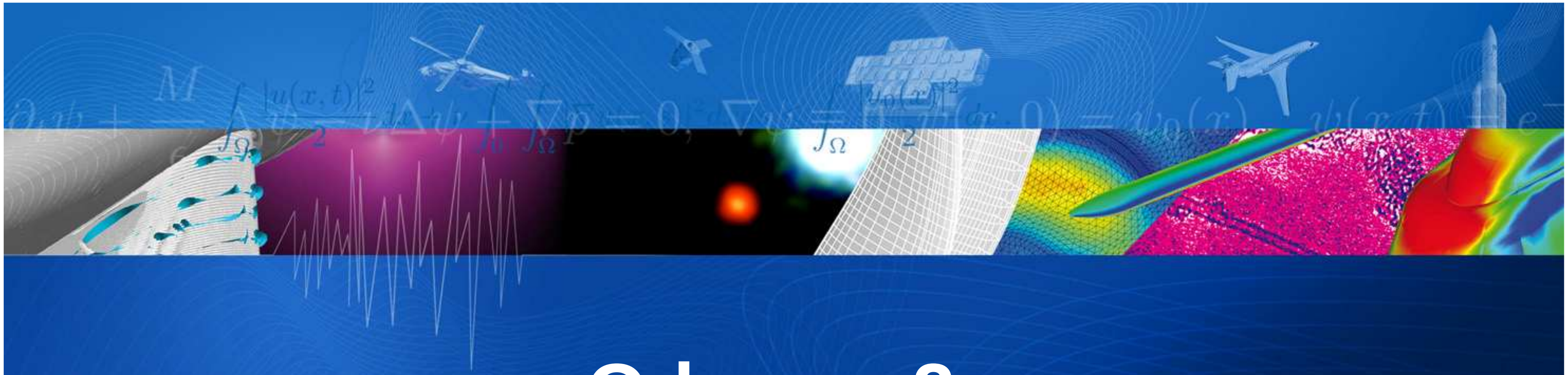

Odyssey2:
A mission toward Neptune and Triton to test gravitation

B. Christophe on behalf of Odyssey2 Team

ONERA
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return on innovation

Journées SF2A

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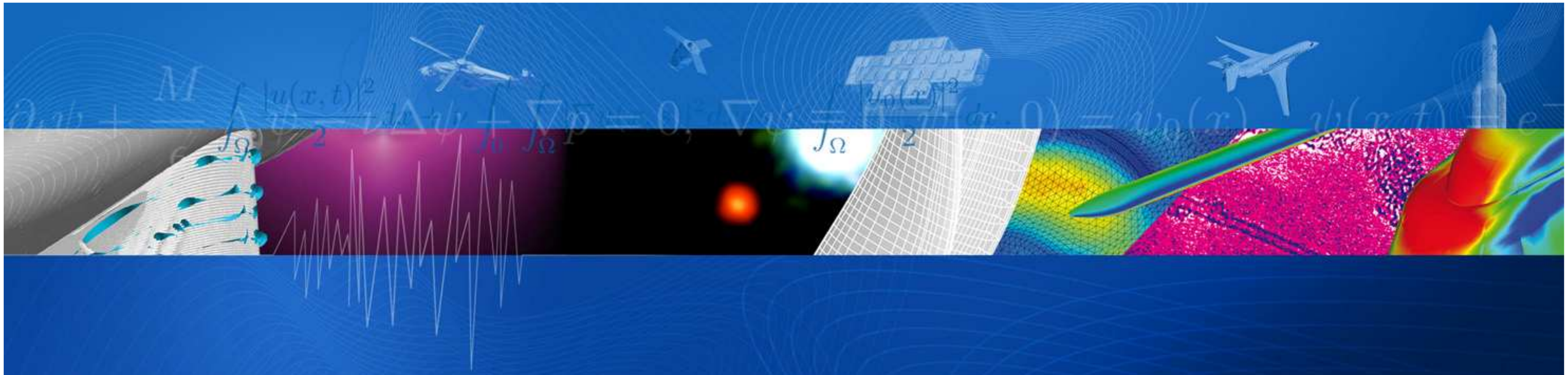
Outline

- Description of the Odyssey2 mission
  - Scientific objectives
  - Instrumentation
  - Preliminary mission analysis

- The Gravity Advanced Package:
  a null-bias electrostatic accelerometer
  - MicroSTAR design and performances
  - Principle of the bias rejection
  - Precision on the acceleration measurement



Description of the Odyssey2 mission

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Fundamental physics scientific objectives

Objectives	Deep space gravity
Target precision	$\Delta a < 10$ pm/s^2

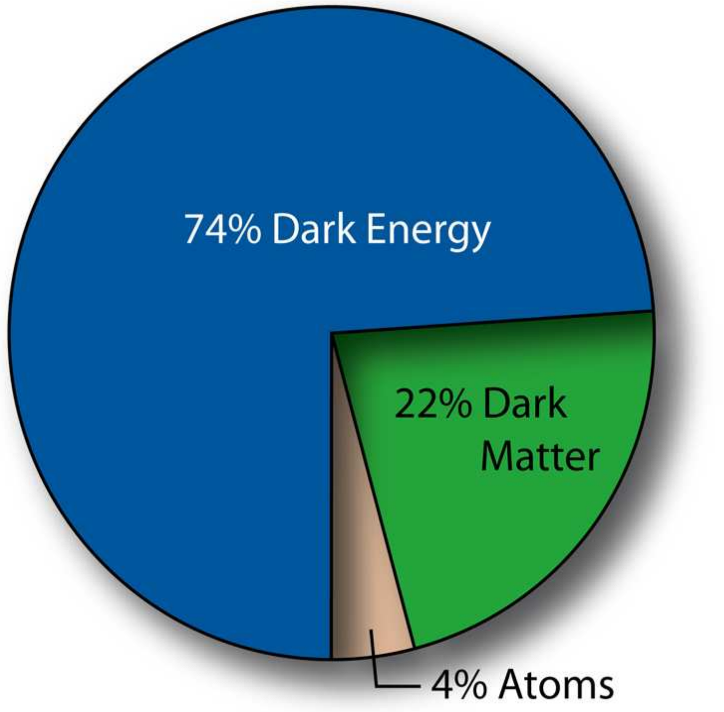
ESA Fundamental Physics Roadmap draft (01/12/2010):

The development of low bias accelerometers, compatible with 10 pm/s^2 spacecraft tracking at frequencies down to 10^{-7} Hz and below is essential for gravity tests using dedicated or planetary missions, and should be pursued.

