Gravity gradiometry for fundamental physics, planetary science and Earth observation -- Heritage from LISA Pathfinder

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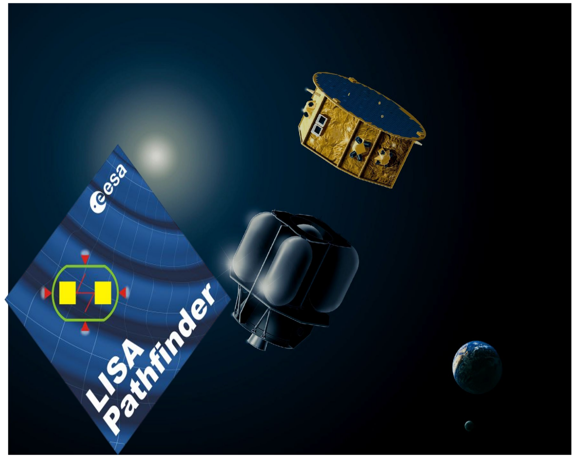
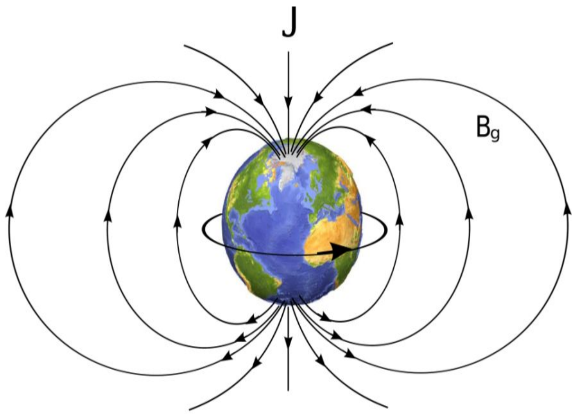
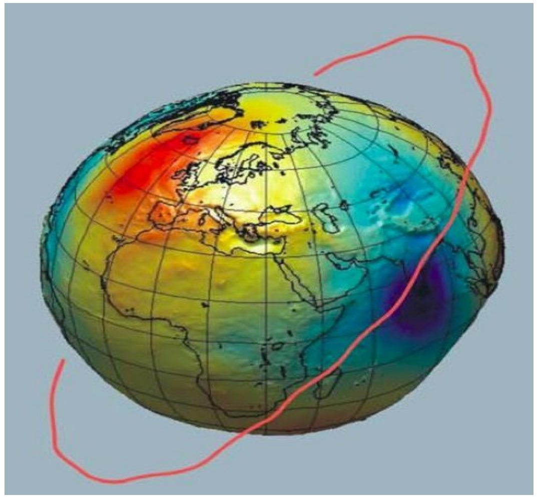
On behalf of the eLISA and CAS GW consortium







The team

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Ongoing Collaboration since 2006
between eLISA consortium and CAS GW consortium

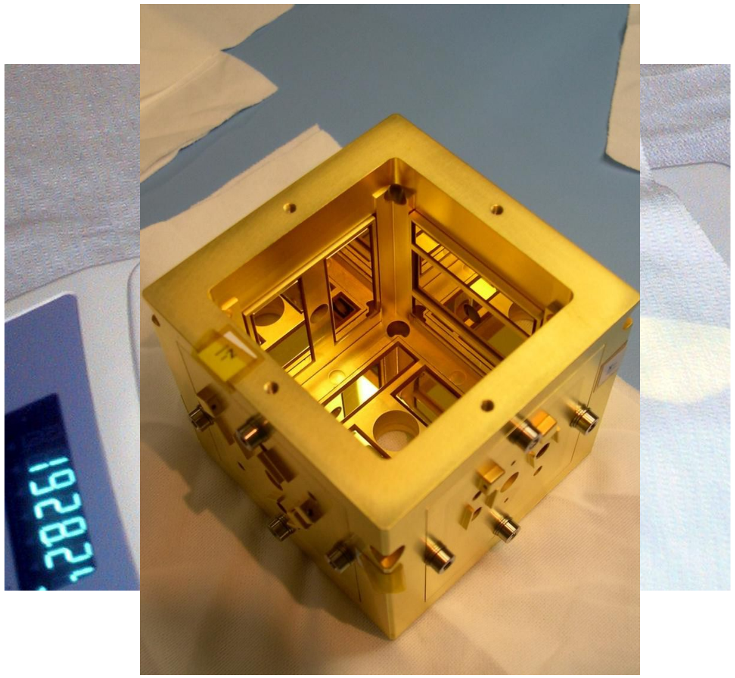
- Accelerometer and weak force measurement development at Wuhan and Trento
- Interferometry and phase measurement developments in Beijing (CAS) and Wuhan collaborating with AEI Hannover
- Joint studies of laser interferometry for gravitational wave detection (LISA) and satellite geodesy
- Joint training of graduate students:
  First graduation at Hannover in April 2014.
- China - Germany exchange jointly funded by DFG and NSFC
  (~15 visits each from both sides only in this program)

Realising free falling test particles in space

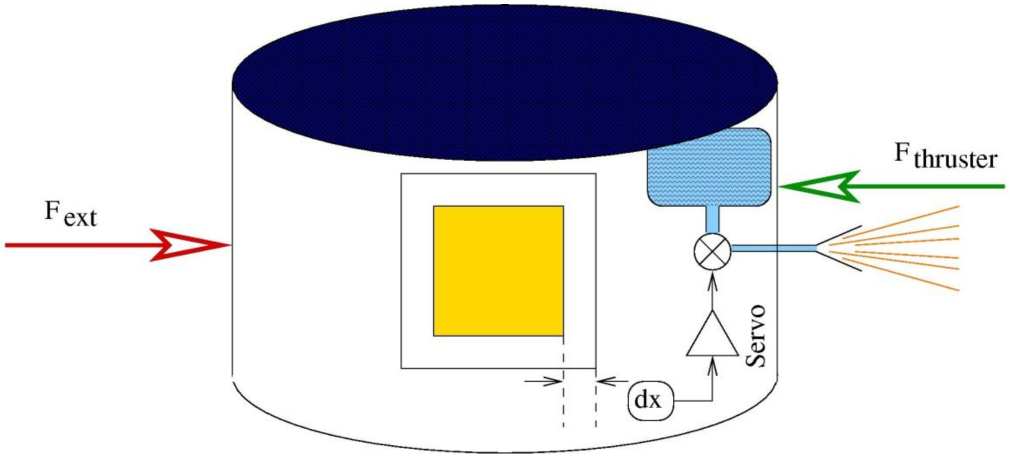
Free falling particle--

- a particle subject only to gravitational force
- pairs of such "geodesic references" can detect tidal acceleration from gravity gradients of planets, gravitational waves, GR effects

- Test masses also used as mirror
- Even in space there are many disturbances: Magnetic fields, solar wind, radiation, ...
- The spacecraft shields the TM
- Distance between TM and S/C must be measured and controlled

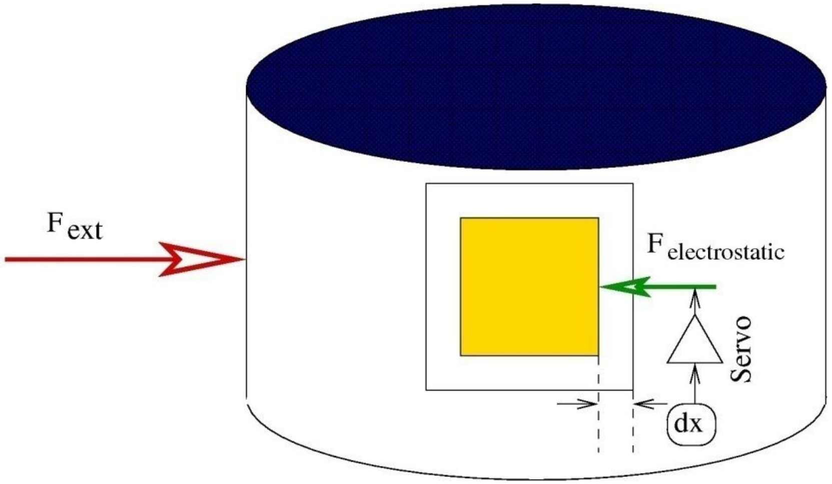


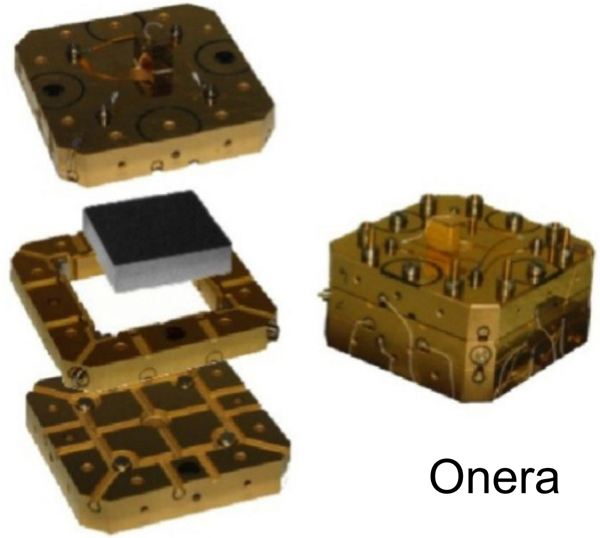
Drag-Free Control



- Separation S/C – TM is monitored with capacitive sensor or laser interferometer
- The S/C follows the test mass by actuating thrusters and torquers
- Problems: many degrees of freedom, complicated dynamics, noise
- Has been realized already, e.g. in GOCE
- Yields optimal disturbance suppression at TM

