High precision orbit simulations for geodesy and fundamental physics missions

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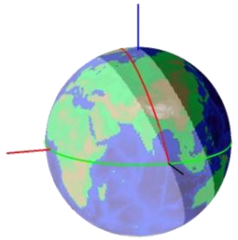
Why high precision simulations?

- Detailed insight into complete system and its interactions before mission launch:
  - Dependencies
  - Aging/degeneration effects
  - Coupling effects into „science“ signal
  - Development of calibration methods based on knowledge of sensors on ground

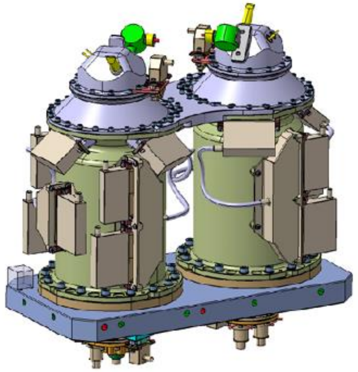
- Preparation of data processing and data analysis methods during mission
  - Development of appropriate routines/applications for data analysis
  - Provide improved models for orbit determination processes

- Support analysis of science signal after mission
  - Explanation of unknown effects in science signal
  - Calibration of sensors

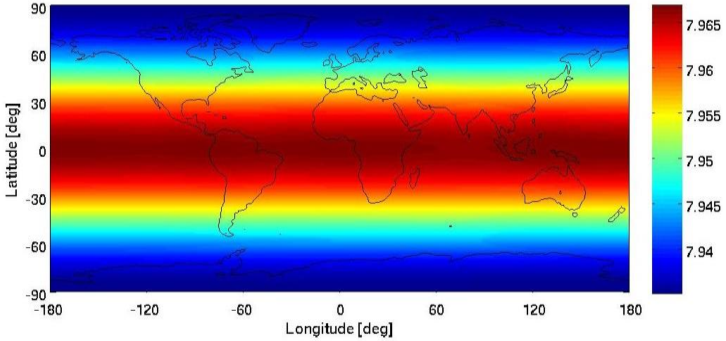
Orbit dynamics



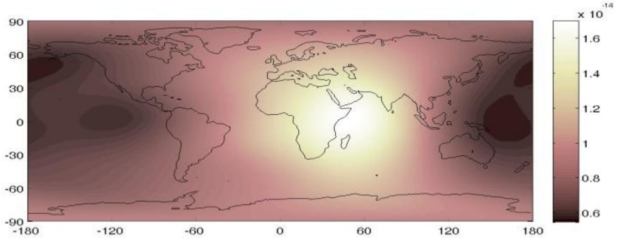
Special requirement of mission: **Payload**



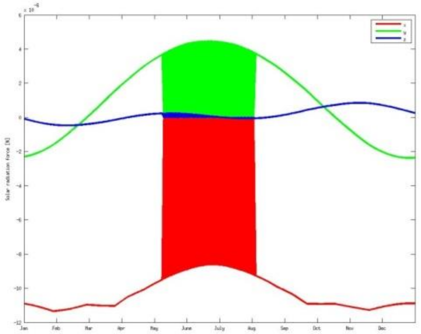
Gravity field of the Earth



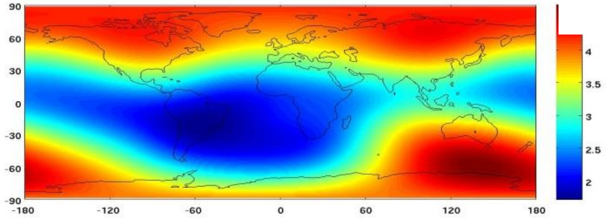
Atmosphere



Solar radiation pressure and eclipse



Magnetic field



- Albedo radiation
- Earth infrared radiation
- Space debris
- Ephemerides
- …

Outline

- HPS: Hybrid simulation Platform for Space systems
  - Concept
  - Structure
  - Moduls
- Fundamental physics: MICROSCOPE
  - Mission and measurement principle
  - Solar radiation pressure
- Geodesy mission: GRACE
  - Mission
  - Calibration
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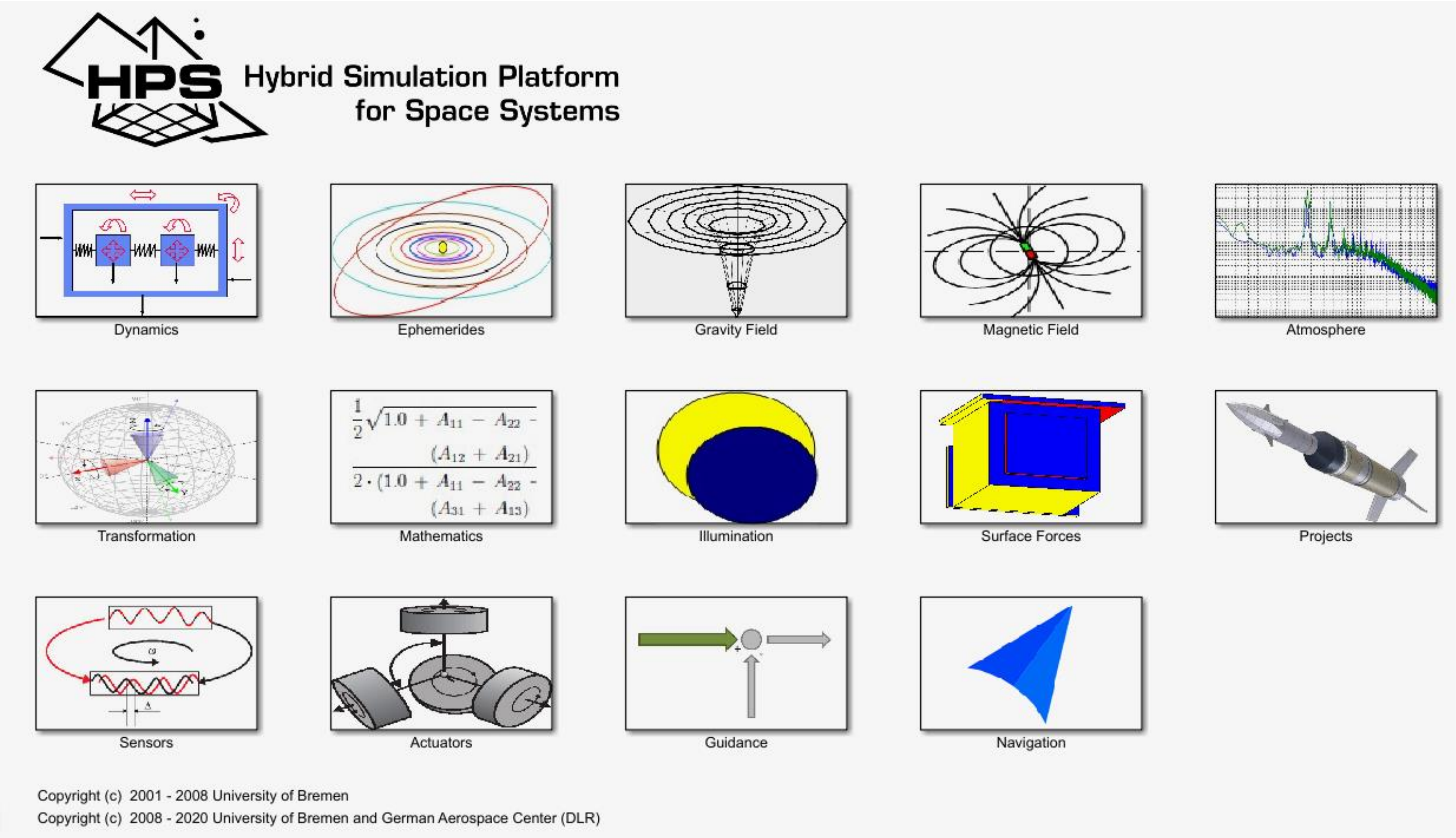
Hybrid simulation platform for space systems



