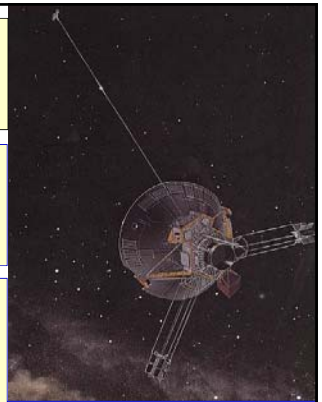
# Large scale tests of the gravity law

Serge Reynaud,
J.-M. Courty & B. Lamine (LKB)
B. Lenoir (LKB & DMPh/ONERA)

Collaborations with
M.-T. Jaekel (LPTENS)
A. Lévy & B. Christophe (ONERA)
G. Métris (GéoAzur OCA)
P. Wolf (SYRTE Obs Paris) …



Laboratoire Kastler Brossel
Physique quantique et applications

http://www.lkb.ens.fr
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## General Relativity (in two slides !)

Gravitation ↔ geometry in space-time

- the equivalence principle as a geometrical foundation
- ideal (atomic) clocks measure the proper time along their trajectory $\quad \mathrm{d}s^2 \equiv g_{\mu\nu}\, \mathrm{d}x^\mu \mathrm{d}x^\nu$
- freely falling probes (test masses and light rays) follow geodesics $\quad \delta\left[\int \mathrm{d}s\right] = 0$

One of the most accurately tested principles of physics :

- free motions of masses with ≠ compositions coincide to an accuracy better than $10^{-12}$ ; this accuracy is reached in the lab as well as in space (Lunar Laser Ranging = LLR)
- atomic clocks working on ≠ transitions give the same time at an accuracy better than $10^{-16}$ per year

Accuracies to be improved soon : MICROSCOPE & ACES

## General Relativity (in two slides !)

Riemannian geometry

- curvature tensors = (non linear) differential expressions built up on the metric tensor
- the Einstein curvature tensor has a null divergence $\quad G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \qquad D^\nu G_{\mu\nu} = 0$
- the stress tensor too (conservation laws) $\quad D^\nu T_{\mu\nu} = 0$

In General Relativity (GR), the coupling between matter and curvature has a specific form

→ Einstein-Hilbert equation $\quad \boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$

- the 2 tensors are simply proportional to each other
- other forms of the coupling are possible, some have been submitted to systematic investigation

## General Relativity in the solar system

Solution for the metric

- with the Sun treated as a point-like motionless source and using spatially isotropic coordinates
- written as a Taylor expansion of the Newton potential

$$g_{00} = 1 + 2\phi + 2\phi^2 + \ldots$$
$$g_{ij} = -\left(1 - 2\phi + \ldots\right)\delta_{ij}$$
$$\phi \equiv -\frac{m}{r} \quad , \quad |\phi| \ll 1$$
$$m \equiv \frac{GM}{c^2} \simeq 1.5\,\mathrm{km}$$

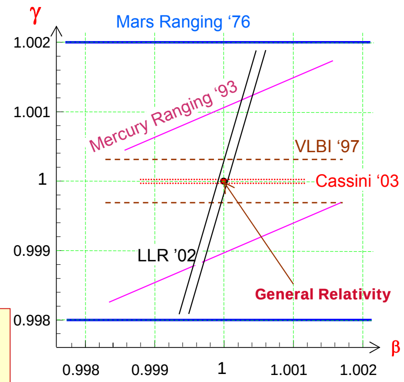
Solution often tested through a confrontation of data with the larger family of PPN metrics

$$g_{00} = \left(1 + 2\phi + 2\beta\phi^2 + \ldots\right)$$
$$g_{jk} = -\left(1 - 2\gamma\phi + \ldots\right)\delta_{jk}$$
$$\beta = \gamma = 1 \text{ in GR}$$

➢ Comparisons between observations and motions predicted as the geodesics of this metric can be expressed in terms of deviations of the PPN parameters $\beta - 1\,,\ \gamma - 1$

# 30 years of PPN tests

- Ranging on planets
- Lunar Laser Ranging (LLR)
- Astrometry and VLBI
- Doppler velocimetry on planetary probes




