Orbit Propagation and non-gravitational force modeling for fundamental physics missions

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Overview

Introduction
- Orbit propagation vs. orbit determination
- Non-gravitational perturbations
- System modelling

Applications
- Pioneer 10
- Rosetta
- Messenger
- MICROSCOPE
- GALILEO
- GRACE/GRACE-FO

Summary

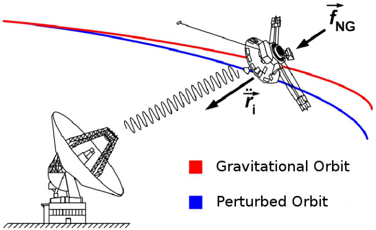
Orbit Determination and Propagation I

What is the goal?

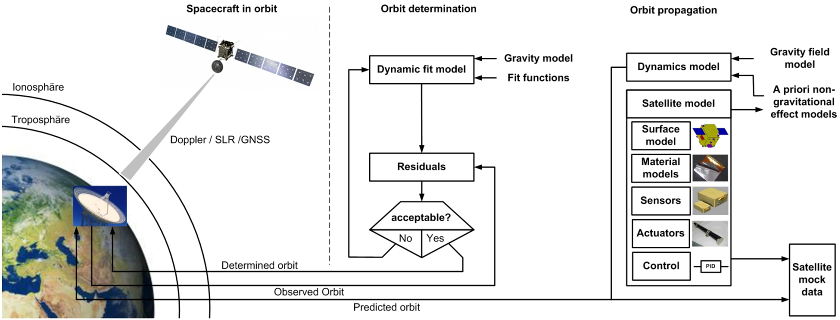
- Accurate determination of the satellite orbit,
- Future prediction of orbit evolution.

What is the challenge?

- Complexity of the gravitational field,
- Non-gravitational perturbations,
- Signal errors,
- Satellite system effects.



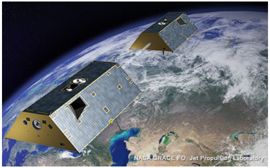
Orbit Determination and Propagation II

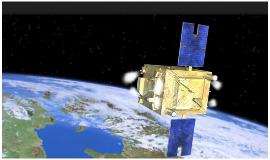


- Orbit determination: Estimation of parameters to realize a good model for the satellite orbit. Fit models do not have to be physically correct.
- Orbit propagation: In order to get a good estimation of the future propagation of the satellite each effect influencing the trajectory has to be included into the integration of motion by means of a physically correct model.

Satellite propagation and satellite system models I

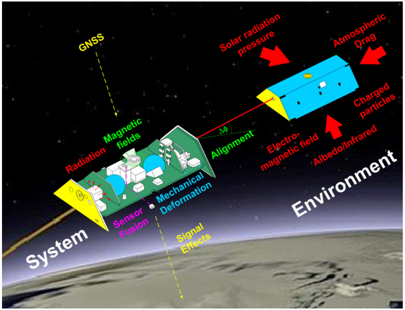
- Modelling in preparation of the mission:
  - Optimisation of the mission scenario,
  - Definition of requirements,
  - Performance evaluation.
- Modelling during the mission:
  - Calibration,
  - Planning and evaluation of manoeuvers,
  - Identification and mitigation of perturbations and systematics.
- Modelling after the mission:
  - Identification of perturbation sources in the science signal,
  - Interpretation of science and housekeeping data.

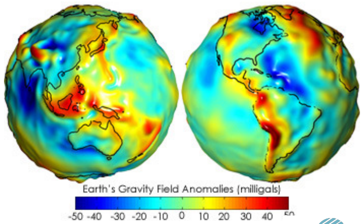




Satellite propagation and satellite system models II

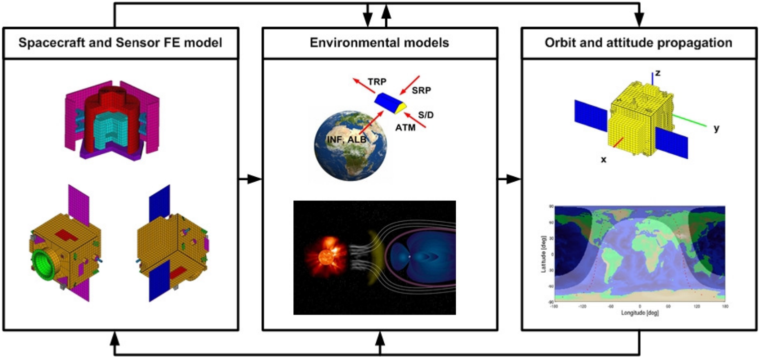
- System effects
  - Thermal budget,
  - Operations,
  - Sensors,
  - External data,
  - Actuators/Controller,
  - Output: Mock data sets.
- Gravitational and non-gravitational disturbances:
  - Atmospheric drag,
  - Radiation pressure (Solar, thermal, infrared, Albedo),
  - Electromagnetic field, dust, charging, outgassing...



