The SAGAS Project

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on behalf of the SAGAS collaboration

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CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

l'Observatoire de Paris SYRTE
Systèmes de Référence Temps-Espace

UNIVERSITE PIERRE & MARIE CURIE
LA SCIENCE A PARIS

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SAGAS

(Search for Anomalous Gravitation with Atomic Sensors)

arXiv: 0711.0304, (2008)

Quantum Physics Exploring Gravity in the Outer Solar System

> 70 participants from:	**France, Germany, Great Britain, Italy, Portugal, Austria, Canada, USA, Australia**

Main contributors:

Science Objectives: O. Bertolami, A. Fienga, P. Gil, J. Laskar, J. Páramos, S. Reynaud, F. Roques, S. Turyshev, P. Wolf.

Accelerometer: E. Rasel, A. Landragin, G. Tino.

Clock: P. Gill, E. Peik, P. Lemonde.

Optical Link: A. Clairon, P. Wolf, E. Samain.

Laser Sources: P. Cancio, P. De Natale, M. De Rosa, G. Galzerano, G. Giusfredi, M. Inguscio, P. Laporta, A. Toncelli, M. Tonelli.

Spacecraft: A. Rathke, C. Jentsch.

Mission profile: A. Rathke, D. Izzo.

Introduction

- Gravitation is well described by General relativity (GR).
- GR is a classical theory, which shows inconsistencies with quantum field theory.
- All unification models predict (small) deviations of gravitation laws from GR.
- Gravity is well explored at small (laboratory) to medium (Moon, inner planets) distance scales.
- At very large distances (galaxies, cosmology) some puzzles remain (galactic rotation curves, SNR redshifts, dark matter and energy, ….).
- The largest distances explored by man-made artefacts are of the size of the outer solar system $\Rightarrow$ carry out precision gravitational measurements in outer solar system.

- Kuiper Belt ($\approx$ 40 AU, $\approx$ 1000 KBOs since 1992), the disk from which giant planets formed is largely unexplored.
- Known mass ($M_{KB} \approx 10^{-1}\, M_E$) about 100 times too small for in situ formation of KBOs.
- KBO masses only inferred from albedo and density hypothesis ($\Rightarrow$ uncertainty).
- “In situ” gravitational measurements yields exceptional information on M_{KB}, overall mass distribution, and individual KBO masses (+ discover new KBOs ?)
- Measurements during planetary fly by (Jupiter) can yield highly accurate determination of planetary gravity.

SAGAS: Overview

Payload:

1. Cold atom absolute accelerometer, 3 axis measurement of local non-gravitational acceleration.
2. Optical atomic clock, absolute frequency measurement (local proper time).
3. Laser link (frequency comparison + Doppler for navigation).

Trajectory:

- Jupiter flyby and gravity assist (≈ 3 years after launch).
- Reach distance of ≈39 AU (15 yrs nominal) to ≈53 AU (20 yrs, extended).

Measurements:

- *Gravitational trajectory of test body (S/C):* using Doppler ranging and correcting for non-gravitational forces using accelerometer measurements.
- *Gravitational frequency shift of local proper time:* using clock and laser link to ground clocks for frequency comparison.