Deep Space Gravity

Good agreement of General Relativity with experiments but…

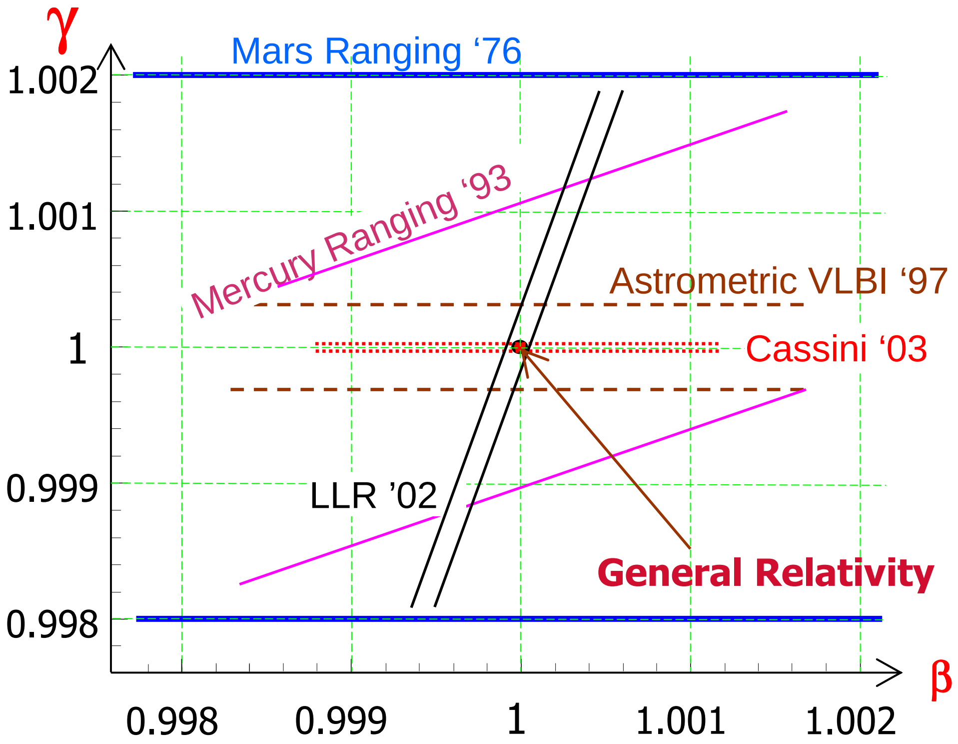
Unification models predict deviations from General Relativity



Importance of testing General Relativity at all possible scales beyond existing tests in the Solar System

Fundamental physics scientific objectives

Objectives	Deep space gravity	PPN parameter γ
Target precision	$\Delta a < 10\ \mathrm{pm/s^2}$	$\Delta\gamma < 10^{-7}$