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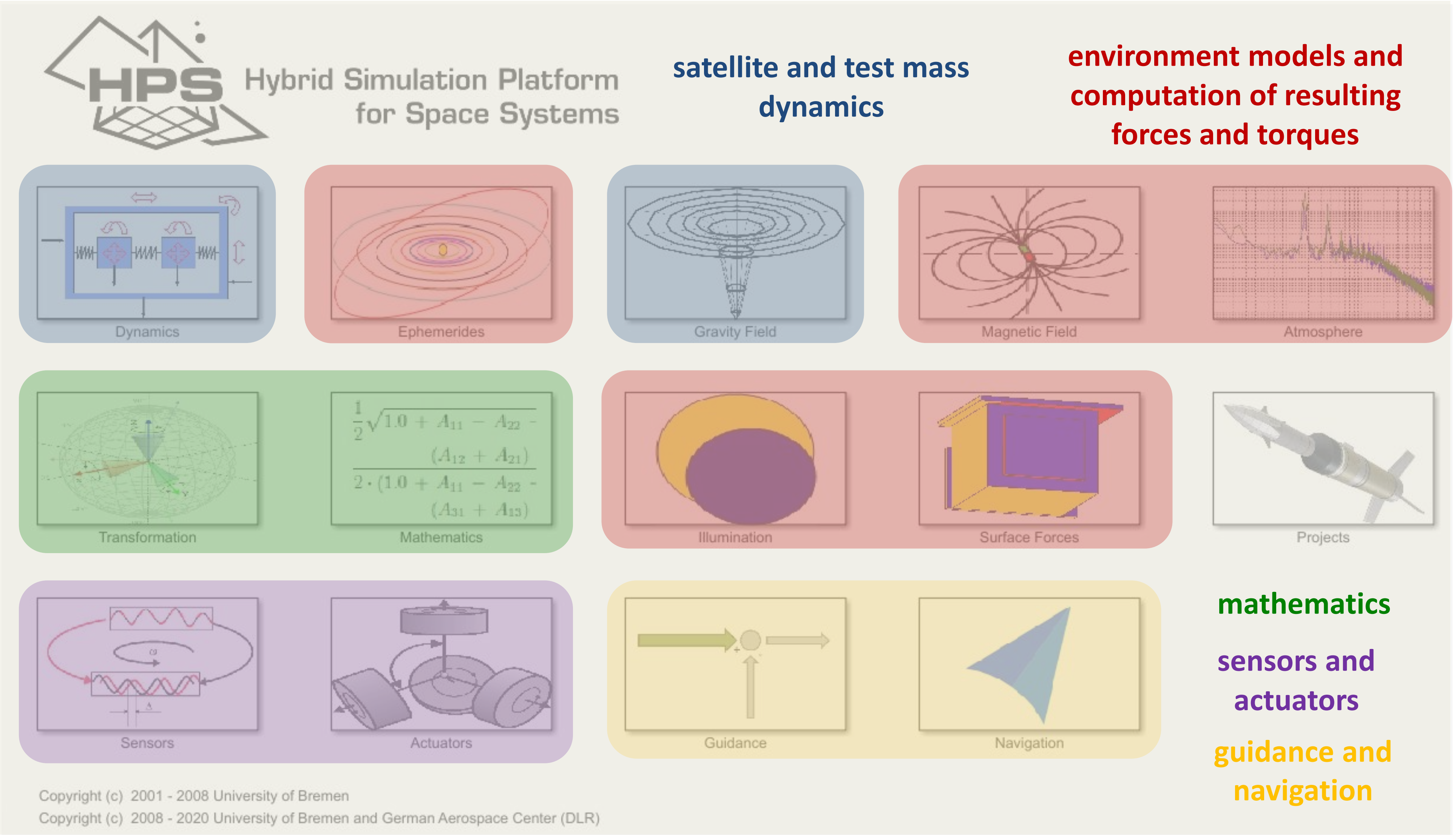
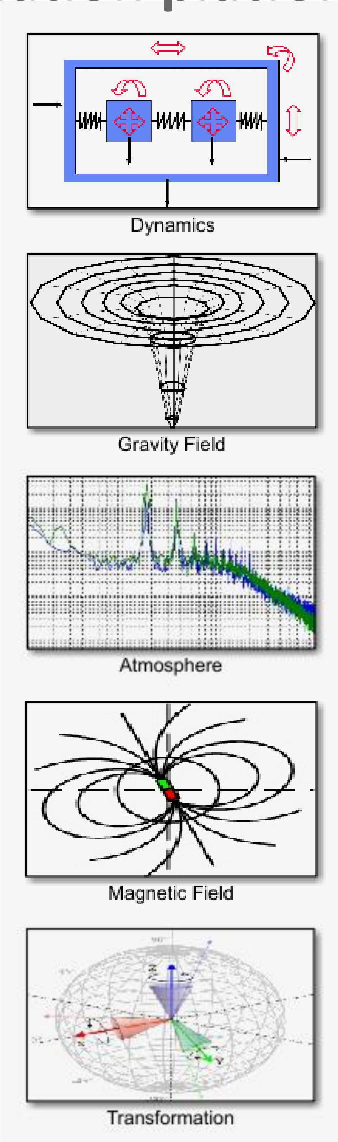
Hybrid simulation platform for space systems



Hybrid simulation platform for space systems



Equations of motion for

- satellite COM, multibody COMs, testmasses (up to 8)
- 13 states each, 6 DOF

Gravitational field of the Earth / Gravity gradient

- spherically symmetric
- including Earth‘s oblateness and rotation (J2)
- full models