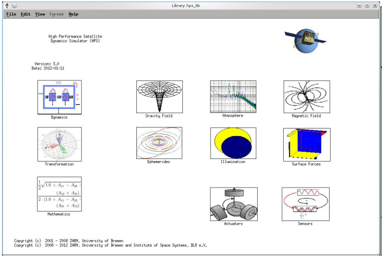


Source: NASA

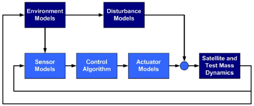
Modeling Approach



The High Performance Satellite Dynamics Simulator

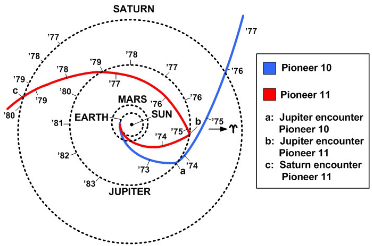


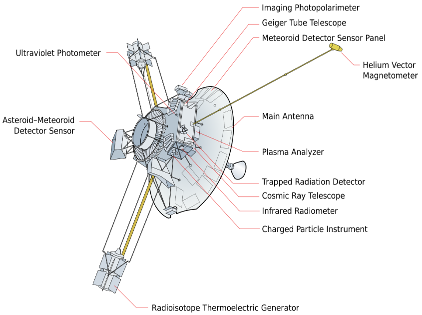
Target		**High Precision, Multi-satellite swarm**
		+ AOCS system (determination and control)
		+ Payload models (Accelerometer / LRI)
Environment models	Gravity	Spherical / EGM2008 / GRACE / **user defined**
	Atmosphere	NRLMSISE-00 / HWM93 / **Free-Molecular Flow**
	SRP	Flat plate / FEM
	Albedo	Reflectivity data from NASA/TOMS archive
	3rd body	Analytical ephemeris **/ DE421 (JPL)**
	+Thermal	**Analytical / Numerical with FEM**
	+Infrared	**NASA/TOMS archive**
	+Relativistic	**e.g. Post-Newtonian approximation**
Interface	Code base	**C/C++**
	GUI	Simulink with function block library



- MATLAB/SIMULINK Library with embedded C/C++ s-functions,
- Toolbox for modelling of satellite mission scenarios, modular approach, highly flexible,
- High precision numerical integration of position and attitude,
- Multi-satellite scenarios implemented by XHPS → CRC geoQ.

Applications: Pioneer 10



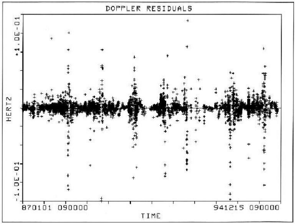


Mission	Pioneer 10	Pioneer 11
Start	02.03.72	05.04.73
Fly-Bys	04.12.73 (Jup)	02.12.1974 (Jup) 01.09.79 (Sat)
Last Contakt	27.04.02 (80,2 AU)	01.10.90 (30 AU)

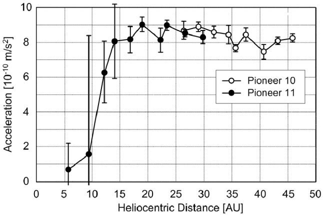
- First flight through asteroid belt,
- First analysis of interplanetary medium,
- Detailed analysys of Saturn and Jupiter,
- More than 150 succesful experiments.

Pioneer 10 was in operation for more than 30 years !

Applications: Pioneer 10



Anderson et al., PRL 81, 1998.



Anderson et al., PRD 65, 2002

- 1998: Discovery of a residual blue shift in the two-way Doppler signal,
- Was interpreted as a constant deceleration of $8.74 \pm 1.33 \cdot 10^{-10}\,\mathrm{m/s^2}$,

$$a_P = \frac{dv}{dt} \sim \frac{d\nu}{dt}\frac{c}{2\nu_0}\,.$$

Central Question: What was the cause of this Pioneer Anomaly (PA) ?

- Signal effects,
- New Physics,
- Unmodeled disturbances → could an anisotropic heat radiation cause the PA ?

Pioneer 10: Situation 2007

- 2nd Meeting of the international “Pioneer Explorer Collaboration” in Bern,
- 3 groups start analysis of thermal effects: NASA(JPL)/Pasadena, Bremen, Lissabon,
- It is clear that simplified analytical models of the thermal effects are not suitable for spacecraft with complex geometrical shape,
- a method for the determination of thermal radiation pressure analysis for complex spacecraft structures including the dynamic thermal behaviour was needed.

