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POD improvements of GNSS satellites through the measurements of their non-gravitational accelerations by means of an onboard accelerometer

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Summary

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6. Preliminary results in terms of accelerometer performance
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Motivations

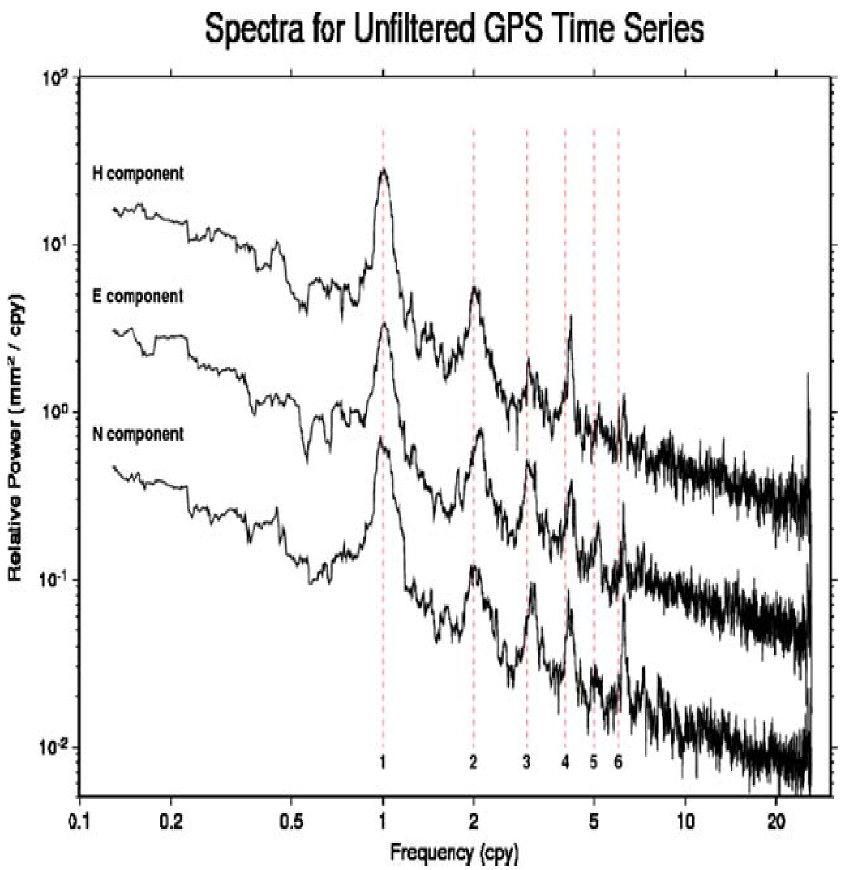
- The solar radiation pressure (**SRP**) represents the largest non-gravitational perturbation (**NGP**) acting on the orbit of a spacecraft of the **GNSS**
- **NGPs** are in general difficult to model, also for spherical in shape satellites, much more for complex in shape satellites such as those of the **GPS**, **GLONASS**, **BEIDOU …** and **GALILEO** constellations
- Eclipses and orbit maneuvers represent additional complications for a refined modelling

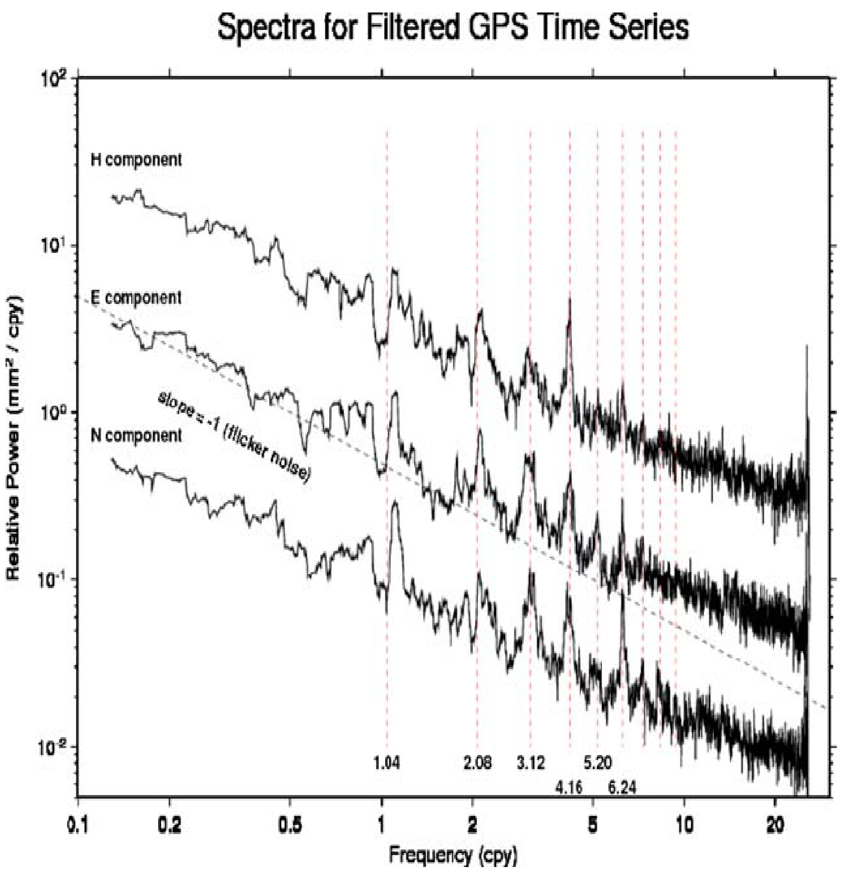
Consequently:

- **Current precise orbit determination (POD) of GNSS satellites is not so precise as desired**
- **Systematic errors found in the orbits of GNSS satellites, as well as in the derived geodetic parameters, show that significant NGPs mis-modelling is still present, as for SRP, thermal effects, …**

Motivations

Evidence for 1.04 cpy and higher harmonics in the stacked (167 stations) and filtered spectra of non-linear position residuals of the weekly IGS stations solutions included in ITRF2005 (Ray et al, GPS Solut **12** (2008)). This frequency is very close to that of the Draconit-year (1.039 cpy) …





The fundamental harmonic @ 1.040±0.008 cpy and its close relation with the Draconitic year could indicate:

- **Systematic errors related with satellites orbit mismodelling also in relationship with the complex Sun-satellite interactions**
- **Aliasing of site-dependent positioning biases**

Motivations

As consequence of the above main points and also to improve the final precision of the **GALILEO** user-segment, the European Space Agency (**ESA**) because of its efforts to provide a **new constellation of GNSS**, and especially in view of **next generation of GALILEO**, beside being interested in possible **improvements of the NGPs models** is also envisaging **to use an onboard accelerometer** to directly measure the **non-gravitational accelerations** and finally **improve the POD** of each spacecraft of the **GALILEO constellation**

The **Experimental Gravitation** group of **IAPS/INAF** has a long experience in developing sensors for **geophysics** and **fundamental physics** measurements

Order-of-magnitude of the perturbing accelerations on GALILEO2-sat

Gravitational and non gravitational perturbations: amplitude of the acceleration and orbital effects over 1-day