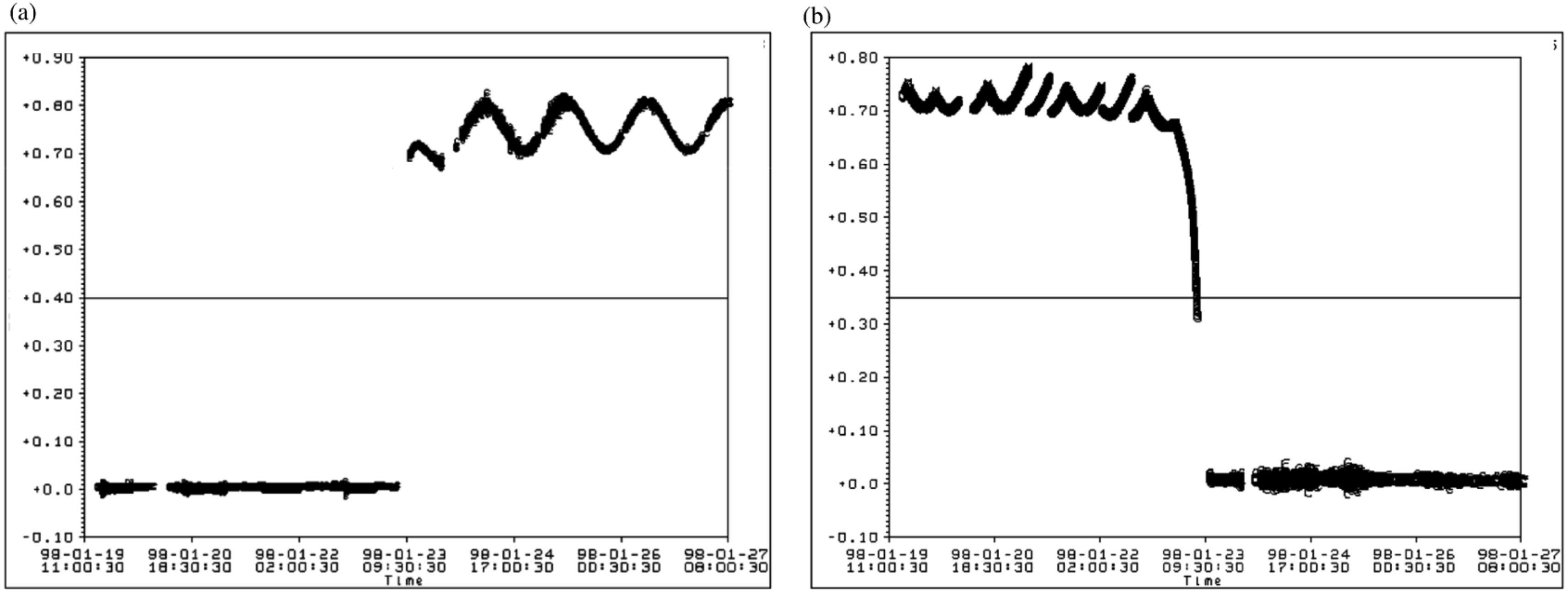


→ 2×10^{-5}

Courtesy: S. Turyshev

Fundamental physics scientific objectives

Objectives	**Deep space gravity**	**PPN parameter γ**	**Fly-by anomaly**
Target precision	$\Delta a < 10$ pm/s^2	$\Delta\gamma < 10^{-7}$	$\Delta V < 20$ µm/s



J.D. Anderson, *et al. Phys. Rev. Lett.* **100**, 091102 (2008)

NEAR fly-by: $\Delta V = 13.5$ mm/s

Planetary scientific objectives

Study of Neptune and Triton*:

- Density profile and composition of the atmospheres
- Gravitational fields and interior structures
- Imaging and composition of the surfaces
- Measurement of the magnetospheres

* Currently under discussion with the planetary community

Instrumentation

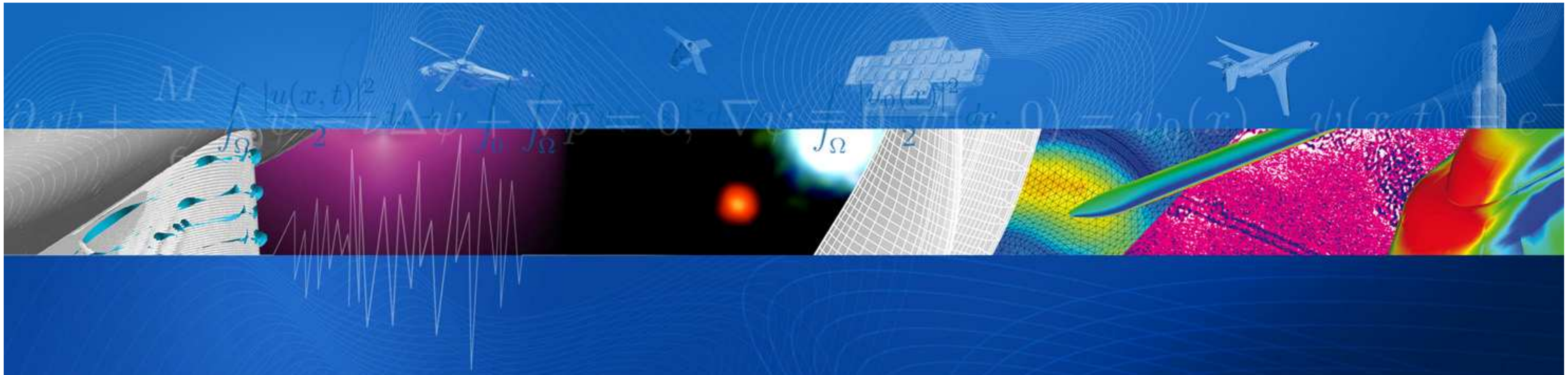
	Fundamental physics	Planetary
Null-bias accelerometer	- Deep-space gravity	- Atmosphere - Gravitational field
Radio-science	- Deep-space gravity - Parameter γ - Fly-by	- Atmosphere - Gravitational field
Laser ranging	- Parameter γ	-
Camera[*]	-	- Imaging of the surface
Spectrometer[*]	-	- Composition of the environment
Particles detector[*]	-	- Composition of the environment
Magnetometer[*]	-	- Magnetosphere

[*] Currently under discussion with the planetary community

Context of Odyssey2 mission

- Under a Phase 0 CNES study for the next M mission Cosmic Vision Call
  - Launch in 2022
  - 470 million € at completion (without instruments)

- Technical and programmatic issues:
  - Date of launch not optimal
  - Nuclear power → US collaboration with Argo ?
  - Duration of the mission
  - Choice of propulsion system



The Gravity Advanced Package: a null-bias electrostatic accelerometer

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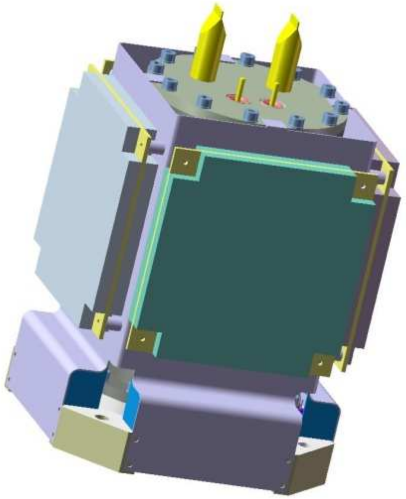
Subsystems

- MicroSTAR:
  an electrostatic accelerometer
  - Developed by ONERA
  - GRACE – GOCE heritage