Select a vicinity of GR in the PPN family

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$
$$\beta - 1 = (12 \pm 11) \times 10^{-5}$$

Courtesy : Slava Turyshev *JPL NASA*

***Living Reviews in Relativity*, C.F. Will (2001)**

# 30 years of scale dependent tests

## *"Fifth-force" tests of the Newton law*

Search for a deviation

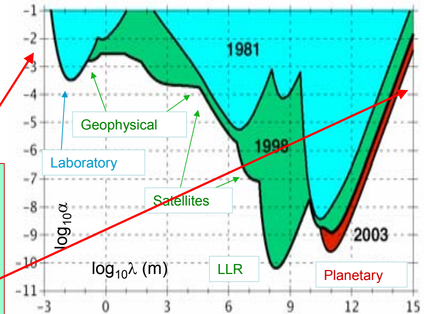
$$g_{00} = [g_{00}]_{\mathrm{GR}} + \delta g_{00}$$

in particular under the form of a Yukawa correction

$$\delta g_{00}(r) = 2\phi(r)\,\alpha \exp\left(-\frac{r}{\lambda}\right)$$

Select a vicinity of GR in the Yukawa family

but …
windows are still open for deviations at short distance or long distance




Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003) ; M.T.Jaekel and S.Reynaud IJMP (2005)

***The Search for Non-Newtonian Gravity*, E. Fischbach & C. Talmadge (1998)**

# Why the tests are going on ?

Gravity law tests are in good agreement with GR but windows are still open for deviations

GR is a classical theory which shows inconsistencies with quantum field theory

And unification models predict (small) deviations to be observed at short or long distances …

"Dark matter" and "dark energy" are introduced to cure defects in gravitational observations at galactic and cosmic scales

A few measurements in the solar system show deviations from the predictions of GR ("Pioneer anomaly")

- It is extremely important to test GR at large scales
- Tests with probes in the solar system

# A broader metric frame for gravity tests

One can preserve the metric interpretation of gravitation, and consider a generalized form for the coupling

- modifications induced for example by the "radiative corrections" of GR which follow from the coupling of gravitational field to the quantum fields

Metric in the (outer) solar system is then (slightly) modified

- two « sectors » in the theory
- two functions to be determined

$$g_{00} = [g_{00}]_{\mathrm{GR}} + \delta g_{00}(r)$$
$$g_{rr} = [g_{rr}]_{\mathrm{GR}} + \delta g_{rr}(r)$$

One may consider that the PPN framework is extended with the constants β and γ becoming functions of *r* …

… or that a scale dependence is looked for on the two components of the metric tensor (and not only one of them)

M.-T. Jaekel, S. Reynaud, Classical and Quantum Gravity **22** (2005) 2135

# The two « sectors »

First sector : modification of the temporal component $\delta g_{00}(r)$

- A “fifth force” acting on material motions
- Strongly constrained by planetary tests
- But the deviation could appear only after Saturn …

See for example J. Moffat, Classical and Quantum Gravity **23** (2006) 6767

Second sector : modification of the spatial component $\delta g_{rr}(r)$

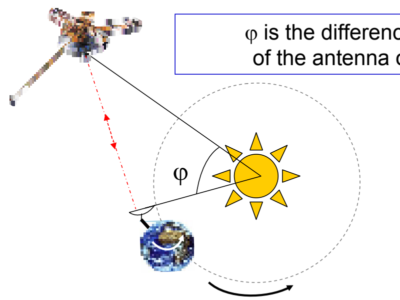
- Affects light propagation, as a parameter $\gamma$ depending on the distance to the Sun
- No effect on circular orbits, small effect of material motions (especially on nearly circular orbits)
- Produces a Pioneer-like anomaly for probes with escape trajectories in the outer solar system !
- This modification cannot be allowed to spoil the agreement with GR of other gravity tests !!