Acceleration term	Formula	GALILEO2 [m/s²]	R [m]	T [m]	W [m]
Main gravitational accelerations					
Earth's monopole	$GM_\oplus/r^2$	0.45	∞	∞	∞
Earth's oblateness	$3(GM_\oplus/r^2)(R_\oplus/r)^2 J_{20}$	3.1×10^{-5}	1780	20713	9709
Low order geopotential	$3(GM_\oplus/r^2)(R_\oplus/r)^2 J_{22}$	1.8×10^{-7}	10	120	56
Moon	$2(GM_m/r_m^3)r$	5.1×10^{-6}	446	2007	33
Sun	$2(GM_\odot/r_\odot^3)r$	2.3×10^{-6}	223	1338	446
Earth's tides	$3k_2(GM_m/r_m)(R_\oplus/r_m)^2(R_\oplus^3/r^4)$	2.1×10^{-9}	0.2	0.8	0.01
Ocean tides	$\approx$ 0.1 Earth's tides	2.1×10^{-10}	0.02	0.08	0.001
General relativity	$(GM_\oplus/r^2)(GM_\oplus/c^2)(1/r)$	6.8×10^{-11}	0.008	0.09	0.04

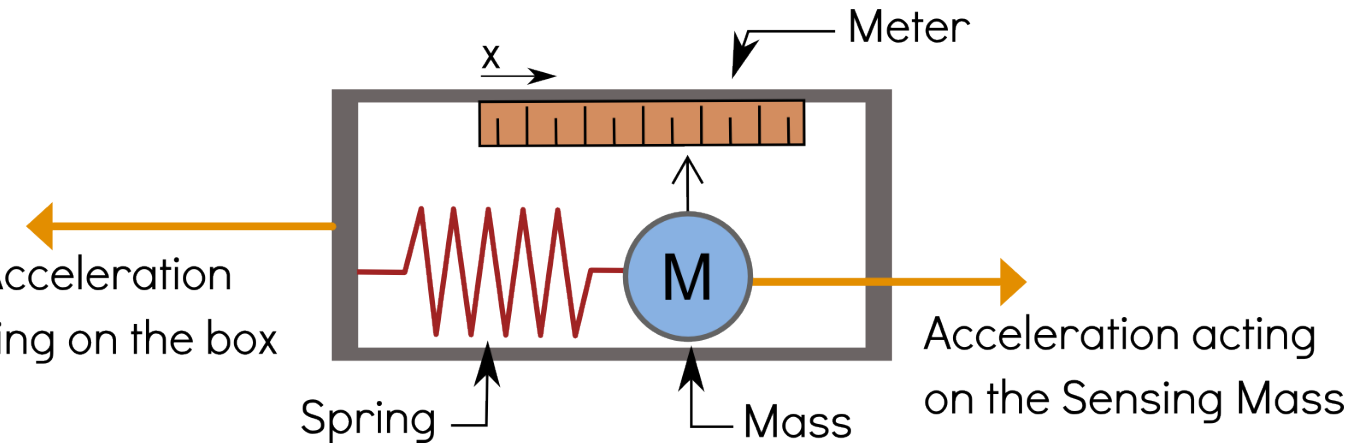
Acceleration term	Formula	GALILEO2 [m/s²]	R [m]	T [m]	W [m]
Main non gravitational perturbations					
SRP	$A\Phi_\odot/Mc$	1.5×10^{-7}	116	279	8
Earth's albedo	$2A_\oplus(\pi R_\oplus^2/4\pi r^2)(A\Phi_\odot/Mc)$	1×10^{-9}	0.8	2.0	0.06
Y-bias	Y_0	1.2×10^{-9}	1.1	10	0.4
Power radiated by the antennas (*)	$\frac{P}{Mc}$	2×10^{-9}	0.05	3.5	0.06
Thermal effects: solar panels only	$(2\sigma A/3Mc)(\varepsilon_1 T_1^4 - \varepsilon_2 T_2^4)$	4×10^{-10}	0.5	4.5	0.01

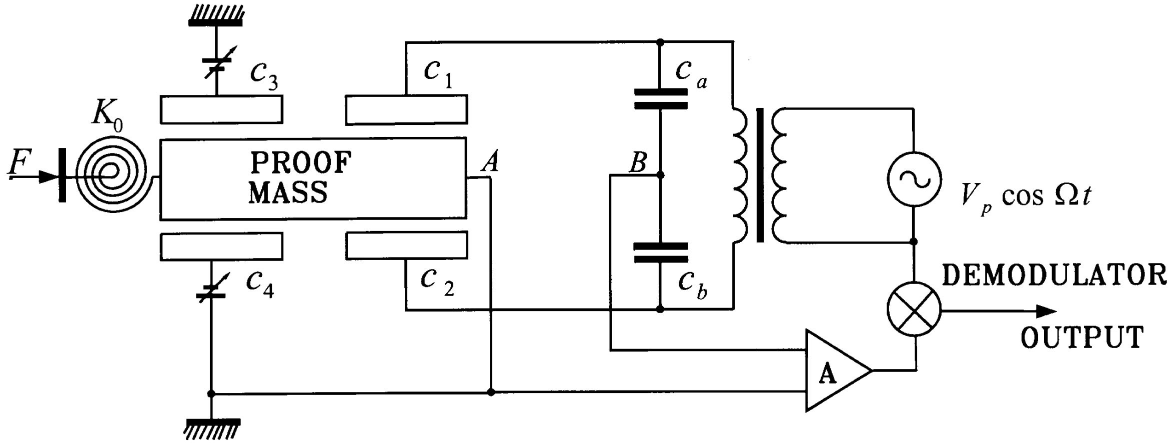
(*) We assumed a misalignment of the antenna of about 1°

a = 29600 km   semi-major axis

Accelerometer: measurements and physical characteristics

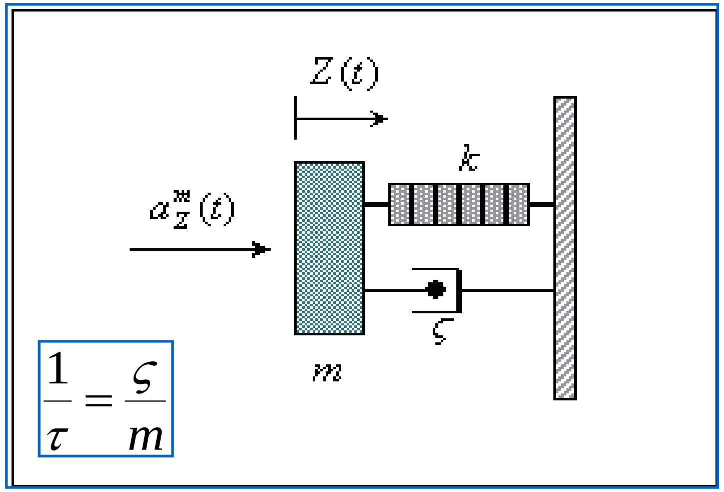
Principle of operation of a spring accelerometer





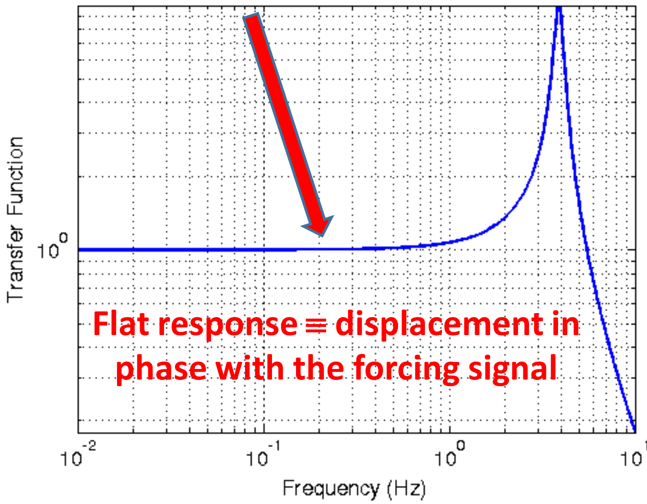
Electrical diagram of one proof–mass pickup system