⇒ ***Measure all aspects of gravity !***

Science Objectives: Overview

Science Objective	Expected Result	Comments
Test of Universal Redshift	$\mathbf{1x10^{-9}}$ of GR prediction	$\mathbf{10^{5}}$ gain on present
Null Redshift Test	$\mathbf{1x10^{-9}}$ of GR prediction	$\mathbf{10^{3}}$ gain
Test of Lorentz Invariance	$\mathbf{3x10^{-9}}$ to $\mathbf{5x10^{-11}}$ (IS or “time dilation” test)	$\mathbf{10^{2}}$ to $\mathbf{10^{4}}$ gain fct. of trajectory
PPN test	$\delta(\gamma) \leq \mathbf{2x10^{-7}}$	$\mathbf{10^{2}}$ gain may be improved by orbit modelling
Large Scale Gravity	- Fill exp. data gap for scale dependent modif. of GR - Identify and measure PA to $< 1\%$ per year of data	Different observation types and large range of distances will allow detailed “map” of large scale gravity
Kuiper Belt (KB) Total Mass	$\delta M_{\mathrm{KB}} \leq \mathbf{0.03}\ M_{\mathrm{E}}$	Dep. on mass distribution and correlation of clock meas.
KB Mass Distribution	Discriminate between different common candidates	Will contribute significantly to solution of the “KB mass deficit” problem
Individual KB Objects (KBOs)	Measure M_{KBO} at $\approx$ **10%**	Depending on distance of closest approach
Planetary Gravity	-Jupiter Gravity at $\leq 10^{-10}$ -Study Jupiter and its moons	10^{2} gain on present for Jupiter idem for other planet in case of 2nd fly-by
Variation of Fund. Const.	$\delta\alpha/\alpha \leq (\mathbf{2x10^{-9}})\ \delta(GM/rc^{2})$	**250**-fold gain on present
Upper limit on Grav. Waves	$\Omega_{h} \leq 10^{-5}$ @ 10^{-5} Hz $h \leq \mathbf{10^{-18}}$ @ 10^{-6} to 10^{-3} Hz	$\mathbf{10^{3}}$ gain @ 10^{-6} to 10^{-3} Hz Integration over one year
Technology Developement	Develops S/C and ground segment technologies for wide use in future missions (interplanetary timing, navigation, broadband communication,…)	

Fundamental Physics: Scale dependent gravity

Search for a deviation

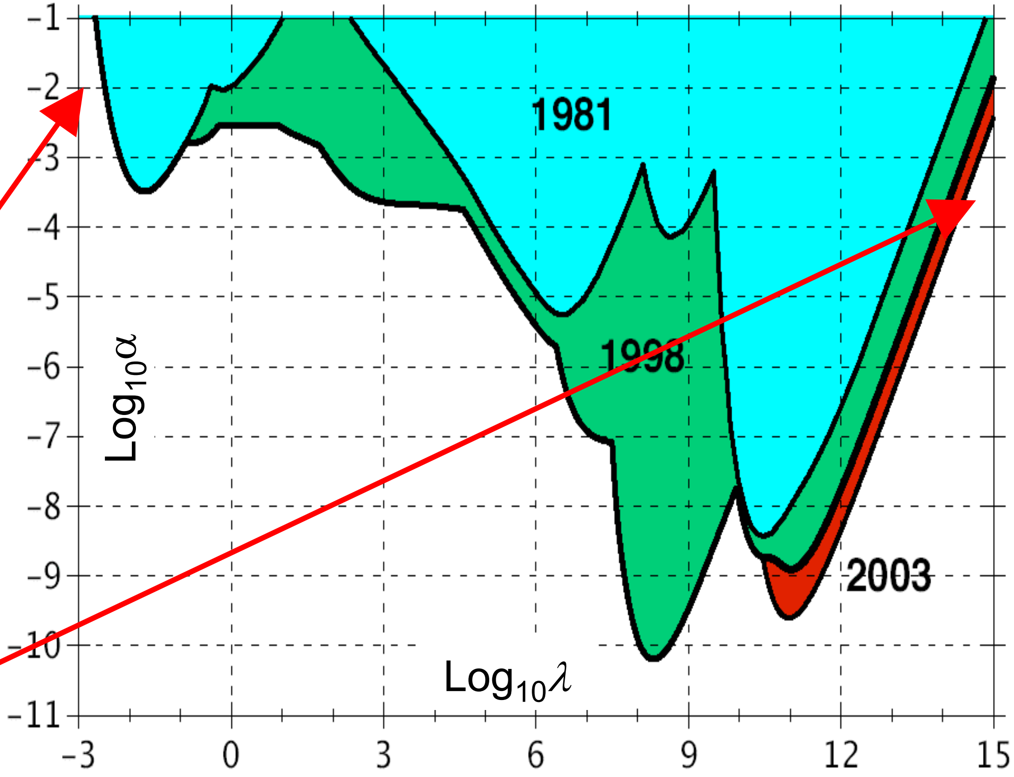
$$g_{00} = [g_{00}]_{\mathrm{GR}} + \delta g_{00}$$