Accelerometry



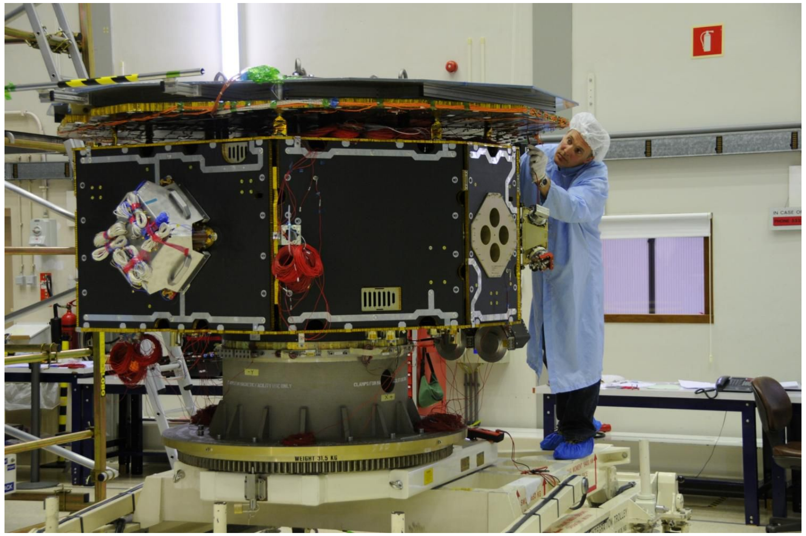


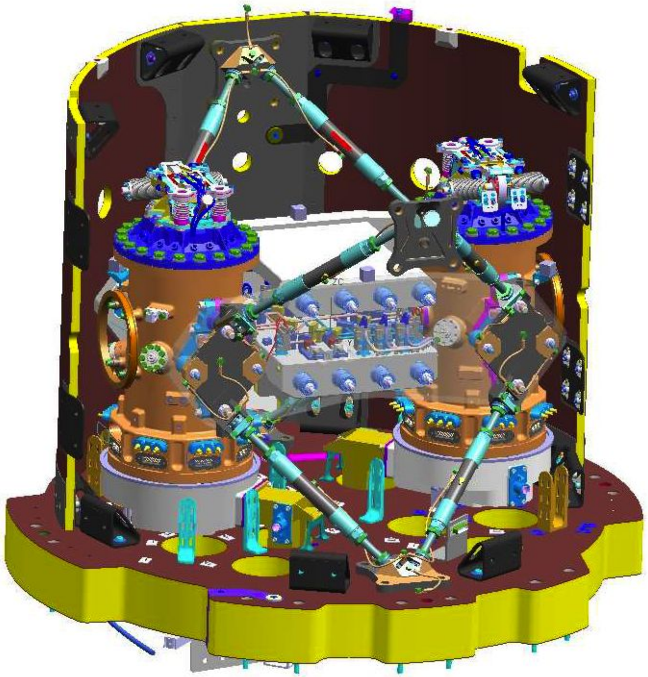
Onera

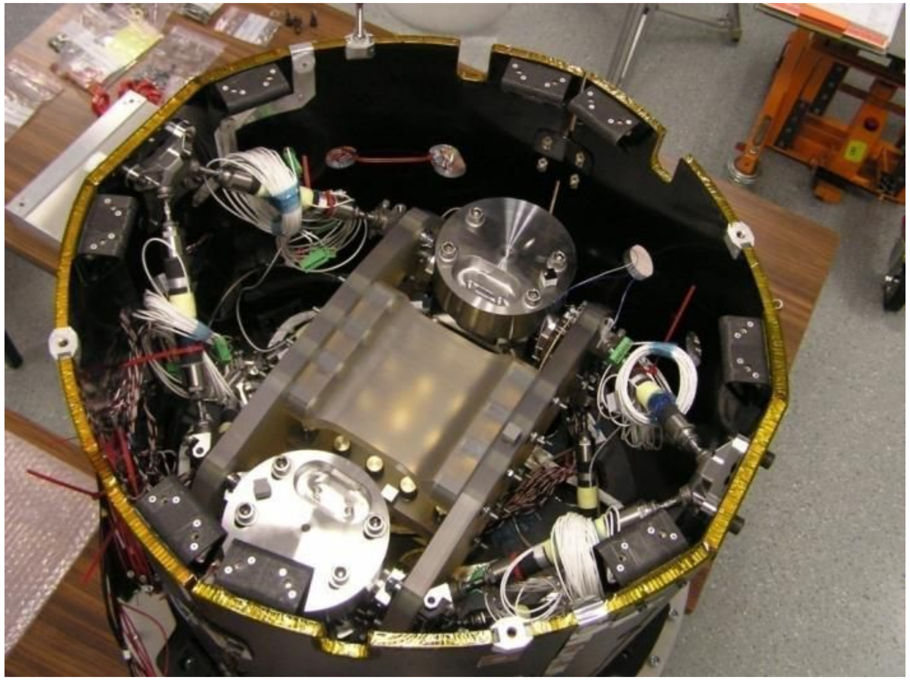
- Separation S/C – TM is monitored with capacitive sensor or laser interferometer
- The test mass is pushed back to the center of the housing by electrostatic forces
- The necessary feedback force is recorded and represents the non-gravitational force, which can be subtracted in data processing
- Simpler than drag free but less disturbance reduction at the test mass

LISA Pathfinder

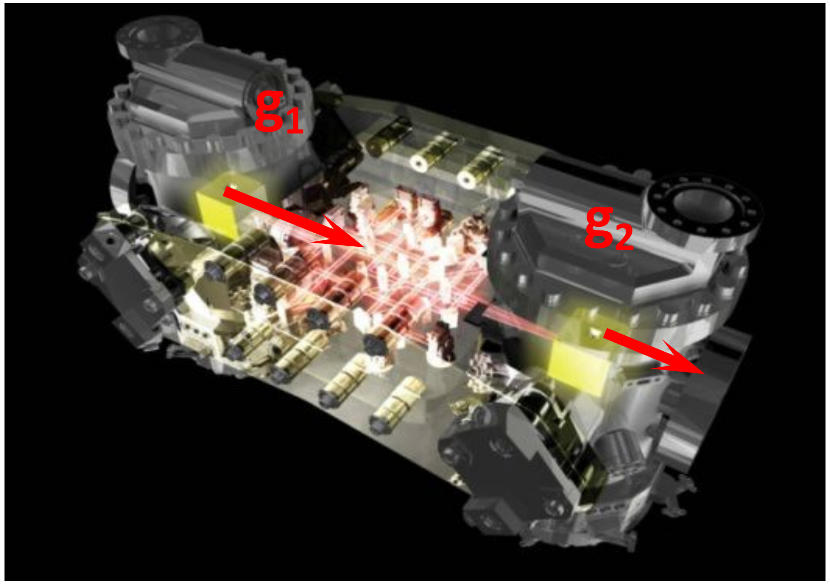
- Technology demonstrator for gravitational wave missions LISA/eLISA/NGO (ESA L3 theme)
- Launch 2015 with VEGA from Kourou







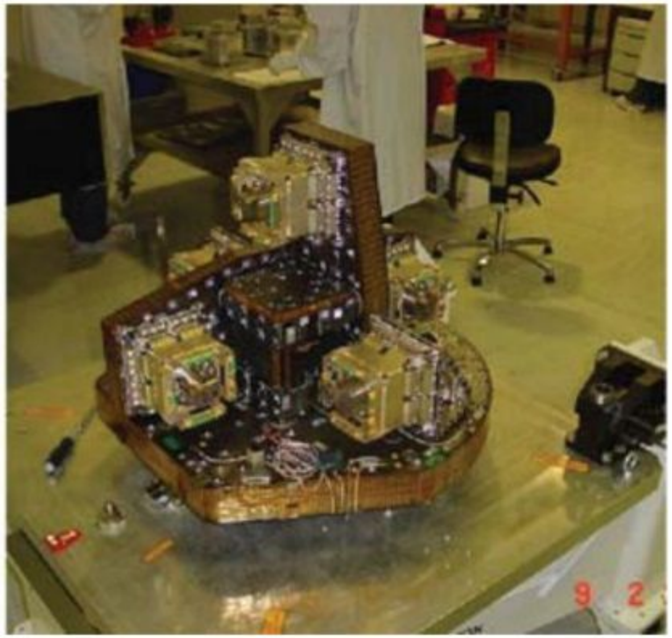
LISA Pathfinder: Einstein's Geodesic Explorer (2015)



- Compress single eLISA arm to 40 cm inside 1 spacecraft
- Drag-free following TM1, low-frequency suspension of TM2
- Measure differential TM acceleration
- Laser interferometric sensing (10 pm/√Hz) along sensitive axis
- Modest capacitive sensing (3 nm/√Hz) in other axes
- **One-axis gravity gradiometer with 10 fm s^{-2}/√Hz resolution at 1 mHz**

Gravity gradiometry

- Pioneered by GOCE (2009-2013), using electrostatic gradiometer by ONERA
- Orders of magnitude improvement possible with LISA Pathfinder Interferometer and GRS hardware (in quiet orbit)



