ISLAND
Inverse Square Law And Newtonian Dynamics
Space Explorer

Joel Bergé (ONERA)
Context: test new physics

- Modified gravity
  - Scalar-tensor theories and their screening mechanism
  - Scalar-vector-tensor theories
  - Scale-dependent gravity (Yukawa potential)
  - ...

- Loop quantum gravity
- String theory
- ...

Predict deviations from General Relativity measurable at laboratory / Solar System scale => can be tested

E.g. by looking for Equivalence Principle violation (MICROSCOPE)
or by testing for deviations from geodetic motion in weak gravity fields (Solar System probe, lab)
Look for deviations from the Inverse Square Law at small and large scales.

\[ V(r) = -G \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

Kapner+ 2007, Wagner+ 2012, Masuda+ 2009
Improve existing constraints at sub-millimetre scales and AU scales by one or two orders of magnitude.
Look for deviations from the Inverse Square Law at small and large scales.

**Gravity on large scales**

**Gravity at small scales**
Large-scale gravity test

GAP and tracking
Testing gravitation in the Solar System

Track an interplanetary probe to check if:

i/ it follows a geodesic
ii/ its motion agrees with General Relativity

It can be done by combining:
- radio-science to track the trajectory
- absolute measurement of non-gravitational accelerations through an on-board precise accelerometer

In its Cosmic Vision program, ESA recommends that planetology probes embark a bias-free accelerometer. This accelerometer should be as precise as 10 pm/s² at very low frequency.

Develop a specific instrument to search for deviations from General Relativity in the Solar System
=> GAP
Precise accelerometer in continuous domain for fundamental physics experiments

Bias rejection system concept: external acceleration modulation by regularly turning the accelerometer

=> Frequential separation of the bias and the external acceleration (offset at the turning frequency)

ONERA’s experience
GRACE - GOCE

MICROSTAR Sensor Unit Front-End Electronic (ONERA)

Volume = 3 l
Mass = 3 kg
Consumption = 3 W
Data rate = 300 bits/10s

Bias rejection system
Turning plateform (ZARM/DLR)

Heritage of space rotary stage or filter wheel
GAP - Bias rejection principle

The bias rejection system is based on the heterodyne principle.

The useful signal is modulated in the measurement by regularly turning-over the accelerometer itself. It allows us to discriminate the bias from the external acceleration and to take advantage of the good accuracy of the accelerometer at the modulation frequency.

Frequential Domain

Ground processing:
Demodulation
Low-pass filtering
Precision = 1 pm.s\(^{-2}\) for a modulation period of 10 min and an integration time of 3 hours.

But the final performance depends also on the integration in the S/C
Microstar accelerometer – Testing under g and in free-fall

Pendulum (ONERA)

ZARM tower (December 2016)
Sub-millimeter scale gravity test

*Electrostatic torsion pendulum*
Torsion pendulum

Based on Eöt-Wash torsion pendulum

Adelberger+ 2003, Hoyle+ 2004

Wire + optical detection

Electrostatic control and detection

FIG. 1. Scale drawing of our detector and attractor. The 3 small spheres near the top of the detector were used for a continuous gravitational calibration of the torque scale. Four rectangular plane mirrors below the spheres are part of the twist-monitoring system. The detector's electrical shield is not shown.
Torsion pendulum: ballpark noise

**Eöt-Wash**

**MICROSCOPE**

ISLAND/MICROSCOPE’s noise 2 orders of magnitude lower than Eöt-Wash => room for significant improvement on Yukawa parameters
Gradiometer

- Surrounds torsion pendulum to finely probe local gravitational environment
- Drag-free on 6 axes to control the gravitational environment
- Inherited from GOCE

Joel Bergé, Rencontres de Moriond, March 31, 2017
Why go to space?

- Science
  o large-scale: obvious…
  o short-scale: different environment than on the ground: test models where modifications to GR depend on the local environment (chameleon…)
  o short- and large-scale test in the same regime

- Technology
  o reduce the acceleration background noise
  o optimize most characteristics of the environment (magnetic field, vacuum, thermal stability…)
  o needed to optimise electrostatic pendulum (projection of g onto angular DoF on the ground)
ONERA’s long experience (30 years) in ultra-sensitive accelerometers: ASTRE, CHAMP, GOCE, GRACE, MICROSCOPE…

**GOCE (ESA)**
Gravity Field and Steady State Ocean Circulation Explorer, 2009-2013

**GRACE (NASA-JPL):** Gravity Recovery and Climate Experiment, 2002-2015

\[
\Gamma_n = 10^{-10} \text{ms}^{-2}/\text{Hz}^{1/2} \\
\Gamma_{\text{max}} = 5 \times 10^{-5} \text{ms}^{-2} \\
[10^{-4}, 10^{-1}] \text{Hz}
\]

\[
\Gamma_n = 2 \times 10^{-12} \text{ms}^{-2}/\text{Hz}^{1/2} \\
\Gamma_{\text{max}} = 6 \times 10^{-6} \text{ms}^{-2} \\
[5 \times 10^{-3}, 10^{-1}] \text{Hz}
\]

Current:
GRACE Follow-On (JPL)

MicroSCOPE (CNES)
Conclusion

Proposal submitted to ESA call for New Science Ideas 2016. Unfortunately, not selected, but very good feedback from ESA: mature the concept.

• Preliminary predictions are encouraging
• Some technology ready (almost-off-the-shelf gradiometer and accelerometers)
• Work needed on the torsion pendulum

Team
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