Model for thermal radiation pressure

Photon momentum:

$$E = \sqrt{(m_0\,c^2)^2 + (|\vec{p}_{\mathrm{Ph}}|\,c)^2}$$

$$\rightarrow E_{\mathrm{Ph}} = |\vec{p}_{\mathrm{Ph}}|\,c \ \text{ mit } \ E_{\mathrm{Ph}} = h\,\nu_{\mathrm{Ph}}\,.$$

Change of momentum due to absorption:

$$\frac{d|\vec{p}|}{dt} = \frac{h\,\nu_{\mathrm{Ph}}\,dN}{c\,dt} = |\vec{F}_{\mathrm{TRP}}| = \frac{P}{c}\,.$$

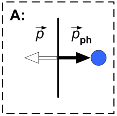
Change of momentum due to emission:

$$d\vec{F}_{\mathrm{TRP}} = -\vec{n}\,\frac{1}{c}\,dE\,\cos\theta$$

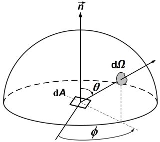
$$\rightarrow \vec{F}_{\mathrm{TRP}} = -\vec{n}\,\frac{2\,P_{\mathrm{tot}}}{3\,c} = -\vec{n}\,\frac{2\,\varepsilon\,\sigma\,A\,T^4}{3\,c}\,.$$

Absorption and reflection:

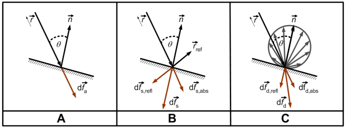
$$\mathrm{d}\vec{f}_{\mathrm{res}} = \mathrm{d}\vec{f}_{\mathrm{a}} + \mathrm{d}\vec{f}_{\mathrm{s}} + \mathrm{d}\vec{f}_{\mathrm{d}} = \frac{-P_{\mathrm{inc}}\cos\theta\,\mathrm{d}A}{c}\left[(1-\gamma_{\mathrm{s}})\vec{r} + 2(\gamma_{\mathrm{s}}\cos\theta + \tfrac{1}{3}\gamma_{\mathrm{d}})\vec{n})\right].$$



Exchange of momentum: Emission (A), Absorption (B)



Emission with $d\Omega = \sin\theta\,d\theta\,d\phi$



A: Absorption, B: Specular Refl., C: Diffuse Refl.

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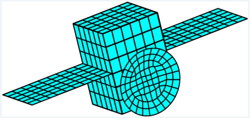
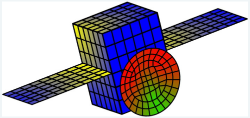
Numerical determination of thermal pressure

1. Modelling



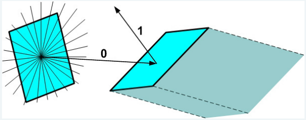
- Model of SC geometry
- Generation of FE mesh

2. Thermal analysis



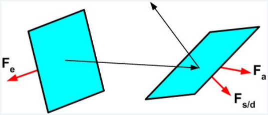
- Definition of boundaries
- Determination of equilibrium

3. radiative fluxes



- Computation of view factors
- Raytracing

4. Force calculation



- Element forces
- Effective sum

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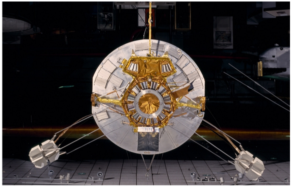
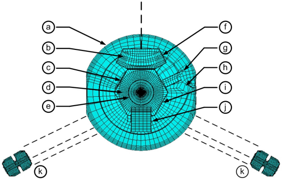
Applications: Pioneer 10



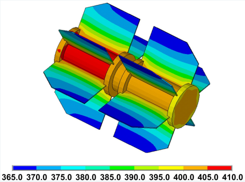


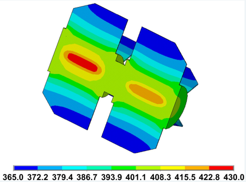
a) High gain antenna, b) Sec. Louver system, c) Radiator, d) Prim. Louver system, e) Launch Adapter, f) Experimentsection, g) Sunshield, h) Detectors, i) Equipmentsection, j) Met. shield, k) Radioisotopic generators

- 3D FE Modell with hexaedric elements for 3D heat conduction,
- About 50000 conductors and 17000 radiation sources,
- Internal and external heat exchange,
- Full multi-sheet MLI model,
- Trajectory und Housekeeping Data (Thermistors, voltage and current sensors) defined as boundaries,
- Modular ANSYS APDL Macro with more than als 30000 lines of code,
- Thermal pressure analysed for 30 years with a resolution of 1 year.

Application: Pioneer 10

RTG

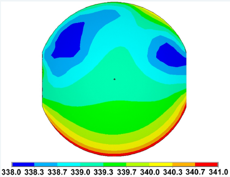


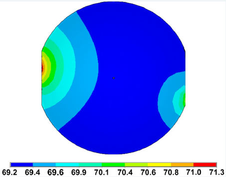


- Inward RTG is warmer.
- Temperatures decrease at fin tips.