M.-T. Jaekel, S. Reynaud, Classical and Quantum Gravity **23** (2006) 777 & 7561

# A difference between the two sectors

Modifications in the first sector are equivalent to an anomalous force acting on the probe

Modifications in the second sector affect the propagation of the electromagnetic link → they induce modulated effects

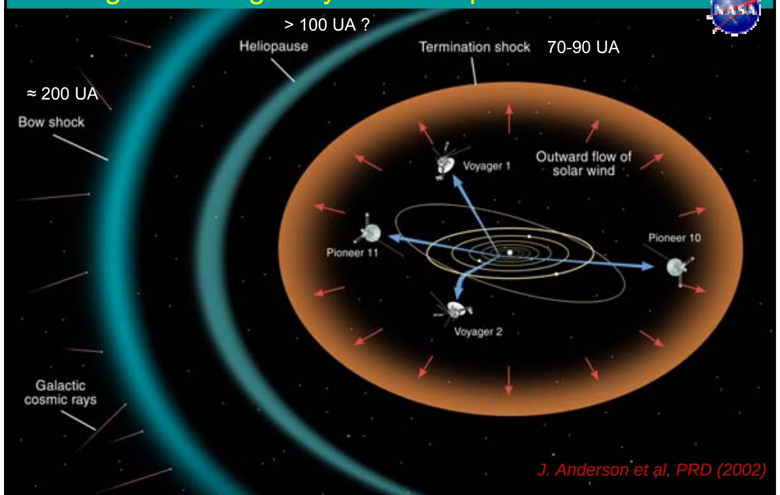



$\varphi$ is the difference $\varphi_A$- $\varphi_P$ of azimuth angles of the antenna on Earth and on the probe

This angle shows diurnal and annual modulations (motion of the Earth antenna)

M.-T. Jaekel, S. Reynaud, Classical and Quantum Gravity **23** (2006) 7561

# The largest scale gravity test ever performed …



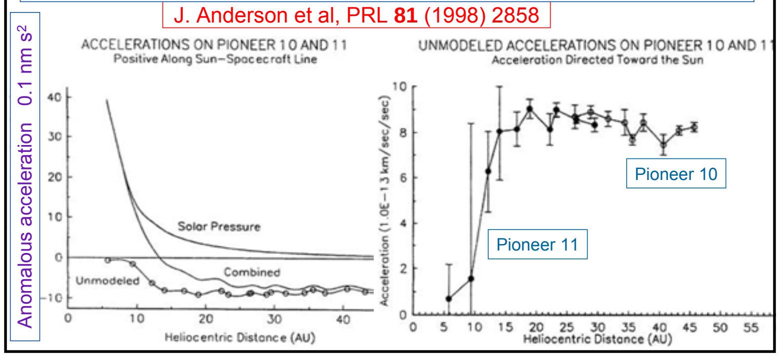

… did not confirm the known laws !

THE DEEP SPACE GRAVITY PROBE SCIENCE TEAM

# Detection of the Anomaly

- Search for unmodeled accelerations started in 1979:
  - The effect of solar radiation pressure was $\simeq 0.5\,\mathrm{nm\,s^{-2}}$
- Detection of the anomaly by JPL orbit determination in 1980
  - The analysis found a constant bias in the acceleration residuals towards the Sun $a_P \simeq 0.8 \pm 0.3\,\mathrm{nm\,s^{-2}}$

J. Anderson et al, PRL **81** (1998) 2858



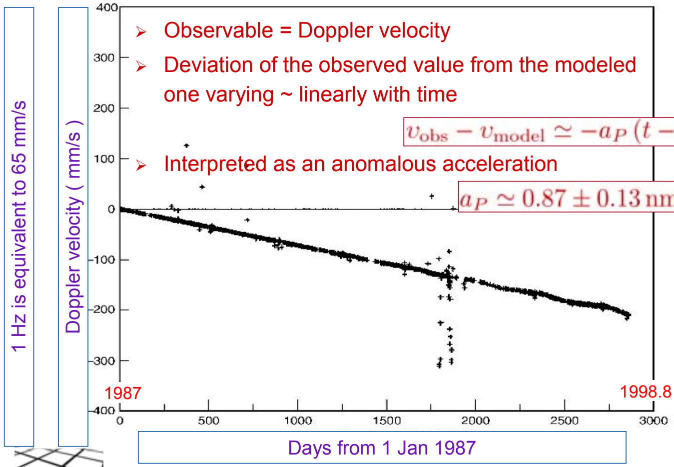
## Characterization of the anomaly

- Observable = Doppler velocity
- Deviation of the observed value from the modeled one varying ~ linearly with time

