Data analysis, orbit propagation, and the future of MICROSCOPE

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Gewinnerin in der Exzellenzinitiative
CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
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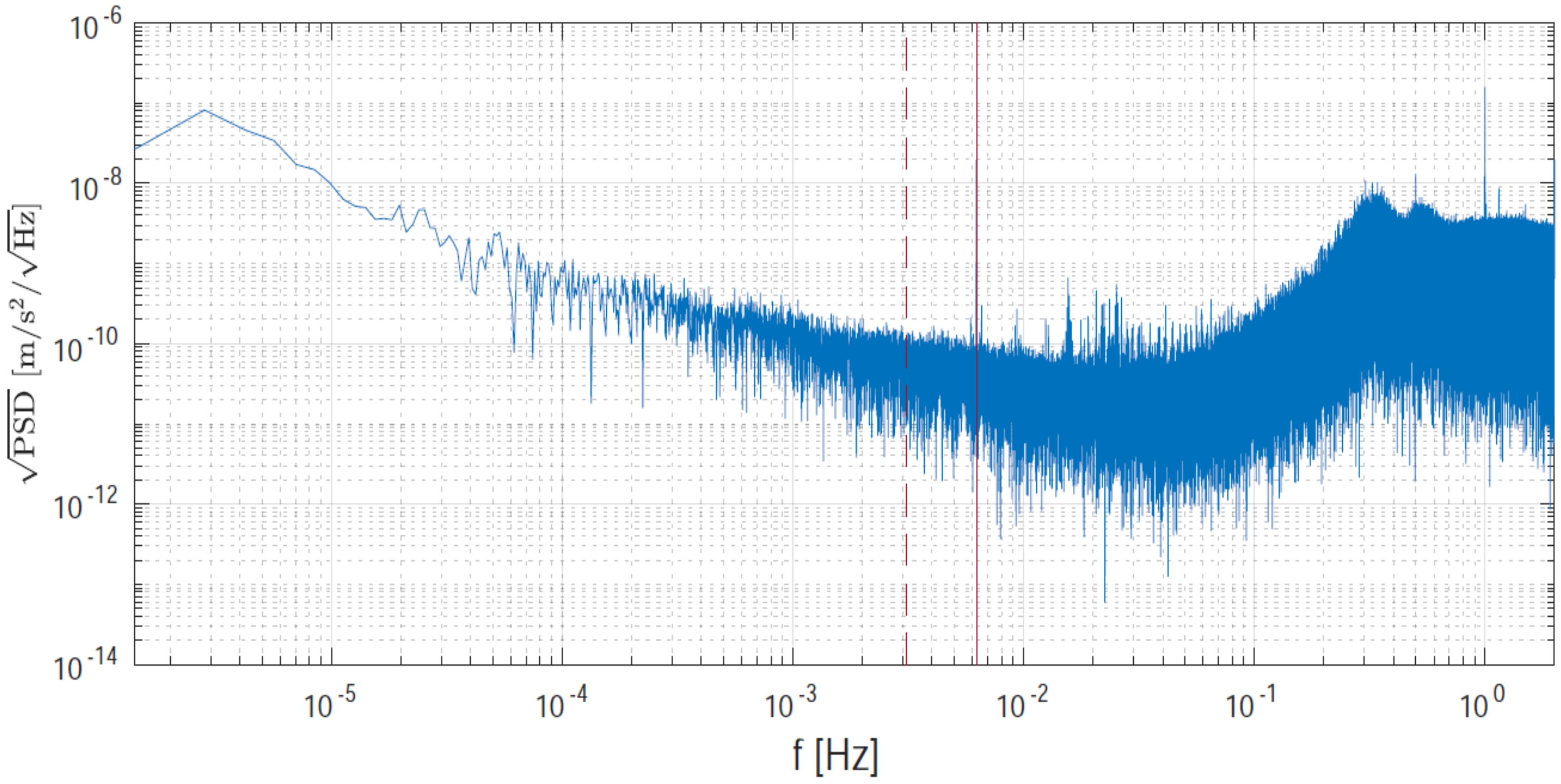
Contents

- ✓ Mission data analysis:
  Time-dependent frequency analysis by using wavelets
- ✓ Modeling of non-gravitational disturbances
  - ✓ Motivation
  - ✓ SRP/TRP modeling approach
  - ✓ Example: MICROSCOPE
- ✓ Outlook: post WEP test mission goals
- ✓ Conclusion

Contents

Typical MICROSCOPE acceleration spectrum
Session with 120 orbits



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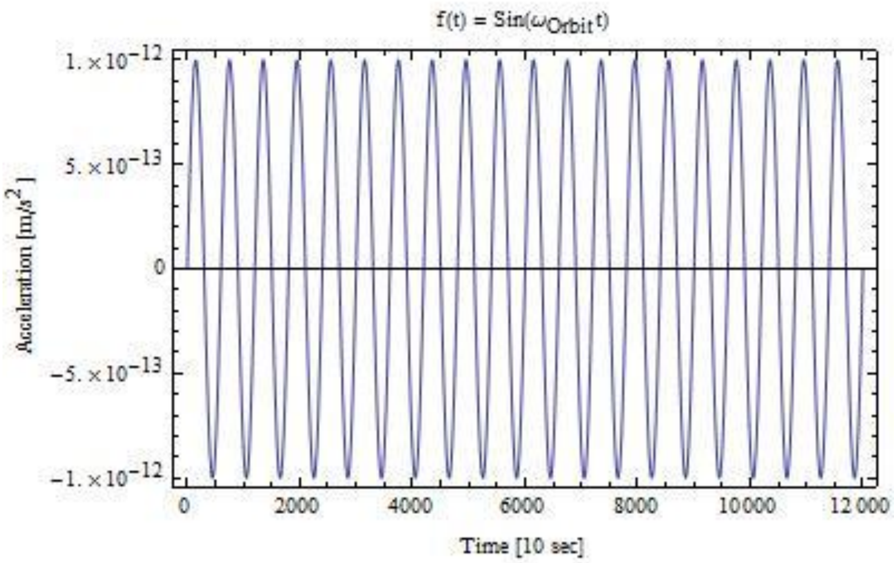
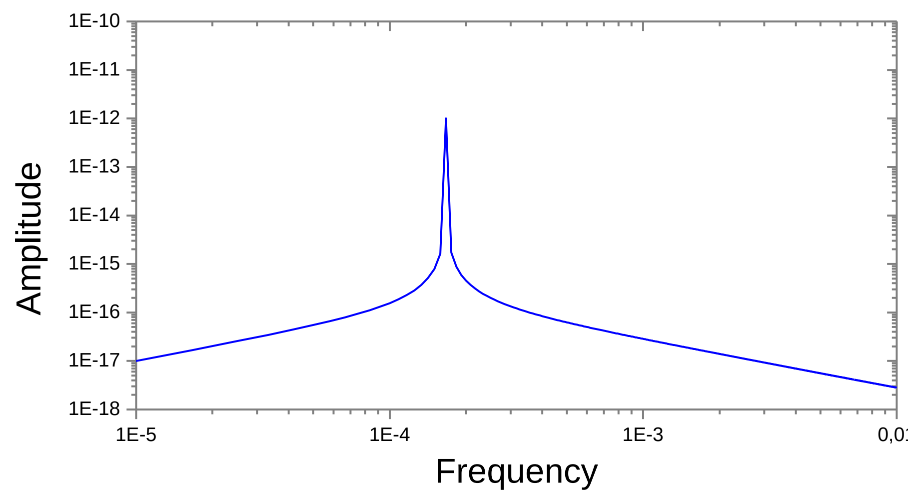
Classical frequency analysis





Limitation

The classical frequency analysis (FT of the complete time signal) shows the best possible frequency resolution

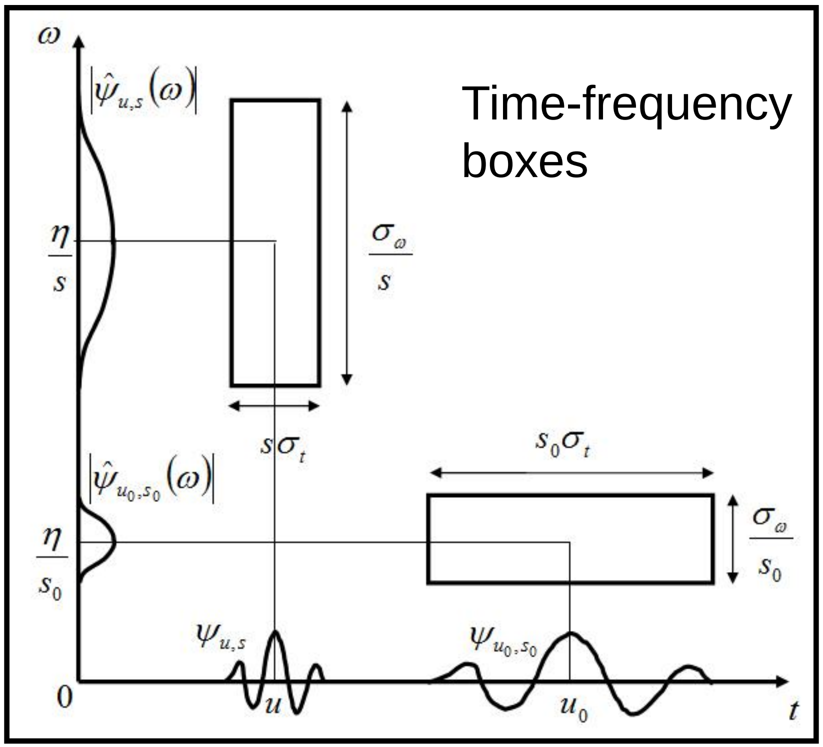
but masks any temporal information
→ best for stationary signals

Wavelet analysis

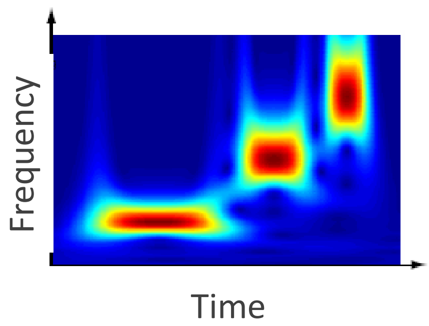
$$WT(u,s) = \frac{1}{\sqrt{|s|}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-u}{s}\right) dt$$

u: translation
s: dilation

$$\int_{-\infty}^{\infty} \psi(t)dt = 0$$



$s_{t,w}$: uncertainty



recommended Literature: S. Mallet *A wavelet tour of signal processing* Academic Press (1998)

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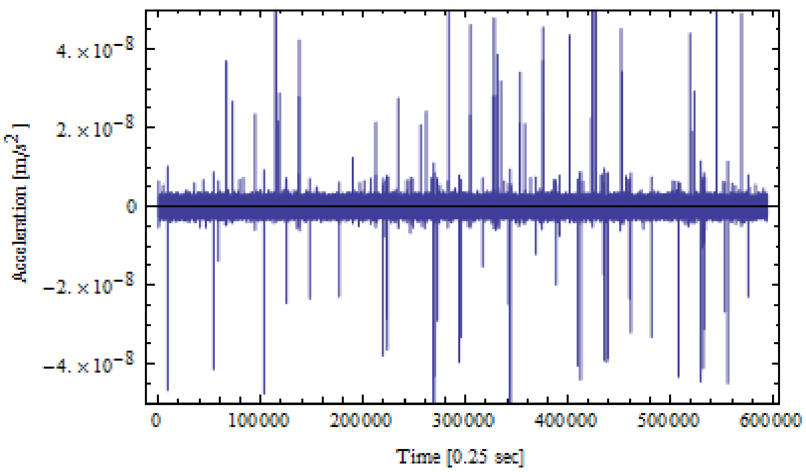
Example with simulated data set