For example under the form
of a Yukawa correction

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

Windows remain open for deviations at short ranges

or long ranges



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

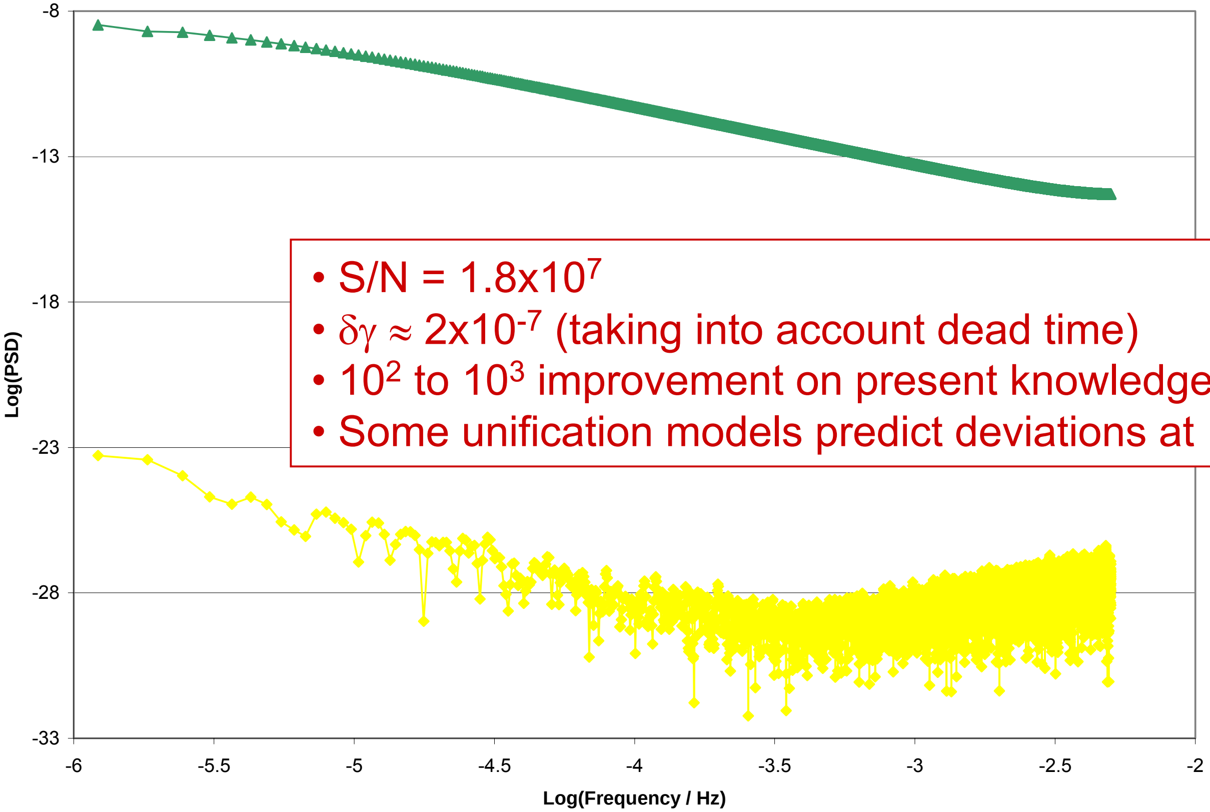
The Search for Non-Newtonian Gravity, E. Fischbach & C. Talmadge (1998)

