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# The Pioneer Anomaly and Space Accelerometers for Gravity Tests

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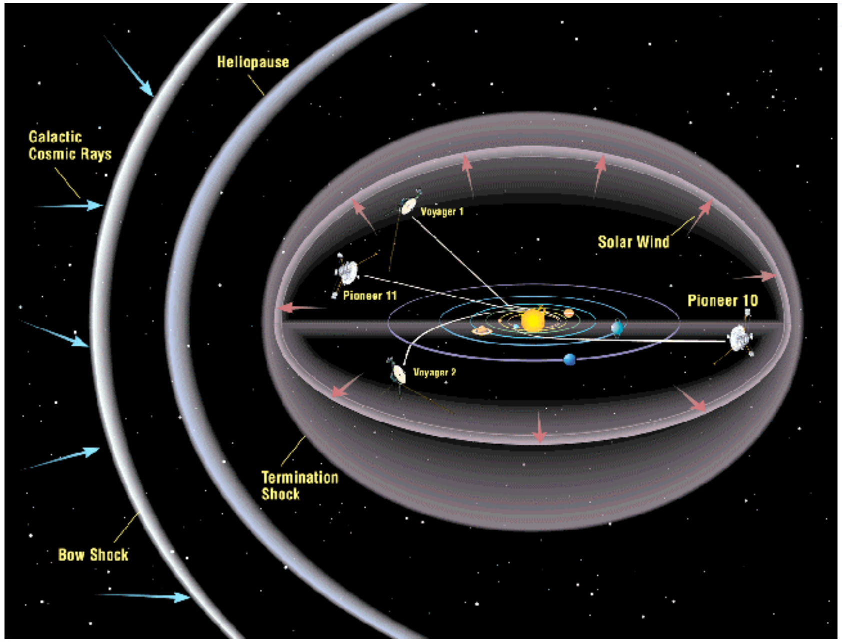
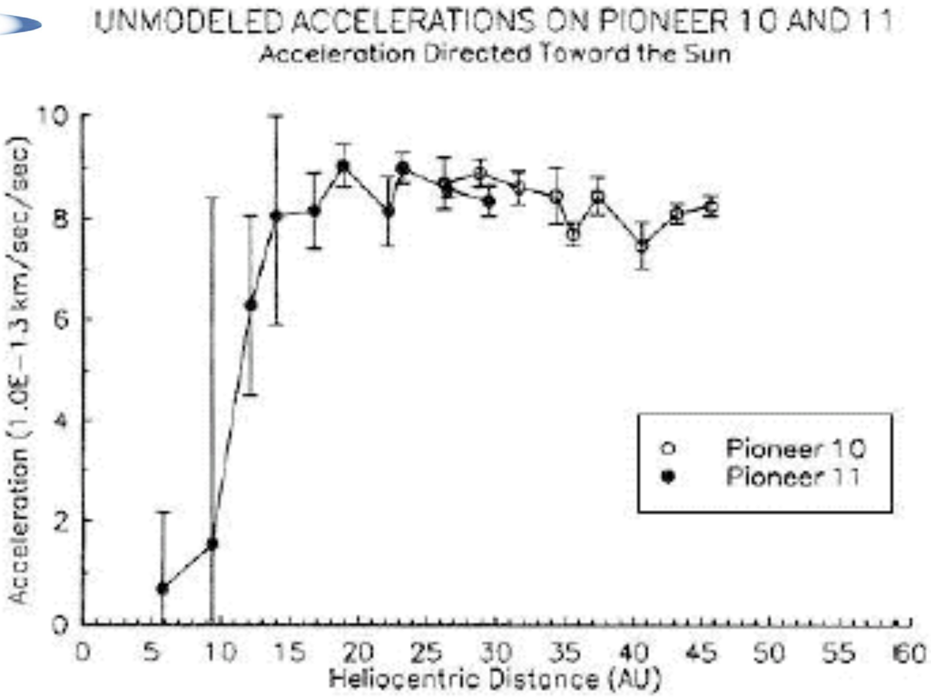
# The Pioneer Anomaly