HGA

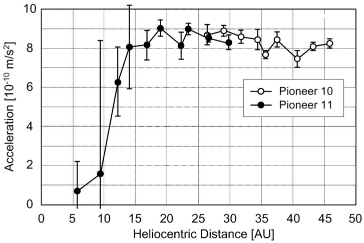
- Higher temperatures at start of mission.
- Decreasing temperatures during the course of the mission.



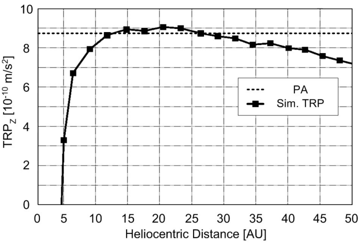


Result of the Pioneer 10 analysis

- TRP shows resemblance to the PA w.r.t. magnitude and characteristics,
- The Pioneer anomaly can be explained completely with an unmodeled TRP,
- Final JPL Doppler analysis shows a decrease of the residual acceleration over time,
- Independent models of Turyshev et al., Francisco et al. and Modenini et al. confirm the effect.



Anderson et al., PRD 65, 2002

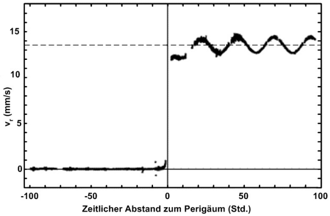


Rievers et al., ADP 523, 2011

The Rosetta mission

- Orbit determination performed by European Space Operations Center (ESOC) in Darmstadt,
- Anomalies in the determined solar pressure model (solar constant 10 % too high).

- Detailed analysis of the dominant NGOs → SRP and TRP,
- In addition: analysis of earth fly-by anomaly: velocity increase caused by SRP or TRP ?



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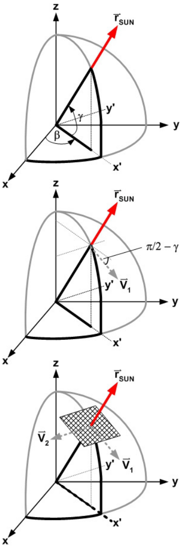
Analytic model for SRP



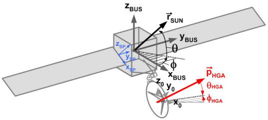
- Modelling of sun by pixel plane.
- SRP depends on sun direction, spacecraft geometry and optical surface properties.
- Raytracing and force computatuin analog analog to TRP procedure.

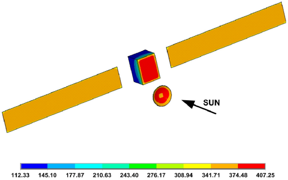
SRP model

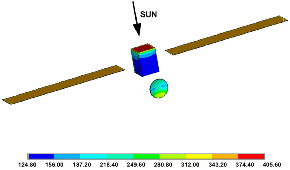
$$\vec{P}_{\mathrm{SRP}} = \frac{-P_{\mathrm{rec}} A}{m\, c} \left((1 - \gamma_{\mathrm{s}})\, \vec{r}_{\mathrm{SUN}} + 2(\gamma_{\mathrm{s}} \cos\kappa + \frac{1}{3}\gamma_{\mathrm{d}}) \right) \vec{n} \cos\kappa$$

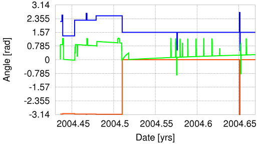
- For every illuminated surface element.
- Tracing of the reflected rays to determine secondary reflection effects.

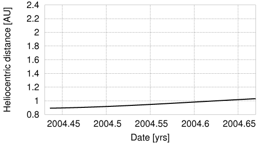
Input parameters





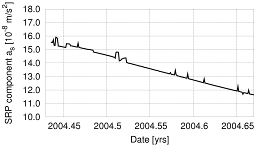


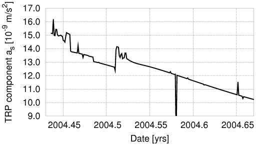




- 5 analysed cruise phases from 2004 to 2007 as well as the first earth-flyby.
- HGA pointing and Sun vector are boundaries for the FE analysis.
- Black Kapton, HGA white paint , spacing on solar panels, bus conductive properties etc.
- Solar panels are always assumed to be in Sun-pointing mode.

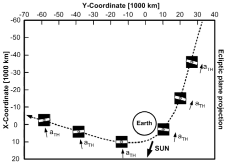
SRP and TRP results

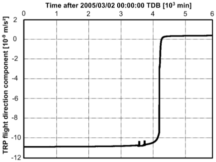




- SRP is dominated by solar panels → surface area.
- TRP is dominated by the bus → temperature gradient.
- TRP is up to 10% of SRP, resolves anomaly in ESA/ESOC SRP model.