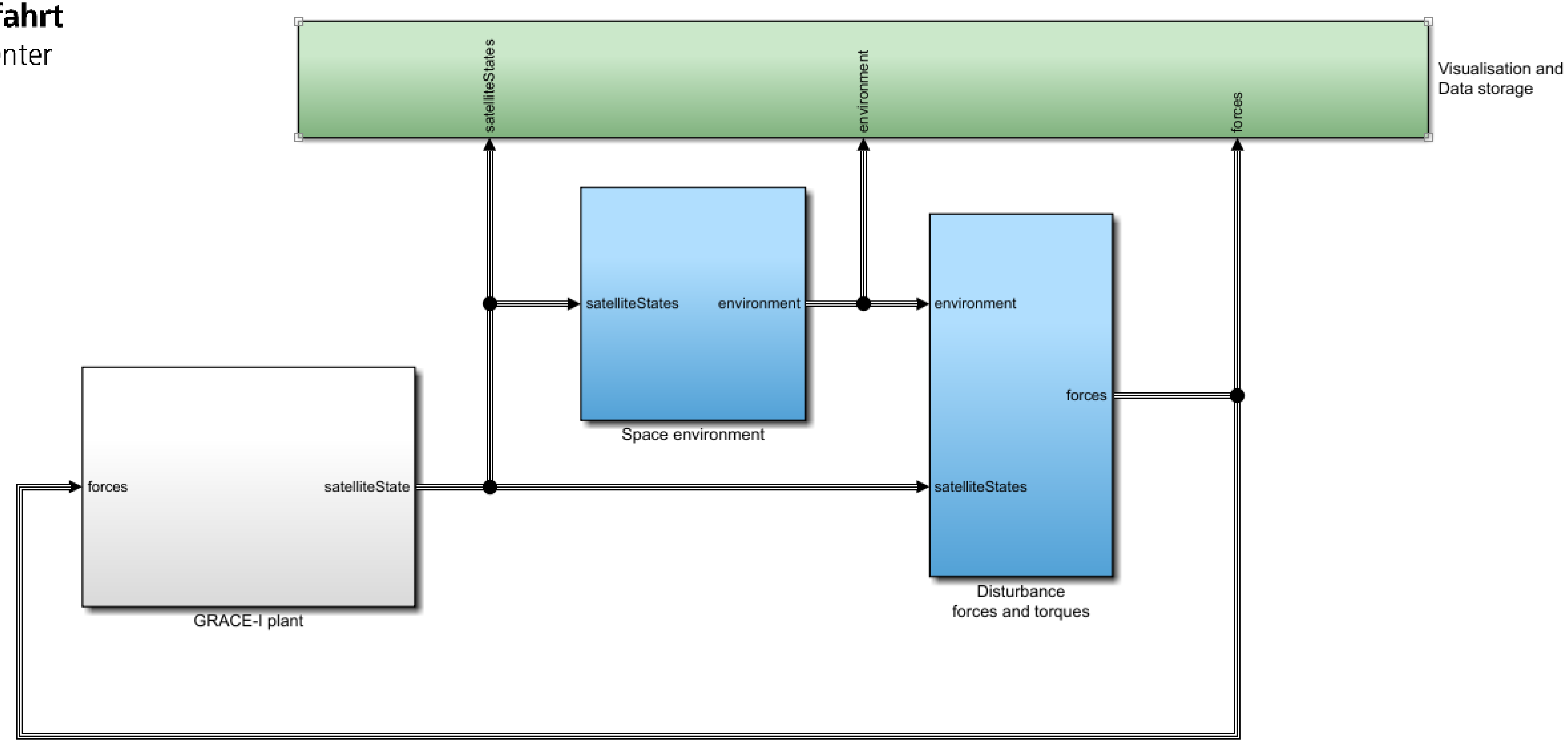
- HWM93
- NRLMSISE00
- Harris Priester
- Jacchia Bowman

- IGRF
- Tsyganenko

- Time frame conversions
- Direction consine matrices between coordinate frames

Hybrid simulation platform for space systems

Deutsches Zentrum
DLR für Luft- und Raumfahrt
German Aerospace Center



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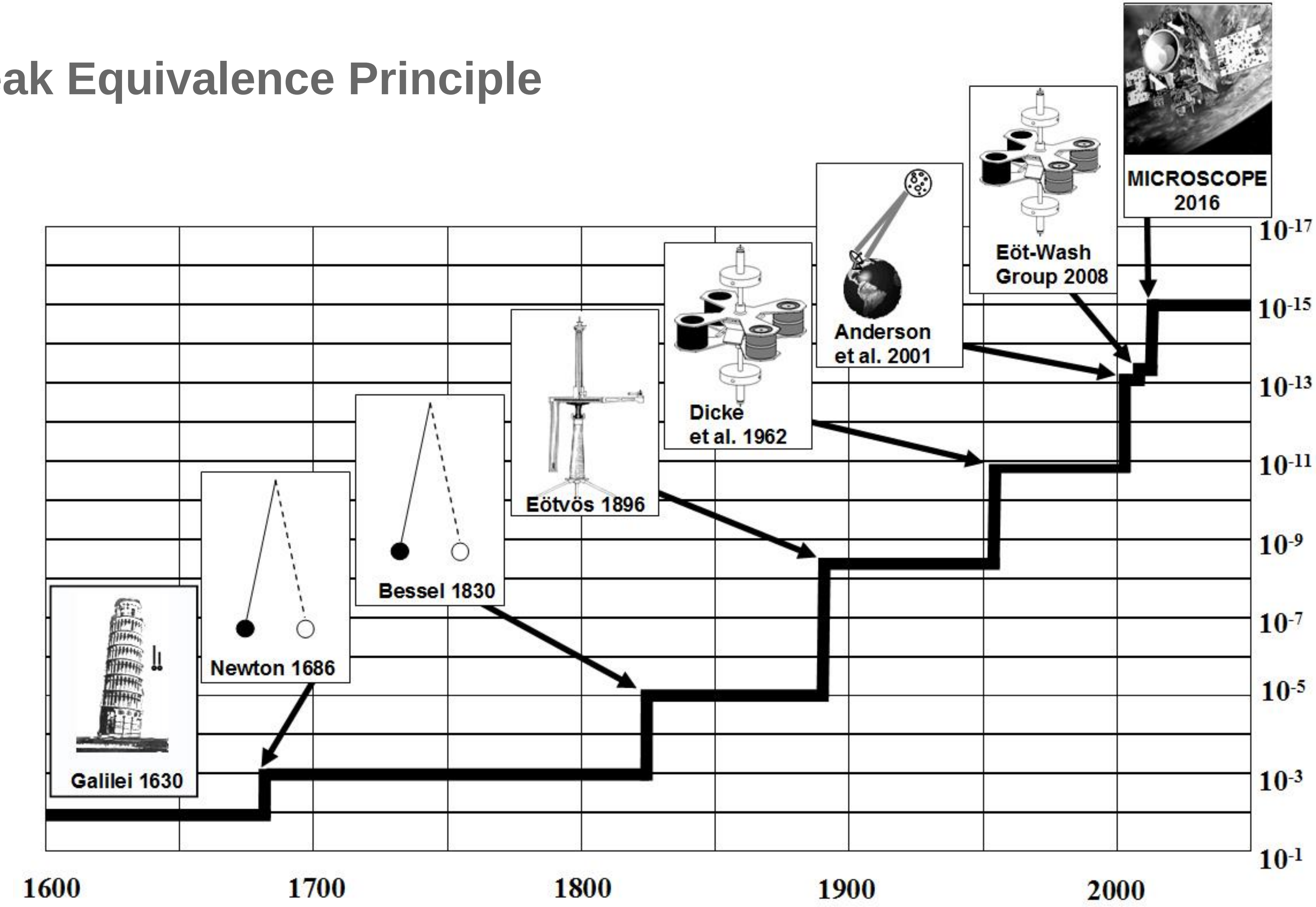
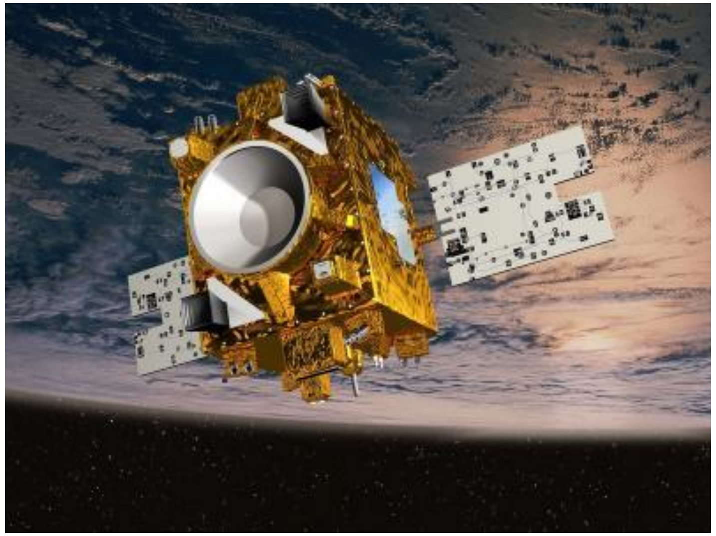
The Weak Equivalence Principle