**Pioneer 10 launched March 2, 1972**
**Pioneer 11 launched April 5, 1973**

**Deceleration : (8.74 ± 1.33) $10^{-10}$ m.s$^{-2}$**




*J. Anderson et al, Phys. Rev. D 65 (2002) 082004*

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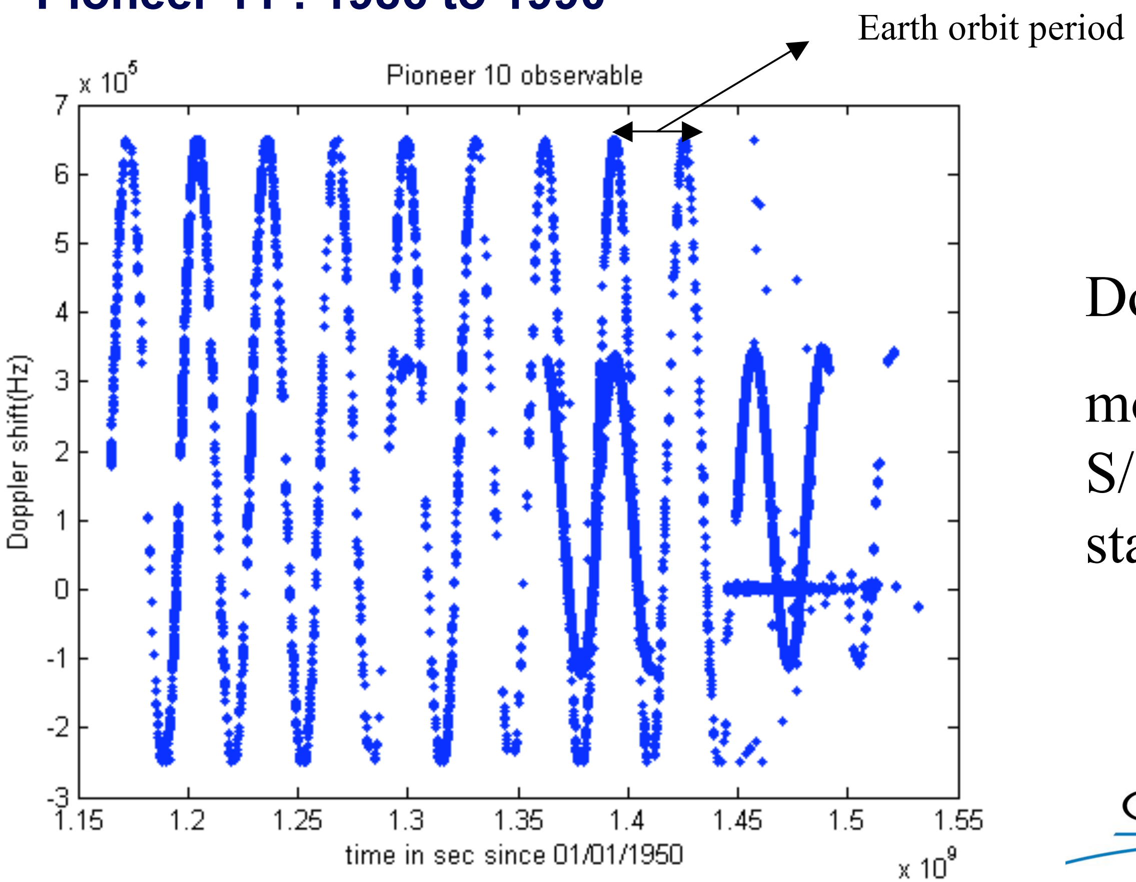
# Various aspects of my work

- Trajectory independant analysis : Pioneer anomaly verification
- Telemetry data analysis : study of the more probable source, residual thrust from S/C itself
- Instrument development : adaptation of an ONERA accelerometer for the Pioneer anomaly measurement

# Doppler data analysis

## Pioneer 10 and 11 binary ODFs (Orbit Data Files)

- Pioneer 10 : 1987 to 1998
- Pioneer 11 : 1986 to 1990




Doppler shift :