Simulation: differential acceleration with noise and short time disturbances (spikes)



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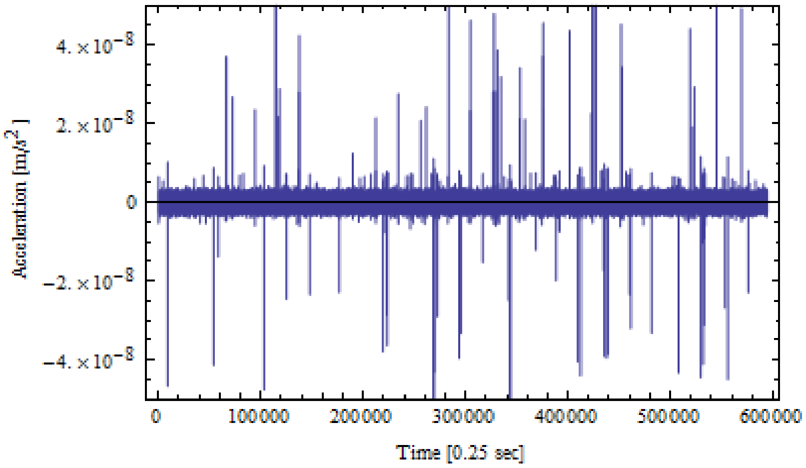
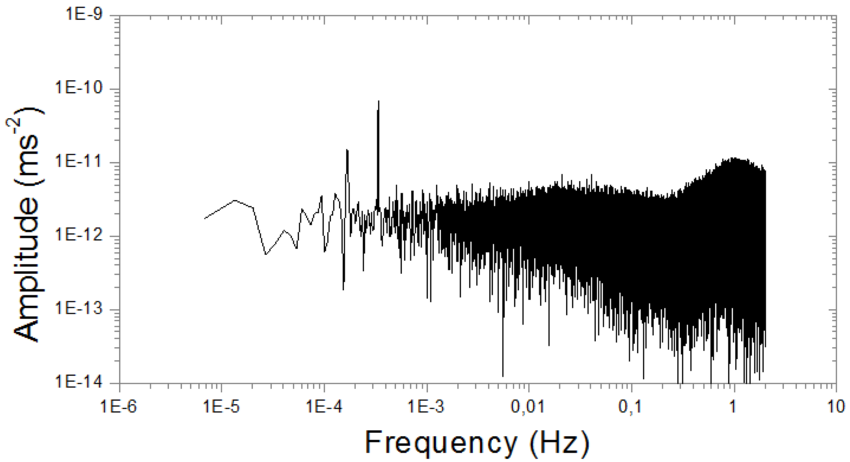


FFT



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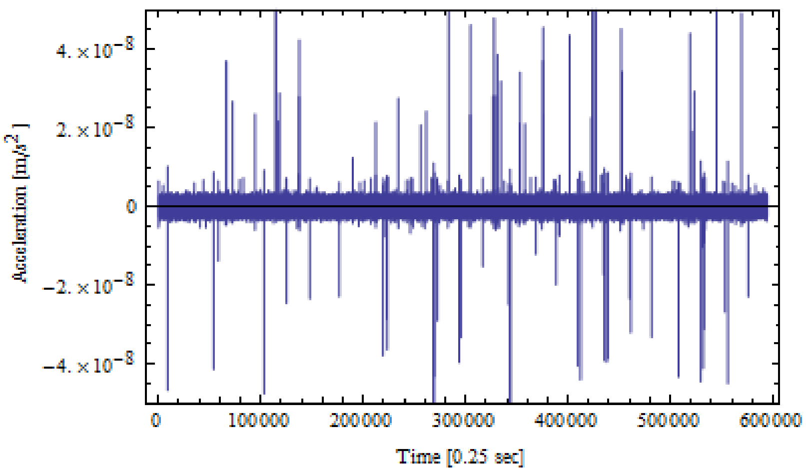

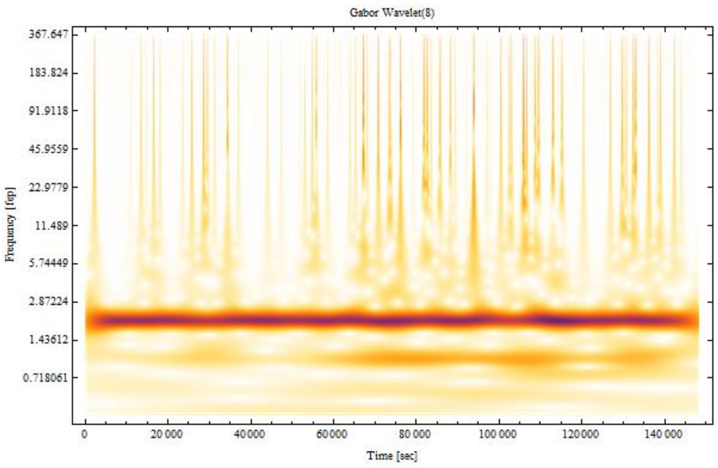

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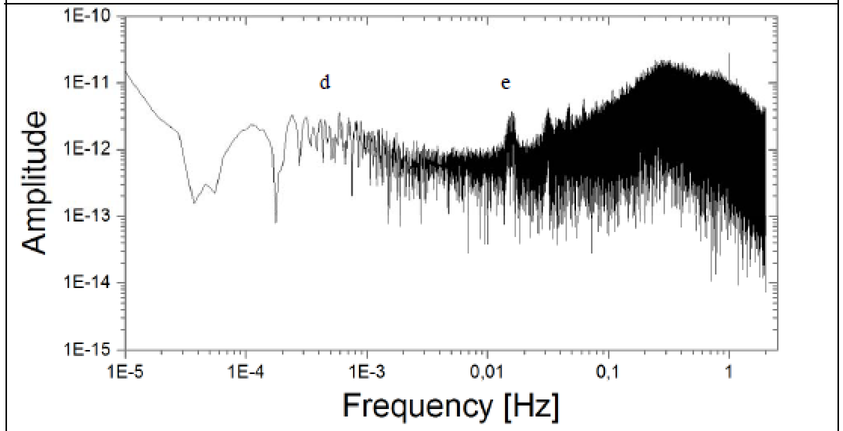
MICROSCOPE data report example (1st version)

ZARM	MICROSCOPE	Ref.: MIC-Data Report Session 80 SUEP IS1-AccXsci Date: 15/10/2016 Page: 10/10
		ZARM

FFT:



Summary:

The scalogram of the AccelerationXsci of IS1-SUEP-N1a-Session 80 shows a strange non-stationary behaviour.

The origin of the frequency shifts of the signal (scalogram pattern b, starting at arround 2 mHz, then decreasing to 0.2 mHz and then increasing again in a symmetrical way) is not yet understood.

The origin oft the other signal component (scalogram pattern c) with crossing lines in the scalograms (mean frequency ~ 15 mHz) is also not yet understood.

It is not yet clear whether the frequency behaviour is based on a real physical effect or on an effect caused by the measurement system (electronics).

ZARM	MICROSCOPE	Ref.: MIC-Data Report Session 80 SUEP IS1-AccXsci Date: 16/10/2016 Page:5/10
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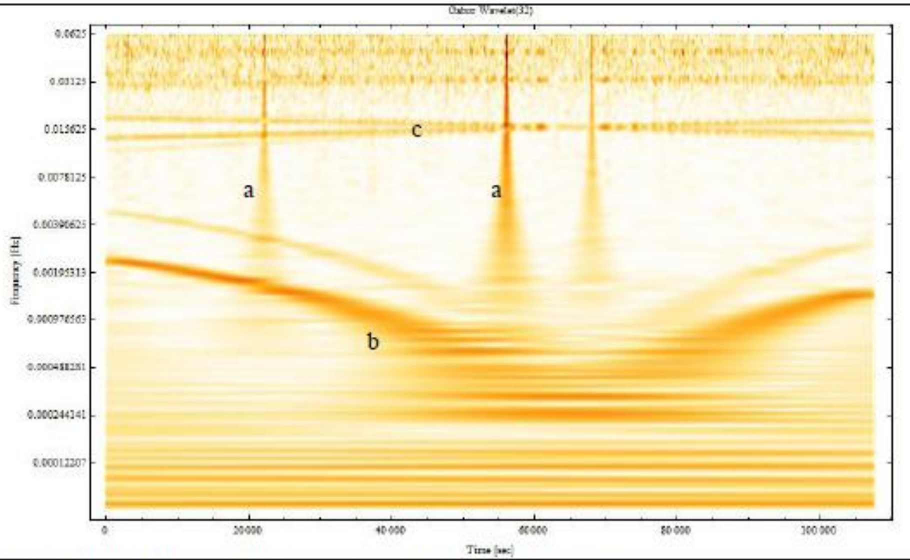

Session 80-N1a_SUEP_S-05-IS1-AccXsci minus bias - Scalogram

Ref:	Remarks:	File:	Analysis settings:
Session_80_EPR_V2DFIS1_01_SUEP/N1a_S_05/SUEP/IS1/AccelerationXsci	Bias substracted for the Wavelet analysis to reduce border effects	Session 80-N1a_SUEP-S-05-IS1-AccXsci-minus bias.dat	CWT Gabor (32) Padding -> 0.0

Description:

Same scalogram but with another setting for frequency/time resolution (Mother wavelet: Gabor(32) -> better frequency resolution, worse time resolution)

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MICROSCOPE data report example (2nd version)

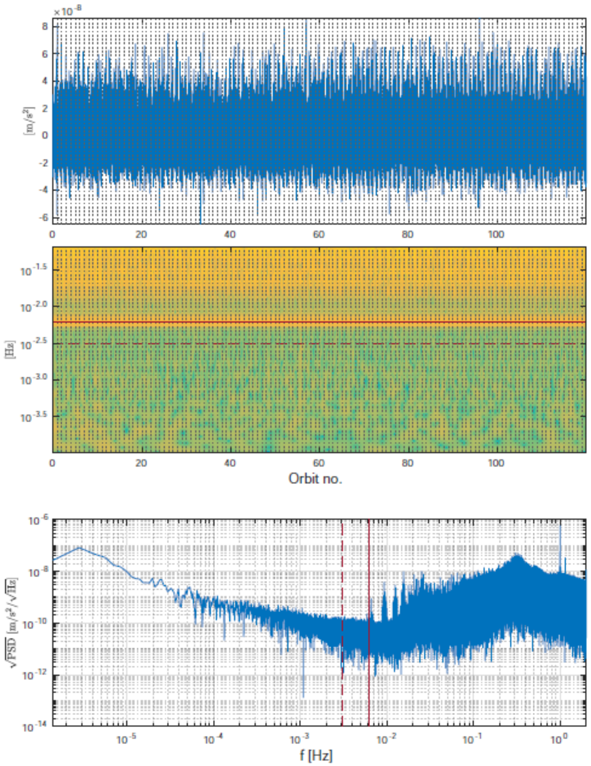

Figure 1: IS1 AccelerationXscaa: Time signal after removing 3rd order polynomial fit, wavelet analysis, and square root of PSD.