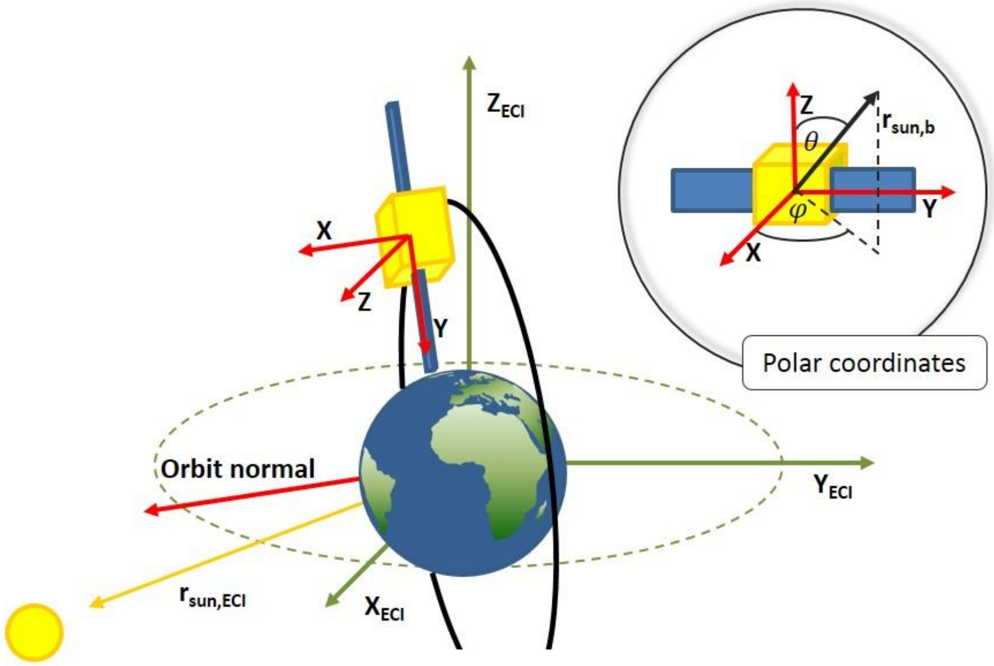
MICROSCOPE - Overview

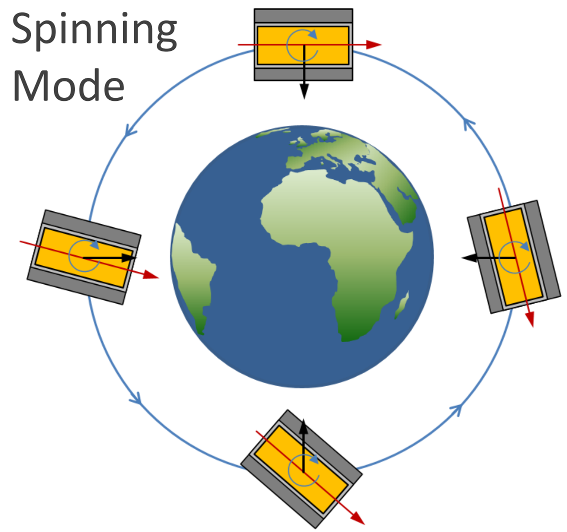


- Aim of the MICROSCOPE mission:
  Test of WEP → $\eta = 10^{-15}$
- Satellite: CNES
- Payload: ONERA
- Planned launch date: 22.4.16

ZARM/DLR:
- Free-fall tests of Payload
- Data processing and analysis (member of SWG)
- Analysis of post-mission data sets
- Validation of mission simulator

Measurement

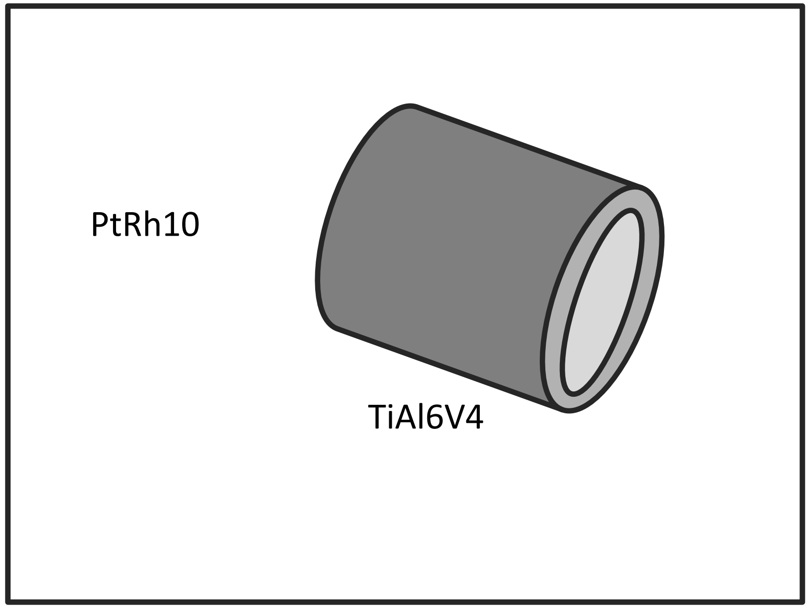


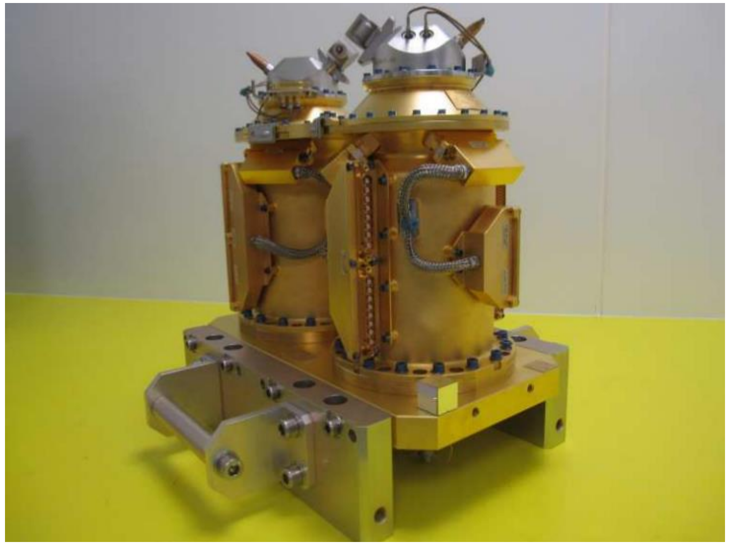


$f_{EP} = f_{orbit} + f_{spin}$ = 0.9E-03 Hz / 3.1E-03 Hz

- Sun-synchronous orbit (SSO),
  Dawn/Dusk orbit, 710 km height
- Two modi of measurement
  - inertial
  - spinning

Payload





- T-SAGE
- Servo-loop control of position of test masses: 18 electrodes each (engraved on silica parts)
- Electrostatic forces are exerted capacitively without any mechanical contact
- thermally isolated, centered in satellite bus
- Thermal stability @f_{EP}:
  - 1mK (SU), 8mK (FEEU)
- Relative position resolution:
  - 3×10^{-11} m/Hz$^{-1/2}$
  - (bandwidth: 2×10^{-4} Hz, 1 Hz)