movement of the S/C wrt to Earth stations

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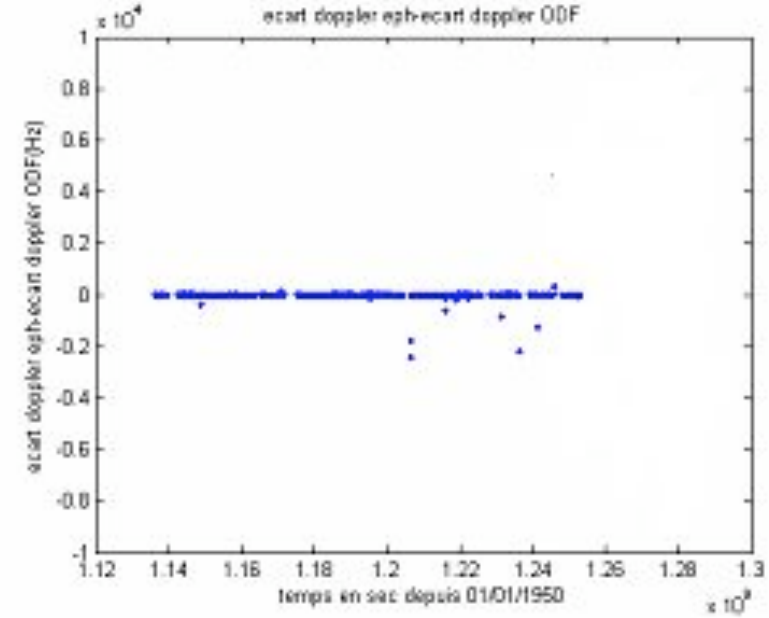
# Development of independant software

- **Evaluate the doppler shift**
  - **Develop an overall simulation**

  **by using software developed at the Observatoire de la Côte d'Azur**

→ computed doppler shift




- **Comparison to Pioneer measure data**

→ Observation of an anomaly ?

- **Simulation of new mission**

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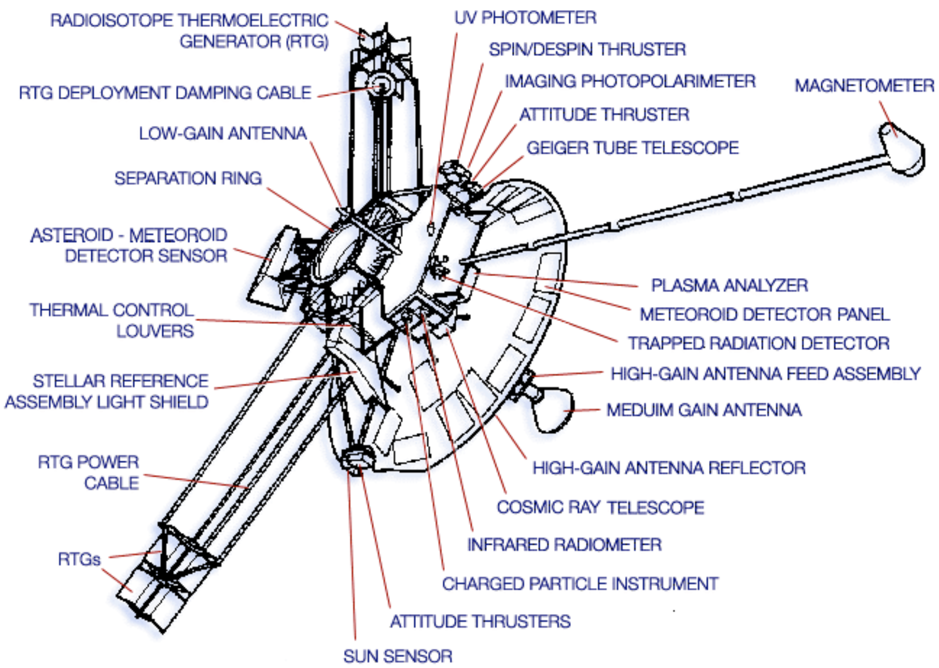
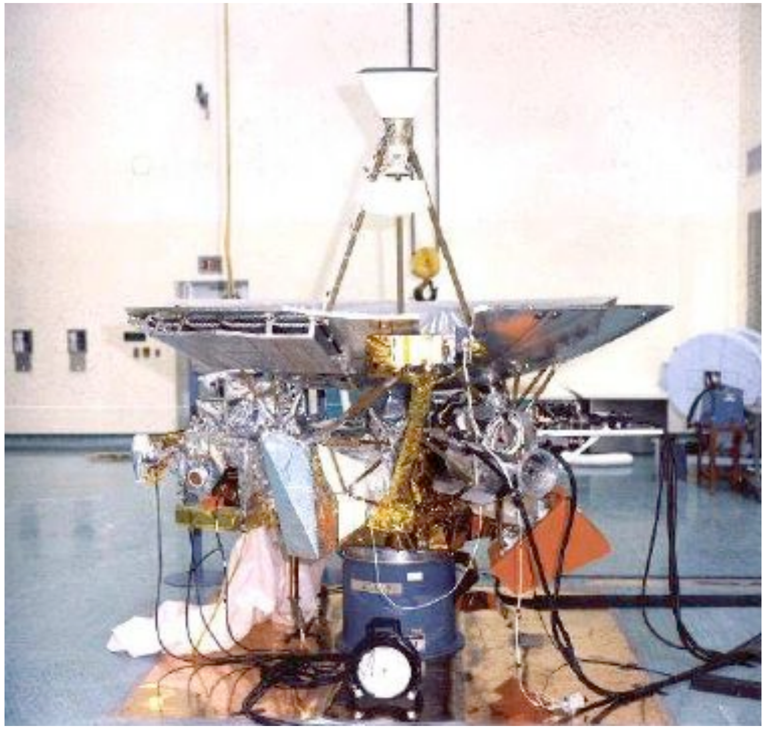
# Telemetry data analysis : S/C behaviour