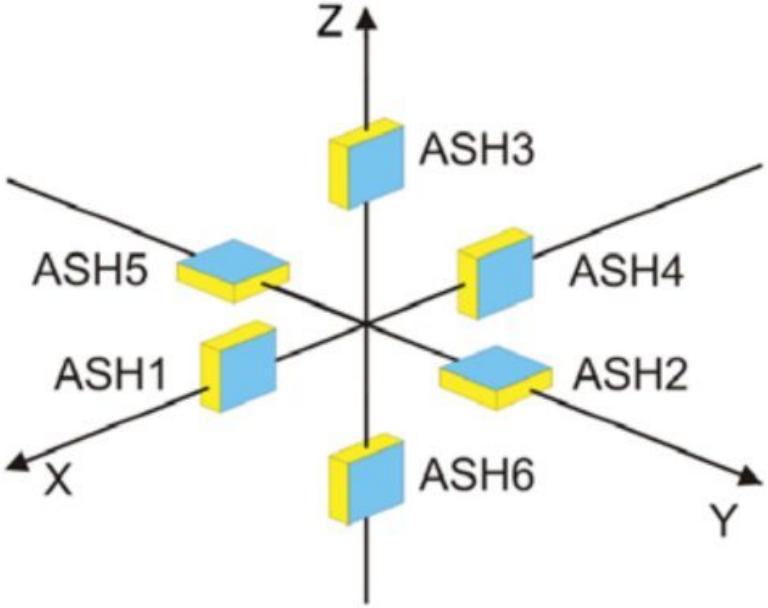
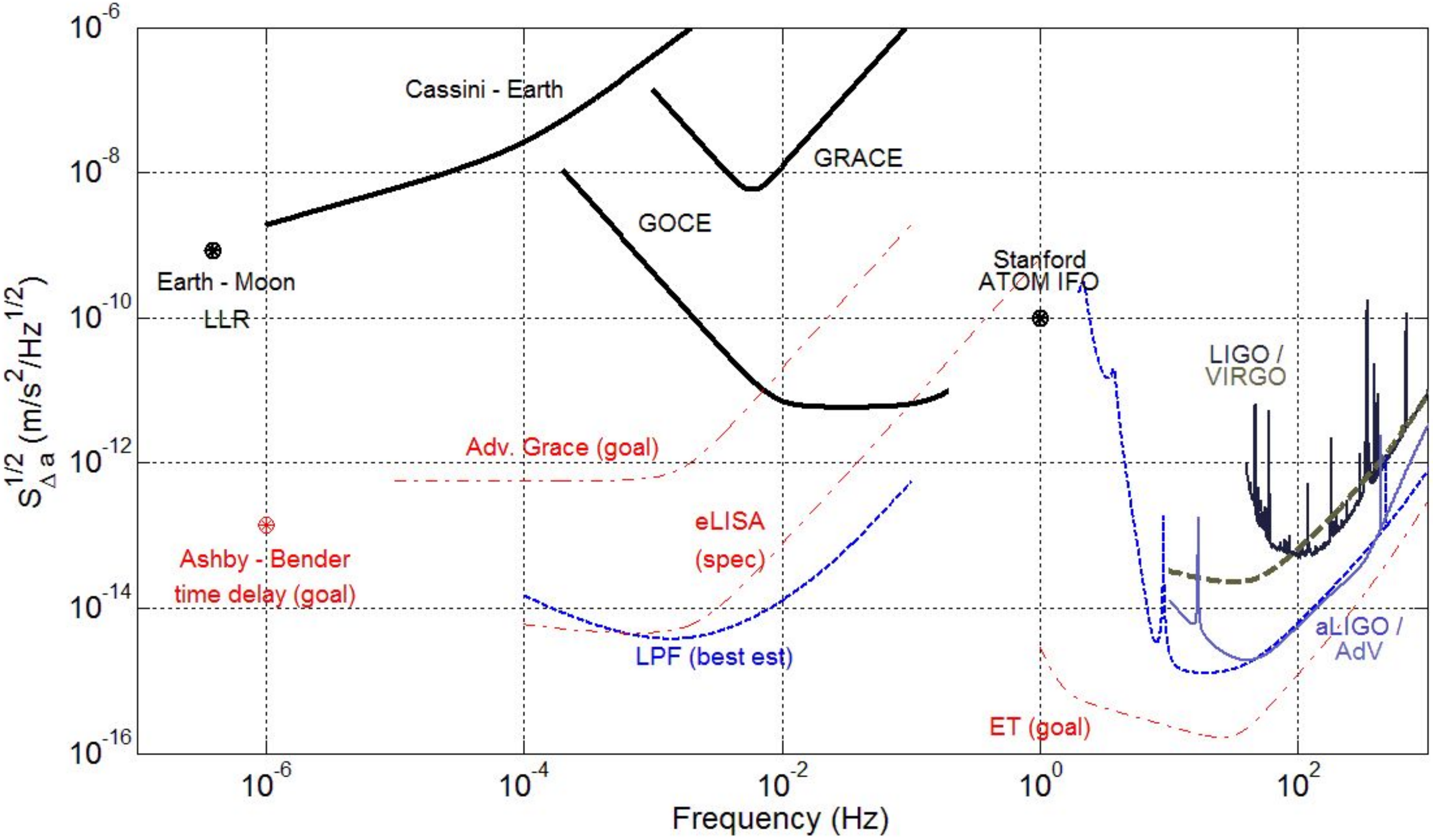


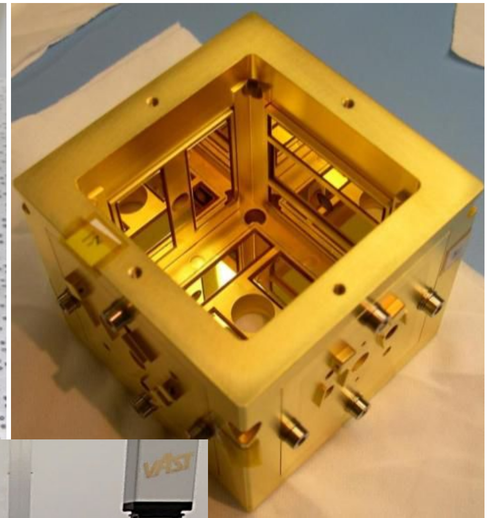
Image credit: ESA

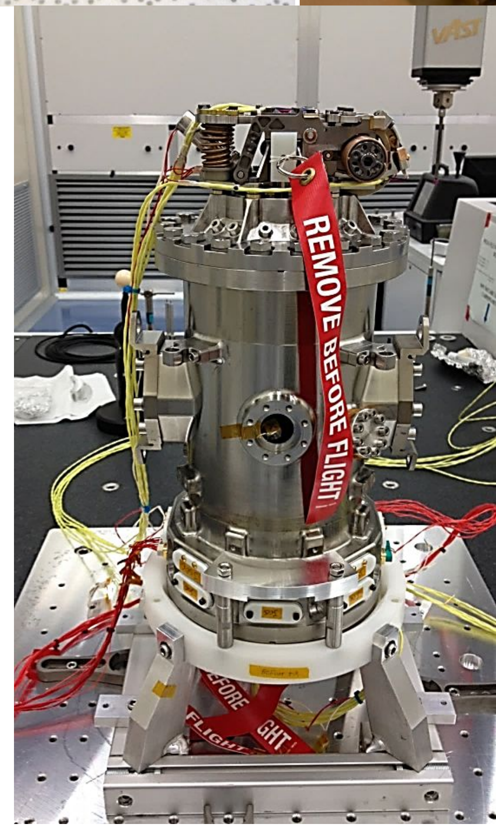
LPF /eLISA GRS in experimental gravitation

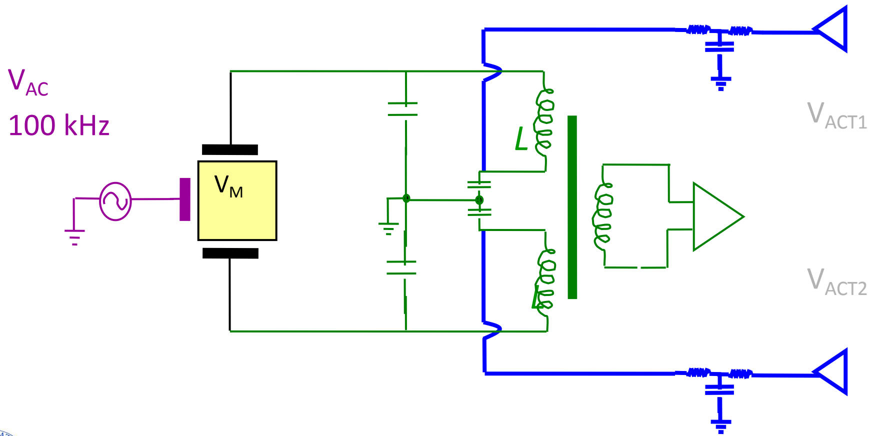


GRS innovations for sub-femto-g/Hz$^{1/2}$ free-fall:

- Heavy Au/Pt test mass
- Large (3-4 mm) gaps
- No discharge wire and contact free injection
- Charge control with UV light
- Audio carrier frequency for «DC» actuation forces