Fundamental Physics: Metric gravity (PPN test)

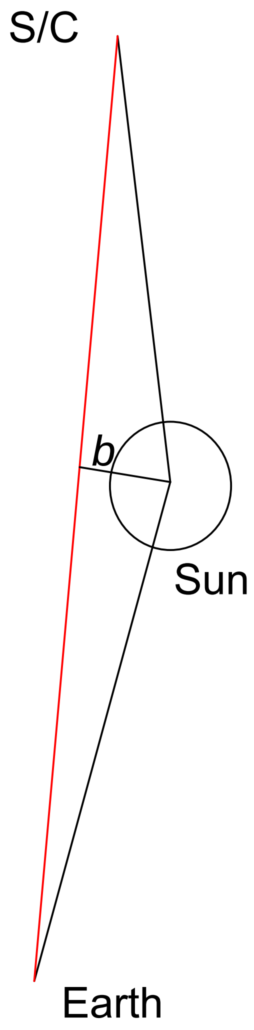
$$\delta\left(\frac{f_r - f_e}{f_0}\right) \approx \frac{d}{dt}\left[2(1+\gamma)\frac{GM}{c^3}\ln\left(\frac{4r_S r_G}{b^2}\right)\right] \approx -4(1+\gamma)\frac{GM}{c^3 b}\frac{db}{dt}$$

PPN parameter, in GR $\gamma=1$

- Gravitational time delay (Shapiro delay)
- Large variation during occultation ⇒ effect on Doppler observable



- S/N = 1.8×10^7
- $\delta\gamma \approx 2\times10^{-7}$ (taking into account dead time)
- 10^2 to 10^3 improvement on present knowledge (Cassini)
- Some unification models predict deviations at 10^{-5} to 10^{-7}



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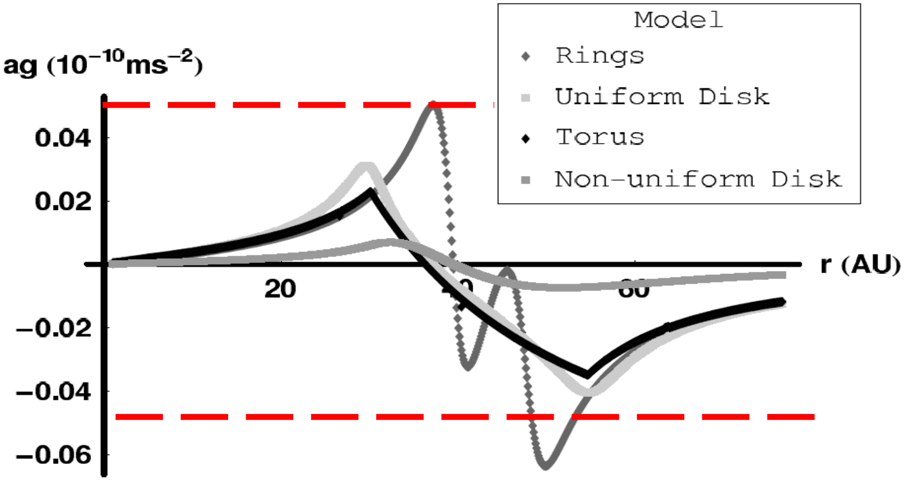
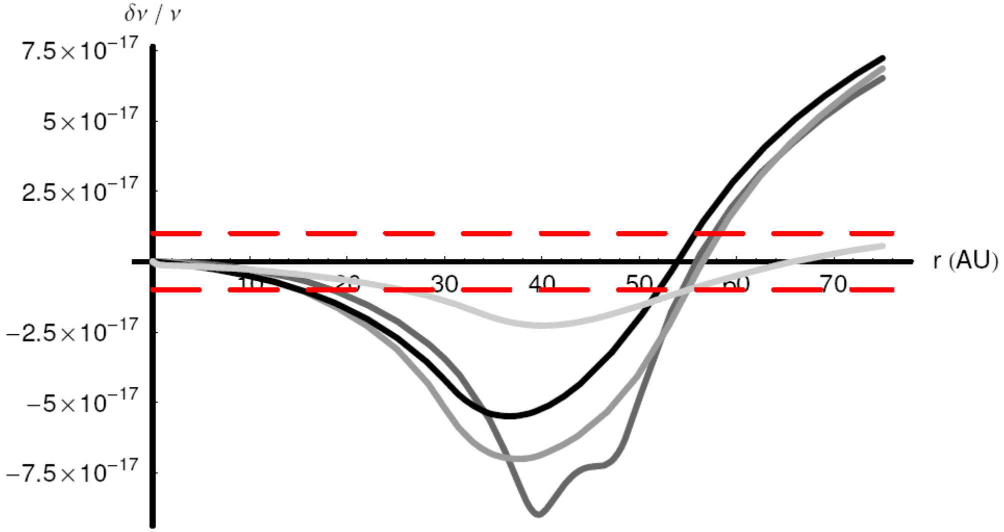
Solar System Exploration: Kuiper Belt