$$v_{\rm obs} - v_{\rm model} \simeq -a_P\,(t - t_{\rm in})$$

- Interpreted as an anomalous acceleration

$$a_P \simeq 0.87 \pm 0.13\,\mathrm{nm\,s^{-2}}$$




J. Anderson et al, PRD 65 (2002) 082004



## Detailed Analysis by NASA (1980-2002)

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

- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated “gas leaks”
  - Nominal thermal radiation due to $^{238}$Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations
- Examples of the external effects:
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Drag force due to mass distributions in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth Orientation Parameters, precession, and nutation
- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others

All the above were rejected as explanations (in the PRD 2002)



## A Drag Through Dust ?

Nieto et al, Physics Letters B 613 (2005) 11–19

- Interplanetary Medium
  - A thinly scattered matter (neutral Hydrogen, microscopic particles) with two main contributions
  - Interplanetary Dust (IPD)
    - Hot-wind plasma (mainly protons and electrons) distributed within the Kuiper Belt starting from 30 to 100 AU
    - $\rho_{\rm IPD} \lesssim 10^{-24}\ \mathrm{g/cm^3}$ is a modeled density, as suggested in *Man, Kimura, J. Geophys. Res. A105, 10317 (2000);*
  - Interstellar Dust (ISD)
    - Fractions of interstellar dust (characterized by greater impact velocity);
    - $\rho_{\rm ISD} \lesssim 3\times10^{-26}\ \mathrm{g/cm^3}$ was directly measured by the Ulysses spacecraft
- Effect on the Pioneers
  - The drag on a spacecraft is given by $a_s(r) = -\mathcal{K}_s\,\dfrac{\rho(r)\,v_s^2(r)\,A_s}{m_s}$
  - One needs an axially-symmetric dust distribution within 20 and 70 AU with a constant uniform and unreasonably high density of

$$\rho_P(r) \lesssim \rho_0 = 3\times10^{-19}\ \mathrm{g/cm^3} \simeq 300,000\cdot(\rho_{\rm IPD}+\rho_{\rm ISD})$$

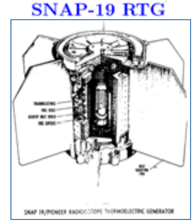
❖ Dust can hardly be the origin of the Pioneer Anomaly

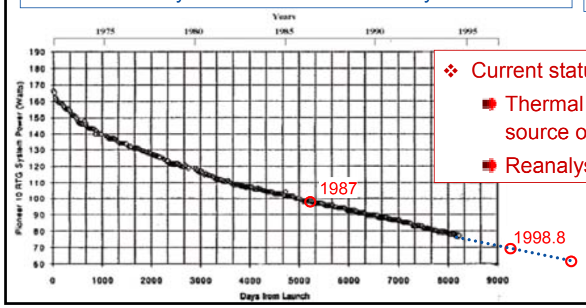


## The thermal issue

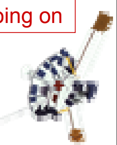
- Initial analysis at JPL (PRD 2002 paper) :
  - Effect calculated to be too small
  - Exponential decrease not seen
- Problem now reevaluated :
  - New thermal models of the probe
  - Telemetry data recovered and analysed

SNAP-19 RTG

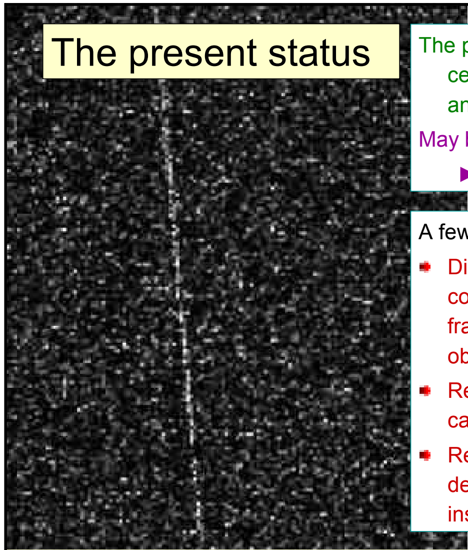





❖ Current status :
- Thermal budget is a source of concern
- Reanalysis is going on