Forced harmonic oscillator



$$m\ddot{Z}(t) + \varsigma\dot{Z}(t) + kZ(t) = F_Z(t)$$

$$\ddot{Z}(t) + \dot{Z}(t)/\tau + \omega_0^2 Z(t) = a_Z(t)$$



Accelerometer: measurements and physical characteristics

The obtain a **POD** we need to write the **equations of motion, containing the dynamical parameters** of interest, with respect to a reference point of the spacecraft

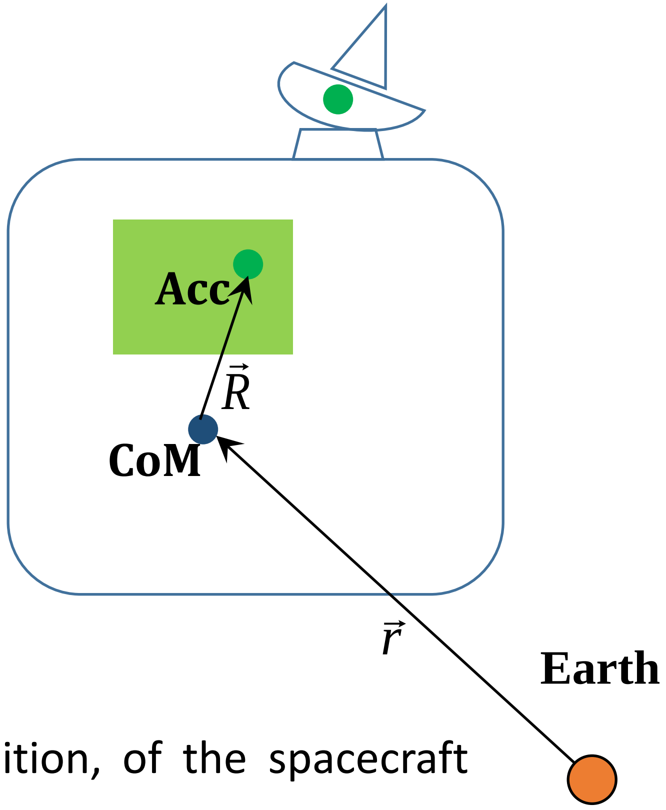
Usually, this point is the spacecraft center-of-mass (**CoM**)

On board measurements

$$\ddot{\vec{r}} = -\nabla U(\vec{r}) + \vec{A}_{NGP}$$

$$\vec{a}_{accel} = (\vec{\nabla} \cdot \vec{g})\vec{R} - \vec{\omega} \wedge (\vec{\omega} \wedge \vec{R}) - \dot{\vec{\omega}} \wedge \vec{R} - \vec{A}_{NGP} - \vec{a}_{CM} - \left.\frac{\Delta \vec{V}}{\Delta t}\right|_{Man.}$$

1.	**Non–gravitational accelerations (NGA)**	$-\vec{A}_{NGP}$
2.	Accelerations due to **gravity gradients**	$(\vec{\nabla} \cdot \vec{g})\vec{R}$
3.	**Apparent accelerations**	$-\vec{\omega} \wedge (\vec{\omega} \wedge \vec{R}) - \dot{\vec{\omega}} \wedge \vec{R}$
4.	**Spacecraft center-of-mass** accelerations	$-\vec{a}_{CM} = -2\vec{\omega} \wedge \dot{\vec{R}}_{rot} - \ddot{\vec{R}}_{rot}$
5.	Accelerations due to **thruster maneuvers**	$-\left.\frac{\Delta \vec{V}}{\Delta t}\right\|_{Man.}$



All these aspects impose requirements on the knowledge of the test masses position, of the spacecraft attitude, and on the spacecraft **CoM** drifts and accelerations

Accelerometer: measurements and physical characteristics

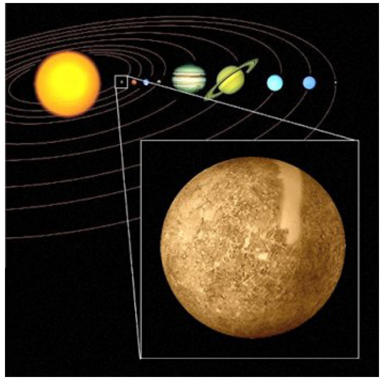
<u>BepiColombo Radio Science Experiments (RSE)</u>

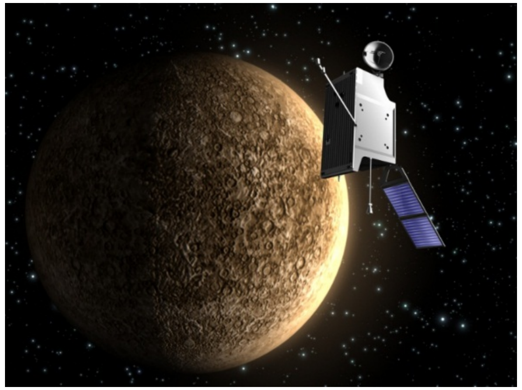
The space mission **BepiColombo**, one of the Cornerstones of **ESA**, aims to perform:

1. a detailed study of the planet **Mercury** and its environment
2. a test of **Einstein's** General Relativity to an unprecedented level of accuracy

Launch window opens on July 10, 2017, arrival January 1, 2024 start of science February 2024:

1 year of nominal duration + 1 year of extended mission

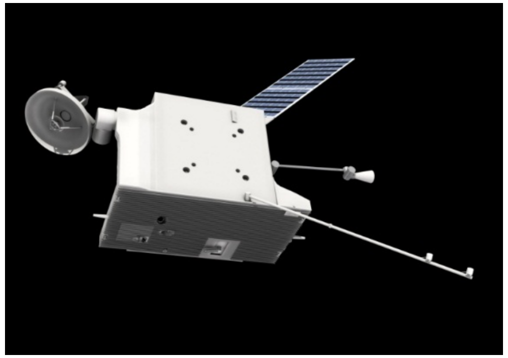




The **RSE** represents a complex mix of measurements and scientific objectives and, very interesting, it is not possible to separate them neatly in independent experiments.

However, we can distinguish:

1) a **gravimetry experiment**
2) a **rotation experiment**
3) a **relativity experiment**



Basically, on–board the MPO, the instruments used for these experiments are:

- Ka–band Transponder
- Star–Tracker
- High Resolution Camera
- Accelerometer

Accelerometer: measurements and physical characteristics

<u>ISA (Italian Spring Accelerometer) role</u>: measurement of the non-gravitational accelerations