Kuiper belt mass distribution models, with $M_{KP} = 0.3\ M_E$

- Remnant of disc from which giant planets formed.
- Mass deficit problem (100 times less than expected from in situ formation of KB objects).
- Acceleration sensitivity insufficient to distinguish between models ($\propto 1/r^2$).
- But clock well adapted for measurement of diffuse, large mass distributions ($\propto 1/r$).
- Depending on distribution SAGAS can determine M_{KB} with $\delta M_{KB} \approx 10^{-2} M_E$ to $10^{-3} M_E$

Provided by O. Bertolami et al.

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Payload: Accelerometer

- Atom interferometer, using laser cooled Cs atoms as “test masses”.
- Interrogation of atoms using Raman laser pulses in 3D (sequentially).
- Ground atom interferometers have uncertainties comparable to best “classical” methods, $\approx 10^{-8}$ m/s^2, limited by vibrations, Earth rotation, atmosphere, tides….

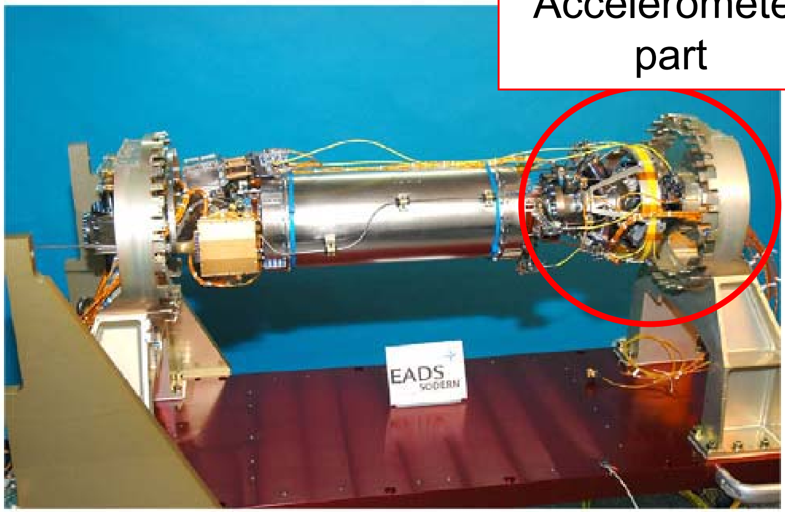
- In a quiet space environment, with possibility of long interrogation times (2 s) expect:

$\sqrt{S_a}(f) = 1.3\ 10^{-9}$ m/s^2 Hz $^{-1/2}$ (limited by RF stability, PHARAO quartz USO)