- **Test the hypothesis of RTG asymmetric radiation**
- **Development of a thermo-electrical model**
- **Modeling of the thermal radiation processes**



*J. Anderson et al, Phys. Rev. D 65 (2002) 082004*

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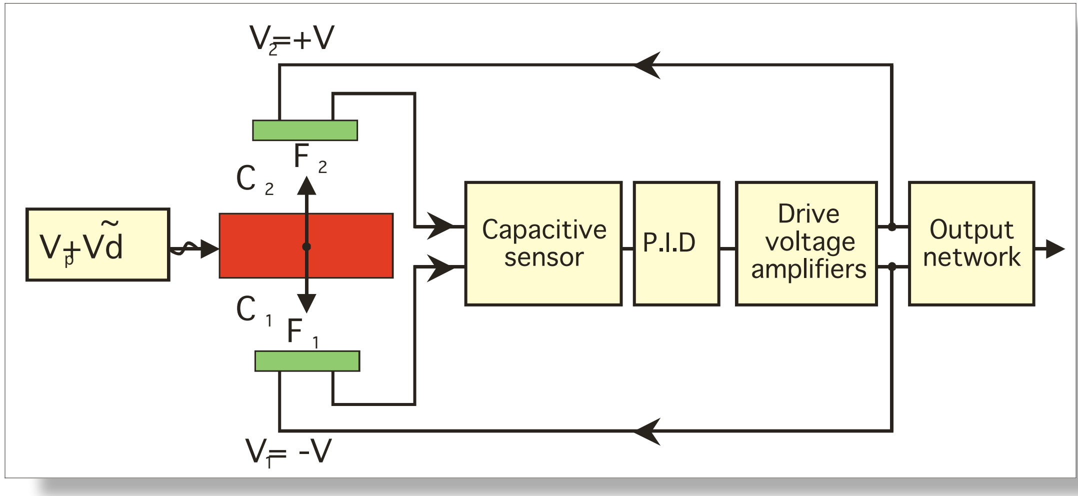
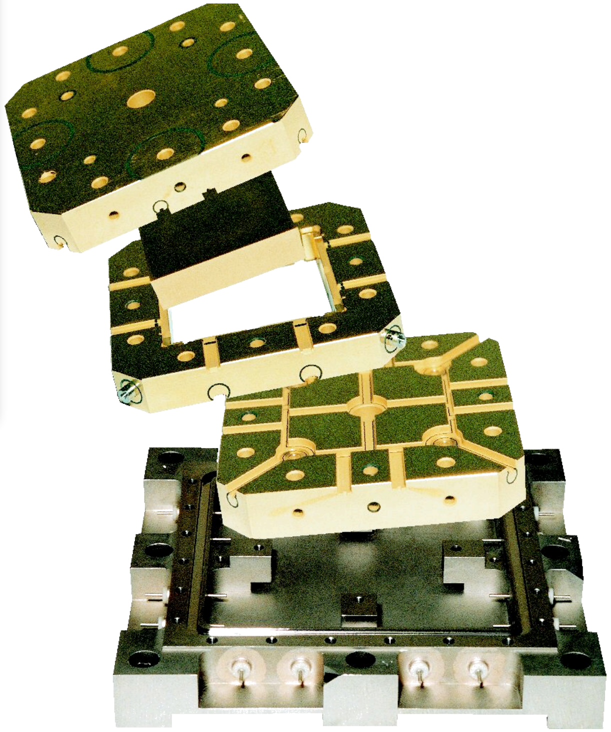
# Space existing electrostatic accelerometer