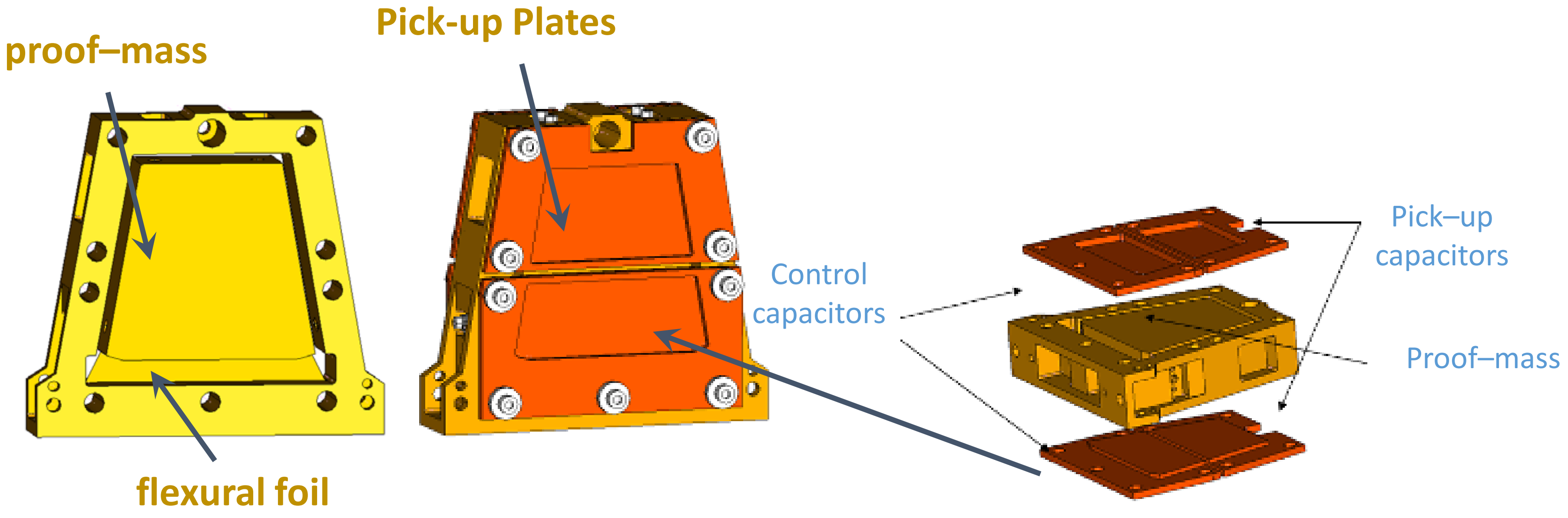
- Indeed, the **modelling** depends on a set of **parameters** related with the physical properties of the satellite surface and structure, which will be **strongly influenced**, and with **unknown laws**, by the **strong radiation environment** in the surroundings of **Mercury**

- Therefore the **MPO** surface will reflect (in the visible) and re-radiate (in the infrared) in a very complex way. Then we have the shadowing effects …

- **ISA** allows to remove the **NGA** from the equations of motion in such a way to reconstruct the **pure gravitational orbit** of a reference point of the **MPO** spacecraft

Each ISA sensing element is a flexural harmonic oscillator presently obtained by working a single piece of Al 7075.

The pick-up system of the accelerometer is a capacitive one



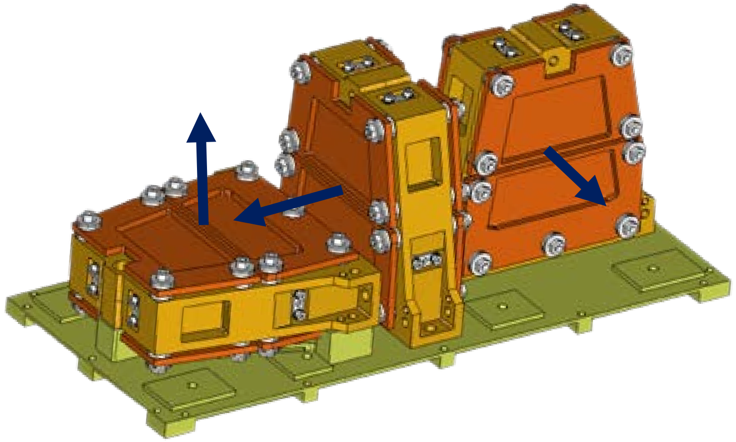
Accelerometer: measurements and physical characteristics

ISA main characteristics

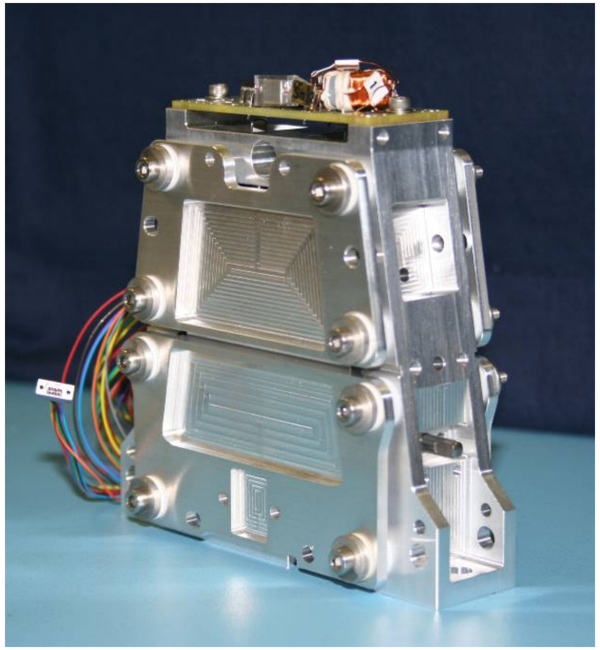
ISA oscillator parameters:	
Mass	200 g
Resonance frequency	3.9 Hz
Mechanical quality factor (Q)	10

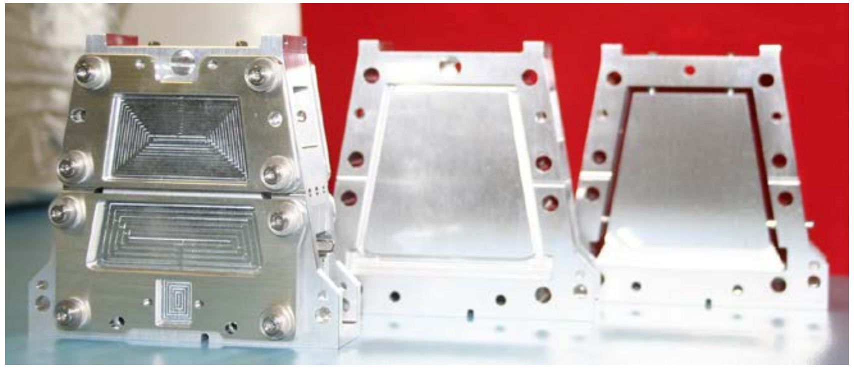
ISA performance:	
Measurement bandwidth	$3 \times 10^{-5} \div 1 \times 10^{-1}$ Hz
Intrinsic noise	1×10^{-9} $m/s^2/\sqrt{Hz}$
Measurement accuracy	1×10^{-8} m/s^2
Dynamics	300×10^{-8} m/s^2
A/D converter saturation	3000×10^{-8} m/s^2

Temperature variations:	
Mercury half sidereal period (44 days)	25°C p-p
MPO orbital period (2.325 h)	4°C p-p
Random noise	10°C $/\sqrt{Hz}$