# The present status



Pioneer 10 as seen recently from Arecibo (coherent signal is lost)

The presence of the anomaly is certain, its origin still remains an enigma

May be an artifact ?

▶ The thermal issue ?

A few perspectives

- Discuss the anomaly in a coherent phenomenological framework (besides other observations)
- Reanalyze the data to try to capture the origin of the effect
- Redo the measurements with a dedicated mission or embarked instruments

THE DEEP SPACE GRAVITY PROBE SCIENCE TEAM

## Deep space gravity collaborations

- Pioneer data recovered
  - Doppler and telemetry data re-analysed
  - Work organized as an international effort (USA, Canada, France, Germany, Portugal, Norway …
  - Information on the website of the team at the International Space Sciences Institute (ISSI Bern) www.issi.unibe.ch/teams/Pioneer

Somewhere in JPL…

- New ideas proposed to space agencies
  - Deep space gravity probe (2004)
  - Solar System Odyssey (2007)
  - SAGAS (2007)
  - GAP on EJSM (2009)

ESA Cosmic Vision

Studies cnes

# Doppler tracking

A radio signal is sent from a DSN station on Earth to the probe, received and transponded back to the Earth, and finally recorded by a DSN station (the same=2-way ; another=3-way)

S Band

≈2,11 GHz

Transponder

$\times \frac{240}{221}$

The Doppler observable is a ratio of frequencies, it may be seen as a velocity, but takes into account all relativistic and gravitational effects

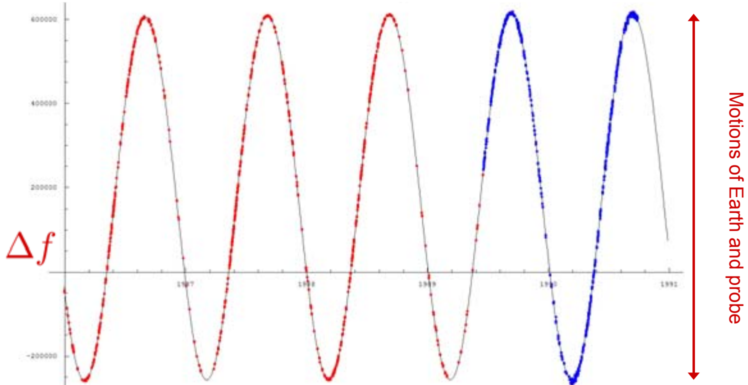
$$\frac{f_{down}}{f_{up}}$$

Furthermore, the observable has to be corrected for propagation effects (atmosphere and solar plasma) and motions of stations….

$f_{up}$ , $f_{down}$

# Doppler shift on Pioneer

2 Way (red) and 3 Way (blue) versus NASA Horizon ephemeris (black)




Data treatment : Agnès Lévy et al

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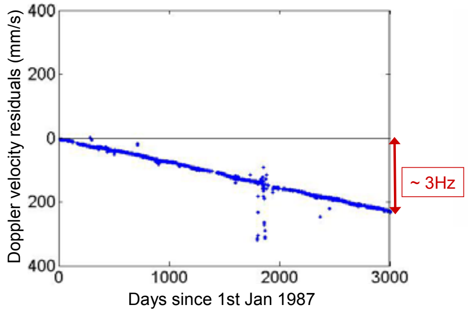
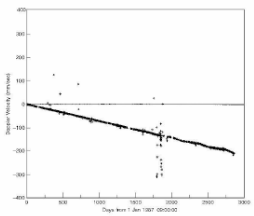
# Reanalysis of Pioneer 10 data



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

The presence of the anomaly is confirmed,
on the same data, with an independent software

A. Levy, B. Christophe, P. Berio, G. Metris, J.-M. Courty, S. Reynaud
Advances in Space Research **43** (2009) 1538

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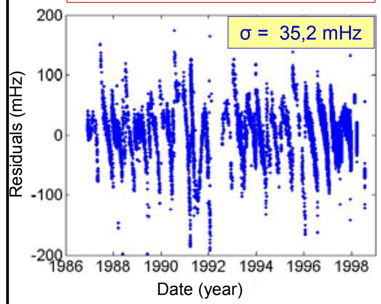
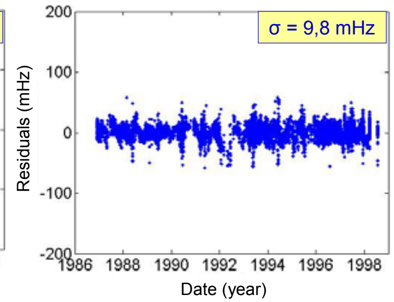
# Residuals = « Observed – Calculated »

Residuals with GR




GR + constant acceleration




Anomaly = large reduction of the residuals

Periodic structures still visible in the residuals

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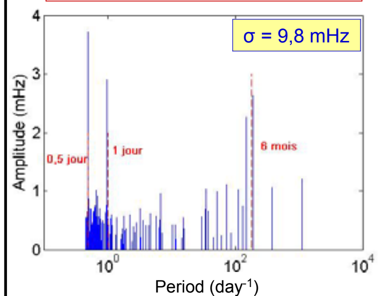
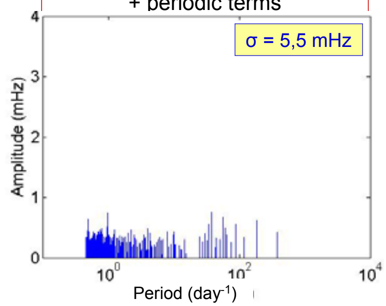
# Spectral analysis of the residuals

GR + constant acceleration




GR + constant acceleration
+ periodic terms




Significant reduction of the variance of the residuals,
as well as of all spectral signatures

A. Levy, B. Christophe, P. Berio, G. Metris, J.-M. Courty,
S. Reynaud, Advances in Space Research **43** (2009) 1538

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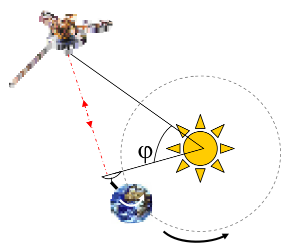
# The geometrical model

A single angle $\varphi$ is used for describing the diurnal and annual motions of the antenna on Earth

The terms $\cos\varphi$, $\sin\varphi$, $\cos 2\varphi$, $\sin 2\varphi$ are sufficient for reducing the data




These results suggest that there is an anomalous effect on the propagation of the radio link

And therefore that the effect cannot be explained entirely as an anomalous force acting on the probe

Other interpretations for the modulated anomalies ?

Errors on the solar plasma model ? On the ephemeris ?

A. Levy et al, Advances in Space Research **43** (2009) 1538

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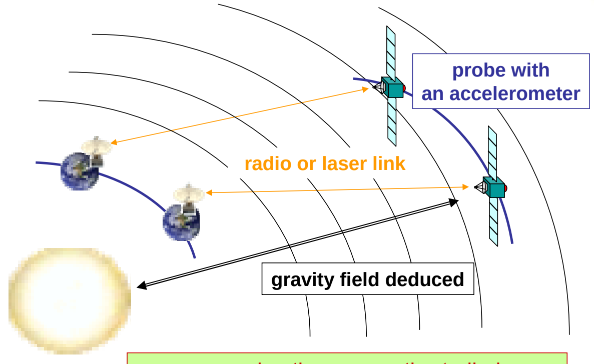
## Towards new missions ?