$$F = F_1 + F_2 = \frac{1}{2}[\nabla C_1 (V_1 - V_P)^2 + \nabla C_2 (V_2 - V_P)^2]$$

$$\nabla C_2 = -\nabla C_1 = \nabla C \text{ and } V_2 = -V_1 = V$$

$$F = [2\nabla C V_P] V = m[\Gamma - g]$$

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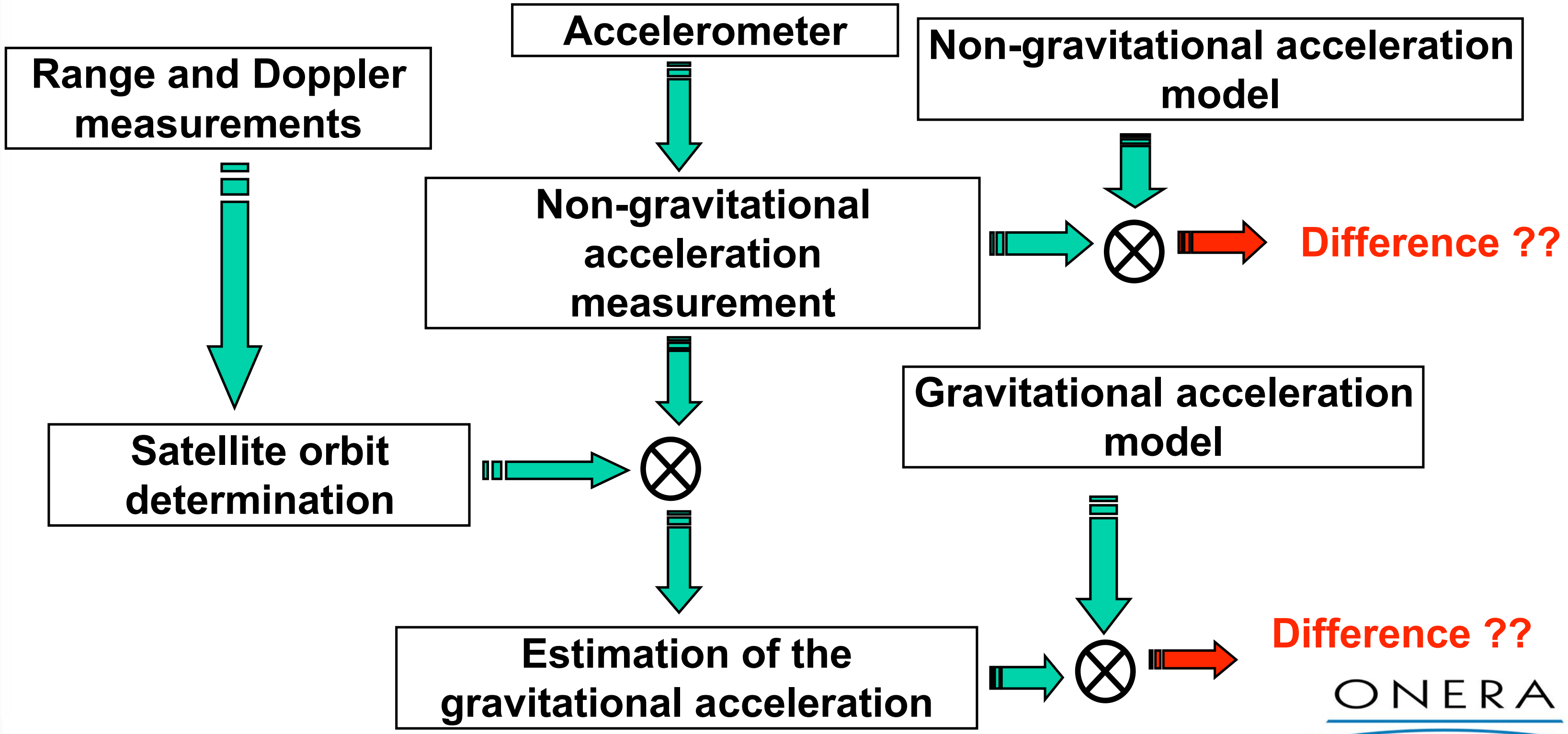
# Motivation for an accelerometer