ISA thermal stability:	
Sensor thermal sensitivity	2.5×10^{-9} $m/s^2/°C$

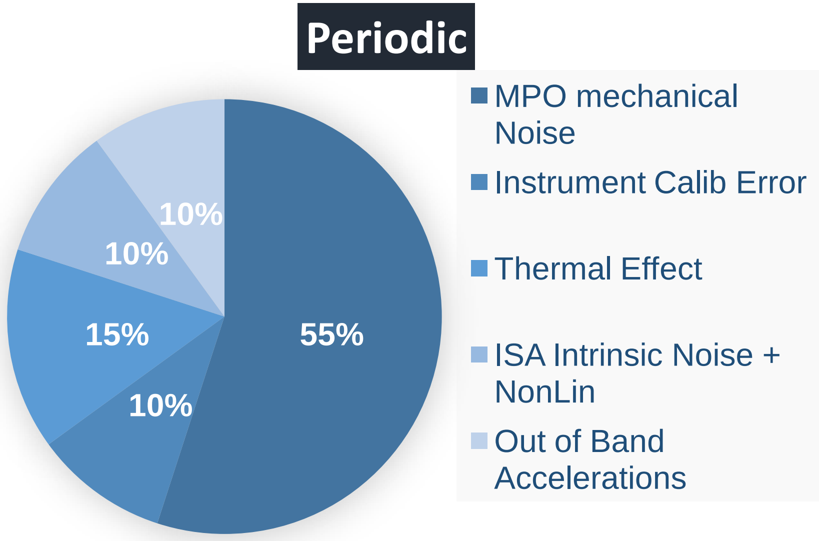


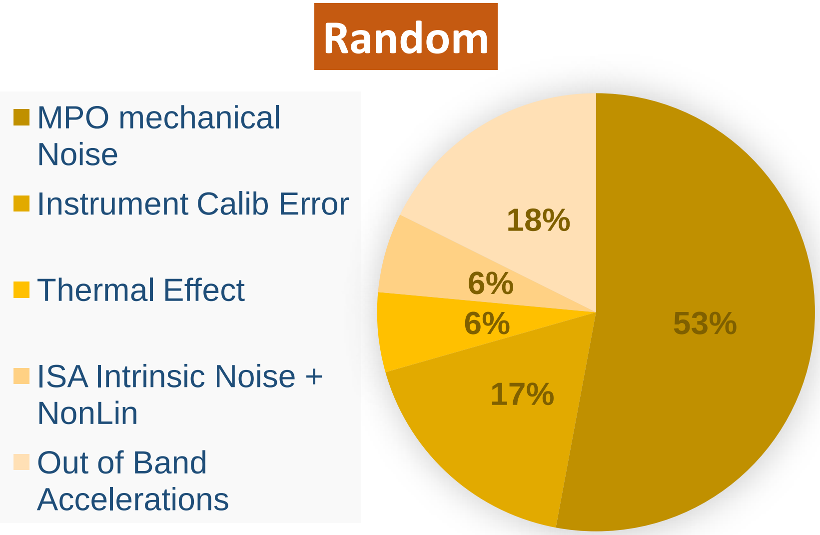


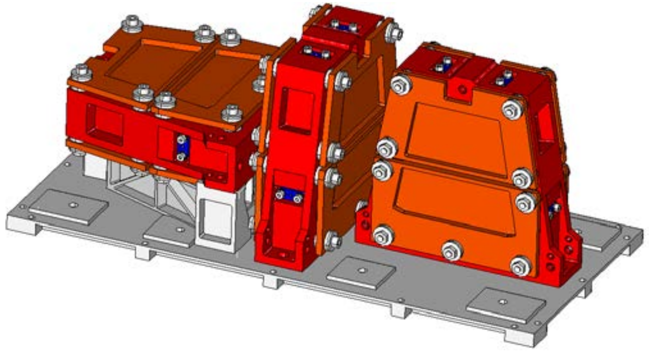
Accelerometer: measurements and physical characteristics

Error budget

Error term	Error Share
MPO mechanical noise **+** **Data reduction residuals** Errors related to the reconstruction of acceleration vector at ISA vertex. Due to ancillary data knowledge accuracy. (MPO motion, attitude, ISA geometry,…)	Periodic 55% Random 90
Instrument Calibration errors	Periodic 10% Random Negl.
Thermal effects	Periodic 15% Random 30%
ISA intrinsic noise (FEE noise, Brownian Noise, dissipation in damping resistors,…) + **ISA response to in-band accelerations** (TF flatness, Non linearity, Crosstalk)	Periodic 10% Random 10%
Out of band accelerations effects	Periodic 10% Random 30%







Accelerometer: measurements and physical characteristics

Under an **ESA** contract, we started a collaboration with our Polish colleagues of **SRC-PAS** Warsaw in order to improve the final **POD** of a **GALILEO2-sat** by the use of an onboard accelerometer

- The final goal it to verify, by means of *ad hoc* simulations, the degree of improvement obtainable by means of the accelerometer readings with respect to the current models for the **NGPs** available in the literature (**SRC-PAS**)
- One of our starting activities has been to provide **SRC-PAS** with a preliminary list of requirements in term of:
  - Measurement band
  - Measurement noise
  - Accuracy
  - Precision
  - Amplitude of the maximum acceleration to be measured

Simplified model for a GALILEO2-sat and for its orbit

The dimensions and mass of a **GALILEO2-sat** that have been used in the simulations are:

- dray mass — 1528 kg
- spacecraft body cross section — 5.82 m^2
- Solar array area — 44 m^2

$$\frac{A}{M} \cong 3.26 \times 10^{-2}\, m^2/kg$$

≈ 47 times LAGEOS A/M ratio
≈ 122 times LARES A/M ratio

Order-of-magnitude: SRP and Albedo RP

$$a_{\odot} = C_R \frac{A}{M}\frac{\Phi_{\odot}}{c}\left(\frac{1AU}{r_{\odot}}\right)^2 \approx 1.55 \times 10^{-7}\, m/s^2$$

$$1 \le C_R \le 2$$

$C_R = 1$ perfect absorption
$C_R \approx 1.21$ solar panels
$C_R \approx 1.30$ HGA
$C_R = 2$ specular reflection

Solar irradiance
@ 1 AU
$\Phi_{\odot} \cong 1380\, W/m^2$

$$a_{\oplus} = 2A_{\oplus}\frac{\pi R_{\oplus}^2}{4\pi r^2} a_{\odot} \approx 1 \times 10^{-9}\, m/s^2$$

$A_{\oplus} \approx 0.3$ Average Bond albedo coefficient

Simplified model for a GALILEO2-sat and for its orbit

We are interested to evaluate the **NGPs** accelerations due to direct **SRP** and Earth's albedo radiation pressure (**ARP**) over a few orbits of a spacecraft in order to fix a preliminary list for the accelerometer requirements. In particular we assumed:

1. An ideal 2-body nominal orbit (*a*, *e*, *I*, *P*) perturbed by the **NGPs**
2. An integration step size of 0.01° (corresponding to about 1.408 s)
3. Three consecutive orbits to evaluate the spectral content of each acceleration component in the Gauss co-moving frame (*R*,*T*,*W*)
4. The position of the Sun, of the ascending node and of the argument of pericenter have always been considered fixed during an orbital revolution of the spacecraft

<u>Nominal orbit</u>:

a = 29600 km	semi-major axis
e = 0.001	eccentricity
I = 56°	inclination
P = 50681.42 s	orbital period

$$\begin{cases} \dot{\Omega} \cong -1.43273 \times 10^{-3}\, deg/day \\ \dot{\omega} \cong -2.58819 \times 10^{-2}\, deg/day \\ \dot{\lambda}_{\odot} \cong +9.856473 \times 10^{-1}\, deg/day \end{cases}$$

Rates for the angular variables

Simulations for SRP and Albedo effects

In the simulations we considered:

- A cannon ball model for the **SRP** and we considered the Sun an extended sources in order to take into account the fraction of sunlight that heats the spacecraft surface during the penumbra transition:

$$\vec{a}_{\odot} = -\mu C_R \frac{A}{M} \frac{\Phi_{\odot}}{c} \left(\frac{1AU}{r_{\odot}}\right)^2 \hat{s}$$

$\mu = 1$	full sunlight
$\mu = 0$	umbra
$0 < \mu < 1$	penumbra

- In the case of the albedo we integrated twice:
  - Over the spherical cap seen by the spacecraft
  - Over one orbital revolution of the spacecraft