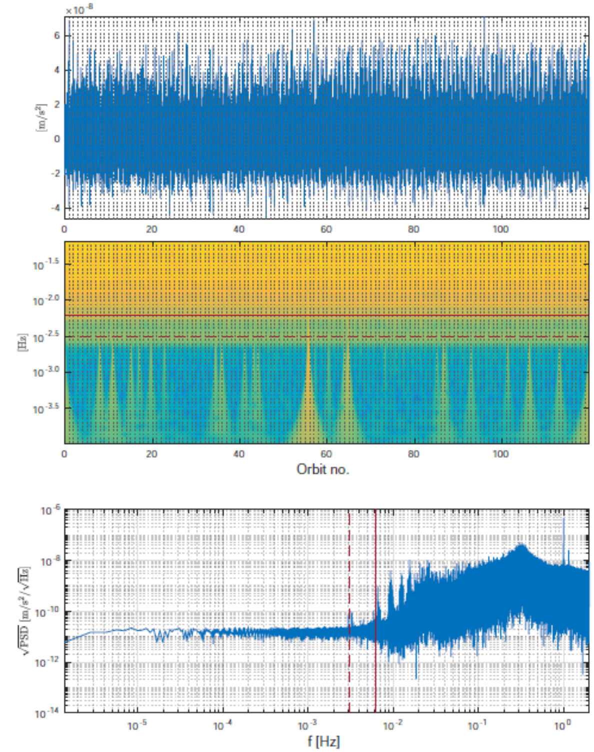

Figure 2: IS2 AccelerationXscaa: Time signal after removing 3rd order polynomial fit, wavelet analysis, and square root of PSD.

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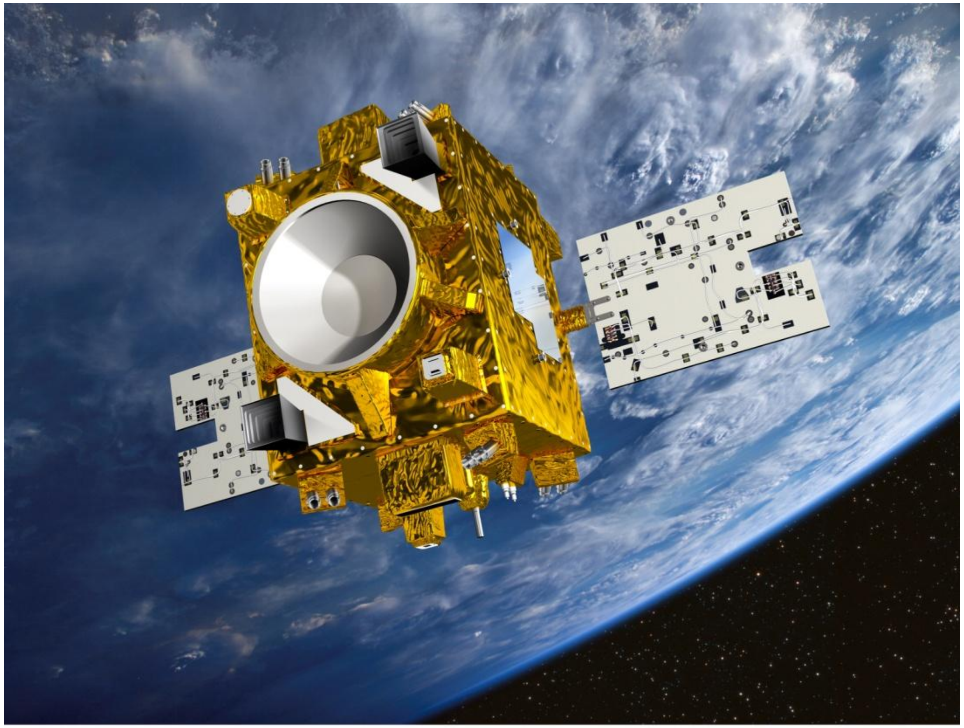
Motivation: Simulation of satellite missions



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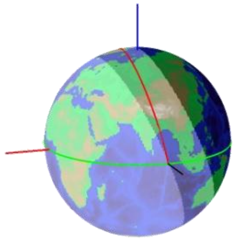
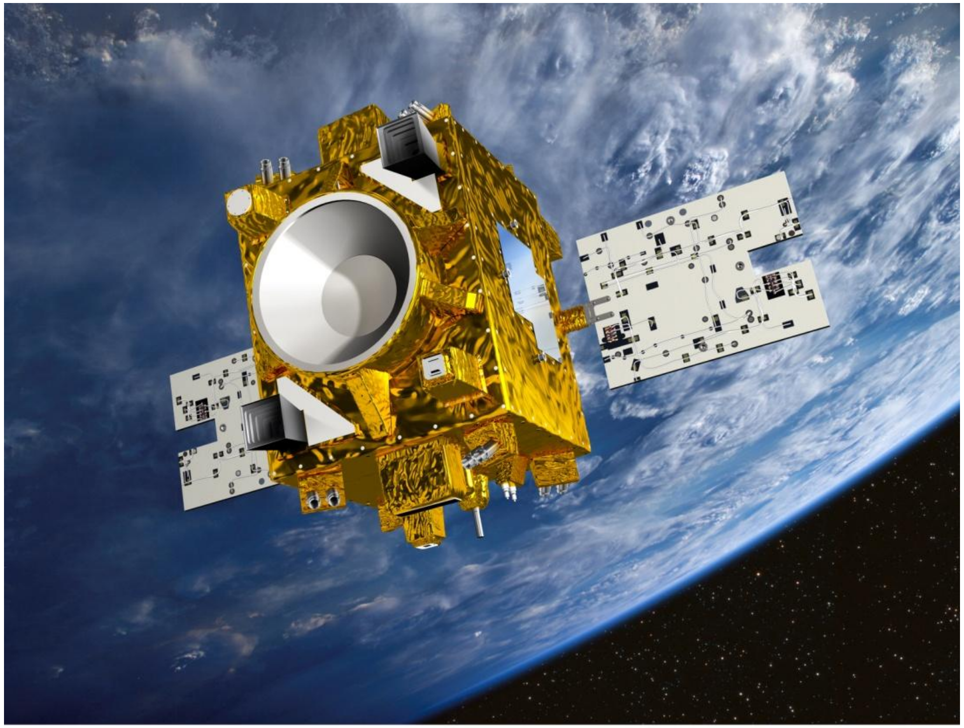
Motivation: Simulation of satellite missions

Orbit dynamics





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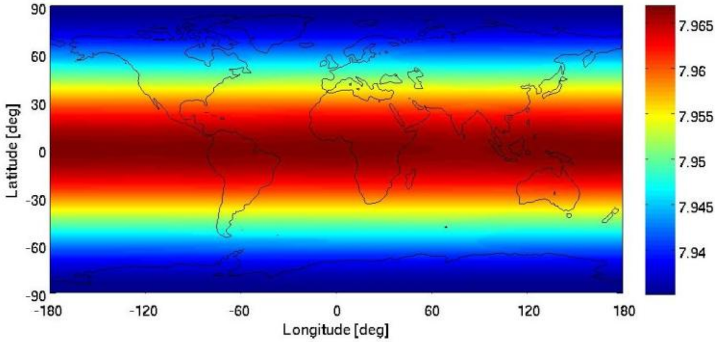
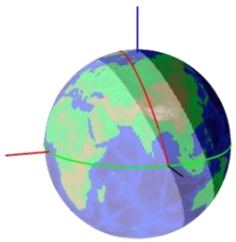
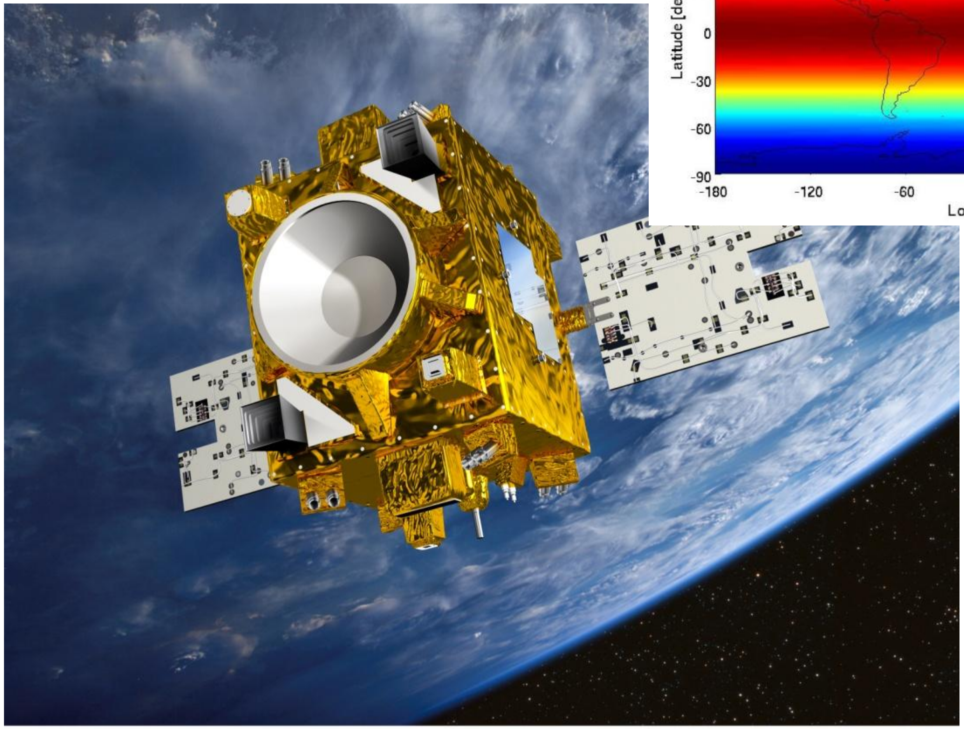
Motivation: Simulation of satellite missions

Gravity field of the Earth



Orbit dynamics





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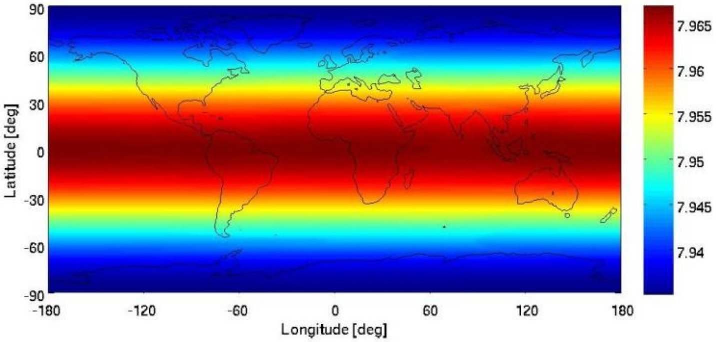

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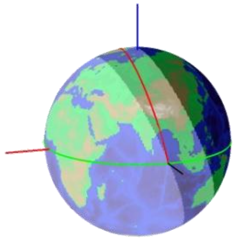