**Required performance**

- Measurement range = depend on the orbit
- Bias < $10^{-11}$ m/s$^2$
- Scale factor *range < $10^{-11}$ m/s$^2$
- Resolution < $10^{-11}$ m/s$^2$ rms

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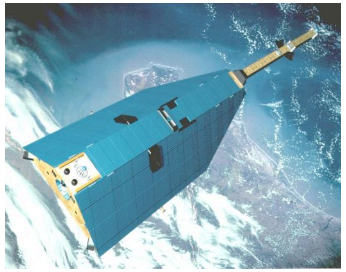
# Accelerometer performance

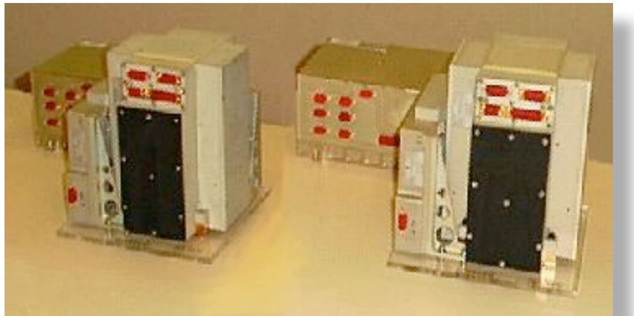
**Earth Observation: geodesy, geophysics, oceanography, hydrography, climatology**

- **CHAMP (CNES-DLR), July 00**

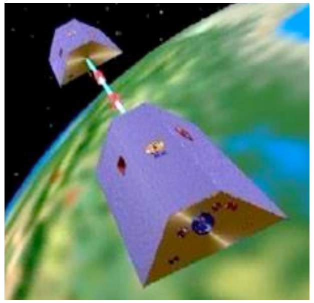


  - **STAR** $10^{-3}$ ms$^{-2}$ - $10^{-8}$ ms$^{-2}$/Hz$^{1/2}$ [$10^{-4}$ - $10^{-1}$ Hz]

Integration time : 100s → $10^{-9}$ ms$^{-2}$

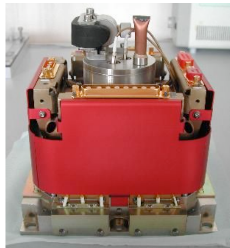


- **GRACE (NASA-JPL), March 02**



  - **SuperSTAR** 2.5 $10^{-5}$ ms$^{-2}$ - $10^{-10}$ ms$^{-2}$/Hz$^{1/2}$ [$10^{-4}$ – 4.$10^{-2}$ Hz]

Integration time : 100s → $10^{-11}$ ms$^{-2}$



- **GOCE (ESA), 2006-2007**

  - **GRADIO**

6.$10^{-6}$ ms$^{-2}$ - 2× $10^{-12}$ ms$^{-2}$/Hz$^{1/2}$ [5.$10^{-3}$ - $10^{-1}$ Hz]