1 kg
1.4 W



- Bias Rejection System
  - Developed by ZARM
  - Rotating stage

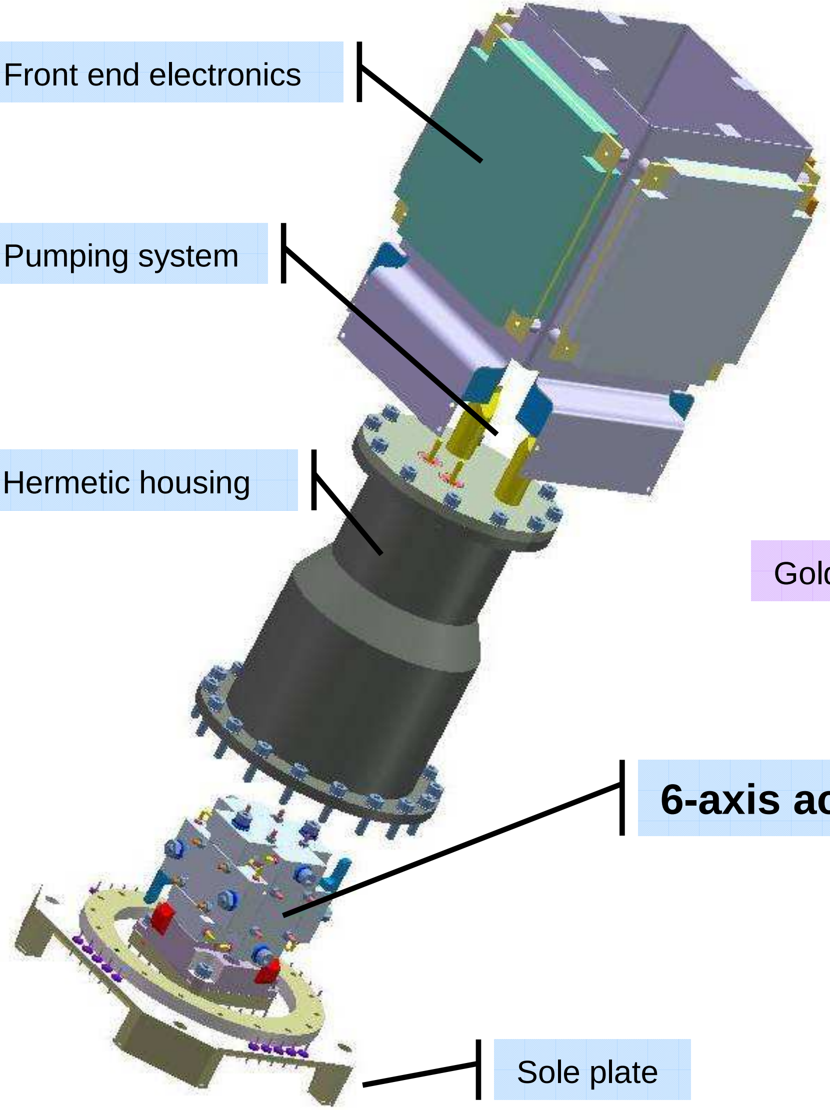
1.1 kg
0.2 W

Total mass = 3 kg
Total power = 3 W

- Interface and Control Unit
  - Developed by ONERA

0.9 kg
1.4 W

MicroSTAR flight model design



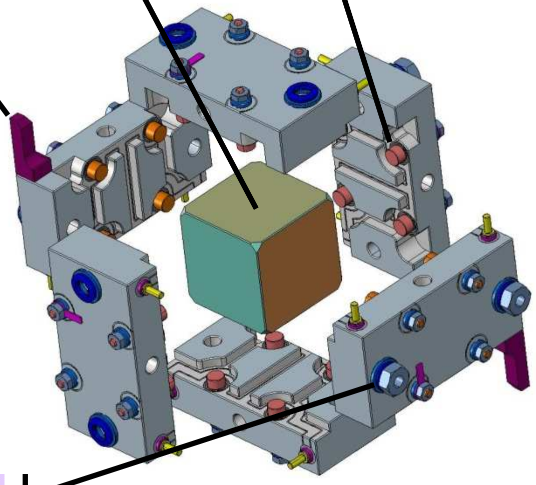
Front end electronics

Pumping system

Hermetic housing

6-axis accelerometer

Sole plate



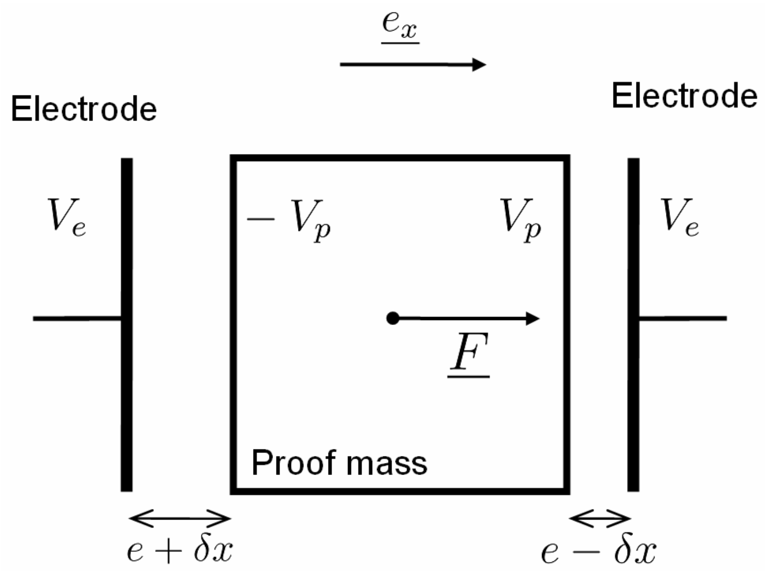
Stops

Proof mass (ULE)

Gold wire holder (ULE)

Electrodes (ULE)

Principle of an electrostatic accelerometer



Force applied by the electrodes on the proof mass :

$$\frac{1}{m_{\mathbf{A}}}\underline{F} = \left[{\omega_p}^2\delta x + G_e V_e + \frac{{\omega_p}^2}{{V_p}^2}\delta x {V_e}^2\right]\underline{e_x}$$

$$\begin{cases} {\omega_p}^2 = \dfrac{2\epsilon_0 S {V_p}^2}{m_{\mathbf{A}} e^3} \\ G_e = -\dfrac{2\epsilon_0 S V_p}{m_{\mathbf{A}} e^2} \end{cases}$$

Electrostatic stiffness

Sensibility factor

- The position of the proof mass is controlled via the potential of the electrodes.
- The potentials on the proof mass are controlled by 2 gold wires for miniaturization purpose.

Principle of an electrostatic accelerometer

Link between the external non-gravitational acceleration acting on the spacecraft and the electrostatic force :

$$\boxed{\left(\frac{1}{m_{\mathbf{A}}}+\frac{1}{m_{\mathbf{S}}}\right)\underline{F^{elec}_{\mathbf{S}\to\mathbf{A}}}=\frac{1}{m_{\mathbf{S}}}\underline{F^{NG}_{ext\to\mathbf{S}}}+\underline{A_1}-\underline{A_2}-\underline{A_3}}$$

Fictitious acceleration

$$\underline{A_1}=\underline{\dot{\Omega}_{2/1}}\wedge\underline{SC}+\underline{\Omega_{2/1}}\wedge\left(\underline{\Omega_{2/1}}\wedge\underline{SC}\right)$$

Accelerometer position

Angular velocity of the satellite

Principle of an electrostatic accelerometer

Link between the external non-gravitational acceleration acting on the spacecraft and the electrostatic force :

$$\boxed{\left(\frac{1}{m_{\mathbf{A}}}+\frac{1}{m_{\mathbf{S}}}\right)\underline{F^{elec}_{\mathbf{S}\to\mathbf{A}}}=\frac{1}{m_{\mathbf{S}}}\underline{F^{NG}_{ext\to\mathbf{S}}}+\underline{A_1}-\underline{A_2}-\underline{A_3}}$$

Other external accelerations

$$\underline{A_2}=\underbrace{\left(\frac{1}{m_{\mathbf{A}}}+\frac{1}{m_{\mathbf{S}}}\right)\underline{F^{G}_{\mathbf{S}\to\mathbf{A}}}}_{\text{Self-gravity}}+\underbrace{\frac{1}{m_{\mathbf{A}}}\underline{F^{NG}_{ext\to\mathbf{A}}}}_{\text{Non-gravitational forces on the proof mass}}+\underbrace{\left(\frac{1}{m_{\mathbf{A}}}\underline{F^{G}_{\mathbf{ext}\to\mathbf{A}}}-\frac{1}{m_{\mathbf{S}}}\underline{F^{G}_{\mathbf{ext}\to\mathbf{S}}}\right)}_{\text{Gravity gradient}}$$

Principle of an electrostatic accelerometer

Link between the external non-gravitational acceleration acting on the spacecraft and the electrostatic force :

$$\left(\frac{1}{m_{\mathbf{A}}}+\frac{1}{m_{\mathbf{S}}}\right)\underline{F^{elec}_{\mathbf{S}\to\mathbf{A}}} = \frac{1}{m_{\mathbf{S}}}\underline{F^{NG}_{ext\to\mathbf{S}}} + \underline{A_1} - \underline{A_2} - \underline{A_3}$$

Gold wire

$$\underline{A_3} = \left(\frac{1}{m_{\mathbf{A}}}+\frac{1}{m_{\mathbf{S}}}\right)\underline{F^{gold}_{\mathbf{S}\to\mathbf{A}}}$$

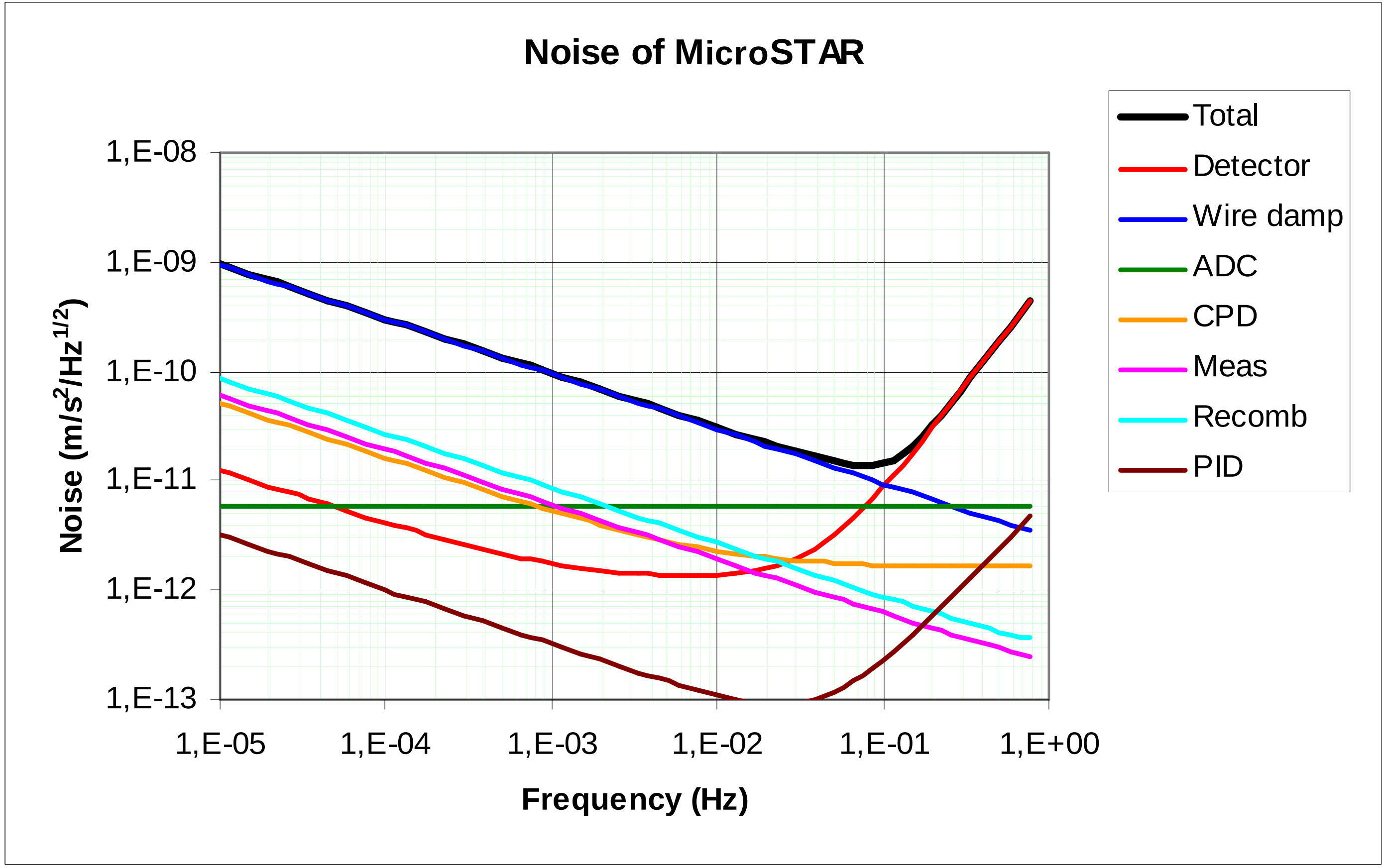
Performance of MicroSTAR

Configuration:

e = 600 µm

V_p = 7 V

V_d = 5 V

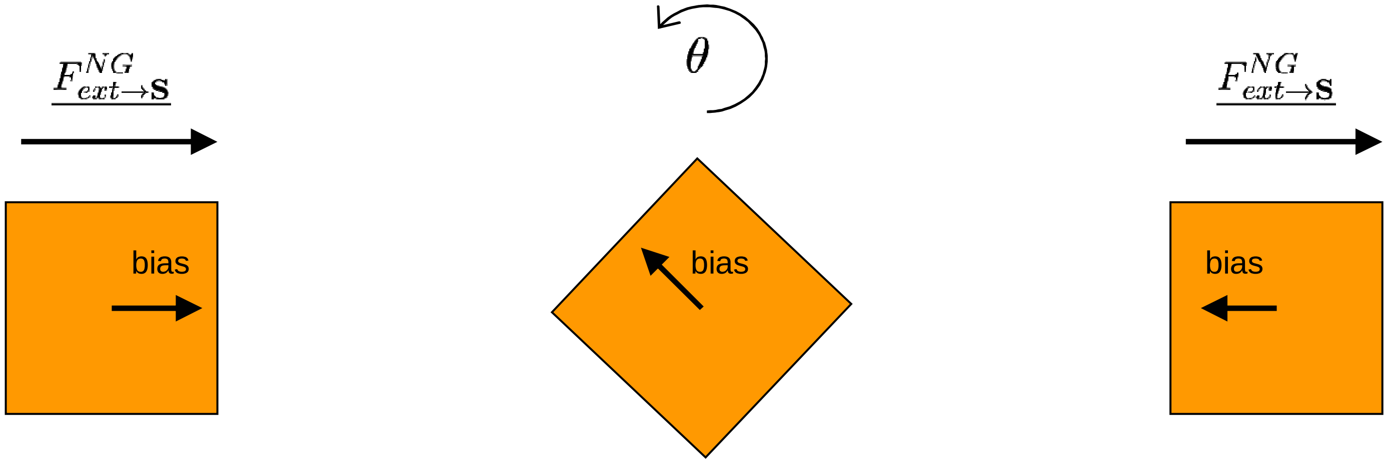


Range: 20 µm/s²

Bias: 10 µm/s²

$$S_n(f) = 9{,}3 \times 10^{-24}\,\frac{1}{f} + 5{,}9 \times 10^{-19}\,f^4$$

Bias Rejection Principle



Rotation of the accelerometer of an angle *θ*:

$$\begin{aligned} m_x &= n_x + (1+\delta k_x)\left[\mu\left(F_x^{NG}\cos(\theta) + F_y^{NG}\sin(\theta)\right) + F_x^{gold}\right] + b_x \\ m_y &= n_y + (1+\delta k_y)\left[\mu\left(-F_x^{NG}\sin(\theta) + F_y^{NG}\cos(\theta)\right) + F_x^{gold}\right] + b_y \end{aligned}$$

Measures

Noise

Bias:

electronic + gold wire

2N measures

4N unknowns

Processing of the modulated signal

- Our goal is to know the mean acceleration.
- Bias = b_0 + K x Temperature

$$\mu F_x^{NG} = \begin{bmatrix}1\\1\\\vdots\\1\\1\end{bmatrix}\begin{bmatrix}\overline{a_x}\end{bmatrix} \qquad b_x + F_x^{gold} = \begin{bmatrix}1 & T[1]\\1 & T[2]\\\vdots & \vdots\\1 & T[N-1]\\1 & T[N]\end{bmatrix}\begin{bmatrix}\overline{b_x} & db_x\end{bmatrix}$$