Main idea : Navigation by radio- or laser-tracking
+ measurement of an accelerometric observable




several options currently studied

## Scientific motivations

*With an accelerometer on board*

- ✓ We obtain an inertial observable
  *(how well does the satellite follow a geodesic)*
- ✓ We get rid of the uncertainties of models on non gravitational forces *(these forces are measured by the accelerometer !)*

Huge interest for fundamental physics :

- Gravity law test performed during the cruise phases with significantly improved accuracy and reliability
- ✓ Planetary flybys monitored in a more precise manner

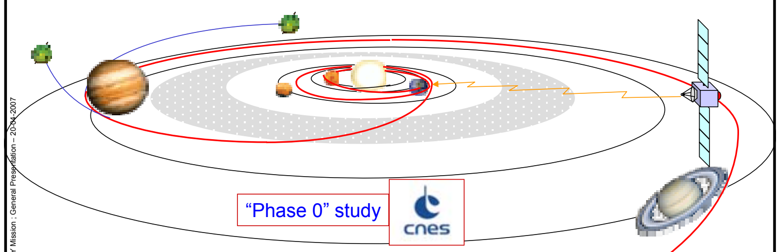
Important information also gained on the visited objects :

- ✓ Gravity field of planets and their moons
- ✓ Study of their environments (aeronomy …)

## ODYSSEY project (PI Bruno Christophe)

Main scenario:
Electrostatic accelerometer
Radio or laser link
Measurements up to 13 AU

ENIGMA option:
Probe launched @ Saturne
May fly up to 50-100 AU



"Phase 0" study

Scientific objectives:
Gravity law test
Investigation of flybys

Scientific objectives:
Gravity law test up to 50-100 AU
Investigation of the Kuiper belt

B. Christophe et al, Experimental Astronomy (2009)

## SAGAS project (PI Peter Wolf)

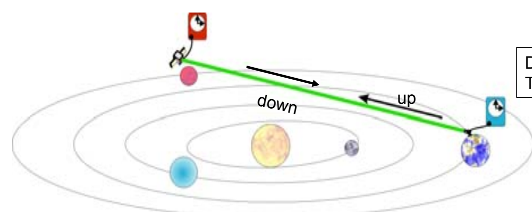
(Search for Anomalous Gravitation with Atomic Sensors)

Exploring Gravity in the
Outer Solar System
with Quantum Sensors :

- Optical clock
- Atomic accelerometer
- Laser link

Cold Atoms

Scientific objectives :
Gravity law test up to 50 AU
Investigation of flybys
Measurement of the gravitational redshift of clocks
Search for gravitational waves at very low frequency (0.01-1mHz)
Exploration of the Kuiper belt

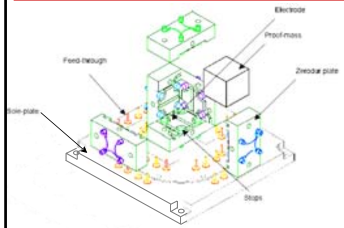



Distance = up + down
Timing = up - down

P. Wolf et al, Experimental Astronomy (2009)

## Gravity Advanced Package (B. Christophe)

After a specific recommendation of ESA advisory groups,
an instrument designed to be embarked on a planetary mission




μSTAR : a low-consumption miniaturized electrostatic accelerometer

Volume = 3 l
Mass = 3 kg
Consumption = 3 W

Objective for the gravity test :
accuracy < 50 pm/s² on [0;0,1mHz]

Development ongoing at ONERA (F) and ZARM (D) :
Bias rejection by periodical flip of the instrument

« Package » proposed for the planetary mission EJSM, candidate for a selection for Cosmic Vision (L mission)

To be traited :
integration constraints, self-gravity …

ONERA

## Thank for your attention

### Collaborations

"Pioneer Anomaly Explorer" Hansjorg Dittus *et al*

"Investigation of the Pioneer Anomaly @ ISSI"
Slava Turyshev *et al*

"Deep Space Gravity Tests" Serge Reynaud *et al*

"Groupe Anomalie Pioneer" Serge Reynaud *et al*

"ODYSSEY" Bruno Christophe *et al*

"SAGAS" Peter Wolf *et al*

"GAP on EJSM" Bruno Christophe *et al*

See the draft report of the "Fundamental Physics Roadmap Advisory Team" http://sci.esa.int/fprat