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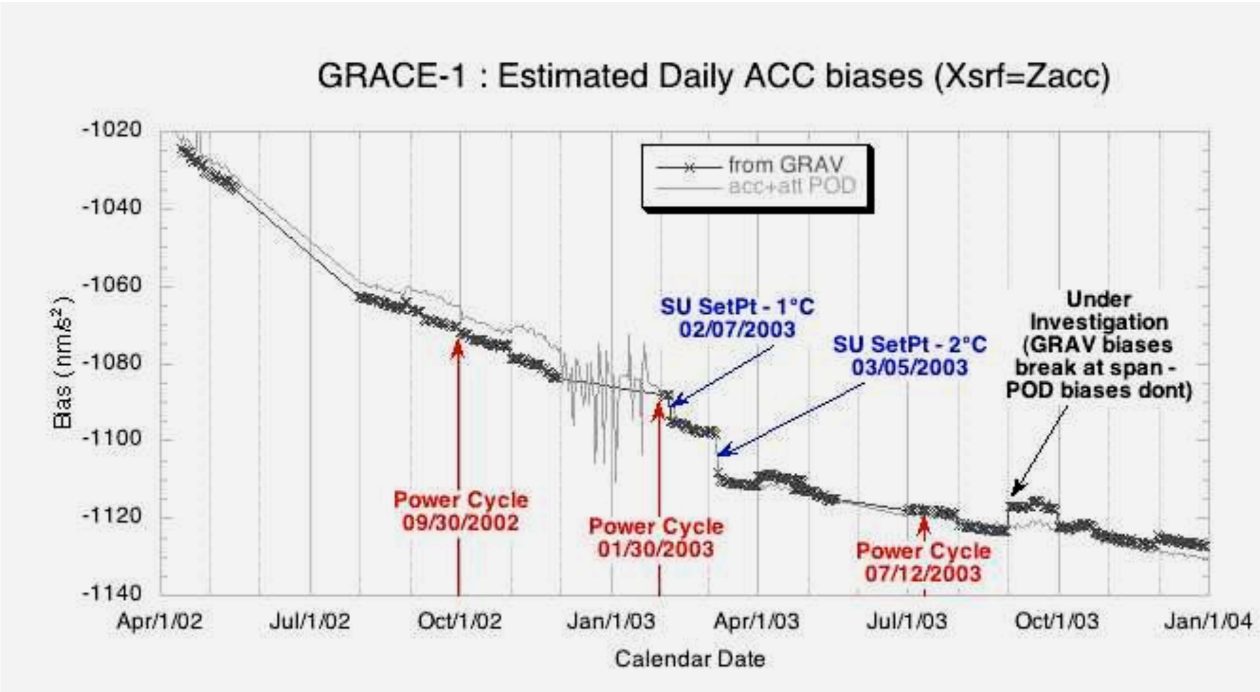
# Evolution of the bias for the GRACE mission

## *GRACE: SuperSTAR Bias long-term evolution*




**Linear variation wrt temperature : ~ 3 nms$^{-2}$ /°C**

**Not sensitive to power cycle**

**Long term drift : ~ - 20 nms$^{-2}$ / year**

→ **bias to be reduced and/or calibrated in orbit**

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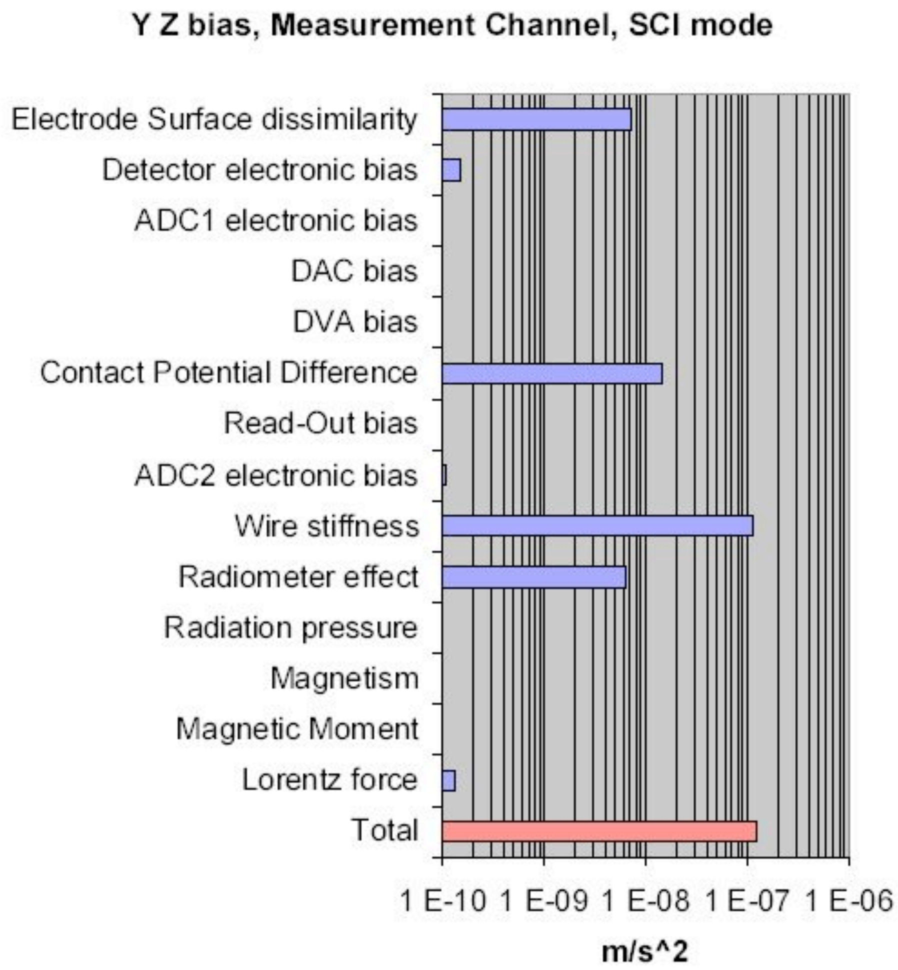
# Bias for GOCE mission