Data analysis: Measurement

$$\vec{\Gamma}_{\mathrm{meas,d}} = \vec{K}_{0,\mathrm{d}} + \mathbf{M}_{\mathrm{c}} \left(\eta\vec{g} + (\mathbf{T} - \mathbf{I})\vec{\Delta} - 2\vec{\Omega} \times \dot{\vec{\Delta}} - \ddot{\vec{\Delta}} \right) + \mathbf{M}_{\mathrm{d}}\vec{\Gamma}_{\mathrm{appl,c}} + \vec{\Gamma}_{\mathrm{meas,quad,d}} + \vec{\Gamma}_{\mathrm{n,d}} + \mathbf{C}_{\mathrm{d}}\dot{\vec{\Omega}}$$

$\vec{K}_{0,\mathrm{d}}$	Instrument bias
$\mathbf{M}_{\mathrm{c}}, \mathbf{M}_{\mathrm{d}}$	Sensitivity matrices
$\vec{g}$	Gravitational acceleration, $g \approx 7.9\mathrm{m/s}^2$
$\mathbf{T}$	Gravity gradient
$\mathbf{I}$	Matrix gradient of inertia, $\mathbf{I} = \dot{\mathbf{\Omega}} + \mathbf{\Omega}\mathbf{\Omega}$
$\vec{\Delta}$	Distance between COMs of inner and outer test mass
$\vec{\Omega}$	Angular velocity of satellite
$\vec{\Gamma}_{\mathrm{appl,c}}$	Mean acceleration (due to non-gravitational forces), limited by DFACS
$\vec{\Gamma}_{\mathrm{meas,quad,d}}$	Differential acceleration (non-linear terms, quadratic response of inertial sensors)
$\vec{\Gamma}_{\mathrm{n,d}}$	Instrument noise (thermal noise, electronic noise, parasitic forces), i.e. stochastic and systematic error sources
$\mathbf{C}_{\mathrm{d}}$	Difference of coupling (angular to linear acceleration) between two sensors

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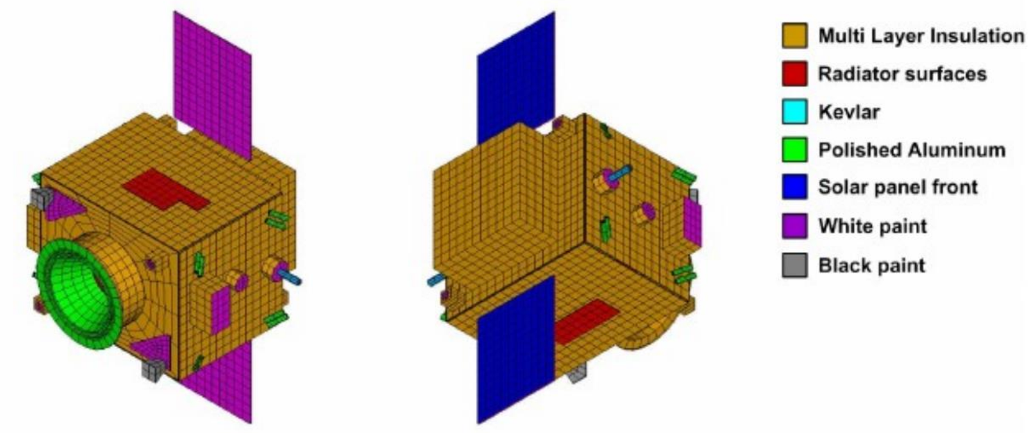
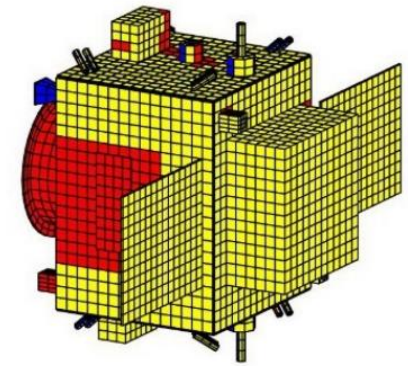
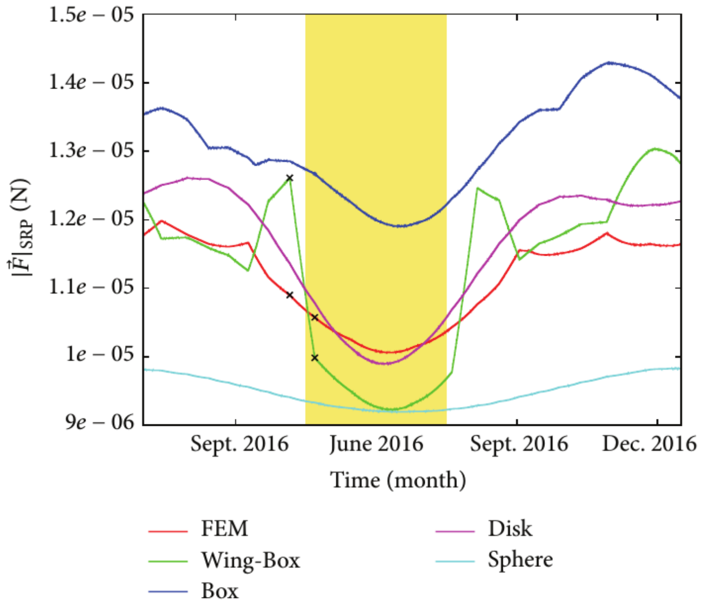
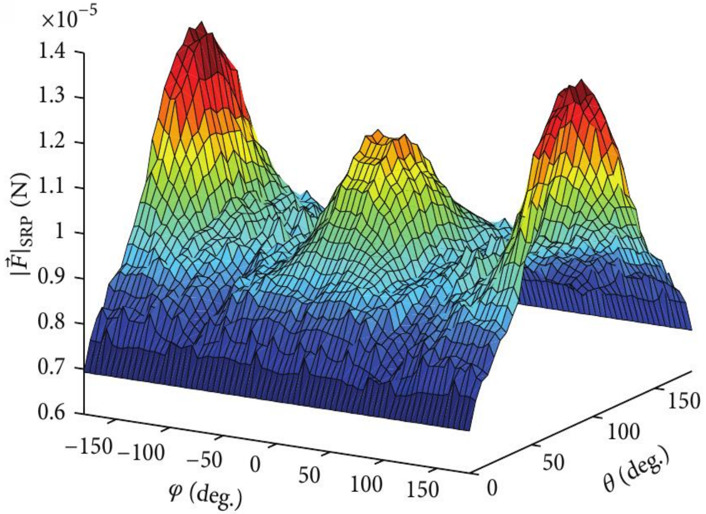
Disturbances (orbit & satellite)