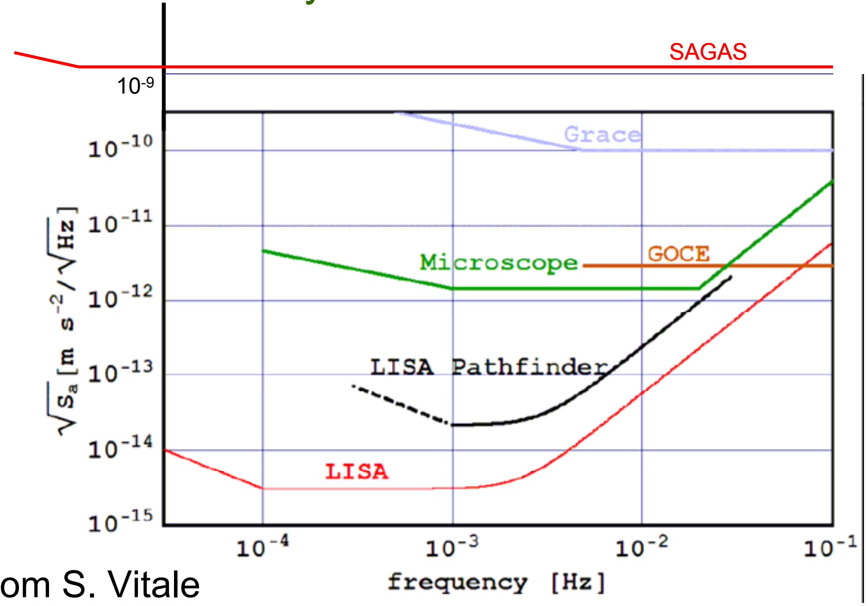
Absolute accuracy (bias determination): 5 10^{-12} m/s^2.

- “Classical” space accelerometers have $\sqrt{S_a}(f) = 10^{-10}$ m/s^2 Hz $^{-1/2}$ (GRACE), or better (10^{-12} GOCE, μSCOPE; 10^{-15} LISA) with bias calibration at 4 10^{-11} m/s^2 (ODYSSEY).

- Based to a large extent on PHARAO technology and HYPER study.



“Accelerometer“ part



From S. Vitale

Payload: Optical Clock

- Single trapped ion optical clock, using Sr^+ with 674 nm clock transition.
- Other options kept open (Yb^+, Ca^+,…) subject to development of laser sources.
- Provides narrow and accurate laser:

Stability: $\sigma_y(\tau) = 1\ 10^{-14} / \sqrt{\tau}$ (τ = integration time in s)

Accuracy: $\delta y \leq 1\ 10^{-17}$ in relative frequency ($y = \delta f/f$)

- Best ground trapped ion optical clocks show $\sigma_y(\tau) = 3\ 10^{-15} / \sqrt{\tau}$ and $\delta y \leq 2\ 10^{-17}$.
- Challenge for SAGAS is not performance but space qualification and reliability.

Courtesy: PTB

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Optical Link

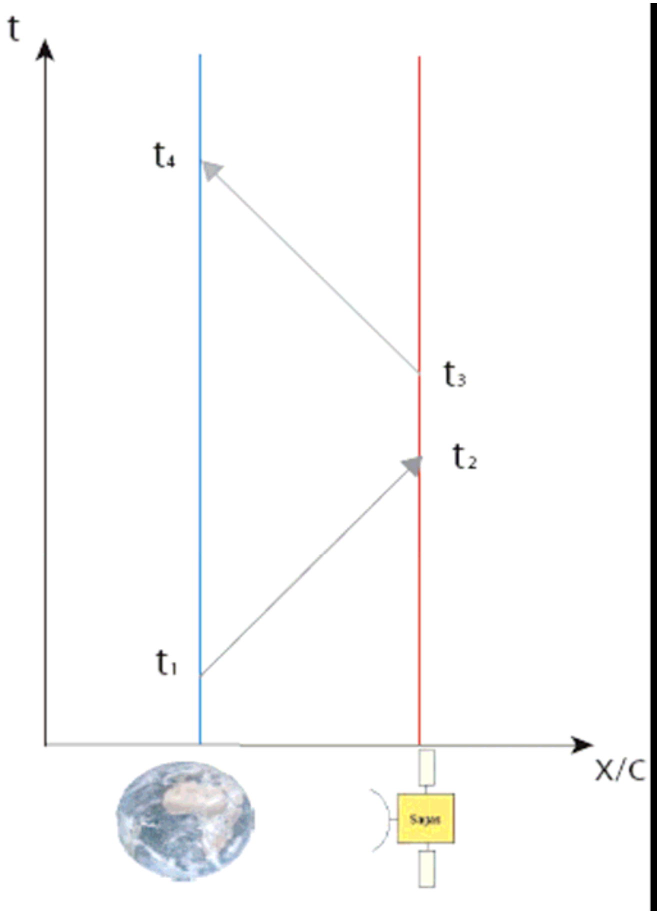
- Independent up and down link.
- Heterodyne frequency measurement with respect to local laser.
- Combine on board and ground measurements (asynchronous) for clock comparison (= difference) or Doppler (= sum).
- 1 W emission, 40 cm telescope on S/C (LISA), 1.5 m on ground (LLR).
- 22000 detected photons/s @ 30 AU. (LLR < 1 photon/s).
- Takes full advantage of available highly stable and accurate clock laser and RF reference.
- Technological challenges are pointing requirements (0.3”) and laser availability and reliability (1 W @ 674 nm).

- Pointing and signal acquisition is based on COROT performance (0.5”) ensuring initial acquisition using the Earth’s image as a target.
- Two-way asynchronous laser link to MESSENGER spacecraft (0.16 AU, Mercury mission) achieved in 2005 [Science 2006].
- Presently available “off the shelf” diode lasers + amplifiers provide 250 – 300 mW @ 674 nm, but upgrades expected.
- Alternative is on-board femtosecond frequency comb ⇒ 1064 nm link, for which space qualified lasers exist.

Measurements and Optimisation

(c.f. Reynaud, Lamine, Jaekel, Duchayne, Wolf, PRD 2008 and arXiv:0801.2896)

- Asynchronous two way link, i.e. independent up and down.
- Measure continuously incoming laser frequency with respect to local laser frequency.
- Combine S/C and ground measurements in post treatment, i.e. choose freely t_2 and t_4.
- Many noise sources on “up” and “down” link are correlated (clocks, S/C and Earth motion, atmosphere, etc…).
- Signal (e.g. Shapiro, GW, planetary gravity, …) affects “up” and “down” link differently ⇒ choose data combination to optimise signal to noise.