| Contributor | Impact on Measurement Channel Bias (m/s²) SCI mode YZ |
|---|---|
| Electrode Surface dissimilarity | 7.03 E-09 |
| Detector electronic bias | 1.50 E-10 |
| ADC1 electronic bias | 1.20 E-12 |
| DAC bias | 0 |
| DVA bias | 0 |
| Contact Potential Difference | 1.47 E-08 |
| Read-Out bias | 4.64 E-11 |
| ADC2 electronic bias | 1.08 E-07 |
| Wire stiffness | 1.12 E-07 |
| Radiometer effect | 6.34 E-09 |
| Radiation pressure | 3.50 E-13 |
| Magnetism | 2.40 E-13 |
| Magnetic Moment | 2.60 E-14 |
| Lorentz force | 1.30 E-10 |
| **Total** | **1.25 E-07** |

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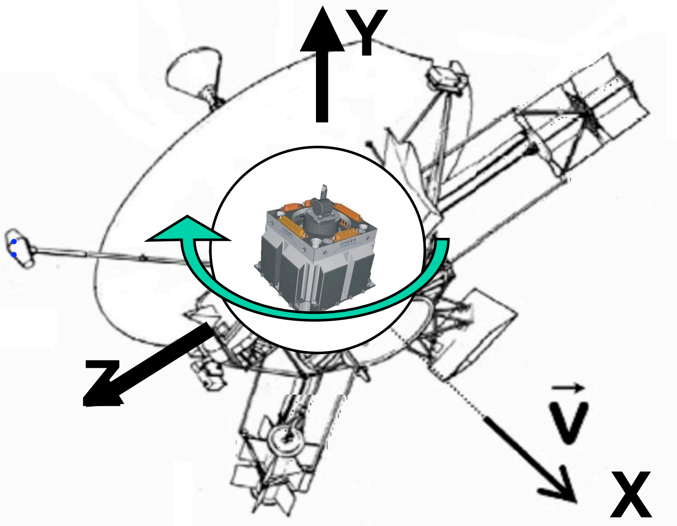
# Proposals to suppress the bias

## « Null Bias » Accelerometer

**Simple method, Rotate the accelerometer sensitive axes wrt satellite :**




- **Calibration with periodic flip during phase measurement :**

$$M_{1x} = B + (\Gamma - g) \;\&\; M_{2x} = B - (\Gamma - g) \rightarrow (\Gamma - g) = 1/2\,(M_{1x} - M_{2x})$$

***bias stability requirement = flip period***

- **Modulation method : sine oscillation**

**Signal about DC shifted @ oscillation frequency, not sensitive to bias instrument**

**Because of the low and steady drift of the bias :**

**→ periodic calibration sufficient and prefered because of :**

- ***low power consumption (piezo stepping motor, LISA)***
- ***low S/C disturbance (slow motion, balanced moving part wrt rotation axis)***
- ***reduced local gravity disturbance (symmetric and balanced device)***

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# Conclusion

- With supplemental data, continuation of trajectory analysis and commencement of telemetry analysis
- Future mission necessary to characterize the nature of the Pioneer anomaly
- Accelerometer mandatory to measure the non-gravitationnal acceleration or assess the S/C free fall motion
- Existing ONERA space accelerometers sufficent for Pioneer follow on mission providing the bias is reduced and/or calibrated : under development

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***Thank you for your attention…***

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