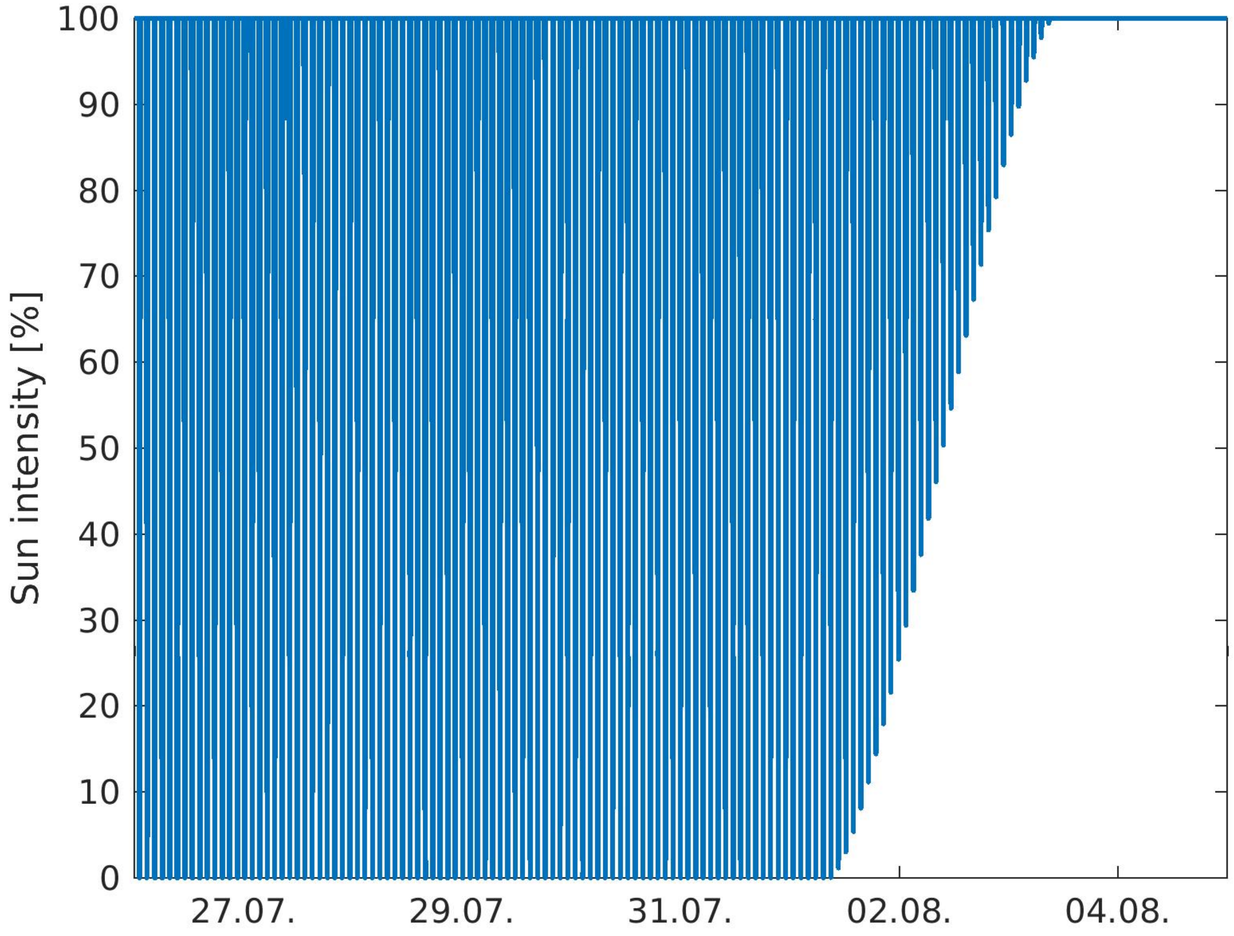






M.List et al, International Journal of Aerospace Engineering 2015 14 (2015)

Disturbances (orbit): eclipse phases



No photons hitting satellite surface when going to Earth eclipse

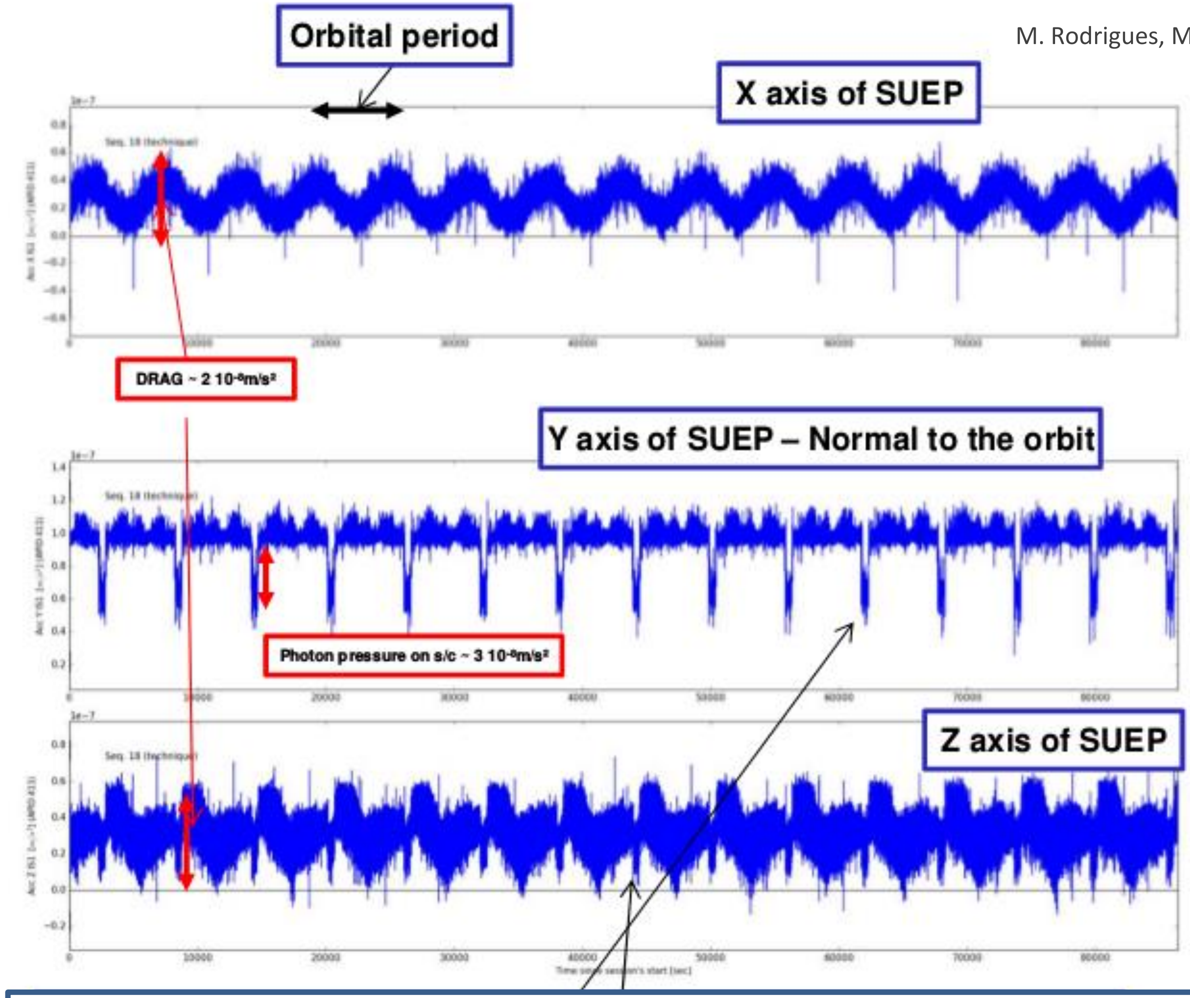
→ value of disturbance force due to Solar Radiation Pressure F_{SRP} ~ 9.5E-06 N

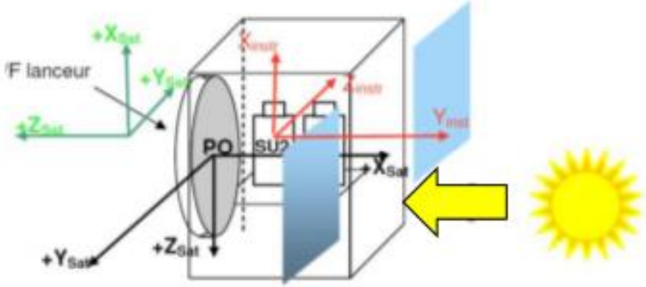
→ a_{SRP} ~ 3.0E-08 m/s^2

No measurements before 3rd of August 2016.