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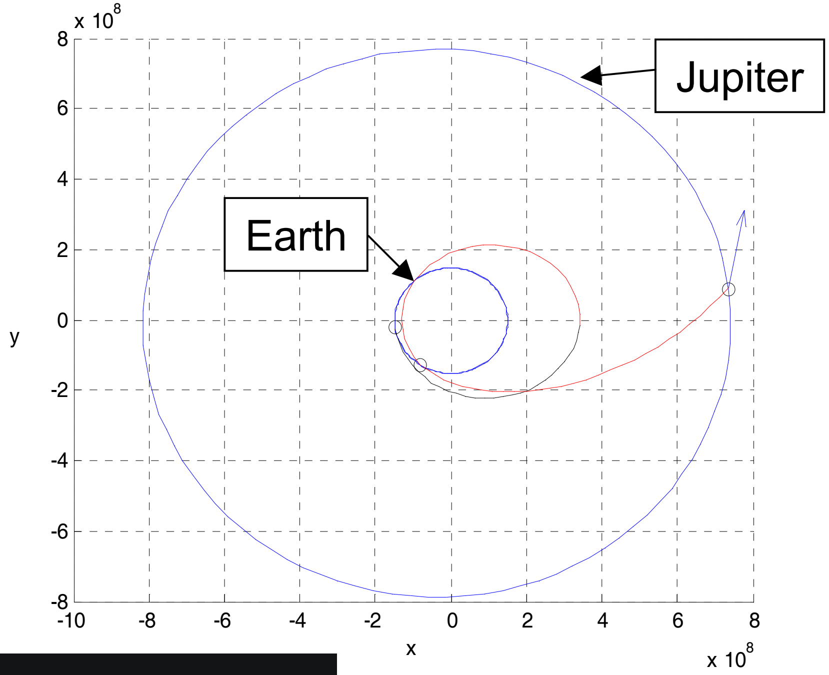
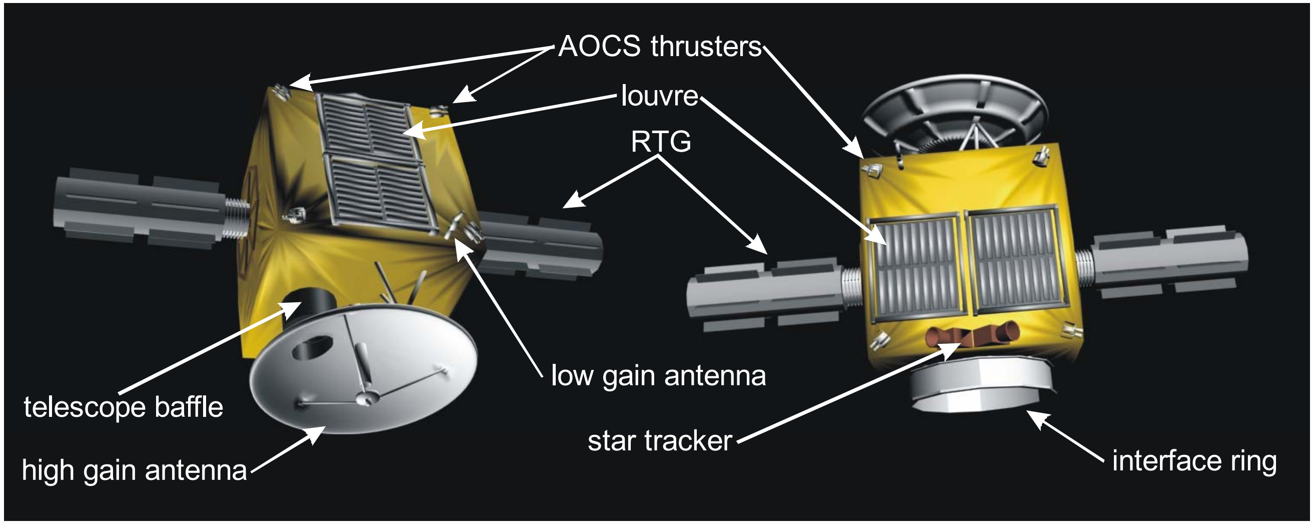
Trajectory and Spacecraft

- Present baseline: Ariane 5 ECA + propulsion module; ΔV-EGA + Jupiter GA @ 22.6 km/s 3 years after launch.
- 39 AU after 15 yrs (nominal), 53 AU after 20 yrs (extended).
- Can be shortened (- 2 yrs) by using larger launcher (Ariane 5 ECB, Atlas 5, Delta IV).
- Total: 950 kg, 390 W (incl. 20% margin).





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Conclusion

SAGAS offers a unique possibility for a mission combining attractive objectives in fundamental physics and solar system exploration.

- **Potential for a major discovery in fundamental physics and major contribution to constraining theoretical models.**
- Kuiper Belt (KB) potentially holds clues for planetary formation processes, and gives rise to fundamental questions (mass deficit?).
- **Contribution to the understanding of planetary formation in the solar system, with potential for new discoveries (KB mass, new KBOs).**

- Onboard clock with asynchronous two-way link allows for large versatility in data analysis

⇒ possibility to optimize S/N for given science objective.