- SRP and TRP mostly decelerate the spacecraft during flyby.
- Observed anomaly: increase of velocity.
- SRP and TRP are not causing the flyby anomaly.





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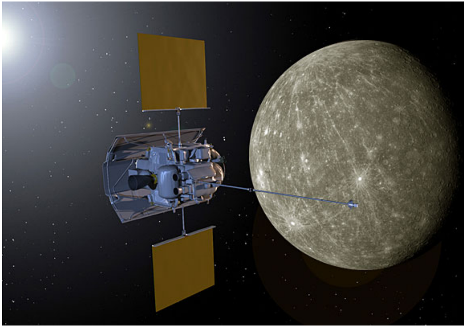
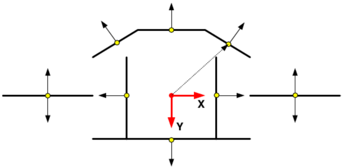
The Messenger mission

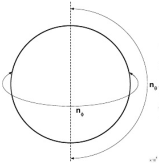


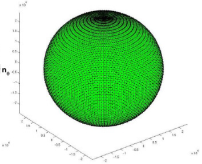
- In orbit around mercury,
- Highly eccentric orbit,
- Very close to the sun (0.307 - 0.467 AU) $\rightarrow$ NGOs caused by radiative effects are about 10 times bigger than in orbit around earth,
- Besides SRP and TRP, albedo and infrared radiation have to be implemented.

Infrared- and albedo pressure: interaction of spacecraft and planetary surface

Satellite and planet are both modeled by a surface mesh approach.





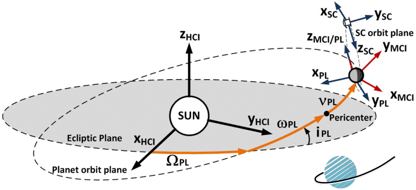


Interface for satellite/planet:

cell surface [m^2]	right ascension [rad]	declination [rad]	cell center [m|m|m]	α_{sc}	$\gamma_{S,sc}$	$\gamma_{D,sc}$

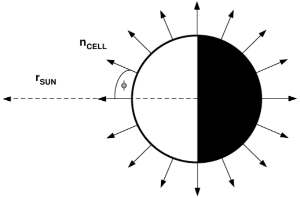
Coordinate frames:

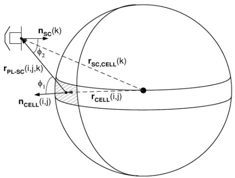
1. J2000 Heliocentric inertial frame,
2. J2000 Mercurycentric inertial frame,
3. Planet fixed mercury frame,
4. Satellite fixed frame.



Infrared radiation pressure model

- Planetary surface distributed in day/night cells,
- Different temperatures on day/night side.





- Radiation view factors $F(i,j,k)$ are computed between PL cell and SC cell,
- $F(i,j,k) = \frac{\cos\phi_{VIS,1}\cos\phi_{VIS,2}}{\pi|\vec{r}_{pl-sc,PL}(i,j,k)|^2} A_{sc}(k)$
- Field of view depends on satellite attitude and position.

$$\vec{a}_{INF,SC}(i,j,k) = \frac{E_{INF}(i,j,k))}{c \cdot m_{sc}} \Bigg[(\alpha_{sc}(k) + \gamma_{D,sc}(k)) \cdot (-\vec{r}_{sc,pl,SC}(k)) + 2\left(\frac{\gamma_{D,sc}(k)}{3} + \gamma_{S,sc}(k)\cos\phi_{VIS,2}(i,j,k) \right) \Bigg] \vec{n}_{sc,SC}(k) \,.$$

Albedo radiation pressure model

Radiative flux at planet surface: $P_{rec,pl}(i,j) = \frac{P_{1AU}}{r^2_{pl,HCI}} \cos\phi_{sun}(i,j)\,.$

Angle of planet cell w.r.t. sun: $\phi_{sun}(i,j) = \arccos(\vec{n}_{pl}(i,j)\cdot\vec{r}_{sun})\,.$

Reflected power: $E_{refl,pl}(i,j) = \gamma_{D,pl}(i,j)P_{rec,pl}(i,j)A_{pl}(i,j)\,.$

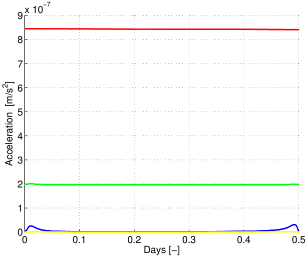
Received power: $E_{ALB}(i,j,k) = F(i,j,k)E_{refl,pl}(i,j)\,.$

$$\vec{a}_{ALB,SC}(i,j,k) = \frac{E_{ALB}(i,j,k))}{c\cdot m_{sc}}\Bigg[(\alpha_{sc}(k)+\gamma_{D,sc}(k))\cdot(-\vec{r}_{pl-sc,SC}(k)) + 2\left(\frac{\gamma_{D,sc}(k)}{3}+\gamma_{S,sc}(k)\cos\phi_{VIS,2}(i,j,k)\right)\Bigg]\vec{n}_{sc,SC}(k)\,.$$

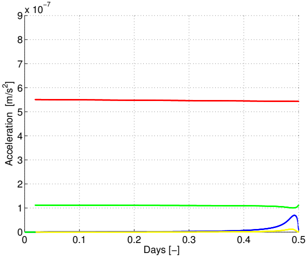
Calculation similar to infrared model, source of radiation is now the Sun
$\rightarrow$ solar photons reflected at planet surface.