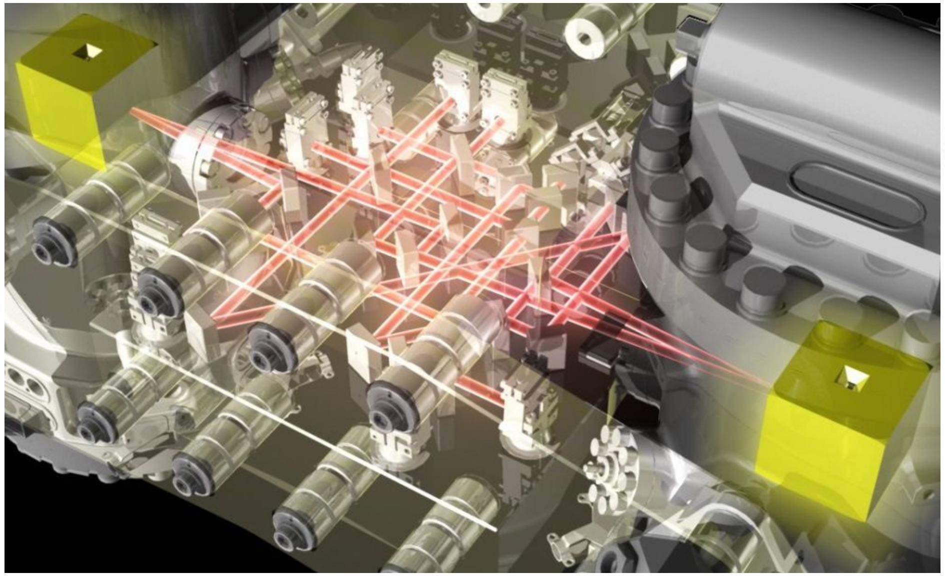


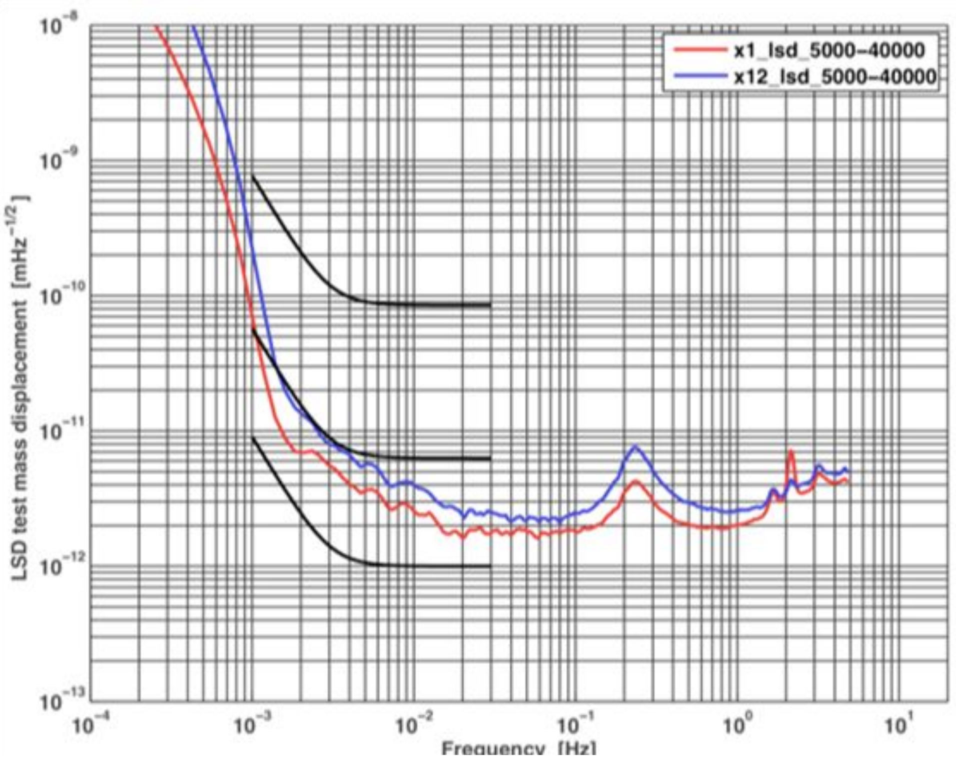




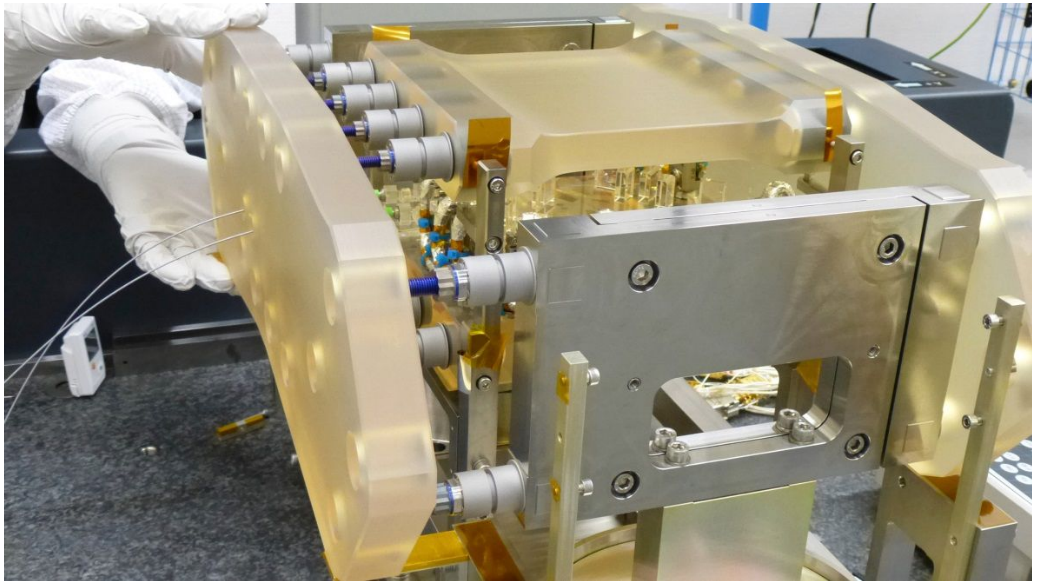
Laser interferometry in LISA Pathfinder

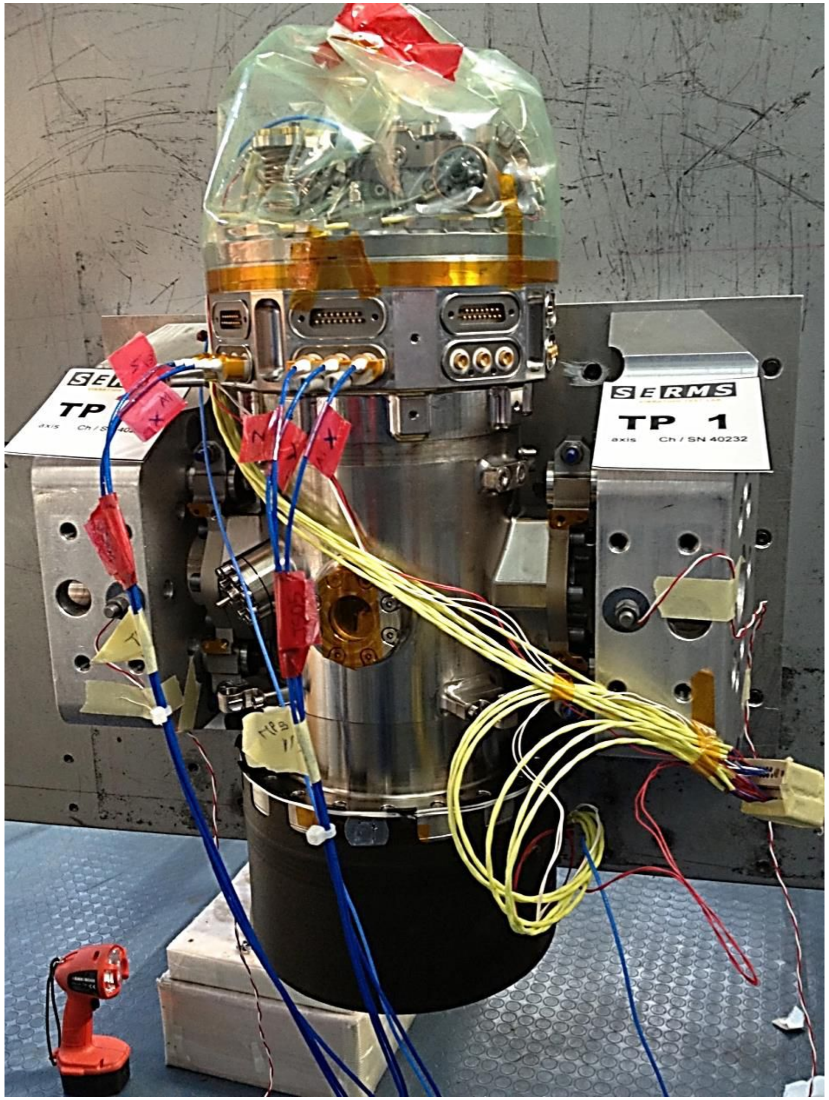
- Heterodyne interferometer using a single laser, kHz heterodyne frequencies, and digital phasemeter
- Measures TM relative motion to pm/√Hz
- Measures TM angles to nrad/√Hz
- Frequency range mHz to Hz
- FM built and tested