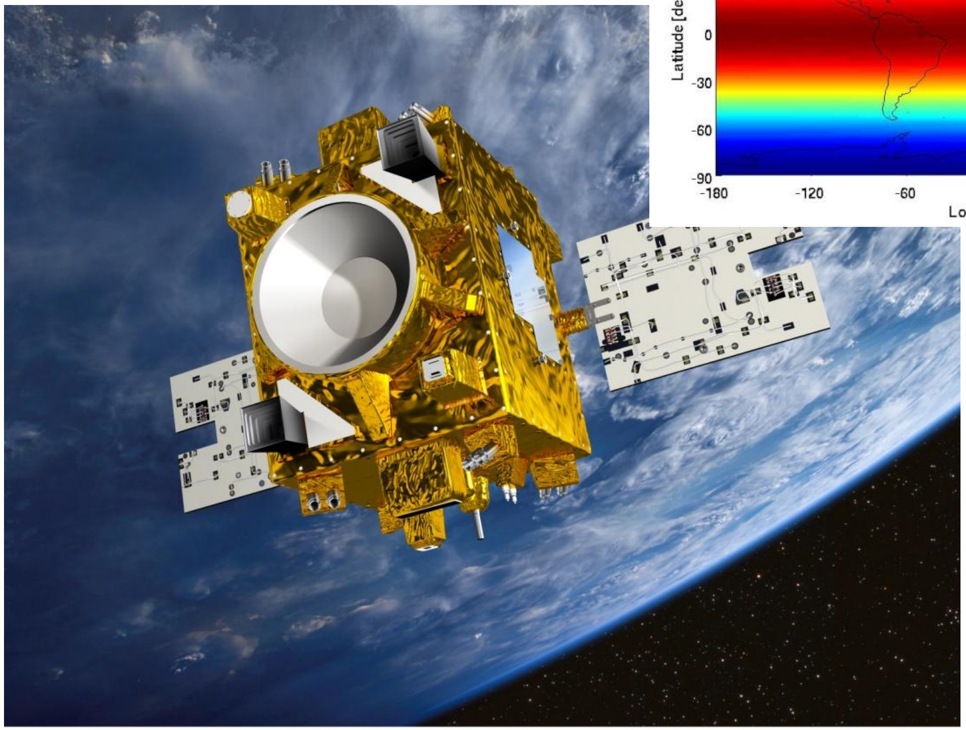

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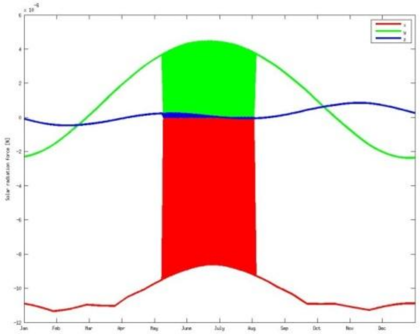
Solar radiation pressure and eclipse



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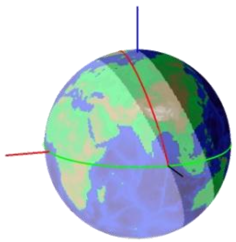
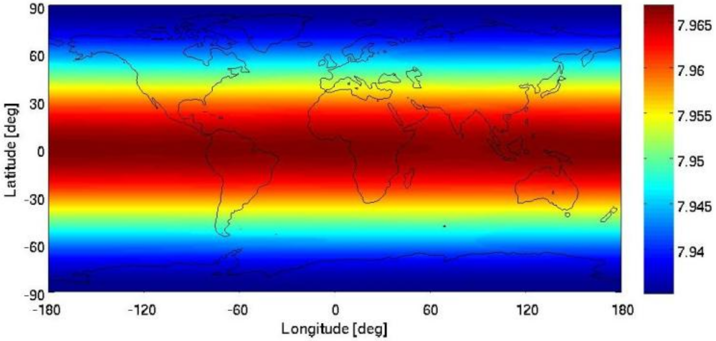
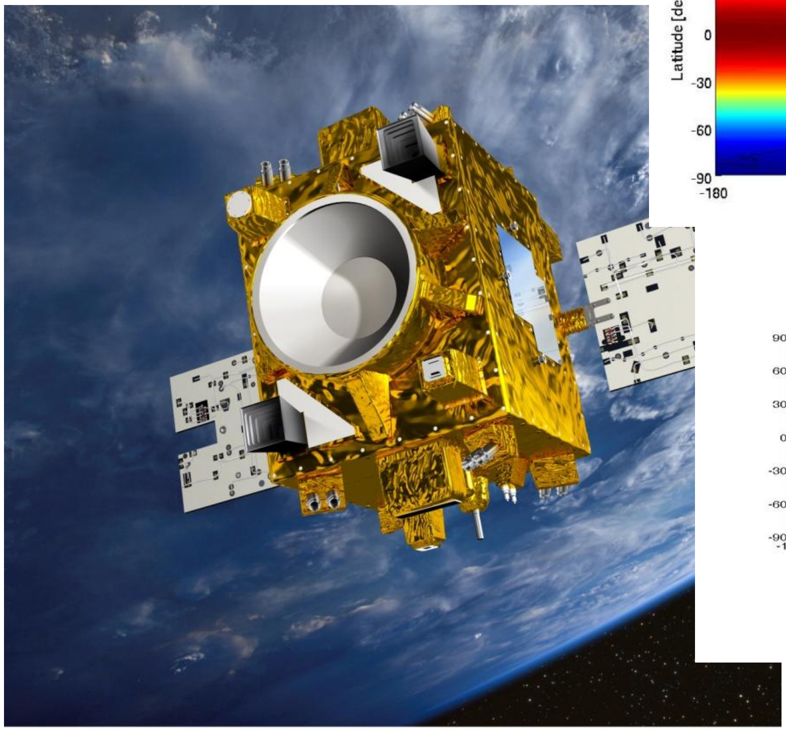


Gravity field of the Earth





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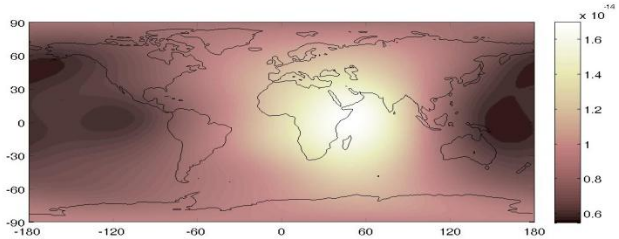
Atmosphere



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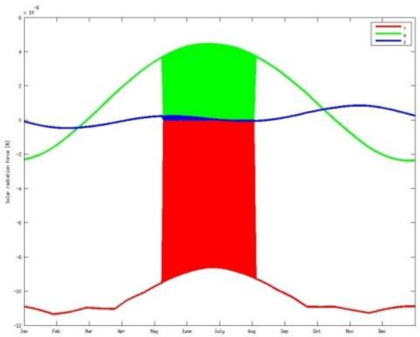

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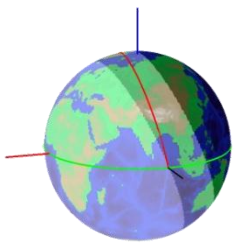

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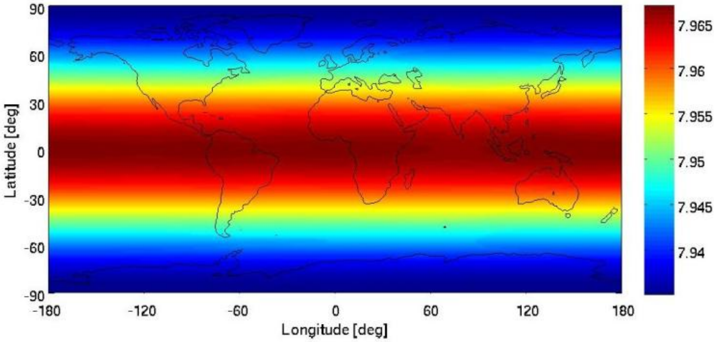

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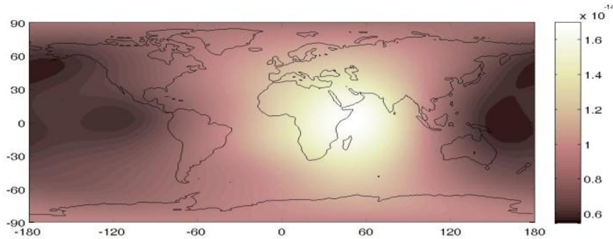

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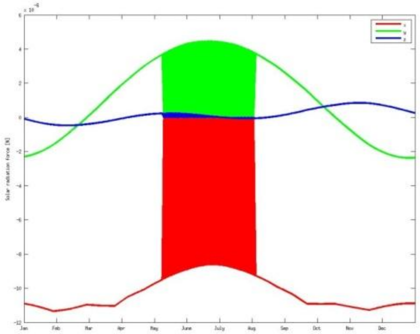
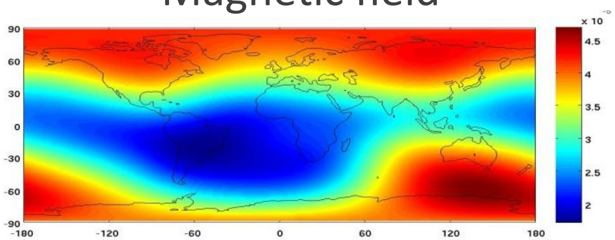


Magnetic field



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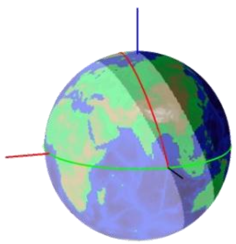
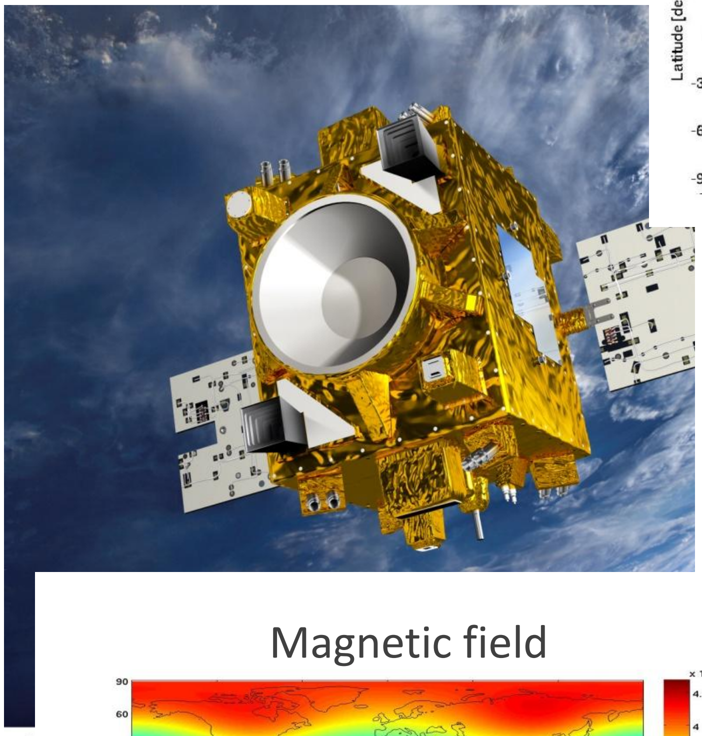
Orbit dynamics





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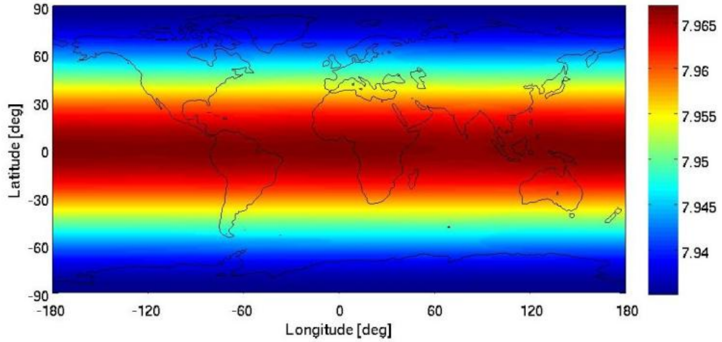

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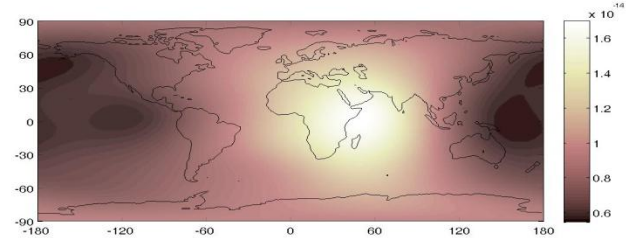

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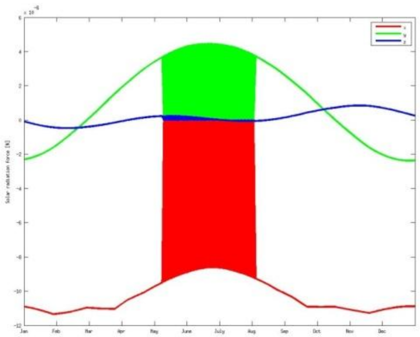
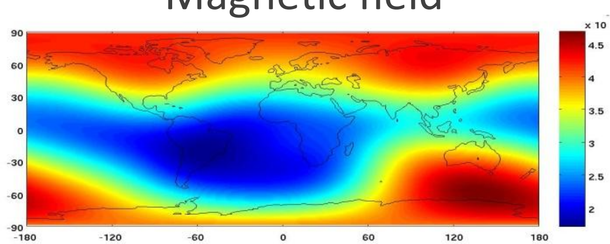


Magnetic field



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

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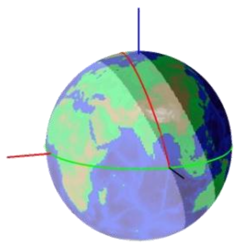
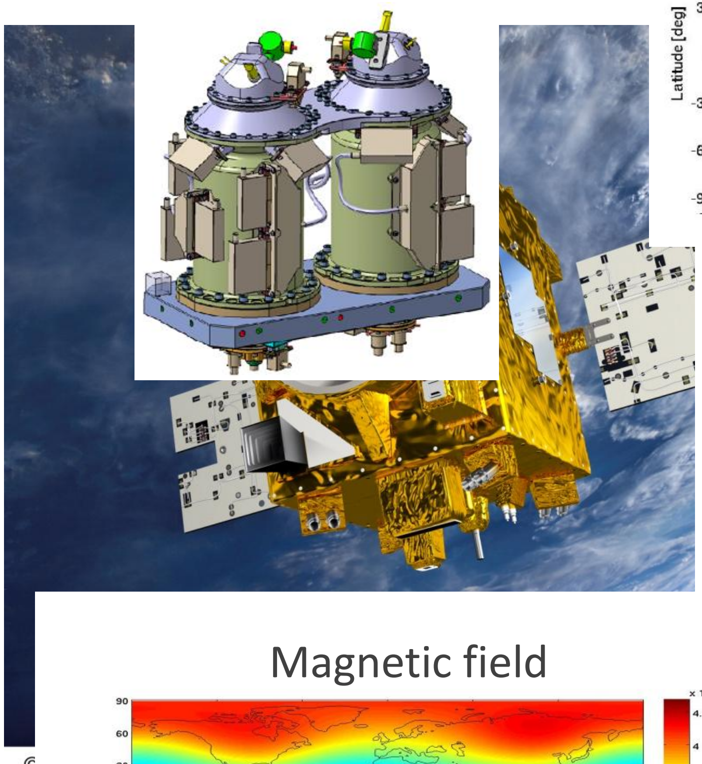
Motivation: Simulation of satellite missions

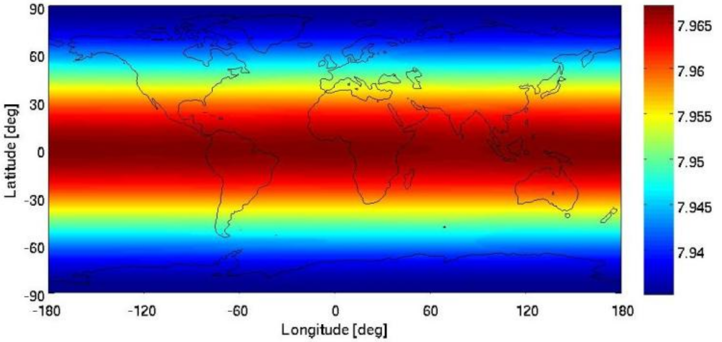
Orbit dynamics



Special requirement of mission:
Payload



Gravity field of the Earth



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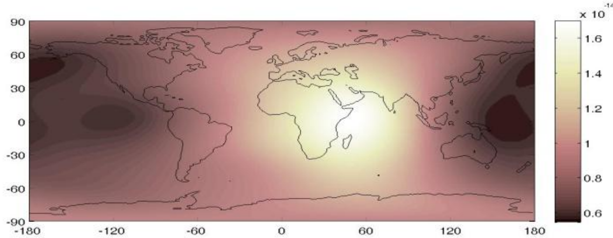

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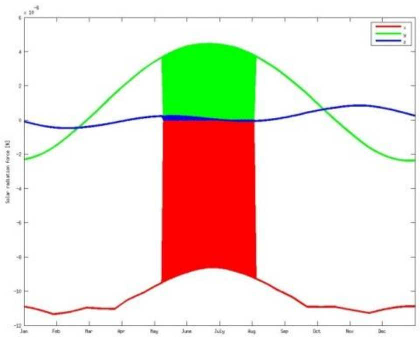

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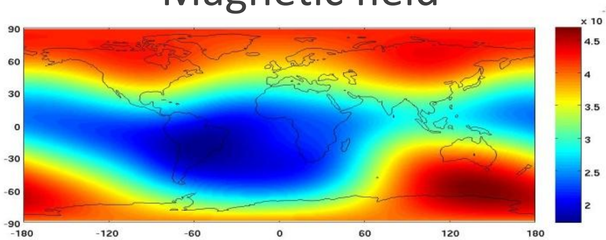

- ✓ Albedo radiation
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- ✓ Ephemerides
- ✓ …

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Motivation

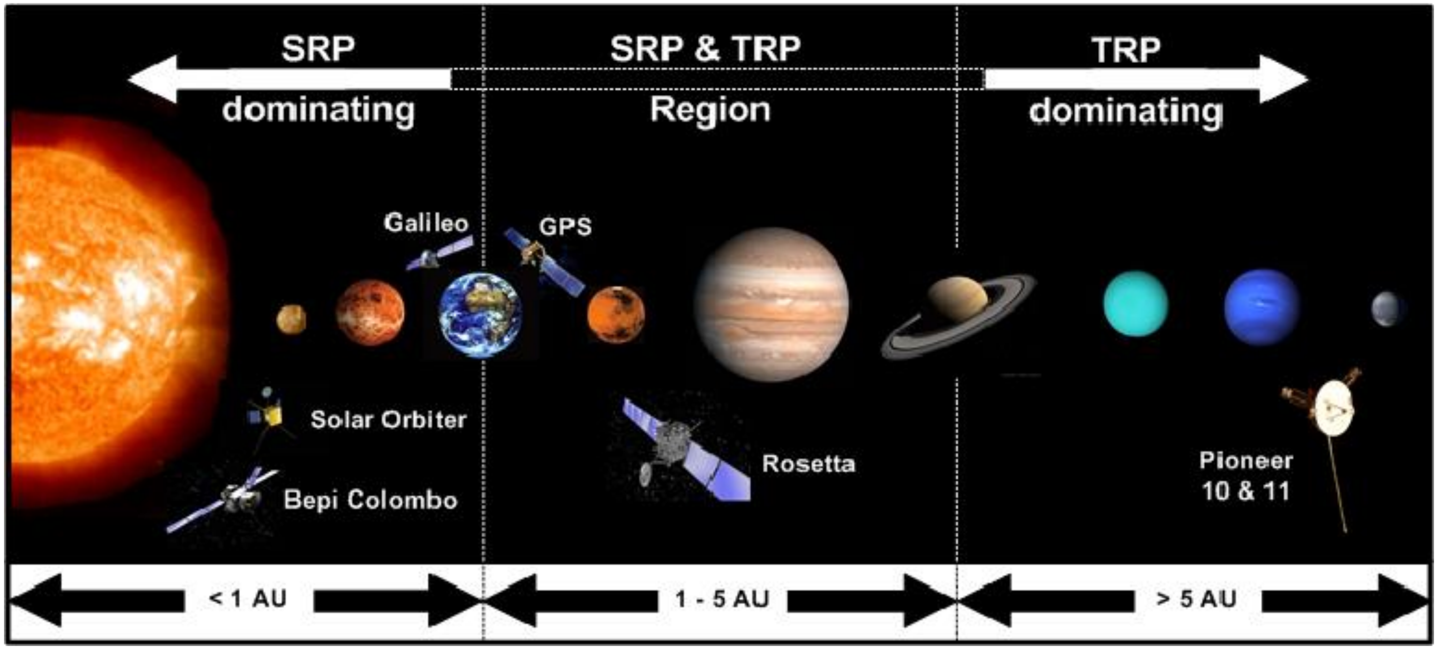
- ✓ Central task for mission analysis:
  Modeling and propagation of the real mission orbit
  → initial conditions and modeling of space environment

- ✓ Satellite motion in the gravitational field of the Earth
  non-uniform mass distribution (zonal and tesseral variations), Earth oblateness
  → non-spherically symmetric Earth gravitational field results in „gravitational disturbances“ of the pure Keplerian orbit

- ✓ „Non-gravitational disturbances“ have a large effect on satellite motion and its attitude
  → Atmospheric drag due to residual atmosphere
  - T. Kato, B. Rievers, M. List, Trans. JSASS Aerospace Tech. Japan Vol. 14, No. ists30, 2016

  → Solar radiation pressure (SRP) and Thermal radiation pressure (TRP)
  - M. List, S. Bremer, B. Rievers, H. Selig, Int. Journal Aerospace Eng., Vol. 2015, 928206, 2015
  - B. Rievers, M. List and S. Bremer, Adv. Astro. Sci. 158, 2997 – 3012, 2016

Motivation



✓ Implementation of TRP model in ESOC Orbit Determination Software based on study of method for modeling satellite surface forces with application to Rosetta

→ Correction of implemented SRP model

B. Rievers, T. Kato, J. C. van der Ha, and C. Lämmerzahl, Adv. Astro. Sci. 143 1123-1142, 2012

✓ Pioneer Anomaly: TRP effect

B. Rievers, C. Lämmerzahl, Ann. Phys. 523 (6), 439-449, 2011

B. Rievers, S. Bremer, M. List, C. Lämmerzahl, H. Dittus, Acta. Astro. 66 (3-4), 467-476, 2010

B. Rievers, C. Lämmerzahl, M. List, S. Bremer, and H. Dittus, New J. Phys. 11 113032, 2009

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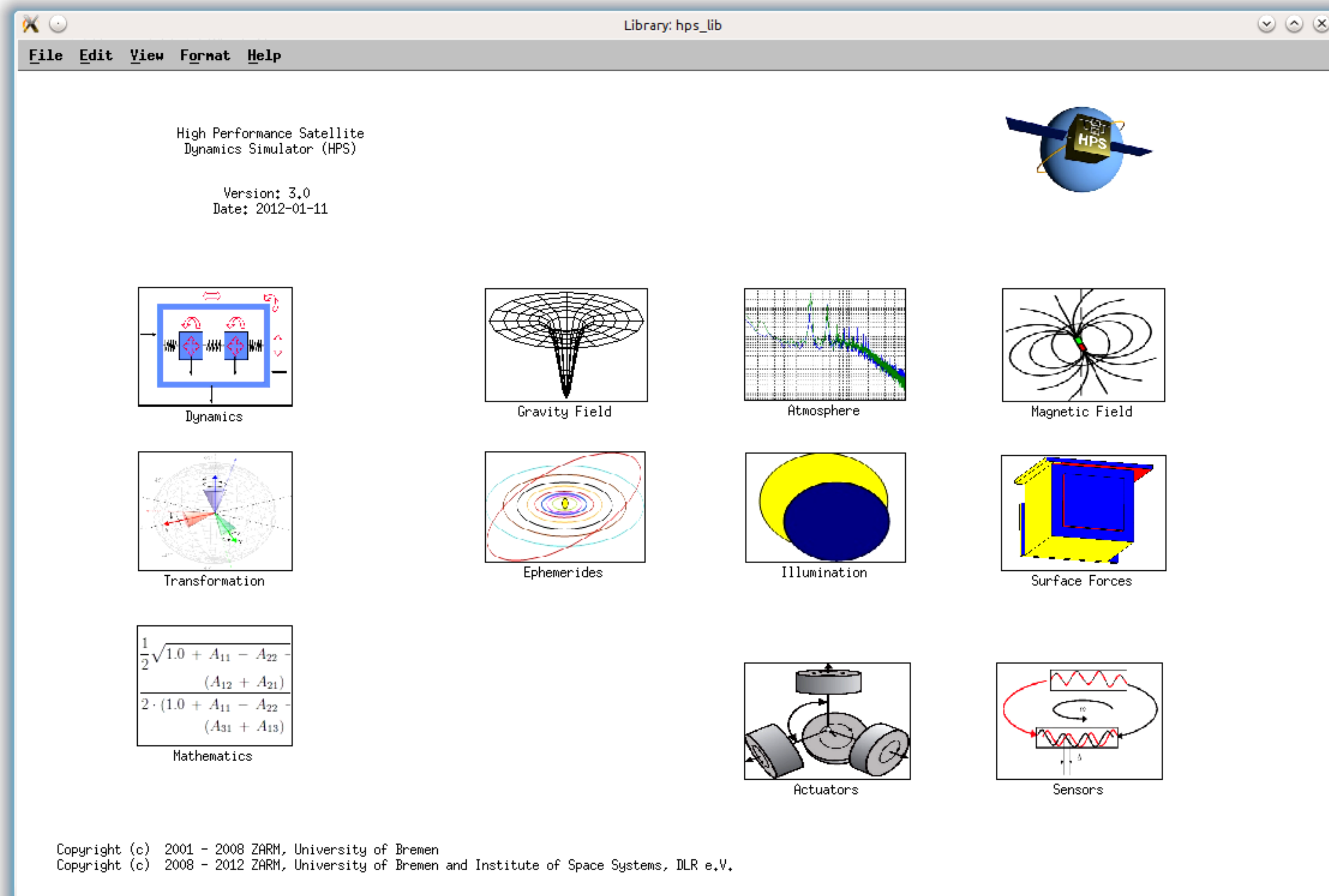
High Performance Satellite Dynamics Simulator



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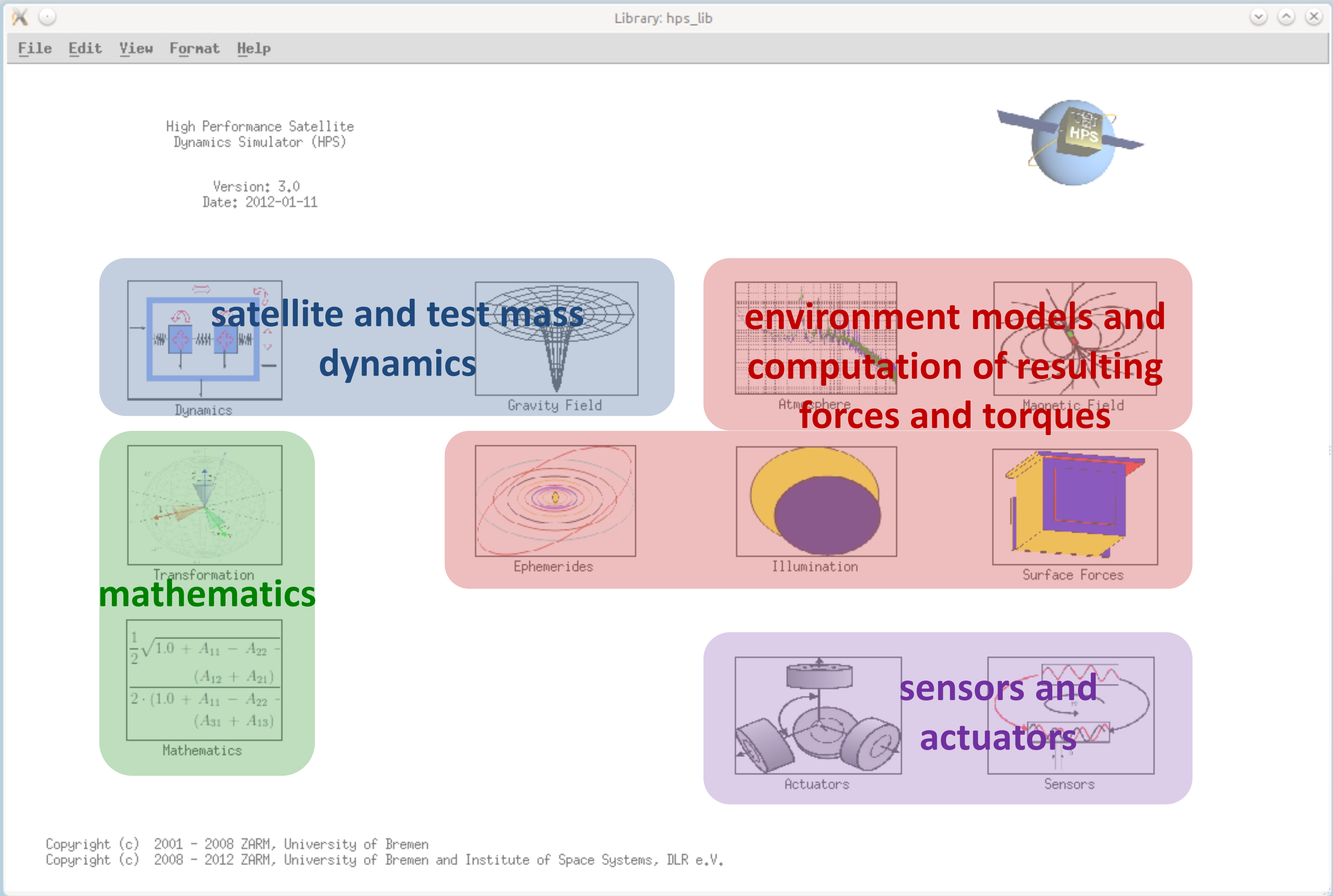

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Modeling of solar radiation pressure

Differential radiation force due to

- ✓ Absorption: $d\vec{F}_\alpha = -P\alpha\cos(\theta)\vec{e}_{\mathrm{Sun}}dA$
- ✓ Specular reflection: $d\vec{F}_{\gamma_S} = -2P\gamma_S\cos^2(\theta)\vec{e}_{\mathrm{N}}dA$
- ✓ Diffuse reflection: $d\vec{F}_{\gamma_D} = P\gamma_D\left(-\frac{2}{3}\cos(\theta)\vec{e}_N - \cos(\theta)\vec{e}_{\mathrm{Sun}}\right)dA$

Resulting force: $\vec{F}_{\mathrm{solar}} = \sum_i \vec{F}_i$

with

$$\vec{F}_i = \int d\vec{F}_{\mathrm{total}} = -P\int\left[(1-\gamma_S)\,\vec{e}_{\mathrm{Sun}} + 2\left(\gamma_S\cos(\theta) + \frac{1}{3}\gamma_D\right)\vec{e}_N\right]\cos(\theta)dA$$

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Geometry

$$\vec{F}_i = \int d\vec{F}_{\mathrm{total}} = -P\int\left[(1-\gamma_S)\,\vec{e}_{\mathrm{Sun}} + 2\left(\gamma_S\cos(\theta) + \frac{1}{3}\gamma_D\right)\vec{e}_N\right]\cos(\theta)dA$$

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Modeling of solar radiation pressure

Differential radiation force due to

- ✓ Absorption: $d\vec{F}_\alpha = -P\alpha\cos(\theta)\vec{e}_{\mathrm{Sun}}dA$
- ✓ Specular reflection: $d\vec{F}_{\gamma_S} = -2P\gamma_S\cos^2(\theta)\vec{e}_{\mathrm{N}}dA$
- ✓ Diffuse reflection: $d\vec{F}_{\gamma_D} = P\gamma_D\left(-\frac{2}{3}\cos(\theta)\vec{e}_N - \cos(\theta)\vec{e}_{\mathrm{Sun}}\right)dA$

Resulting force: $\vec{F}_{\mathrm{solar}} = \sum_i \vec{F}_i$

with

Material degradation (BOL ←→ EOL)

Geometry

$$\vec{F}_i = \int d\vec{F}_{\mathrm{total}} = -P\int\left[(1-\gamma_S)\,\vec{e}_{\mathrm{Sun}} + 2\left(\gamma_S\cos(\theta) + \frac{1}{3}\gamma_D\right)\vec{e}_N\right]\cos(\theta)dA$$

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Modeling of thermal radiation pressure

- ✓ Resulting surface temperature: $$T_i = \sqrt[4]{\frac{P_{\odot,i} P_i}{\sigma A_i \varepsilon_i}}$$
- ✓ Actual mean solar constant: $$P_{\odot,i} = \frac{P_{\odot,1AU}}{r^2} \alpha_i \cos(\xi_i)$$
- ✓ Actual orientation angle: $$\xi_i = \arccos(\vec{e}_{\mathrm{N,i}} \cdot \vec{e}_{\mathrm{Sun}})$$