- We follow Rubincam and Weiss Celest Mech **38** (1986); Rubincam et al. JGR **92** (1987); Lucchesi and Farinella JGR **97** (1992) in order to model the albedo effects:

$$\vec{a}_{alb} = a_{\odot} \varrho^2 f_r A_{\oplus} \cos z_{\odot} \frac{(\cos\theta - \rho)}{(1 - 2\rho\cos\theta + \rho^2)^2} \frac{d\Gamma}{\pi R_{\oplus}^2} \cdot \begin{Bmatrix} (\sin\theta_G \cos\lambda_G - \rho \sin\theta \cos\lambda)\hat{x} \\ (\sin\theta_G \sin\lambda_G - \rho \sin\theta \sin\lambda)\hat{y} \\ (\cos\theta_G - \rho\cos\theta)\hat{z} \end{Bmatrix}$$

Simulations for SRP and Albedo effects

In the simulations:

- We considered different geometrical configuration of the Sun $\lambda_\odot$ with respect to the orbital plane Ω in order to simulate:
  - different heights of the Sun $\beta_\odot$ with respect to the orbital plane
  - different durations of the eclipses

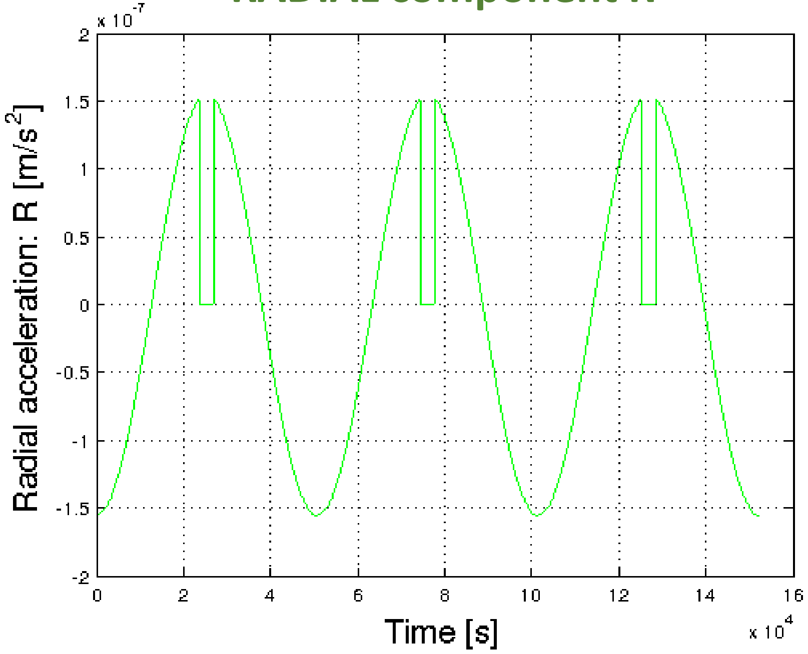
$$0 \leq \beta_\odot \leq \beta_\odot^{max} = \begin{cases} I + \varepsilon_\odot = 79.45° \\ I - \varepsilon_\odot = 32.55° \end{cases}$$

- We performed the spectral analysis (**FFT**) of the components of the perturbing accelerations in order to preliminary fix:
  - the main higher harmonics with respect to the spectral line at the orbital period
  - their amplitudes
  - the upper limit of the accelerometer measurement bandwidth

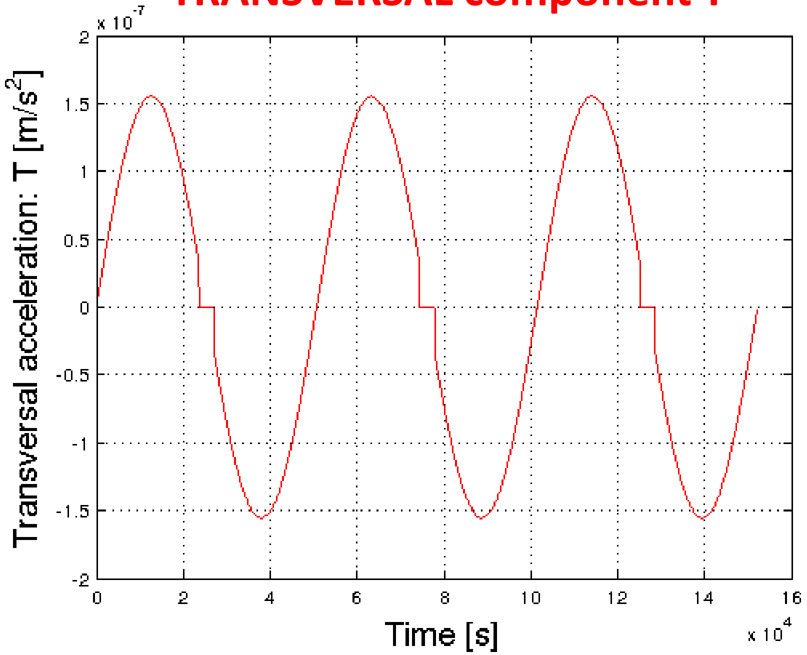
Simulations for SRP and Albedo effects

SRP results: case $\Omega = \lambda_{\odot} = 0 \rightarrow \beta_{\odot} \cong 0$