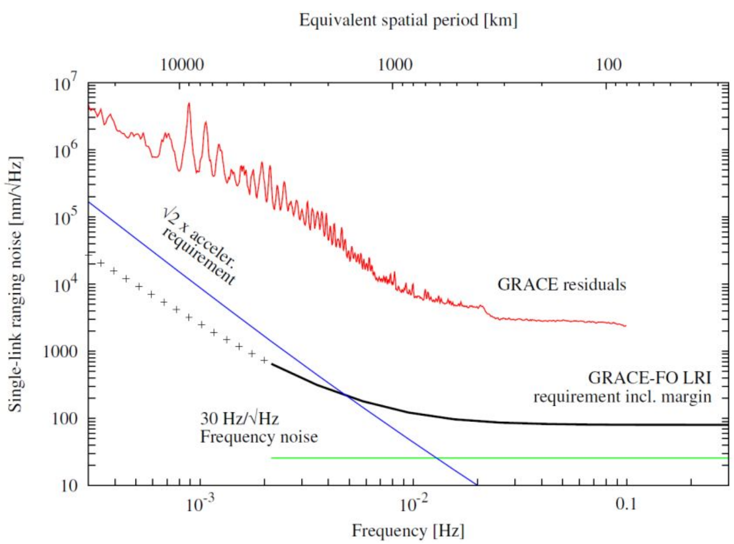
LPF Flight Model Units

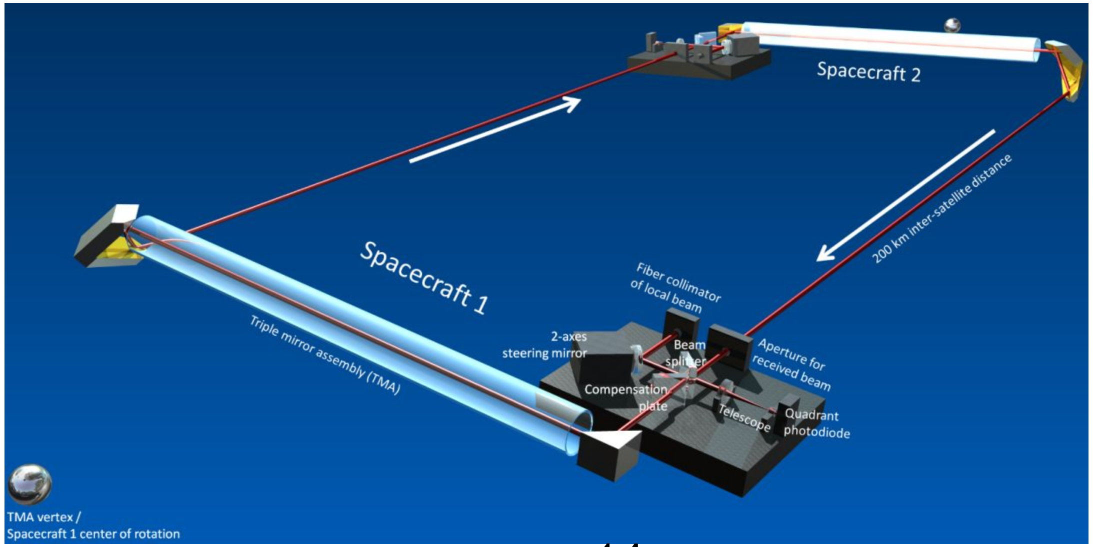




Laser Ranging Interferometer (LRI) on GRACE Follow-On

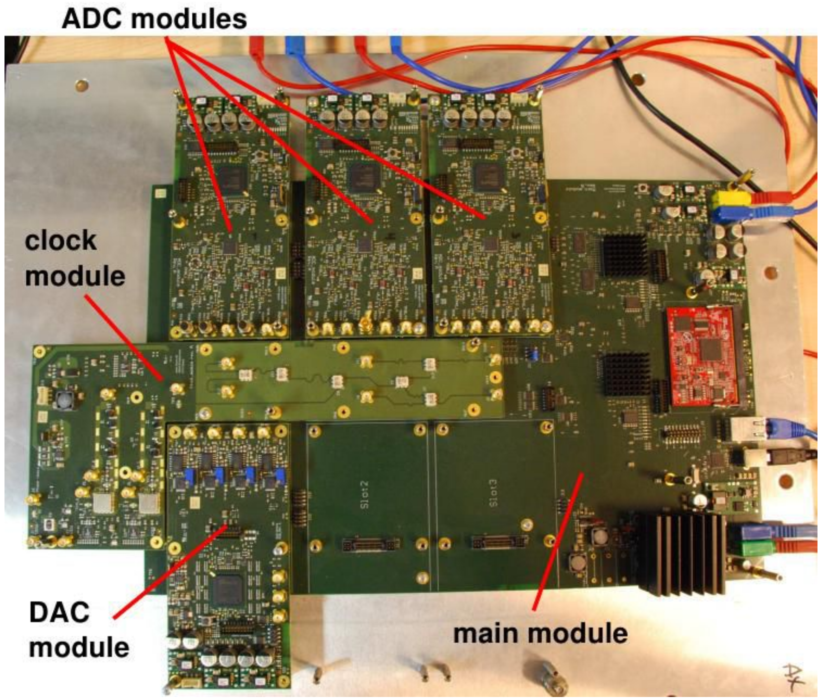
- US-German collaboration, launch in 2017,
- Interferometry design and breadboarding from AEI Hannover,
- First interspacecraft laser interferometer, designed as experimental demonstrator,
  complimentary to traditional µ-Wave ranging system,
- LRI CDR successfully passed in May 2014.

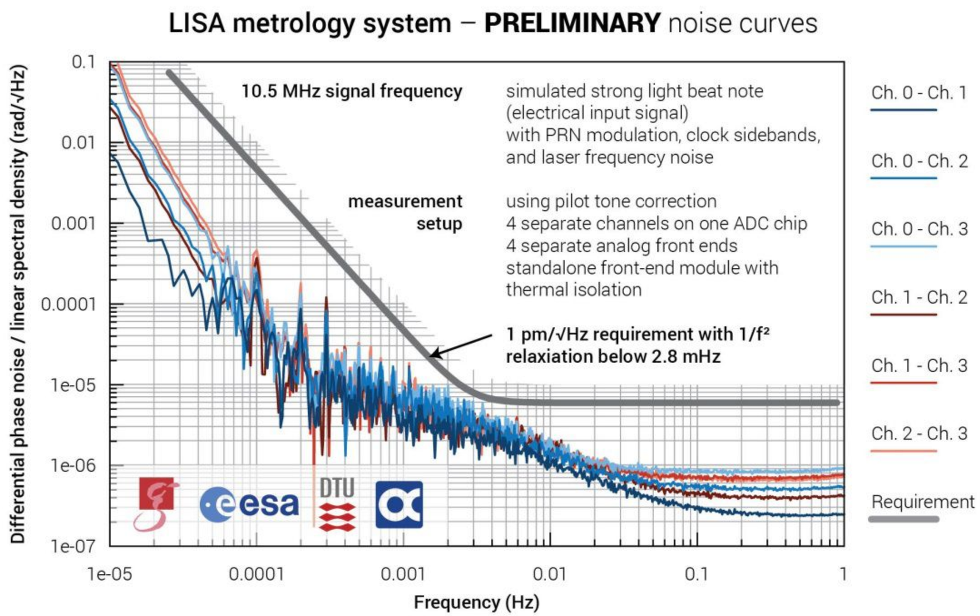




Phase measurement system for intersatellite ranging

- LRI on GRACE Follow-on will use NASA/JPL phasemeter
- ESA development of LISA phasemeter completed (Danish-German consortium, AEI technical lead)
- Fulfills all LISA requirements which are harder then LRI (µrad carrier phase=pm, absolute ranging, data transfer)





Key Technologies availability

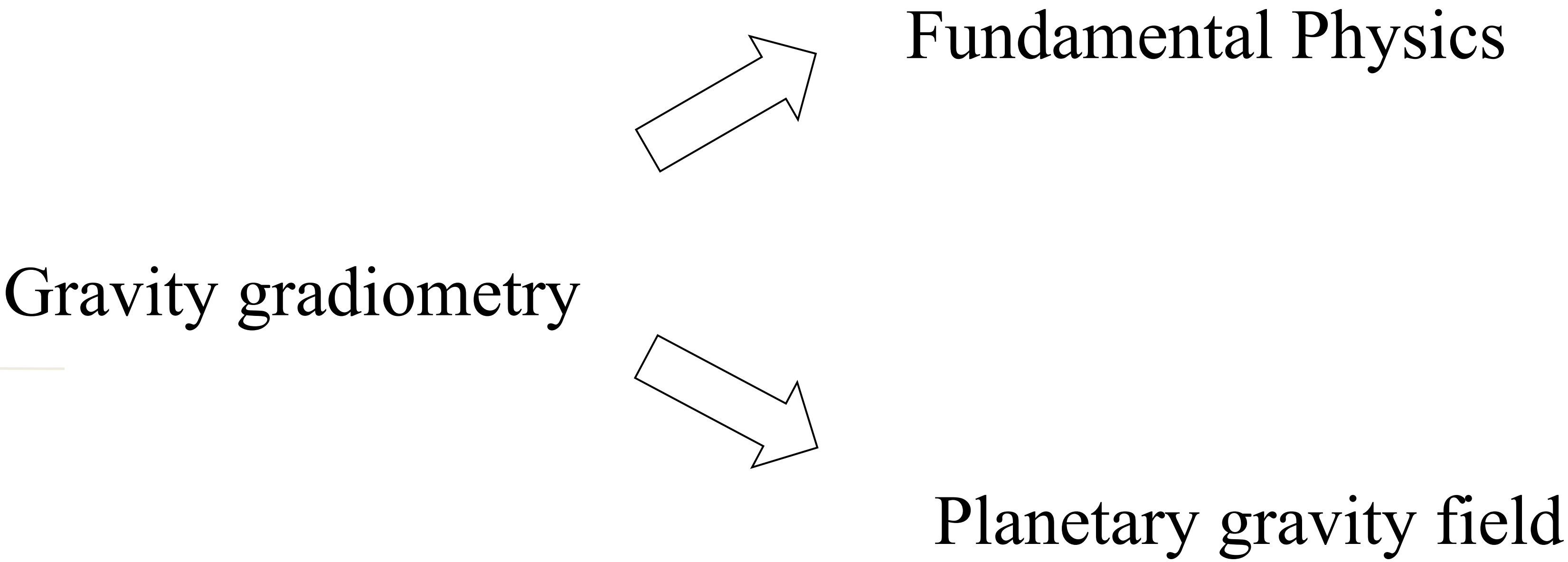
<u>eLISA consortium</u>

- Gravitational Reference Sensor and drag-free control
  (LISA Pathfinder – needs to be adapted)
- Laser interferometry in space
  (development completed for LPF and GRACE Follow-On, detailed LISA studies)
- Phasemeter
  (LPF is ready and to be flown in 2015, LISA at TRL 4)
- Laser
  (TRL 9, ready to fly)

<u>CAS GW consortium</u>

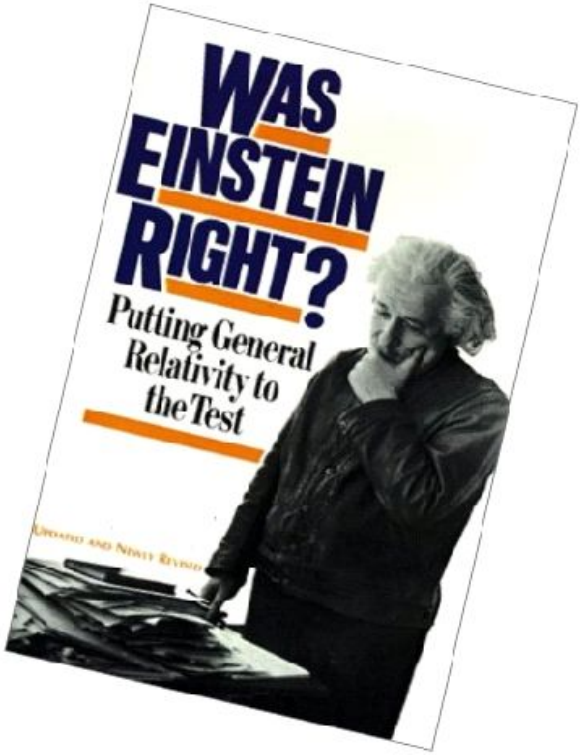
- Accelerometer
  (for geodesy missions)
- Micro-Newton ion thrusters
  (just started)
- Optics in space:
  laser interferometry (100pm/√Hz),
- Phasemeter (prototype development just completed)
- Laser frequency stability
  (just started)

Important parts are all there, lots of options for splitting


Fundamental Physics
Gravity gradiometry
Planetary gravity field

Experimental test of general relativity

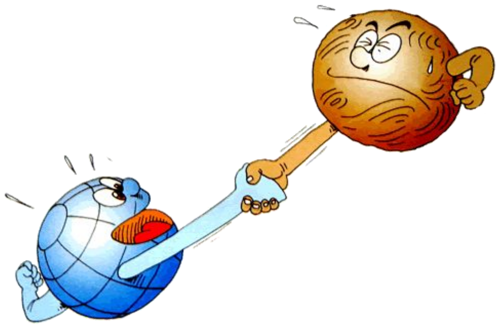
- Mercury perihelion
- Shapiro time delay
- Precision measurement of PPN parameters in solar system
- Tests of equivalence principle
- ....

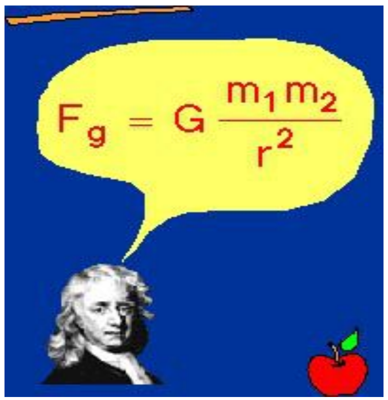


- **Outstanding tests in 21st century**
- Gravitational wave detection ---
- galactic and cosmological scale (eLISA, CAS project).
- **Gravitomagnetic field detection** (e.g. Lens Thirring effect)---
- test on the planetary and solar system scale.

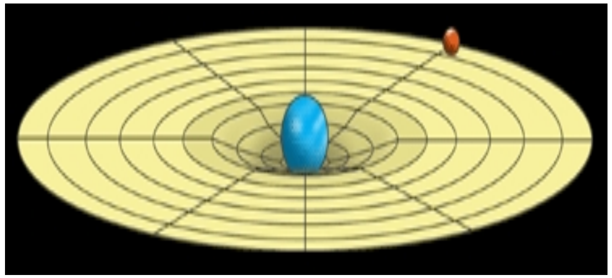
General Relativity —a generalisation of Newtonian theory of gravity

classical mechanics





general relativity



geometry of spacetime

≈universal gravitation

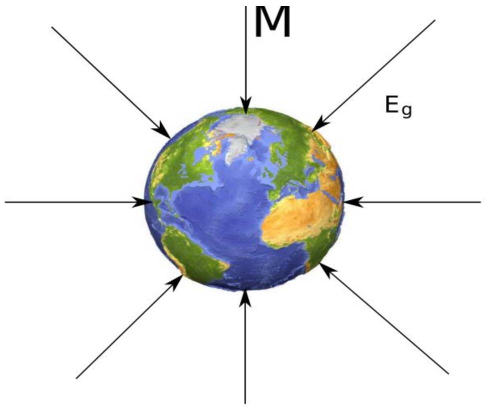
$$g_{ab} = \begin{pmatrix} + & & & \\ & - & & \\ & & - & \\ & & & - \end{pmatrix}$$

Einstein field equations

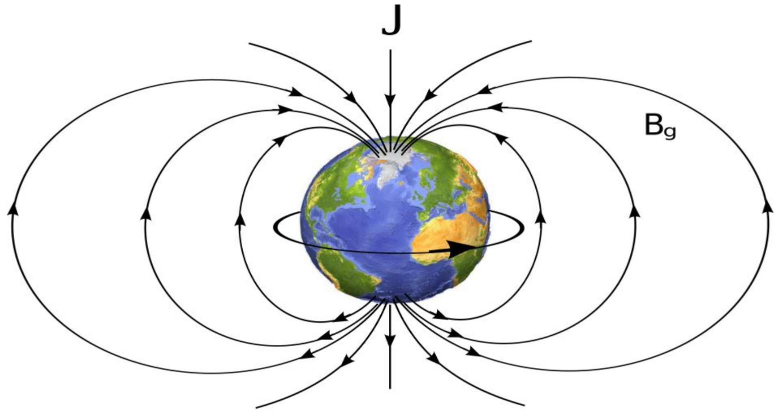
$$R_{ab} - \frac{1}{2}Rg_{ab} = 8\pi T_{ab}$$

Gravitomagnetic field in general relativity

$$\Phi \sim \frac{GM}{r}, \qquad \mathbf{A} \sim \frac{G}{c}\frac{\mathbf{J}\times\mathbf{r}}{r^3}, \qquad \mathbf{E} = -\boldsymbol{\nabla}\Phi - \frac{1}{c}\frac{\partial}{\partial t}\left(\frac{1}{2}\mathbf{A}\right), \qquad \mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A},$$



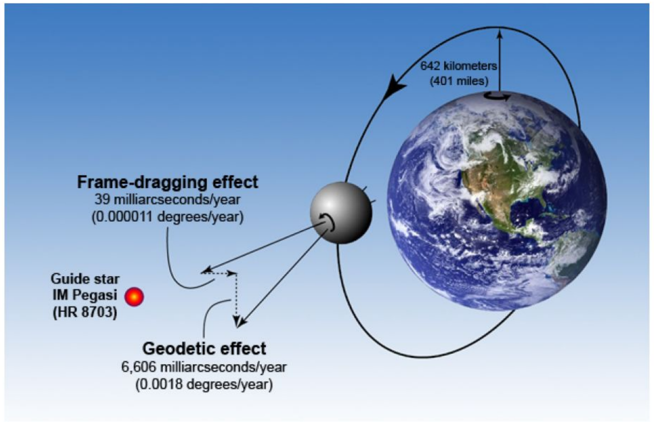
Newtonian gravity field

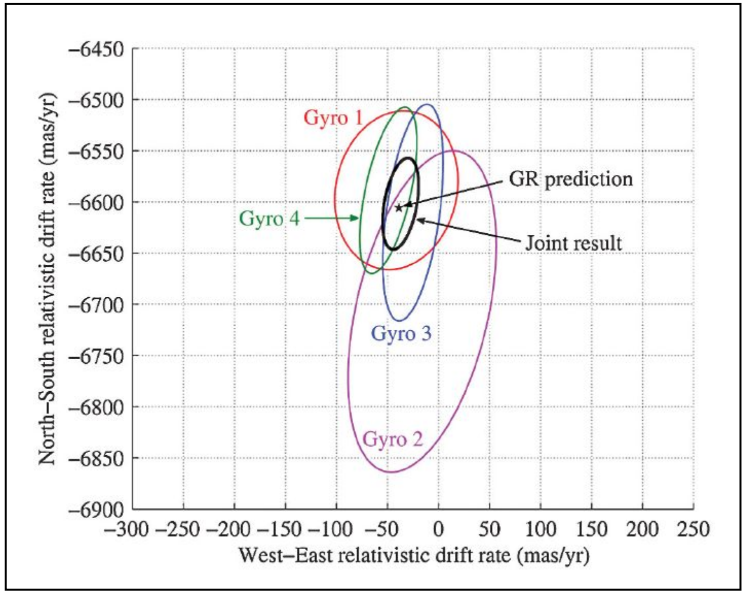


Gravitomagnetic field predicted by Einstein for a spinning body

Einstein field equations ≈ Maxwell equation（1PN）

GPB experiment (1960-2011)





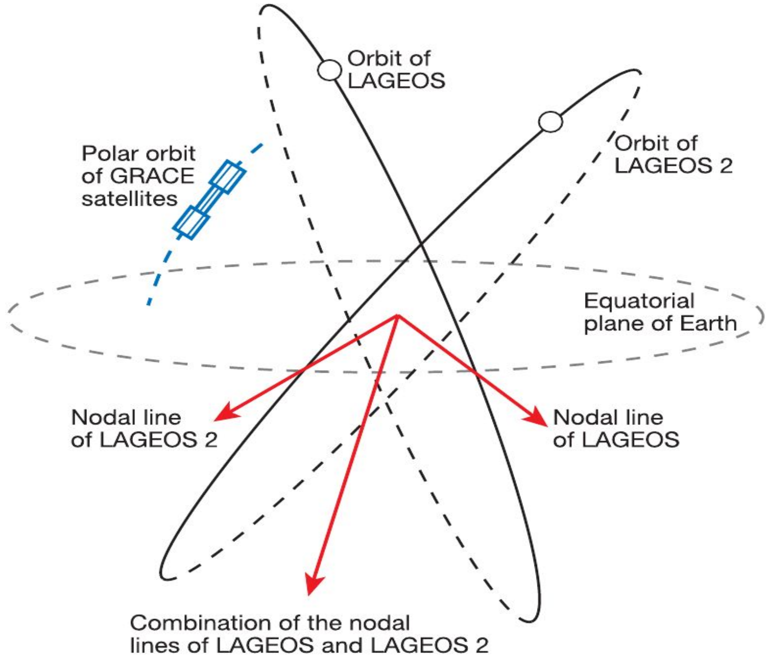
Gravity Probe B – Final Experimental Results		
Gyroscope	$r_{N\text{-}S}$ (Geodetic Measurement)	$r_{W\text{-}E}$ (Frame-Dragging Measurement)
Individual Gyroscope Results		
Gyroscope #1	-6,588.6±31.7 mas/yr	-41.3±24.6 mas/yr
Gyroscope #2	-6,707.0±64.1 mas/ yr	-16.1±29.7 mas/yr
Gyroscope #3	-6,610.5±43.2 mas/yr	-25.0±12.1 mas/yr
Gyroscope #4	-6,588.7±33.2 mas/yr	-49.3±11.4 mas/yr
Weighted-Average Results for All Four Gyroscopes		
All Gyroscopes	-6,601.8±18.3 mas/yr	-37.2±7.2 mas/yr (～19% error)
Schiff-Einstein Predicted Theoretical Values		
Theoretical Gyroscope	-6,606.1 mas/yr	-39.2 mas/yr

The LAGEOS I and II and LARES Missions (2013-)

Measurement in terms of Keplerian elements of spacecrafts

Highly depend on the detailed knowledge of Earth gravity field.

The Gravitomagnetic effect is now confirmed with 10% accuracy, subject to earth gravity field modelling+ non-gravitational force error. .



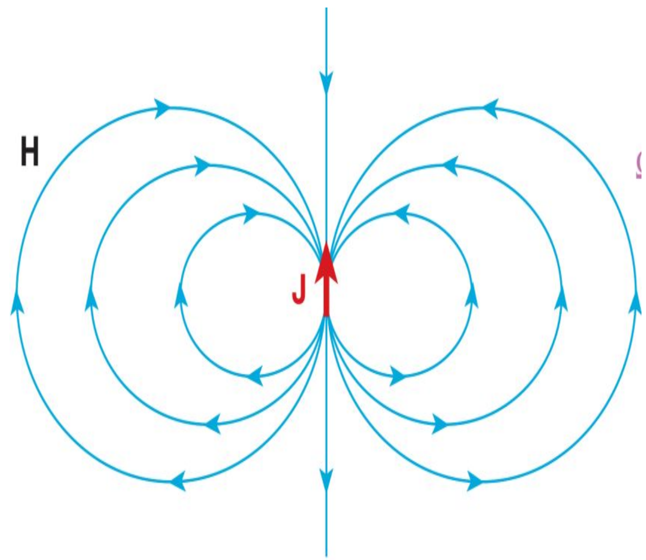
Other controversial claims of detection:
Lunar Laser ranging, Mars orbiter....

Why the interest? 

- Poorly tested, still remain major challenge in experimental relativity

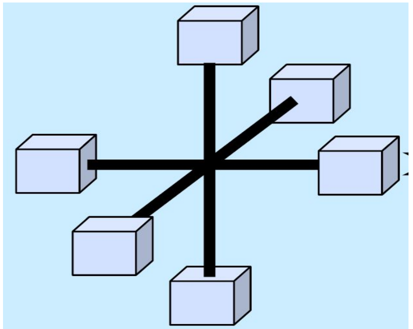
- Impose constraints in post newtonian limit of geometric gravity theories. Provide stringent tests on low energy effective theory coming from string theory and loop quantum gravity.

- Applications in future space science such as ClockSync in space and etc....



Gradiometric measurement of gravitomagnetic field

Braginsky, Polnarev(1981), Mashhoon, Paik, Will (1989) and others



3 axis gradiometer

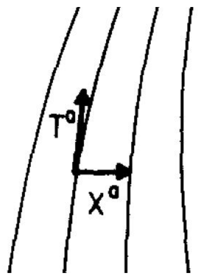
readout →

$$\begin{pmatrix} \frac{\partial^2 V}{\partial x^2} & \frac{\partial^2 V}{\partial x \partial y} & \frac{\partial^2 V}{\partial x \partial z} \\ \frac{\partial^2 V}{\partial y \partial x} & \frac{\partial^2 V}{\partial y^2} & \frac{\partial^2 V}{\partial y \partial z} \\ \frac{\partial^2 V}{\partial z \partial x} & \frac{\partial^2 V}{\partial z \partial y} & \frac{\partial^2 V}{\partial z^2} \end{pmatrix}$$

force gradient tensor

Geodesic deviation (Jacobi) equation

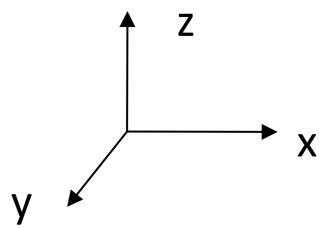
$$\frac{D^2 X^a}{D\tau^2} = -R_{bcd}{}^a T^b T^d X^a$$



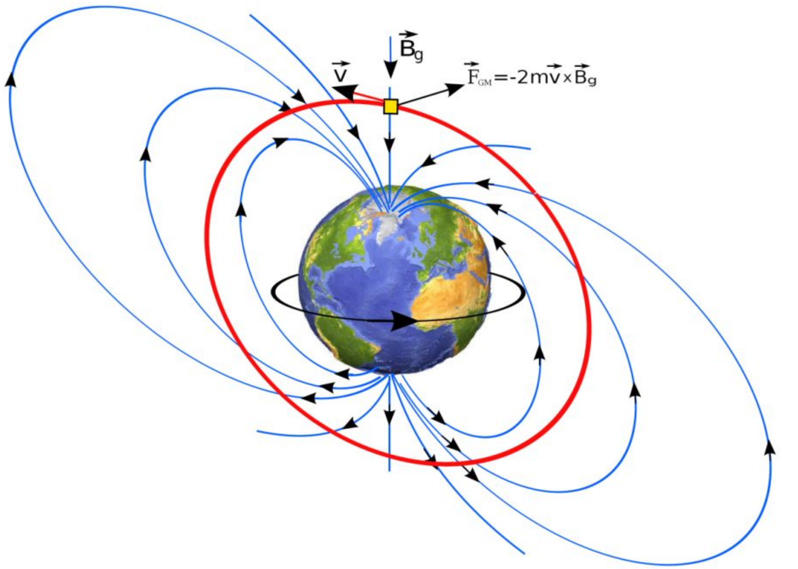
Analytic solution of the geodesic deviation equation at the 1PN level

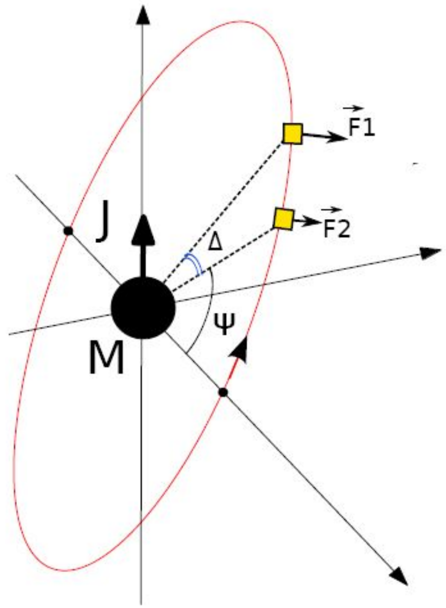
$$x(\tau) \approx \frac{(1+\gamma+\frac{1}{4}\alpha_1) J d \sin I \sin(\omega\tau)}{r^3}\tau,$$

$y(\tau), z(\tau) << x(\tau)$



Lorentz force of gravitomagnetic field





$$\vec{F} = 2m\vec{v} \times \vec{B}_g$$

$$|\vec{F}| = 2m|\vec{v}||\vec{B}_g| \cos\Psi$$

$$|\vec{F}_1 - \vec{F}_2| \sim 2m|\vec{v}||\vec{B}_g|(\sin\Psi)\Delta$$

The Mission Idea for Gravitomagnetic Effects

- Near polar orbits.