Disturbances (orbit): eclipse phases

M. Rodrigues, MICROSCOPE mission – A test of Equivalence Principle in space, Fundamental physics in Space, Bremen 2017





Acceleration due to photon pressure on satellite: 3E-08 m/s^2

Error budget at $f_{EP} = 3.1113 \times 10^{-3}$ Hz

Term in measurement eq.	**Amplitude/Upper bound**	**Method of estimation**
Gravity gradient effect $\mathbf{T}\vec{\Delta}$ along x @ f_{EP}		
$(T_{xx}\Delta x, T_{xy}\Delta y, T_{xz}\Delta z)$	$(<10^{-18}, 10^{-19}, 10^{-17})$ m/s^2	Earth's gravity model and in-flight calibration
Drag-free control		
$\mathbf{M}_d\vec{\Gamma}_{\text{appl,c}}\vec{x}$	$1.7 \cdot 10^{-15}$ m/s^2	DFACS performances and calibration
Instrument systematics and defects		
$\vec{\Gamma}_{\text{meas,quad,d}}$	$5 \cdot 10^{-17}$ m/s^2	DFACS performances and calibration
Thermal systematics	$6.7 \cdot 10^{-14}$ m/s^2	Thermal sensitivity in-orbit evaluation
Magnetic systematics	$2.5 \cdot 10^{-16}$ m/s^2	Finite element calculation
...	...	...
Total of systematics in $\vec{\Gamma}_{\text{meas,quad,dx}}$	$7.1 \cdot 10^{-14}$ m/s^2	
Total of systematics in η	$< 9 \cdot 10^{-15}$	

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Results – current status

PRL **119,** 231101 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

The WEP is valid up to η = 1.9 x 10^{-14}:

$$\eta(\mathrm{Ti,Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \cdot 10^{-15}$$

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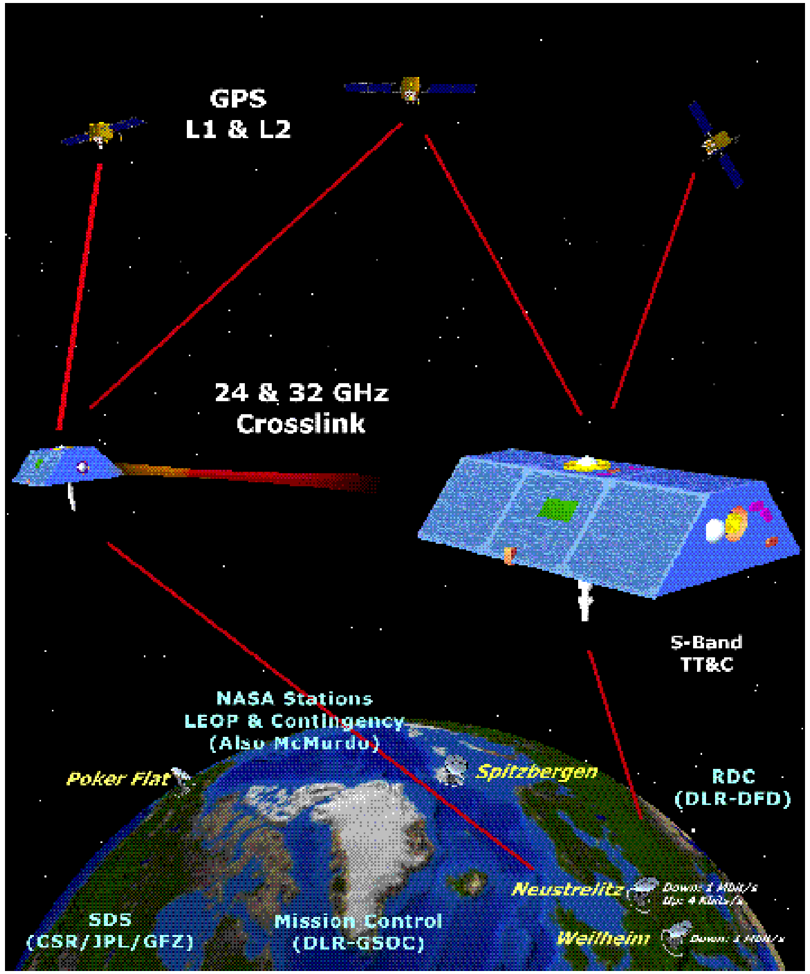
GRACE: Gravity Recovery And Climate Experiment

- Orbit height ~ 500 km
- Initial distance 220 km
- Polar orbit, inclination: i ~ 89º

- Key technologies
  - SST-ll with K/Ka-Band Ranging (KBR) (accuracy: 10^{-6} m)
  - GPS
  - Accelerometer (ONERA: superSTAR)

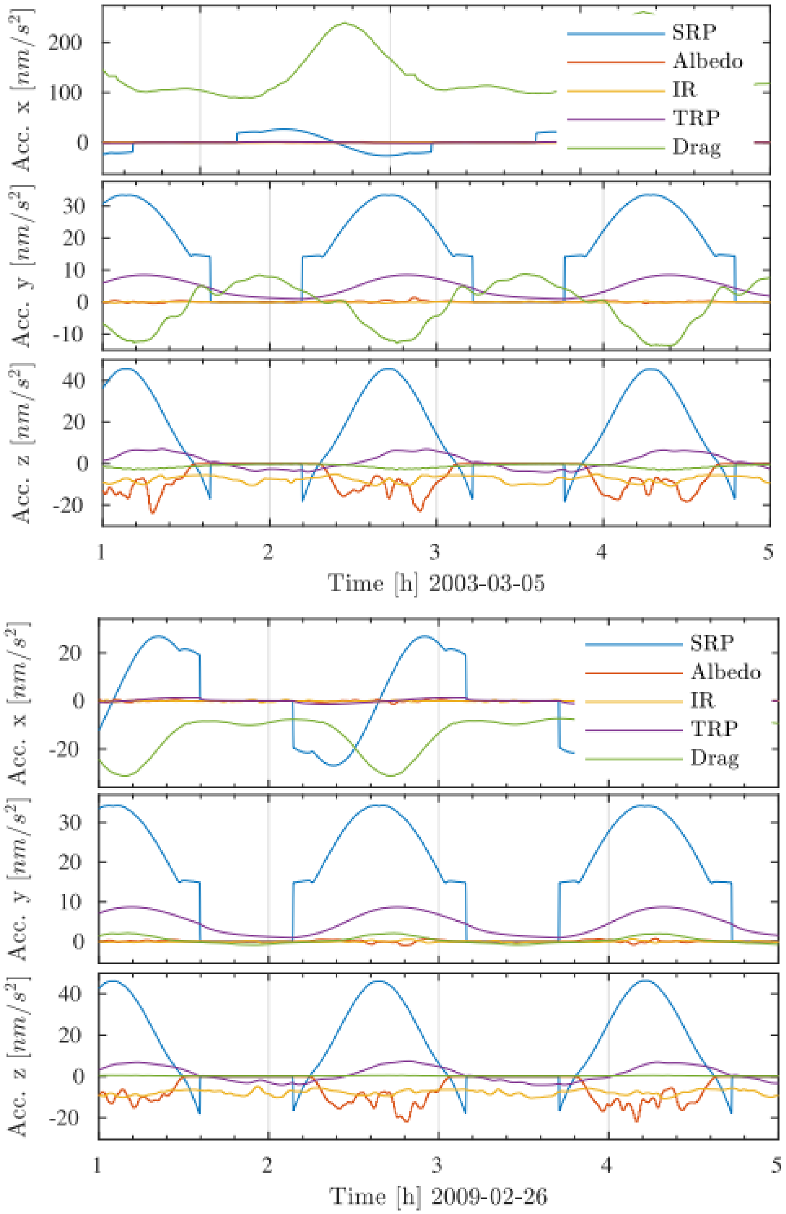
- Observation quantity:
  - distance (range)
  - change of distance (range rate)