NGOs

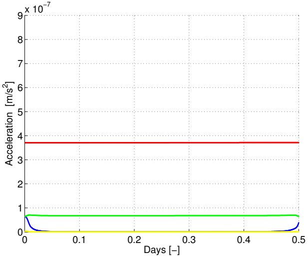
Case 1



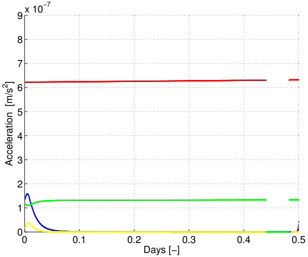
Case 2



Case 3



Case 4



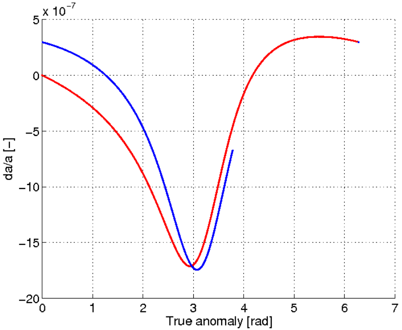
Red: SRP, Green: TRP, Blue: INF, Yelllow: ALB

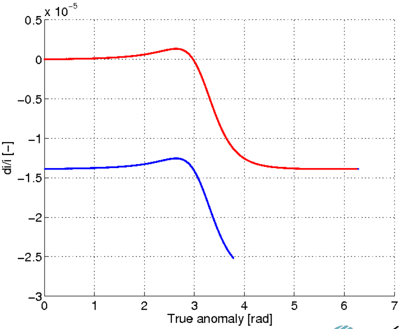
Effects on the orbit I

Max. forces in the range mN $\rightarrow$ considerable unintended change of orbital elements over time.

$$\vec{P}(t) = \vec{P}(t_0) + \mu \int\int -\frac{1}{r^3} \cdot \vec{r} + \vec{a}_{pert}(t)\, dtdt\,.$$

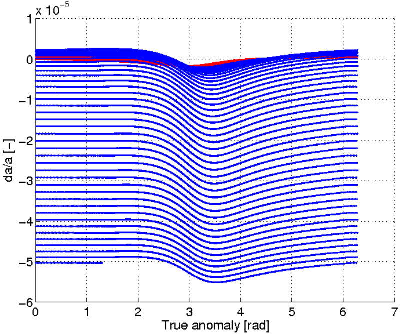
$$\vec{a}_{pert}(t) = \vec{a}_{SRP}(t-dt) + \vec{a}_{INF}(t-dt) + \vec{a}_{ALB}(t-dt) + \vec{a}_{TRP}(t-dt)\,.$$





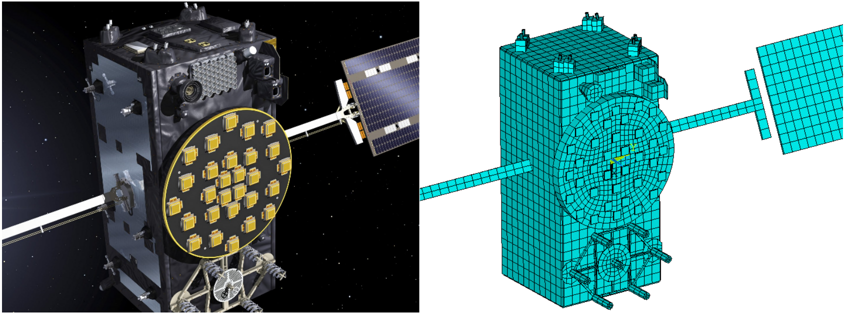
ZARM

Effects on the orbit II



- Buildup of inclination and expansion of orbit, if perturbations are not controlled by AOCS,
- Perturbation analysis gives an estimate on the needed fuel.

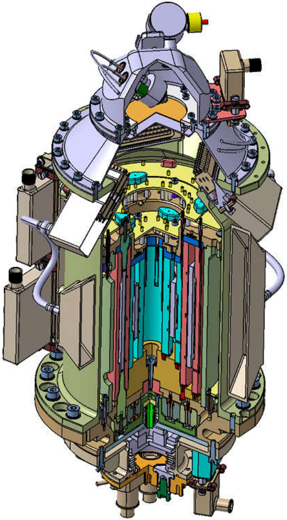
Applications: Galileo



Comparison between real satellite and FE model

- Using a priori SRP model for an improvement of orbit determination,
- Demonstrated successfully with simple box-and-wing model by Montenbruck et al (ECOM).

Applications: MICROSCOPE

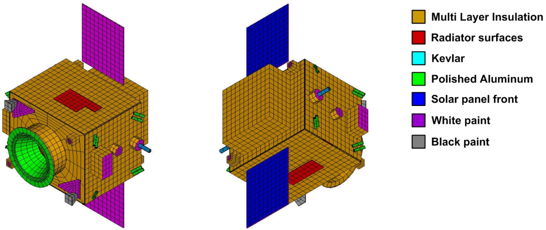


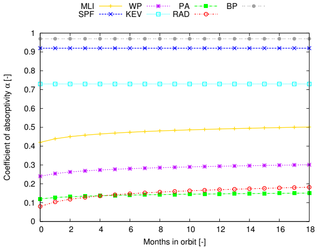
Picture : CNES

Why perturbation modeling?

- T-Sage external housing connected to bus,
- Influence of external perturbations in spite of DFACS, depending on controller performance, electrostatic actuators and alignments,
- Electrostatic coupling between test masses and bus,
- Residual accelerations acting on test mass motion,
- SRP/TRP within the range of the science signal frequency f_{WEP} !

Materials and power



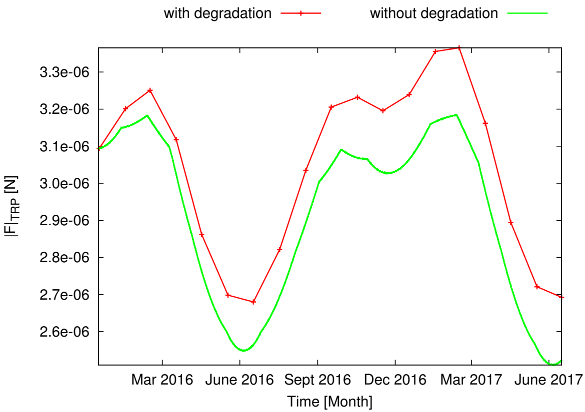


Surf.	MLI	SPF	WP	KV	PA	RAD	BP
α_{BOL}	0.42	0.92	0.24	0.73	0.12	0.08	0.97
α_{EOL}	0.5	0.92	0.30	0.73	0.15	0.18	0.97
ε	0.84	0.85	0.88	0.92	0.04	0.8	0.89
$\gamma_{S,BOL}$	0.29	0.073	0.38	0.246	0.8	0.46	0.015
$\gamma_{S,EOL}$	0.071	0.05	0.099	0.168	0.53	0.116	0.004
$\gamma_{D,BOL}$	0.29	0.007	0.38	0.025	0.08	0.46	0.015
$\gamma_{D,EOL}$	0.429	0.030	0.601	0.102	0.3204	0.704	0.0257

Component	P [W]
MLI faces	3.0
-X Radiator	13.0
+Y Radiator	16.6
-Y Radiator	28.3
Total	60.9

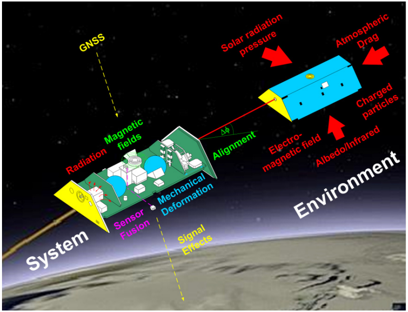
- BOL/EOL properties with exponential degradation model,
- Power in nominal accelerometer measurement mode.

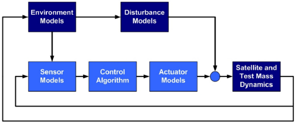
TRP 1 Year with degradation



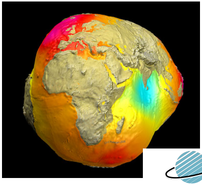
- Difference in TRP solution builds up with time,
- General increase of $\alpha \rightarrow$ increase of TRP.

Applications: GRACE-FO



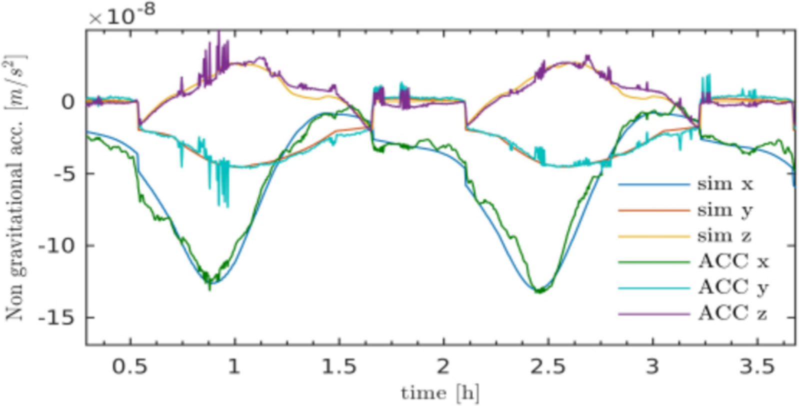


- Complete satellite system simulation needed,
- Simulation of sensors, actuators and control scheme,
- XHPS developed in SFB 1128 : geoQ.