- Resolution by a least squares approach

Precision of the measurement

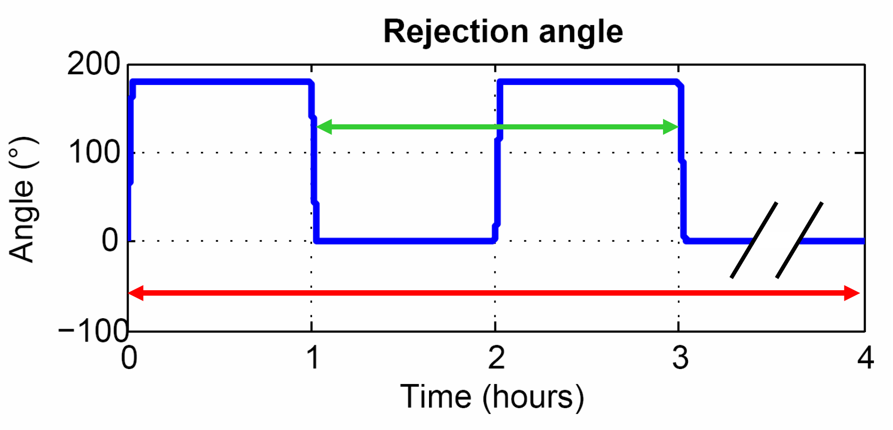
$$\sigma_{\overline{a_x}} \approx \sqrt{\int_{\frac{-1}{2\delta t}}^{\frac{1}{2\delta t}} S_n(f) \left|\frac{\mathcal{F}_{\delta t}[s](f)}{\delta t}\right|^2 df}$$

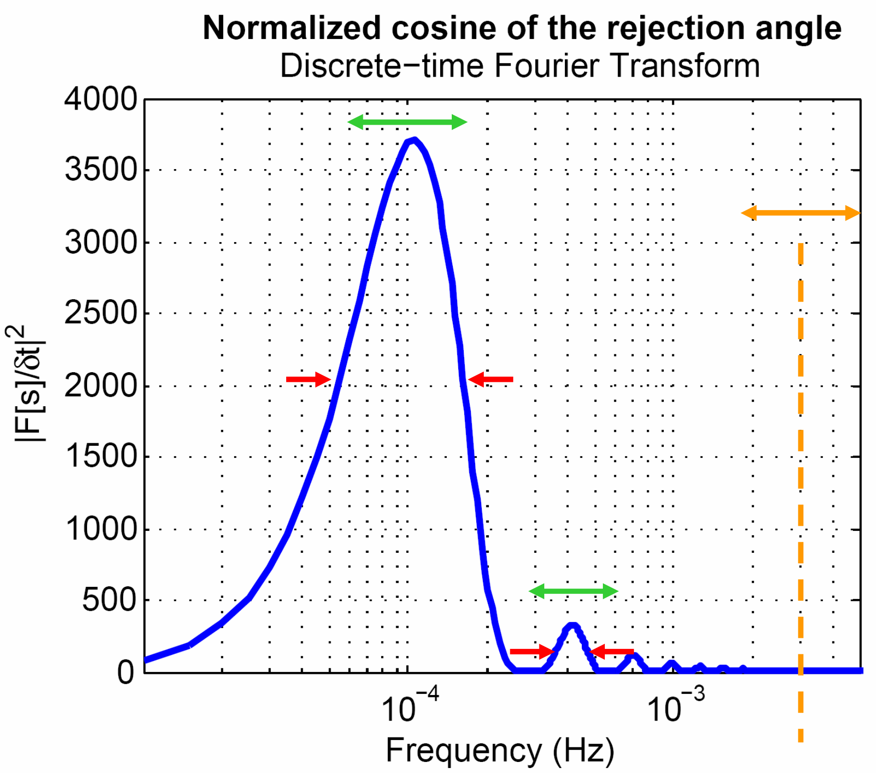
$$s[i] = \frac{\cos(\theta[i])}{||\cos(\theta[i])||}$$

Modulation frequency

Integration time

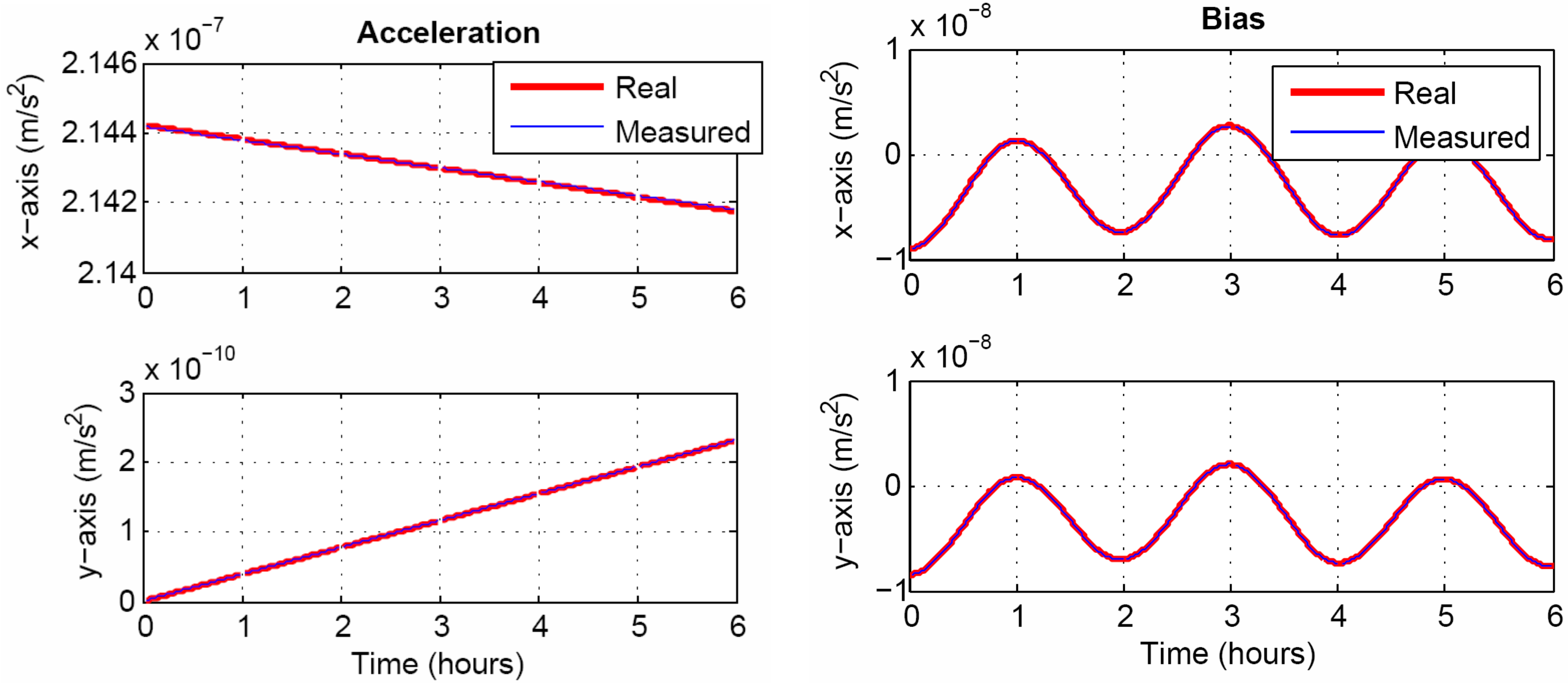
Sampling time


Rejection angle

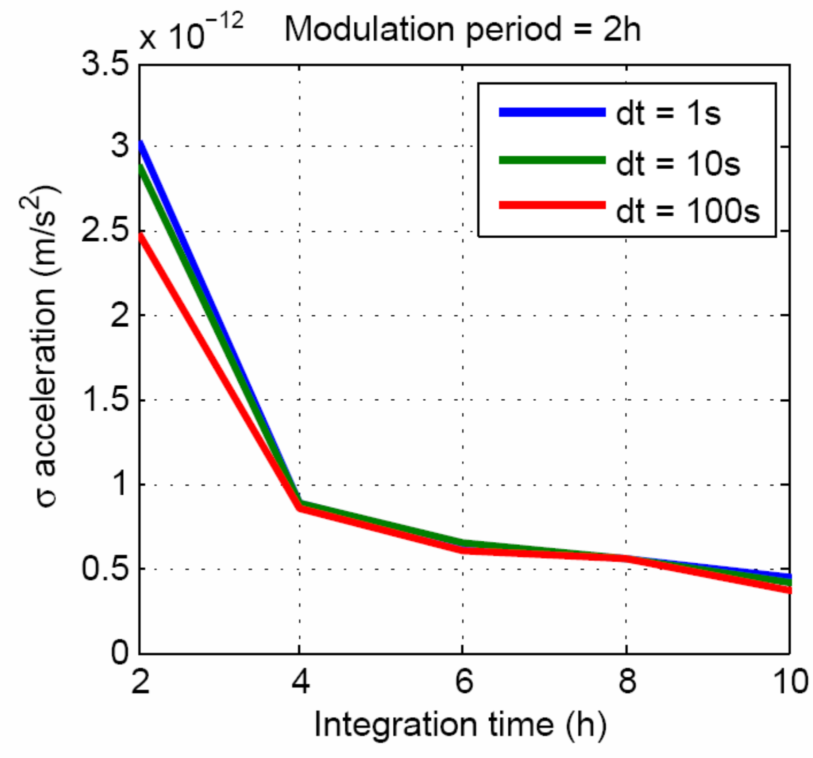

Normalized cosine of the rejection angle
Discrete−time Fourier Transform

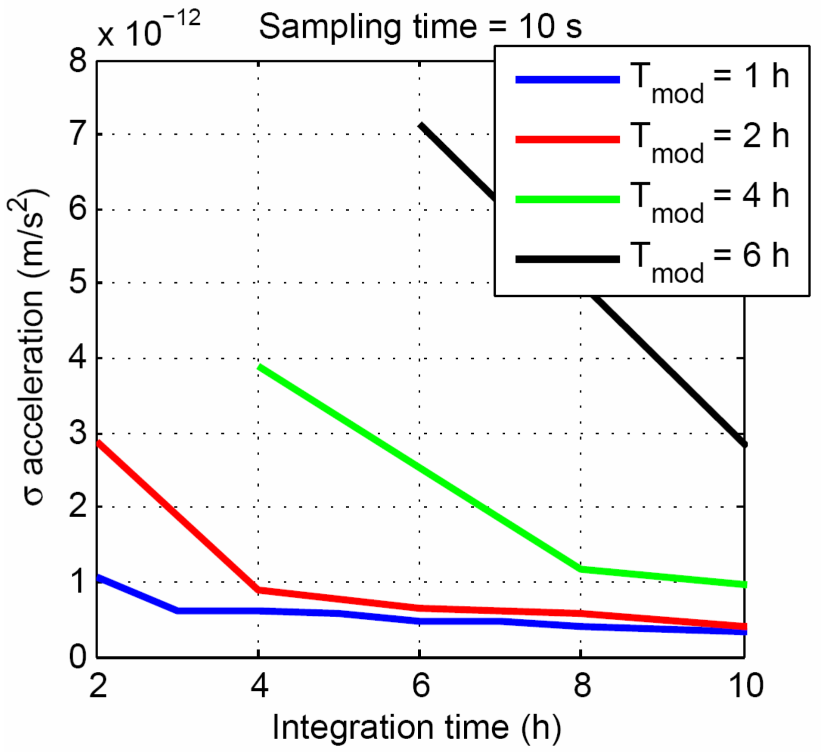
Simulation

- Initial conditions: r = 5 AU, v = 20 km/s
- Radiation pressure only
- Perfect measures of the temperature
- Integration time = 6h, sampling time = 1s



Precision of the measurement





- Independent of the sampling time for dt in [1;100] s
- Higher modulation frequency gives smaller error
- Coherent with analytic formula

Conclusion

Odyssey2 is a fundamental physics mission
with planetary objectives
proposed for next Cosmic Vision M3 mission

Main fundamental physics instrument is
a null-bias electrostatic accelerometer
accurate at 10 pm/s^2 at low frequency

Planetary objectives under discussion with
planetary community