Calibration

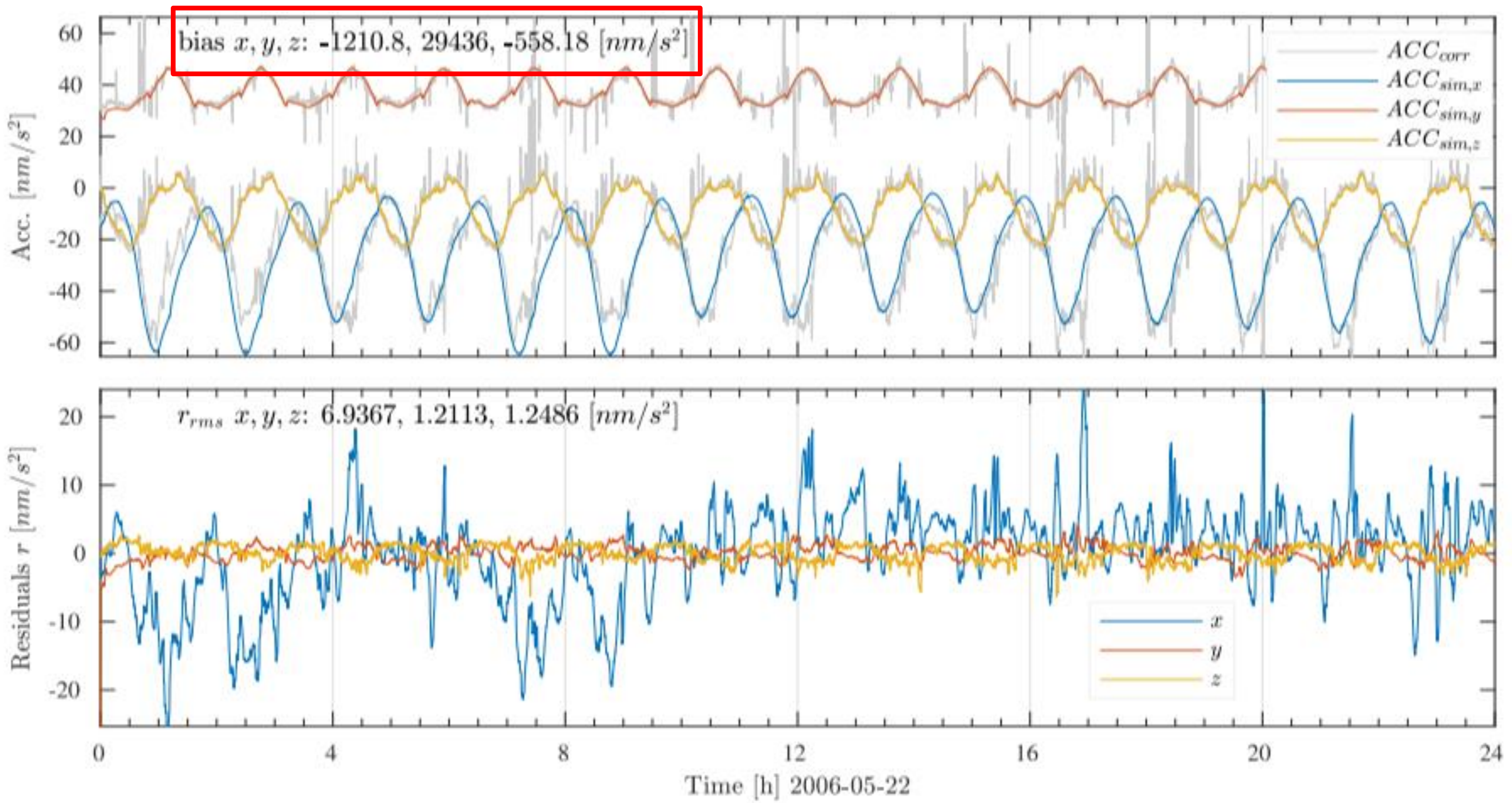
Simulation of:

- Atmospheric drag (Drag): JB08, HWM93
- Solar radiation pressure (SRP)
- Albedo radiation (Albedo): CERES data
- Infrared radiation (IR): CERES data
- Thermal radiation pressure (TRP)



F. Wöske et al, Advances in Space research, 63(3), 2019

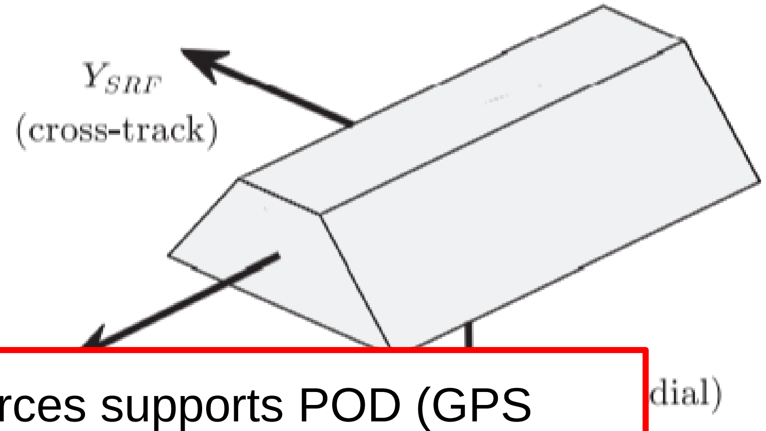
Calibration



F. Wöske et al, Advances in Space research, 63(3), 2019

- Scale factors are taken from GRACE TN-02
- Spikes refer to attitude thruster firings

Calibration



- Modeled data is in very good agreement with GRACE data for cross-track (y) and radial (z) directions:

  → $r_{rms,y} = 1{,}21\ nm/s^2$ and $r_{rms,z} = 1{,}25\ nm/s^2$

- Along-

  → $r_{rms,x} = 6{,}94\ nm/s^2$

Calibration method based on modeling of non-gravitational forces supports POD (GPS based) which is working well for along-track but lacks accuracy in cross-track and radial directions

Reason is expected to be the deficiency of atmospheric drag modeling: better models of atmospheric density are needed!

(c.f. B. Rievers et al: „Evaluating Atmospheric density with MICROSCOPE data“, Proceedings of the 70th IAC Congress, Paper ID: 50951, 2018)

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Summary

- High precision simulation of satellite missions is necessary to understand system behaviour

- Considering numerous boudary conditions (e.g. due to environmental disturbance effects) gives full picture of the whole system

- Support correct interpretation of science signal/observed phenomenon

- Calibration of payload by using high precision orbit modelling

BUT:

- A lot of environment modelling approaches aren‘t sufficiently good enough (e.g. Earth‘s Atmosphere): improvement needed

University of Bremen’s contribution was supported by the German Space Agency of DLR with funds of the BMWi (FKZ 50 OY 1305) by DFG (CRC 1128 geoQ).

Gefördert durch
DFG Deutsche Forschungsgemeinschaft

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag