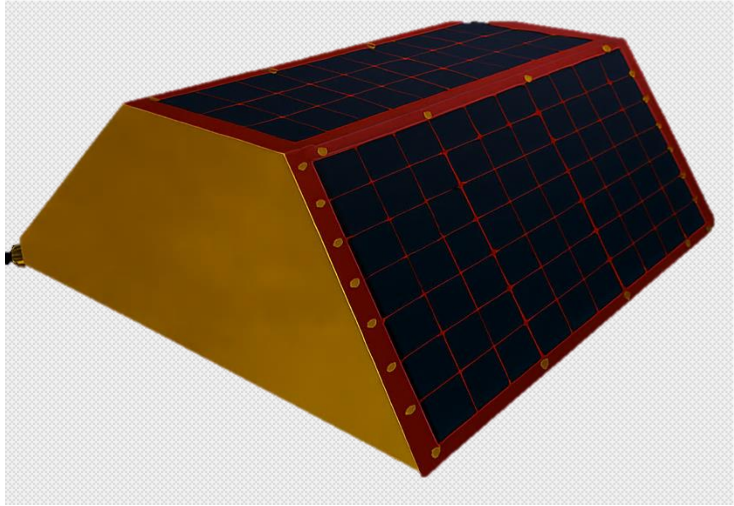
Aerodynamic models



Constant drag coefficient (2.4)

Drag

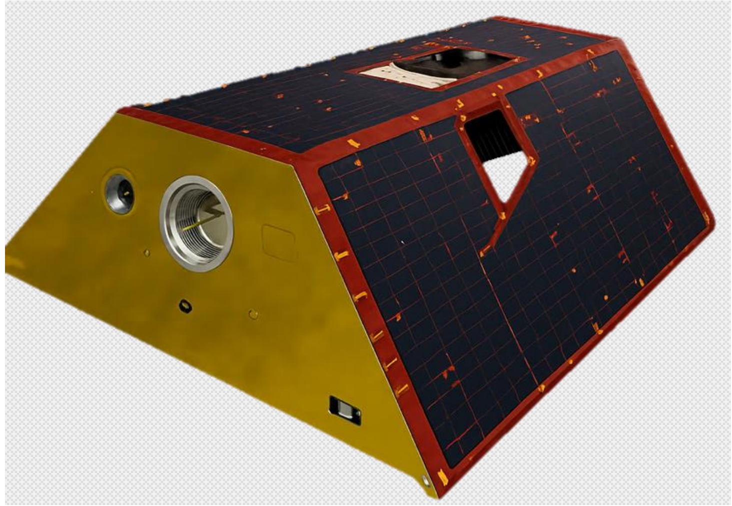
$$\vec{F}_D = \frac{1}{2}\rho v C_D A_{proj}\vec{v}$$



Panel model (Sentman, 1961)

Drag and lift

$$\vec{F}_D = \sum_i \frac{1}{2}\rho v^2 A_i\left(C_{D,i}\vec{e}_D + C_{L,i}\vec{e}_{L,i}\right)$$



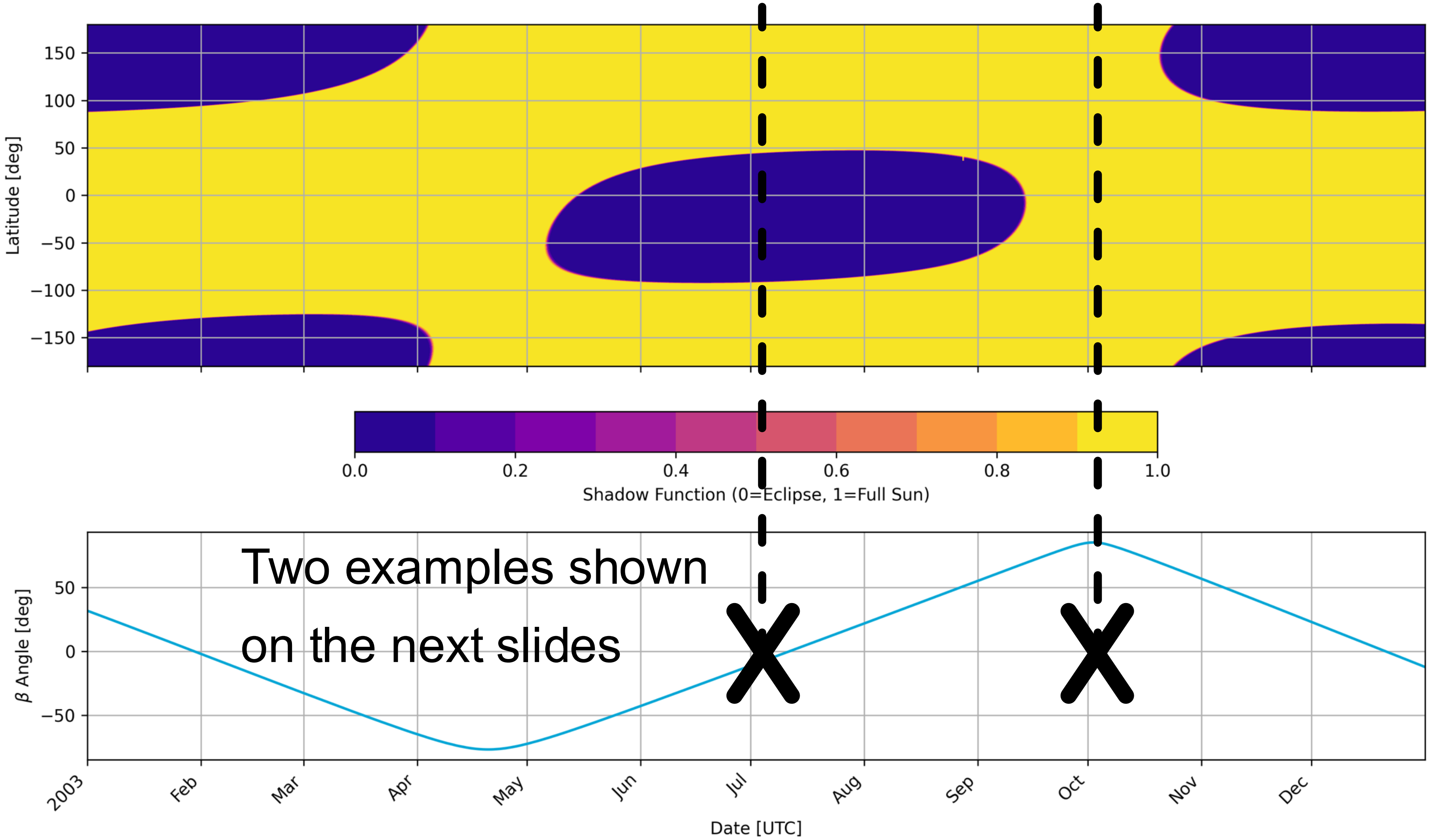
DSMC simulations (Bird, 1994)

Drag, lift, multiple reflections and shadowing

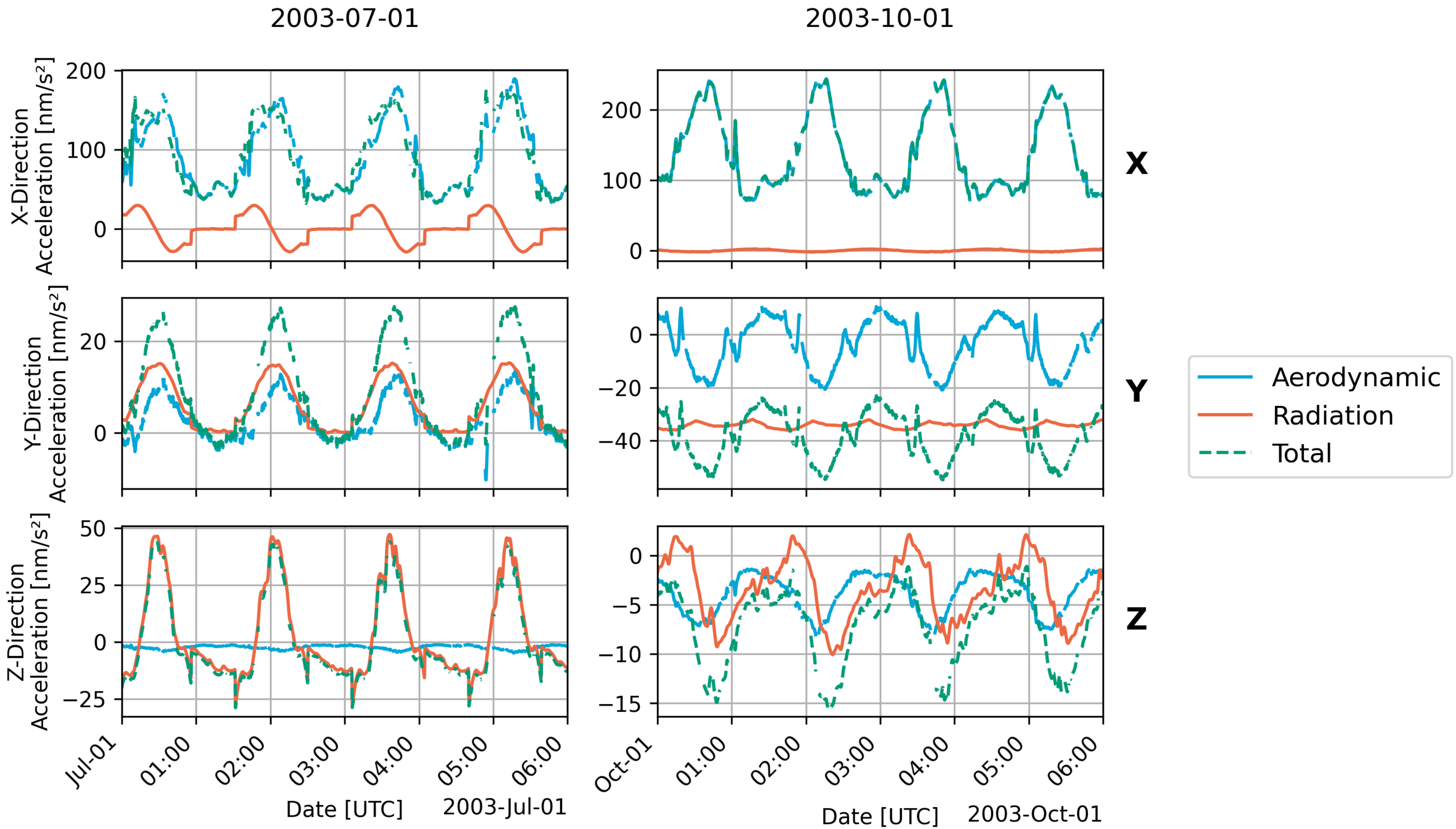
$$\vec{F}_D = \frac{1}{2}\rho v^2 A_{ref}\vec{C}$$

Image adapted from https://gracefo.jpl.nasa.gov/mission/overview/

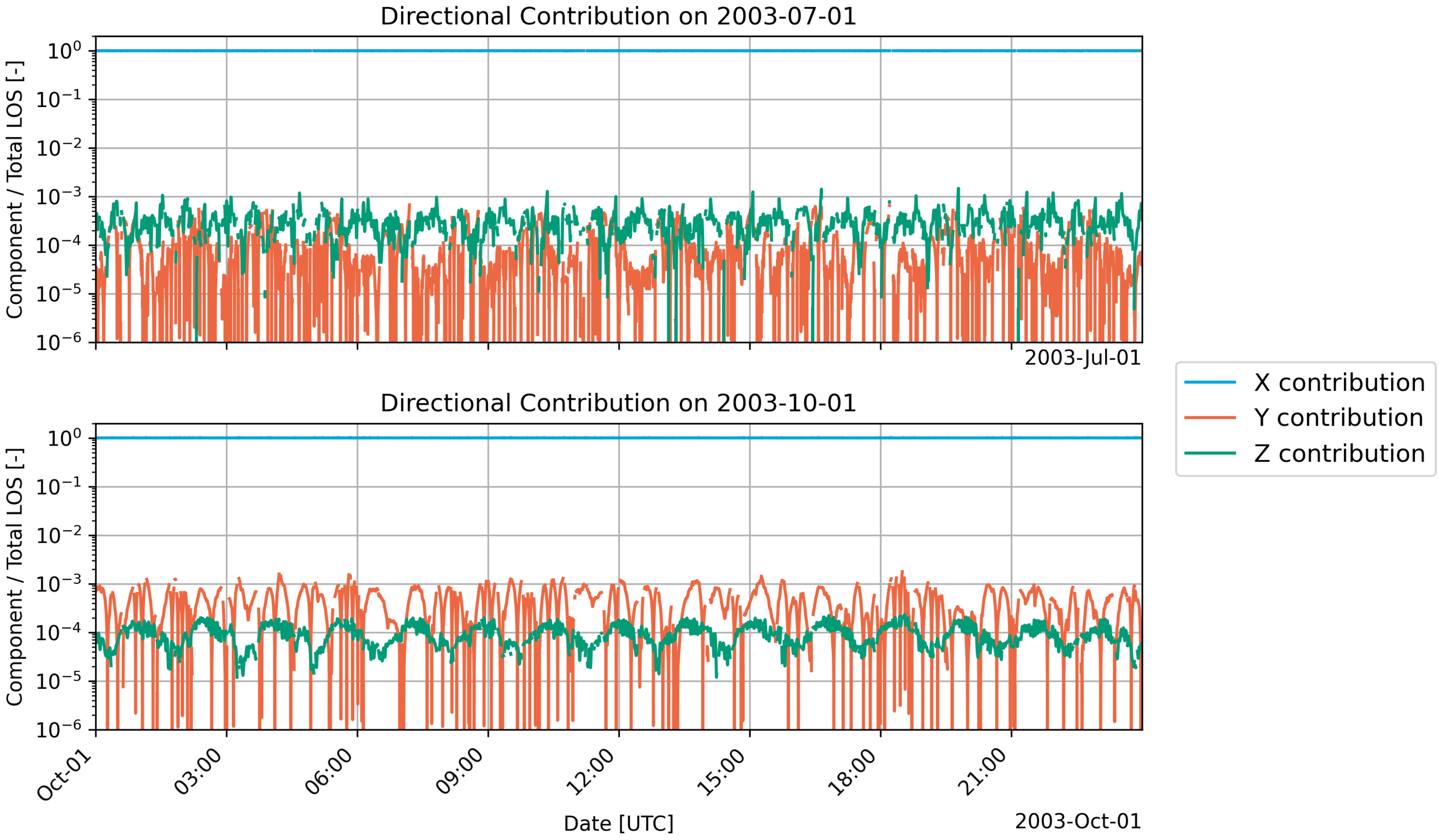
Shadow function and β angle sun



Two examples shown on the next slides

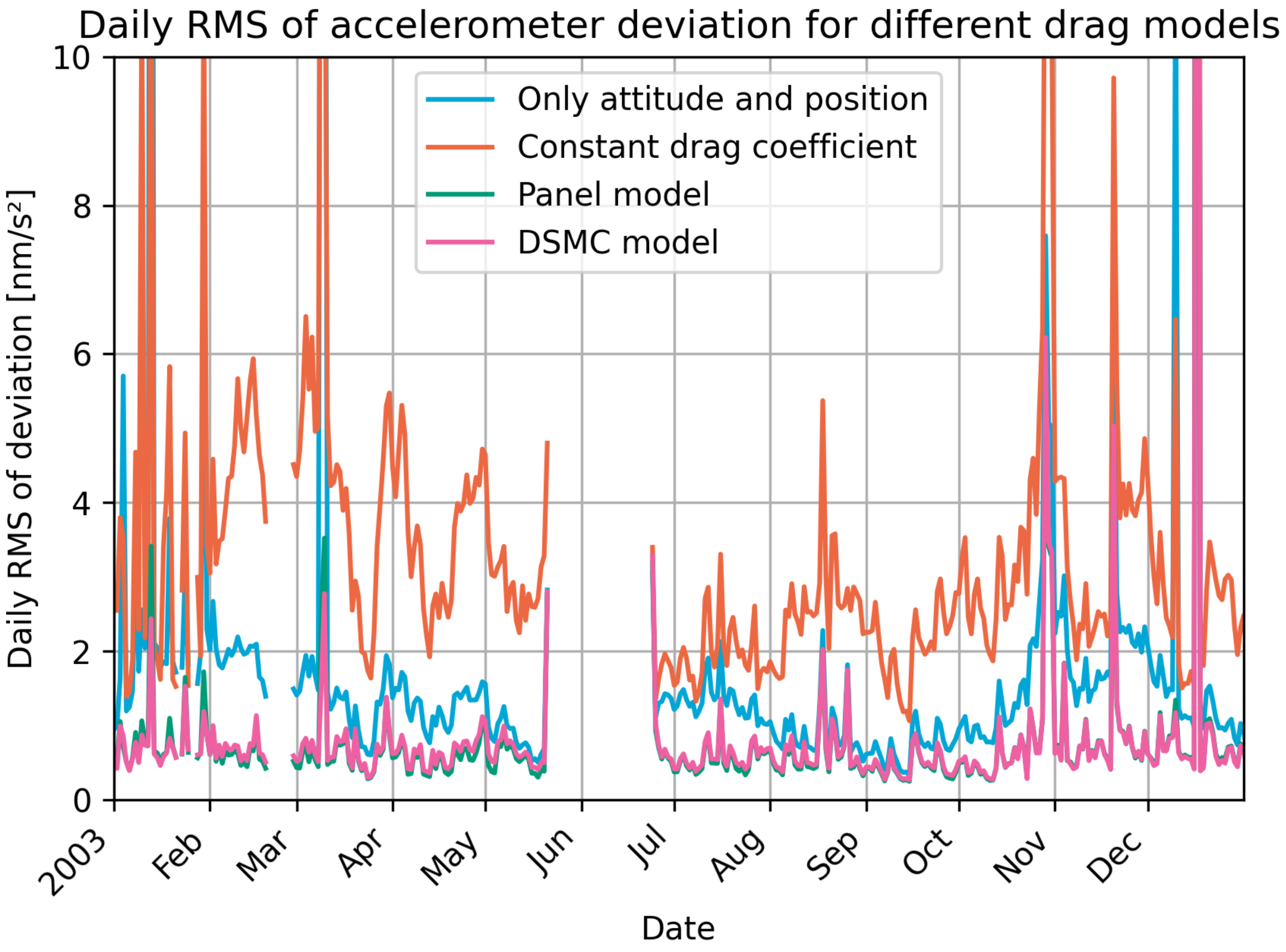


2003-07-01
2003-10-01
X-Direction Acceleration [nm/s²]
Y-Direction Acceleration [nm/s²]
Z-Direction Acceleration [nm/s²]
X
Y
Z
Aerodynamic
Radiation
Total
Date [UTC]
2003-Jul-01
2003-Oct-01

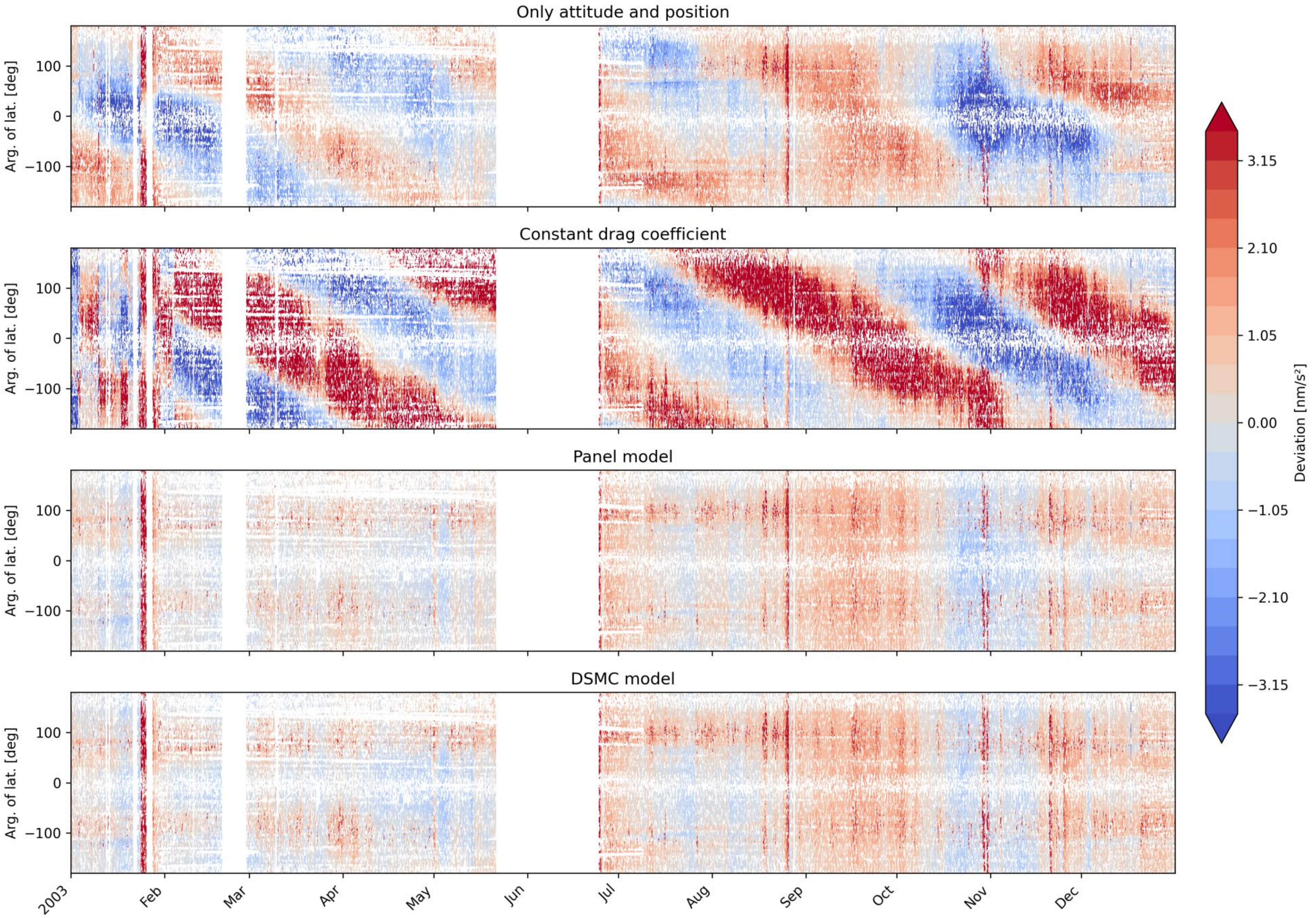


Directional Contribution on 2003-07-01
Component / Total LOS [-]
2003-Jul-01
Directional Contribution on 2003-10-01
Component / Total LOS [-]
Oct-01
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Date [UTC]
2003-Oct-01
X contribution
Y contribution
Z contribution

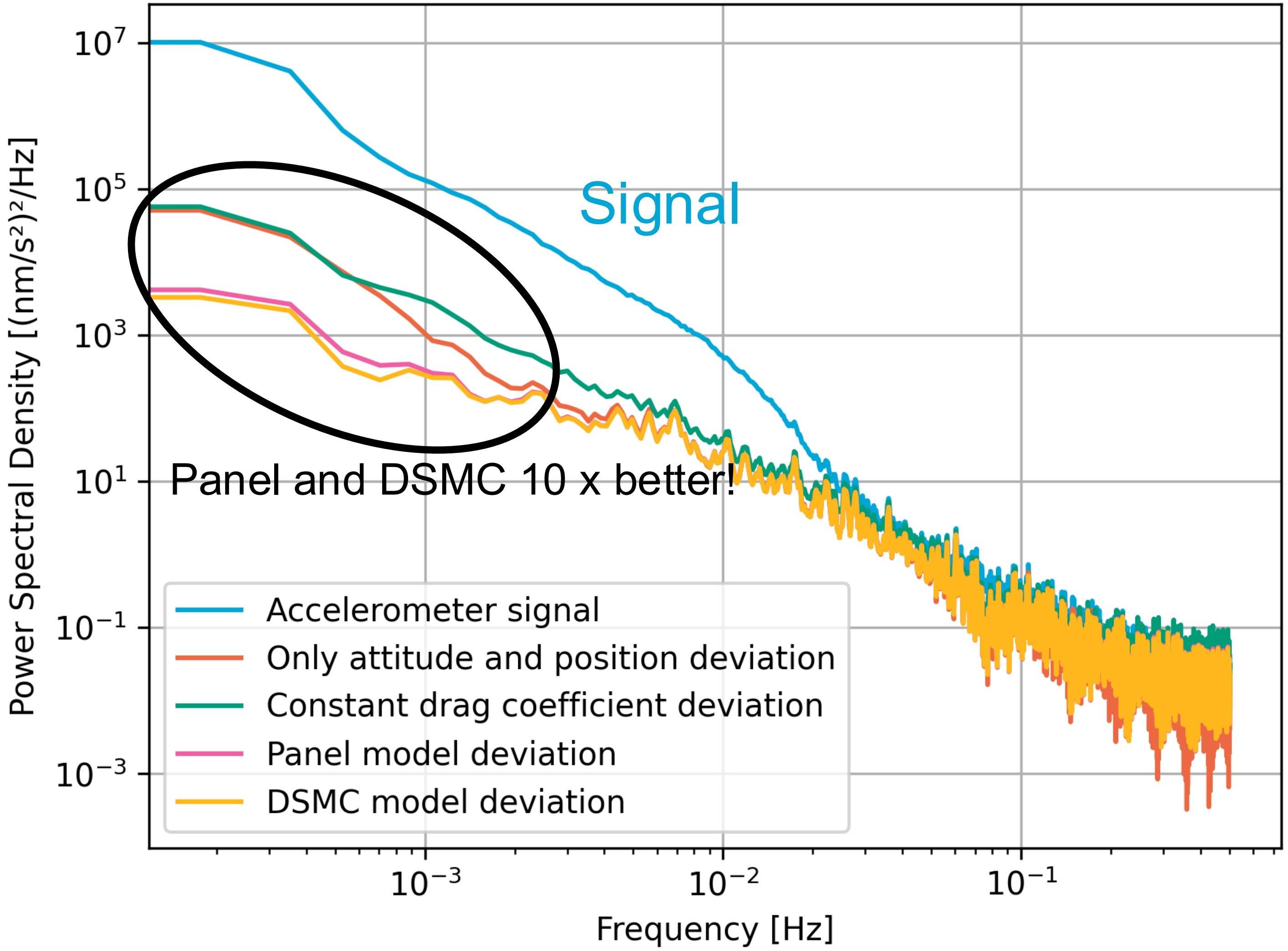
Case study: aerodynamic model LOS



The deviation between transplant and accelerometer



PSD – window 1 orbit



Conclusions and looking forward

Aerodynamic model matters!

- Constant drag coefficient performs worst
- Panel and DSMC perform (almost) equally well

Future research

- Radiation model effect
- Thruster firings
- Investigate the effect of improved transplant on gravity field models

Transplant software (Python) will be made open-source after first publication

Questions? → Frederik Jacobs: F.Jacobs@tudelft.nl

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