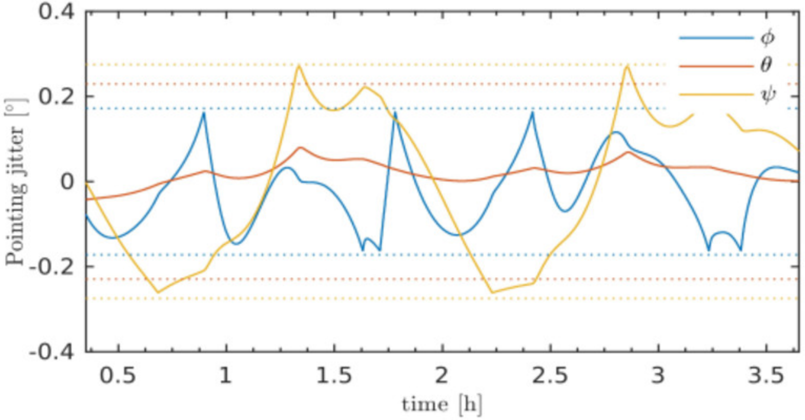
- Laser-based gravimetry with high requirements,
- Needed modelling accuracy: μm on 200 km $\rightarrow$ numerically challenging,
- NGOs possess a direkt influence on the measurement $\rightarrow$ all models have to be implemented in adquate precision.

Applications: GRACE-FO



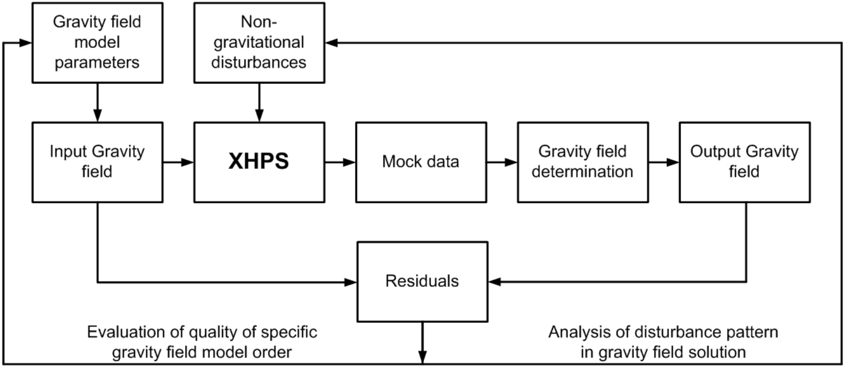
- Simulated Accelerometer signal resembles GRACE Level 1B accelerometer data

Anwendungen: GRACE-FO

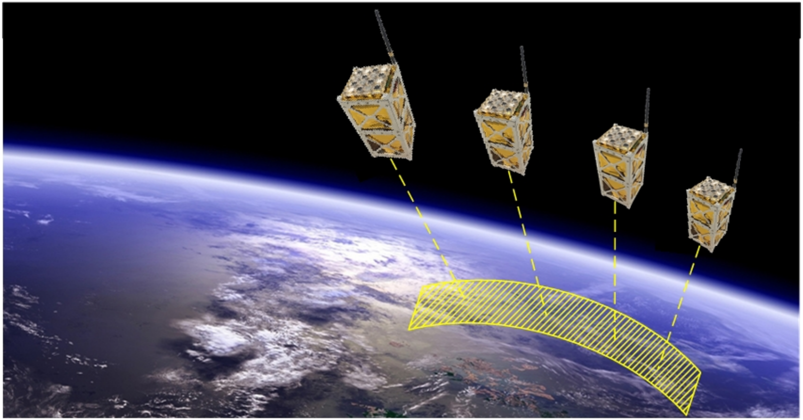


- Realistic simulated jitter

Closed loop simulations



Mission analysis



- Evaluation of mission scenarios,
- e.g. constellation of many nano satellites vs. large single satellite.

Summary

- High precision non-gravitational force modeling needed to accurately predict satellite behaviour,
- Modeling of radiative forces is a complex task,
- Orbit propagation together with system modeling useful before, during and after the mission, can improve orbit determination,
- Approach on mission analysis: Virtual satellite in virtual orbit producing virtual data,
- Analysis of concept, performance and data evaluation procedures.