Resulting TRP force vector of each cell:

$$\vec{F}_{\mathrm{TRP,i}} = -\frac{2}{3} \vec{e}_{\mathrm{N,i}} A_i \frac{P_{\odot,i} + P_i}{c}$$

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Material degradation influence

- ✓ Assumption: surface degradation leads to microscopic cratering
  → increase of absorptivity due to increase of surface area (resulting from roughened surface)

$$\frac{d\alpha}{dt} = p\frac{1}{t} \implies \alpha = \alpha_{\mathrm{BOL}} + \frac{p}{\ln(t)} \;,\quad p = \frac{\alpha_{\mathrm{EOL}} - \alpha_{\mathrm{BOL}}}{\ln(T_{\mathrm{lifetime}})}$$

- ✓ Roughening of surfaces changes ratio between spectral and diffuse reflectivity

$$\mu_{SD}(t) = \frac{\gamma_{S,\mathrm{BOL}}}{\gamma_{D,\mathrm{BOL}}} e^{-\lambda t}$$

$$\gamma_S(t) = (1-\alpha)\,\frac{\mu_{SD}(t)}{\mu_{SD,BOL}+1} \qquad \gamma_D(t) = \frac{1-\alpha}{1+\mu_{SD}(t)}$$

Contents

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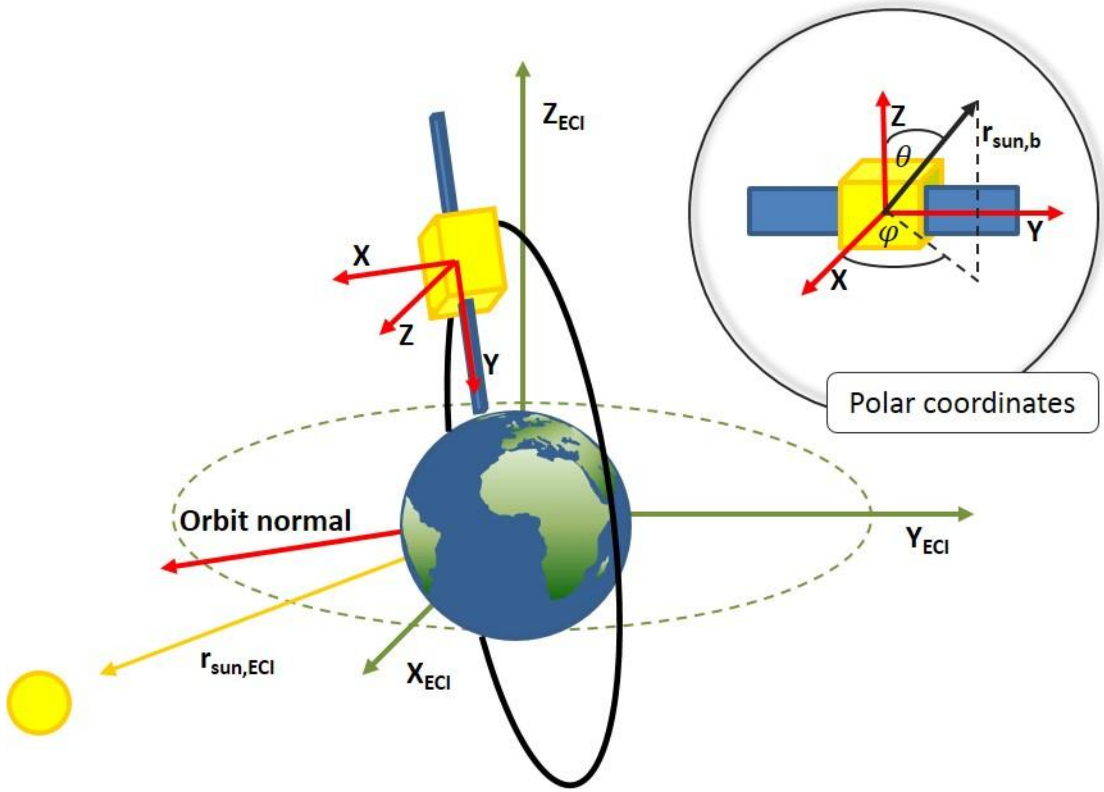
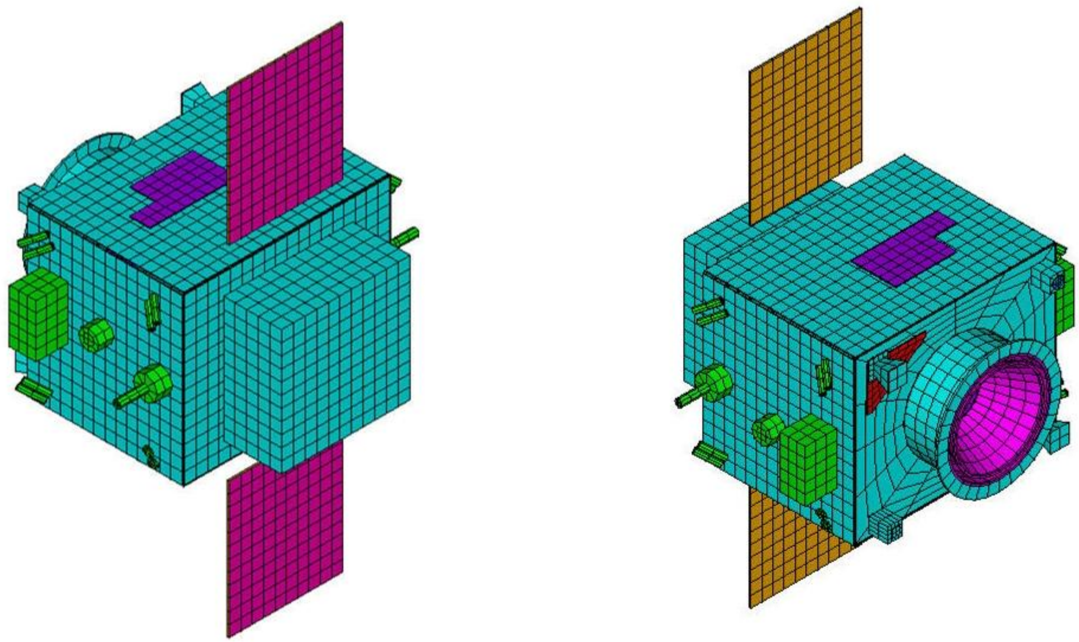
MICROSCOPE: orbit



✓ MICROSCOPE orbit: altitude 710 km, circular and polar orbit (SSO)

MICROSCOPE: detailed geometry model



MLI | Ant_e (Kevlar) | Ant_i (Kevlar, Composite) | white coating

Solar panel (front) | Radiator surfaces | Solar panel (rear face)

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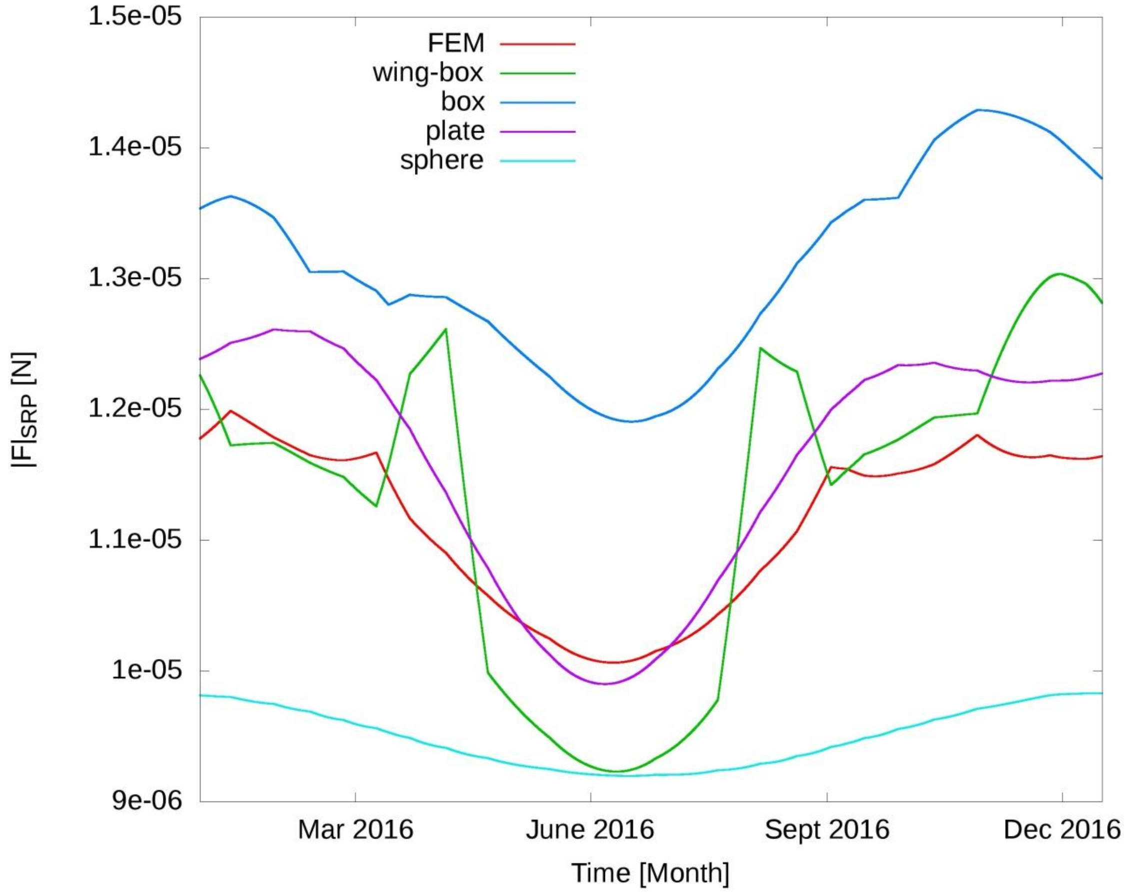
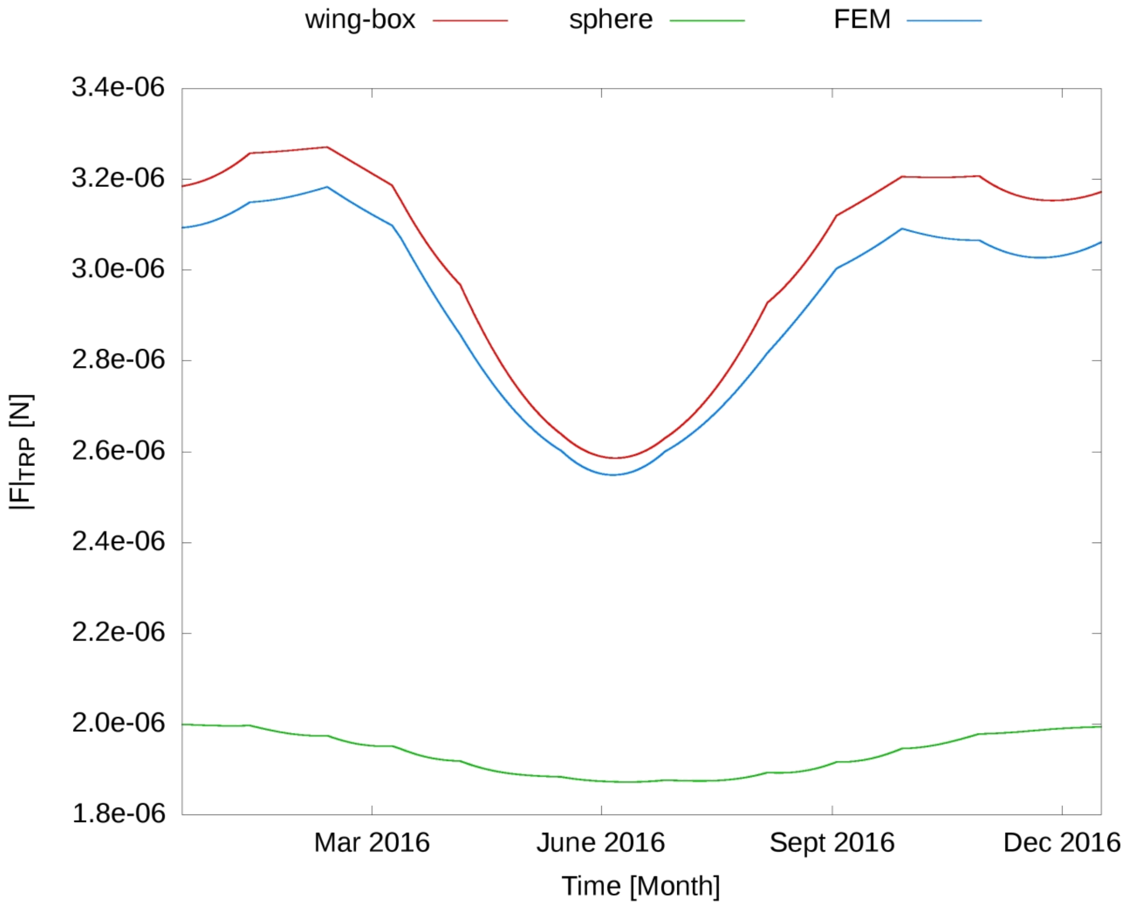
SRP: influence of geometry models



✓ Magnitude of the computed SRP force (simulated period of time: one year)

→ **different geometry models**, const. material coefficients for absorptivity and reflectivity, variation of angle between sun vector and orbit normal

TRP: influence of geometry models



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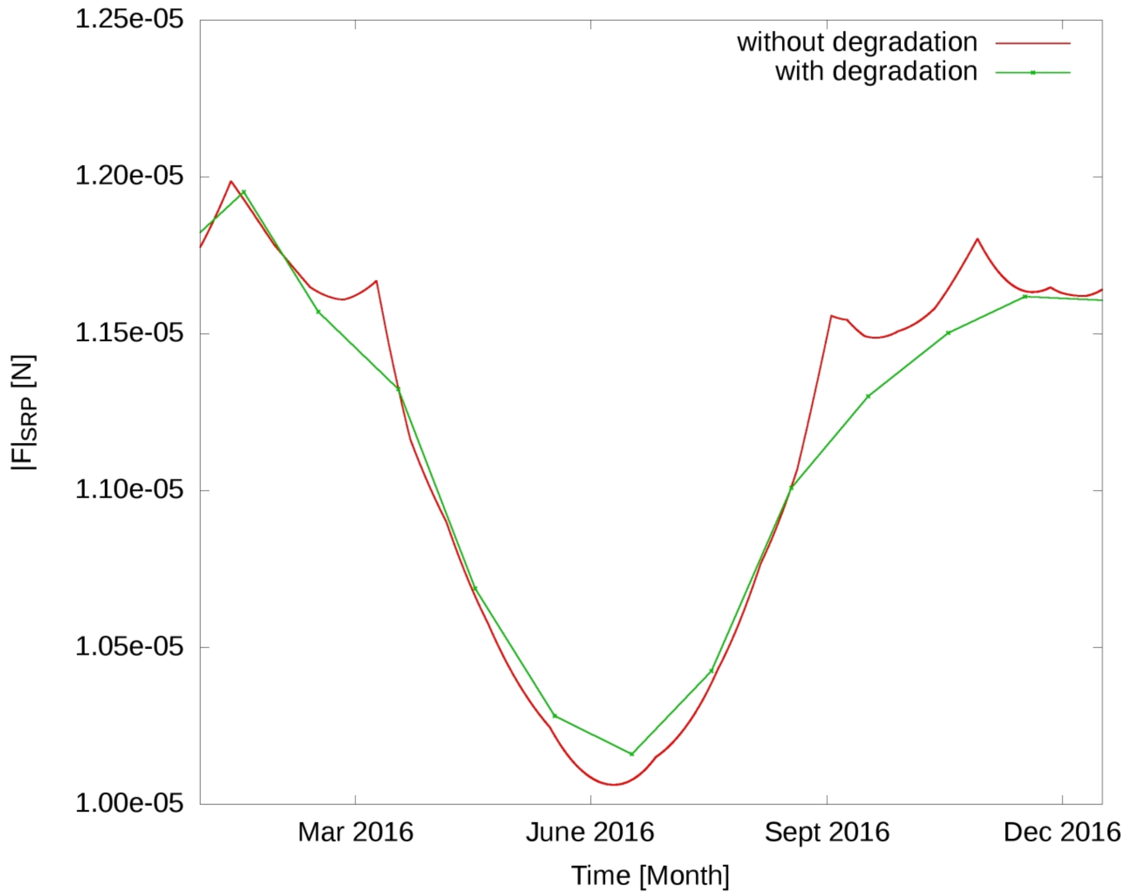
SRP: influence of material degradation



✓ Magnitude of the computed SRP force (simulated period of time: one year)

→ detailed geometry model, **degradation of material properties → coefficients for absorptivity and reflectivity are time-dependent**, variation angle between sun vector and orbit normal

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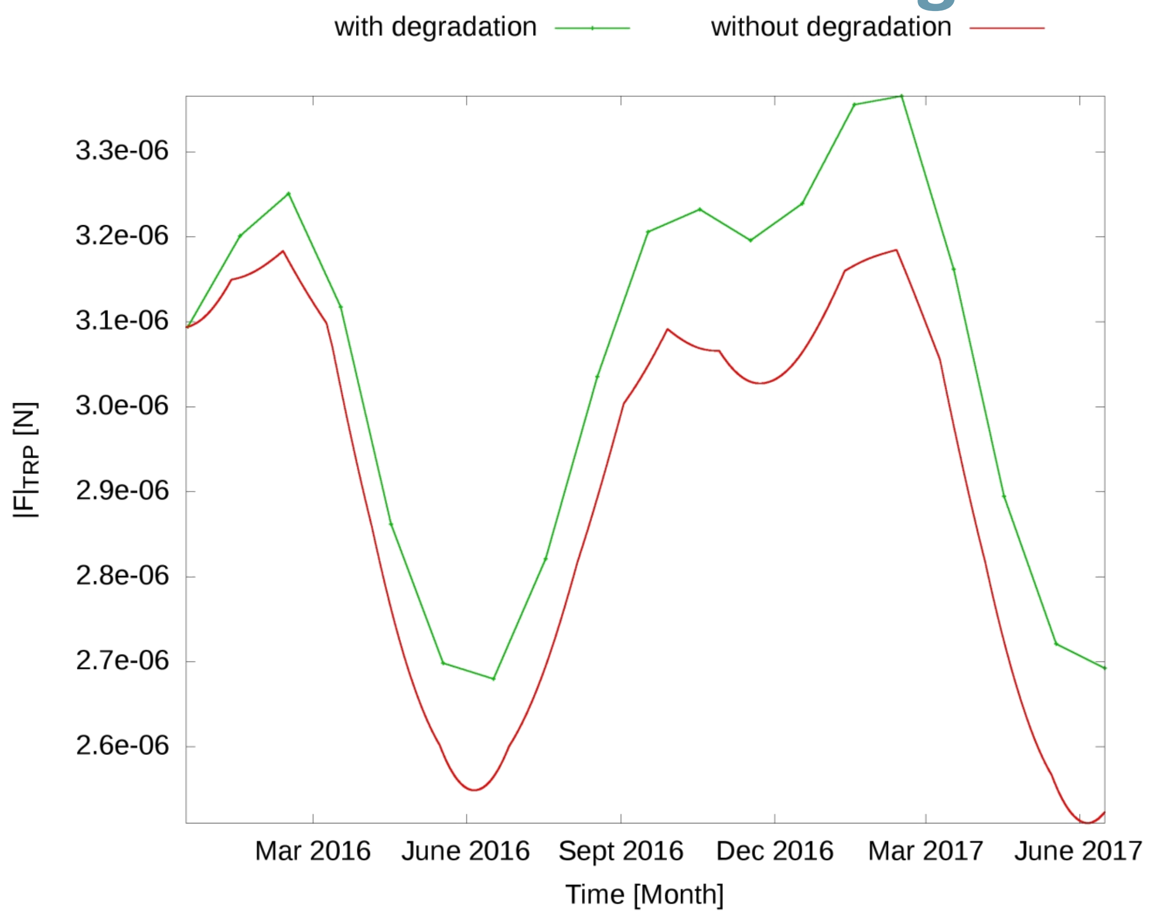
TRP: influence of material degradation



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  Time-dependent frequency analysis by using wavelets
- ✓ Modeling of non-gravitational disturbances
  - ✓ Motivation
  - ✓ SRP/TRP modeling approach
  - ✓ Example: MICROSCOPE
- ✓ **Outlook: post WEP test mission goals**
- ✓ Conclusion

Outlook: post WEP test mission goals

- ➔ Data collection in most critical altitude range for spacecraft conjunction assessment and collision avoidance

- ➔ **Evaluation and improvement of existing thermosphere models**, e.g. NRLMSIS, JB2008

- ➔ **Improvement and evaluation of satellite non-gravitational force modeling** including disentanglement of different effects (SRP/TRP/drag etc.) by collecting unique data in non-drag-free mode

- ➔ Proposal for a technological experiment : CNES / TU Delft / ZARM

- ➔ SPP 1788 DynamicEarth

Proposed mission details (measurement modes, duration, etc.)

- ✓ **Measurement without drag-free control** → Disturbances are directly visible in accelerometer axis
- ✓ If possible **variation/modulation of pitch angles** → Changing cross-sectional drag surface
- ✓ In addition **measurement during eclipse encounter** → Resolution of transient thermal effects and SRP evolution

→ **As many orbits as feasible**
→ **Optimal**: 1 year to cover seasonal effects

Needed data, support

- ✓ Accelerometer data (MNOG/FRM) in non-drag free mode, full set of housekeeping data (→ N_0 data sets)
- ✓ Operations by CNES
- ✓ Data evaluation and modeling: funding by national agencies

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Conclusion

- ✓ ZARM data report: focusing on time-dependent frequency analysis based on wavelet analyis of the time signals

- ✓ With the help of standard cannonball and Box-And-Wing models it is not possible to diagnose and identify SRP/TRP disturbance effects with highest precision.

- ✓ Material degradation effects cannot be neglected for determining a complete “disturbance force and torque budget“

- ✓ Post mission goals: **measurement of non-gravitational forces** in non-drag free mode ➔ new for field of research which has been nearly stagnant for decades

Thank you for your attention.

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