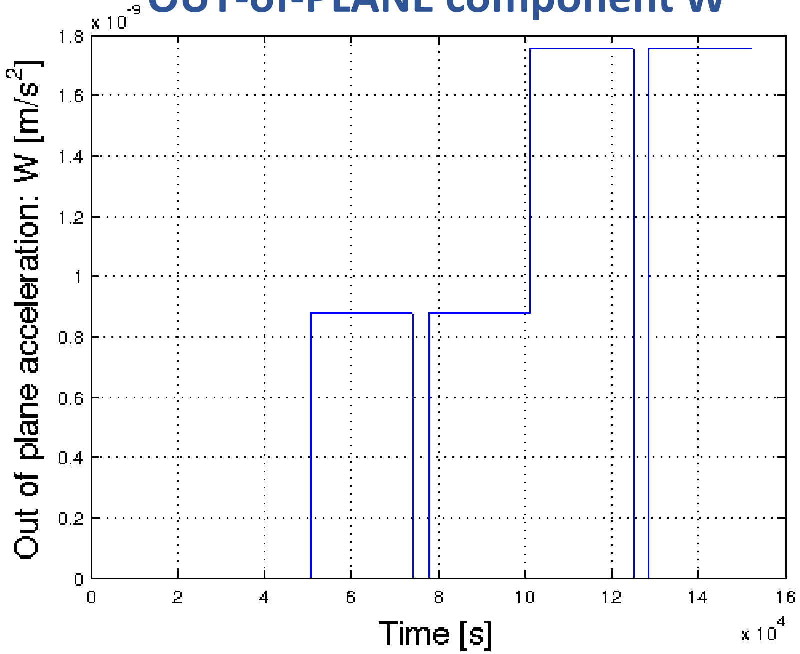
RADIAL component R



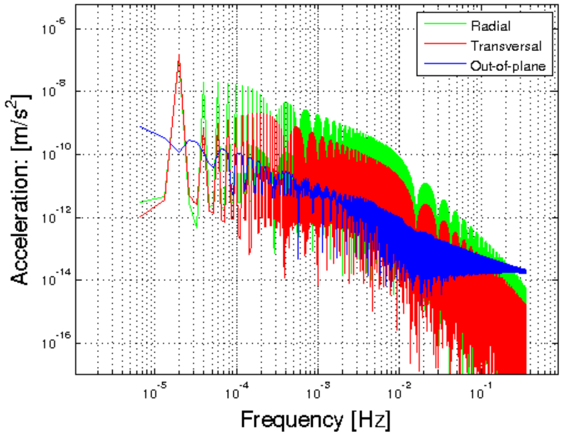
TRANSVERSAL component T



OUT-of-PLANE component W



FFT

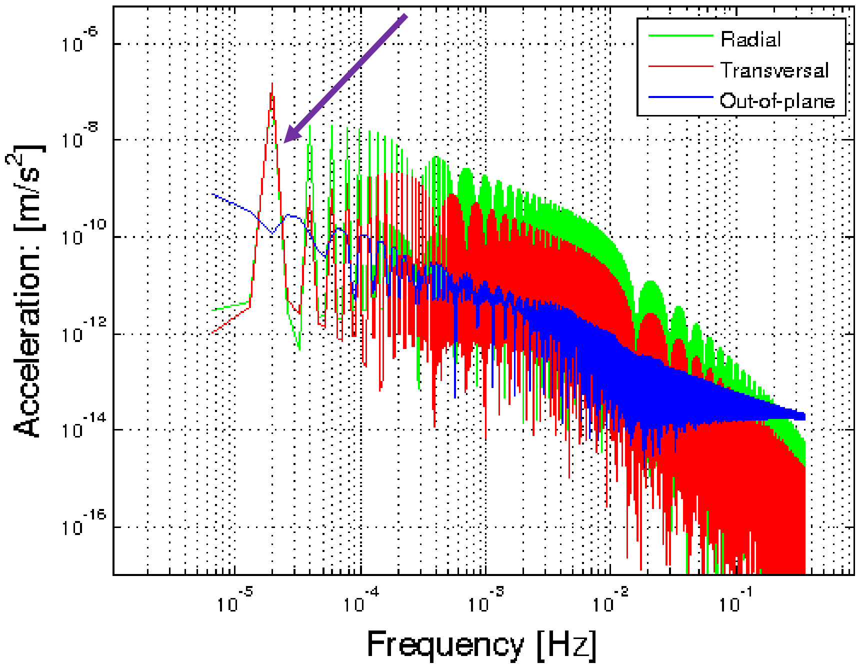


Acceleration	Mean	Max	Min	Peak- to- peak	Amplitude FFT @P
R	-1.06×10^{-8}	$+1.515 \times 10^{-7}$	-1.553×10^{-7}	3.068×10^{-7}	1.342×10^{-7}
T	$+4.36 \times 10^{-15}$	$+1.553 \times 10^{-7}$	-1.553×10^{-7}	3.106×10^{-7}	1.550×10^{-7}
W	$+8.17 \times 10^{-10}$	$+1.75 \times 10^{-9}$	0	1.75×10^{-9}	1.20×10^{-10}

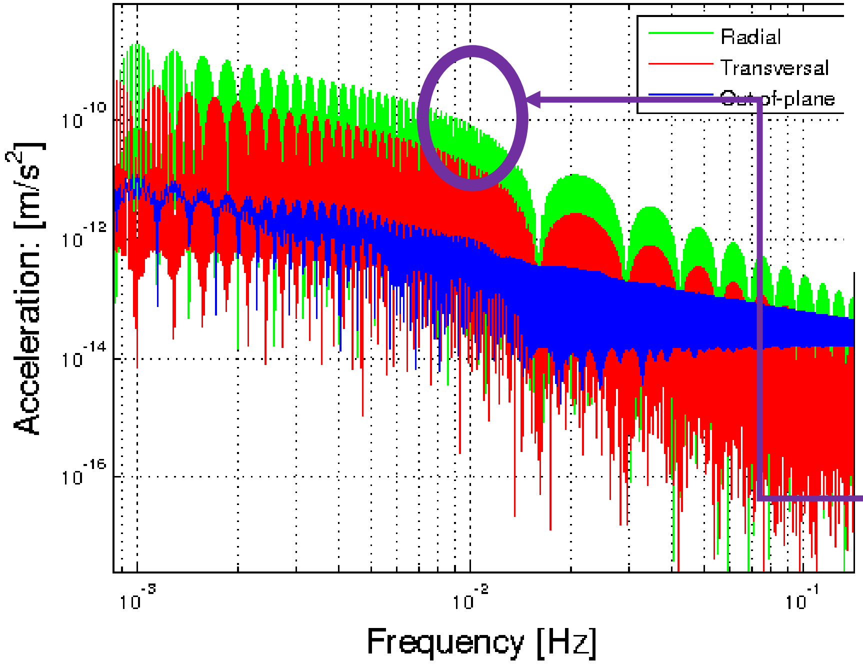
Simulations for SRP and Albedo effects

SRP results: case $\Omega = \lambda_{\odot} = 0 \rightarrow \beta_{\odot} \cong 0$

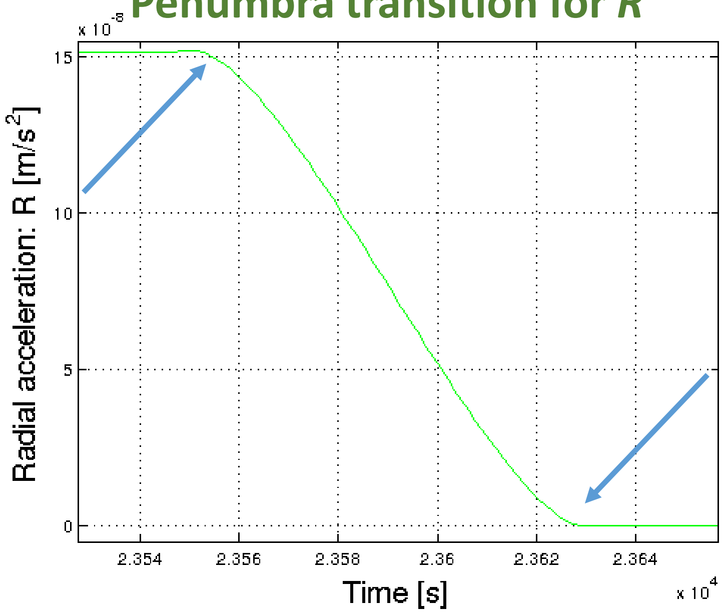
Fast Fourier Transform (FFT)



FFT details around 10^{-2} Hz



Penumbra transition for *R*



Penumbra ≅ 76 s
Eclipses ≅ 57 min

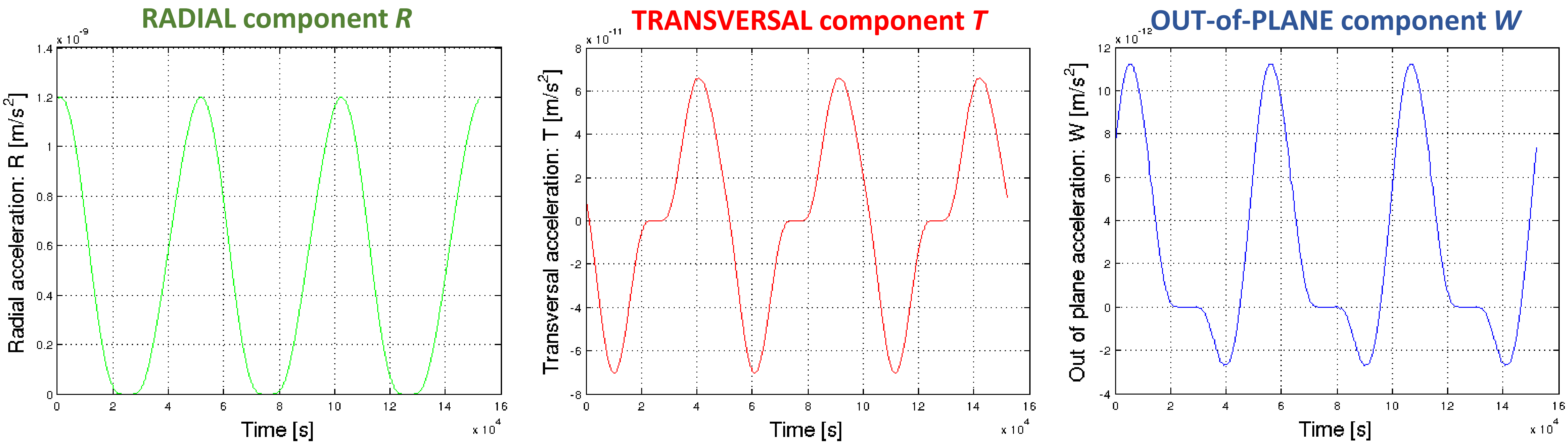
$\simeq 10^{-10}\ m/s^2 @ 10^{-2} Hz$

Possible upper limit of the accelerometer measurement band

- For the **Radial** and **Transversal** accelerations we have a main line at the inverse of the orbital period ($\nu_{orb} \cong 1.973 \times 10^{-5}$ Hz) plus higher order harmonics, which are an integer multiple of the harmonic at the orbital period
- For the **Out-of-Plane** component, the FFT is less representative of its real behavior because of the underlying approximations …

Simulations for SRP and Albedo effects

Earth's Albedo results: case $\Omega = \lambda_{\odot} = 0 \rightarrow \beta_{\odot} \cong 0$



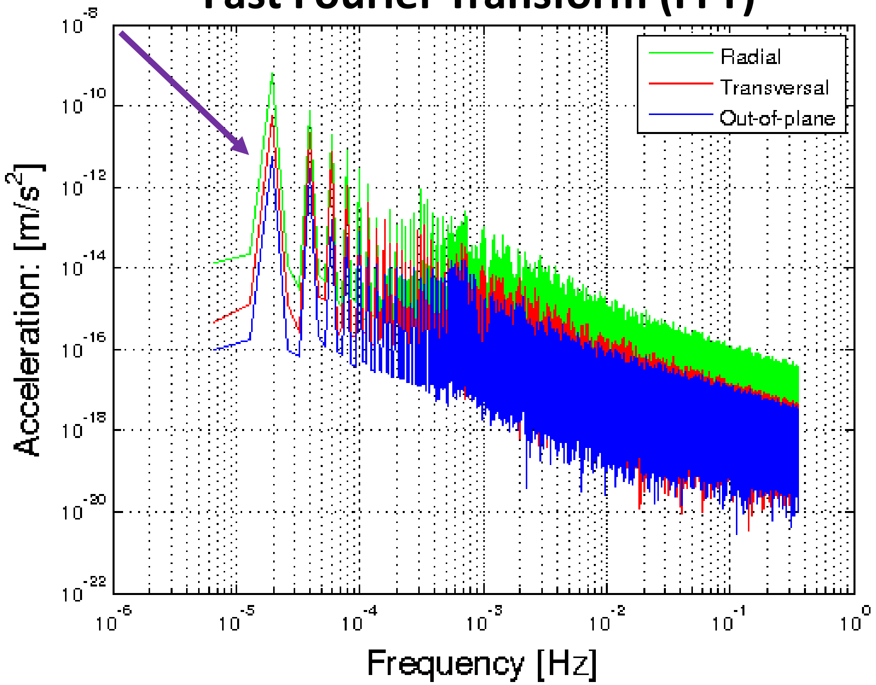
It is clear the much smaller impact of the albedo acceleration with respect to that of the **SRP**:

- the amplitudes of the **Radial** and **Out-of-Plane** accelerations of Earth's albedo are more than two orders of magnitude smaller than the corresponding amplitudes from the direct **SRP**
- the amplitude of the **Transversal** acceleration of albedo is more than three orders of magnitude smaller than that from the direct **SRP**

Simulations for SRP and Albedo effects

Earth's Albedo results: case $\Omega = \lambda_{\odot} = 0 \rightarrow \beta_{\odot} \cong 0$

Fast Fourier Transform (FFT)



The three components of the **Albedo** acceleration have a quasi-sinusoidal behavior. From their **FFT** it is apparent:

- A main component at the inverse of the orbital period
- Higher-order harmonics characterized by frequencies at integer multiples of the main spectral line
- Very small amplitudes, also at the orbital period

Acceleration	Mean	Max	Min	Peak-to-Peak	Amplitude FFT @P
R	$+5.17 \times 10^{-10}$	$+1.20 \times 10^{-9}$	0	$+1.20 \times 10^{-9}$	6.15×10^{-10}
T	$+1.47 \times 10^{-12}$	$+6.57 \times 10^{-11}$	-7.04×10^{-11}	1.36×10^{-10}	5.37×10^{-11}
W	$+2.58 \times 10^{-12}$	$+1.13 \times 10^{-11}$	-3.00×10^{-12}	1.43×10^{-11}	5.59×10^{-12}

Preliminary results in terms of accelerometer performance

From previous assumptions/simulations we are able to provide the main requirements for an onboard accelerometer for what regards:

- Measurement frequency band
- Sensitivity and accuracy (to improve the **POD** with respect to the current models)
- Maximum amplitude for the in-band signal (it contributes to fix the dynamics of the accelerometer)

	ISA-GALILEO2	ISA-BepiColombo
Measurement band (*)	1.9×10^{-5} Hz — 1×10^{-2} Hz	3×10^{-5} Hz — 1.0×10^{-1} Hz
Amplitude max. acceleration (**)	2×10^{-7} m/s^2	3.0×10^{-6} m/s^2
Measurements noise floor (***)	$\leq 1 \times 10^{-9}$ m/s^2/$\sqrt{\text{Hz}}$	1×10^{-9} m/s^2/$\sqrt{\text{Hz}}$
Accuracy	$\approx 1 \times 10^{-9}$ m/s^2	1.0×10^{-8} m/s^2
Precision	$<10^{-10}$ m/s^2	$<10^{-9}$ m/s^2

(*) The lower limit should contain the frequency corresponding to the orbital period: $\nu_{orb} \cong 1.973 \times 10^{-5}$ Hz
(**) Summarizes the contribution of the NGPs plus the gravity gradients and apparent accelerations
(***) Superposition of the accelerometer noise + noise coming from the external environment

Conclusions

With regard to **ESA** request of possible **POD** improvements for next generation of **GALILEO** satellites by the use of an onboard accelerometer, we have shown some of the results of the preliminary activities performed at **IAPS/INAF** in term of:

- Spectral content of the accelerations (measurement band)
- Accuracy and precision of the measurements
- Maximum acceleration to be measured in order to fix the dynamic and, consequently the saturation level (both electronics and mechanics)

Forthcoming activities will focus on the following issues:

- provide to **SRC-PAS** the accelerometer error budget (**IAPS/INAF**)
- specify the requirements of the accelerometer in terms of an experimental activity based on bread boards (**AGI**)
- Provide a **POD** of a **GALILEO2-sat** with simulated data of the accelerometer readings and errors and compare the results with those of a **POD** based on current models of the **NGPs** (**SRC-PAS**)

Accelerometer: measurements and physical characteristics