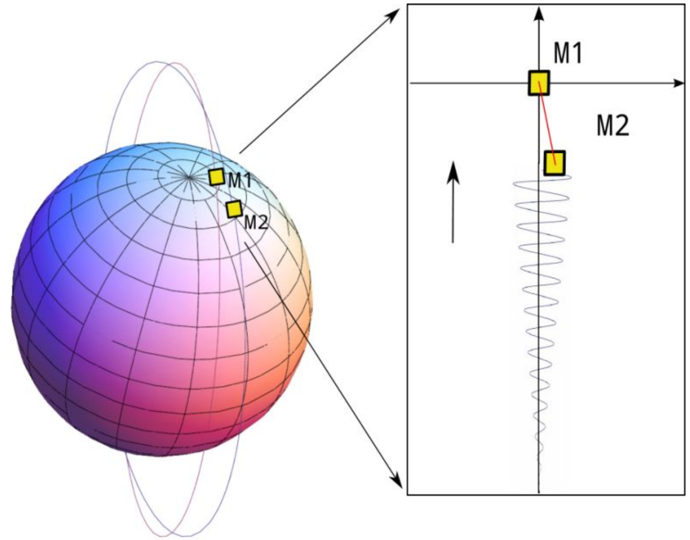
To increase the GM signal while suppress the noises from gravitoelectric field.

- Altitude options: 3000km to 6000km (even to 10000km).

Higher altitude will suppress the noises from higher order gravity multipoles.

- Eccentric orbits.

Distinguish gravitomagnetic field signal from J_2 signal of earth gravity



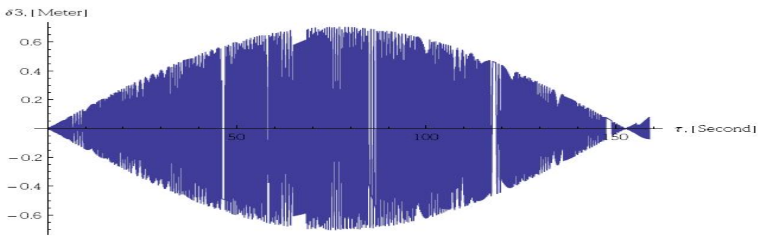
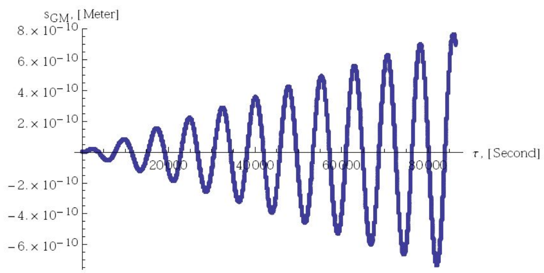


Figure 8: The full period of the relative motions between the two orbiting masses along the transverse measurement direction. The orbit is set to be nearly circular polar orbit with semi-major $a = 800m$. The separation d between the two masses is about $70cm$.



(a) The GM signal along the fixed transverse direction.

The scientific objectives of a possible gravitomagnetism mission

- Direct, precision measurement of earth's gravitomagnetic field predicted by Einstein's theory of general relativity .
- Improve the accuracy in the measurement of some post-Newtonian parameters in our solar system.
- New tests and constraints on alternative theories of gravity,
- low energy effective theory related to string theory and quantum gravity.

Precision measurement of PPN parameter

Parameter	Effect	Limit	Remarks
$\gamma - 1$	(i) Time delay	2.3×10^{-5}	Cassini tracking
	(ii) Light deflection	4×10^{-4}	VLBI
$\beta - 1$	(i) Perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	(ii) Nordtvedt effect	2.3×10^{-4}	$\eta = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	Gravimeter data
α_1	Orbital polarization	10^{-4}	Lunar laser ranging
			PSR J2317 + 1439
α_2	Solar spin precession	4×10^{-7}	Alignment of Sun and ecliptic
α_3	Pulsar acceleration	2×10^{-20}	Pulsar $\dot{P}$ statistics
η^{a}	Nordtvedt effect	9×10^{-4}	Lunar laser ranging
ζ_1	–	2×10^{-2}	Combined PPN bounds
ζ_2	Binary motion	4×10^{-5}	$\ddot{P}_p$ for PSR 1913 + 16
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration
ζ_4	–	–	Not independent

(Will, Theory and experiiments in general relativity)

- Improve the accuracy in the measurement of α_1 to 10^{-5}!
- α_1--- a measure of local Lorentz invariance of gravity theories.
- A test of quantum gravity violation of Loretnz invariance!

Possible Tests and Constraints for the Predictions from Quantum Gravity

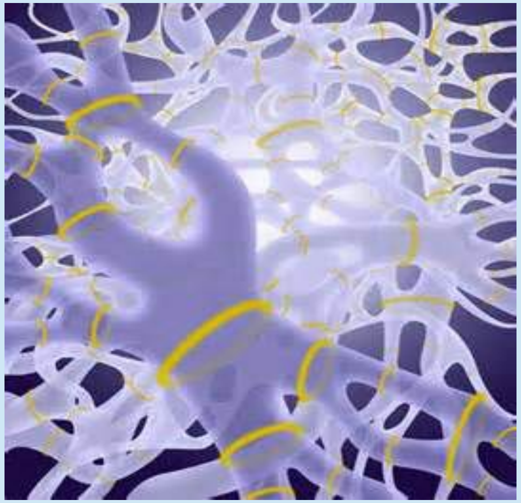
Chern-Simons modified gravity serves as a representative phenomenological model predicted by string theory and loop quantum gravity

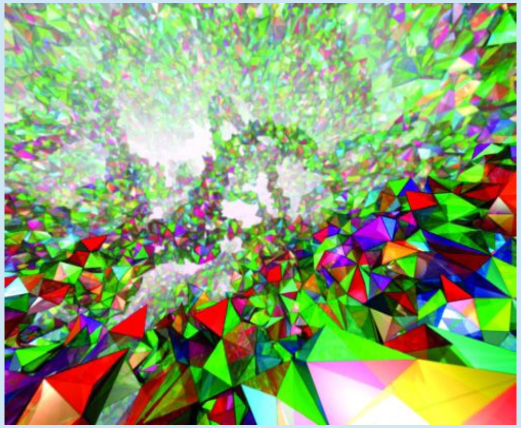
$$S_{CS} = \frac{1}{16\pi G}\int d^4x \frac{1}{4} f R^{\star} R,$$

A characteristic and rather large signal in the in-line direction in our experiment.

$$-\frac{dJ\chi \sin I(\tau\omega \sin(\tau\omega) + \cos(\tau\omega))}{2r^3\omega}$$

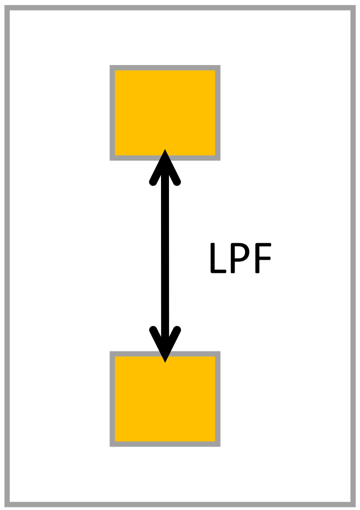
The dimensionless parameter $\chi = 2\frac{\dot{f}}{r}$ describes the magnitude of the Chern-Simons action, which can be precisely measured or constrained to 10^{-15} *!*

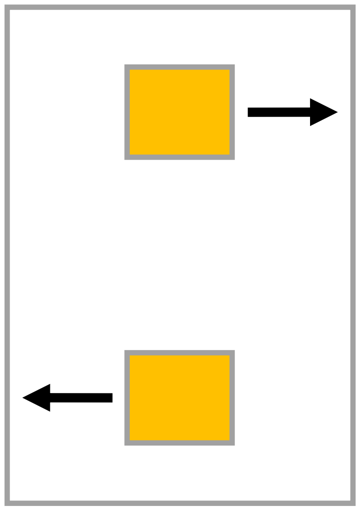




Technical Challenges of Gravitomagnetism mission

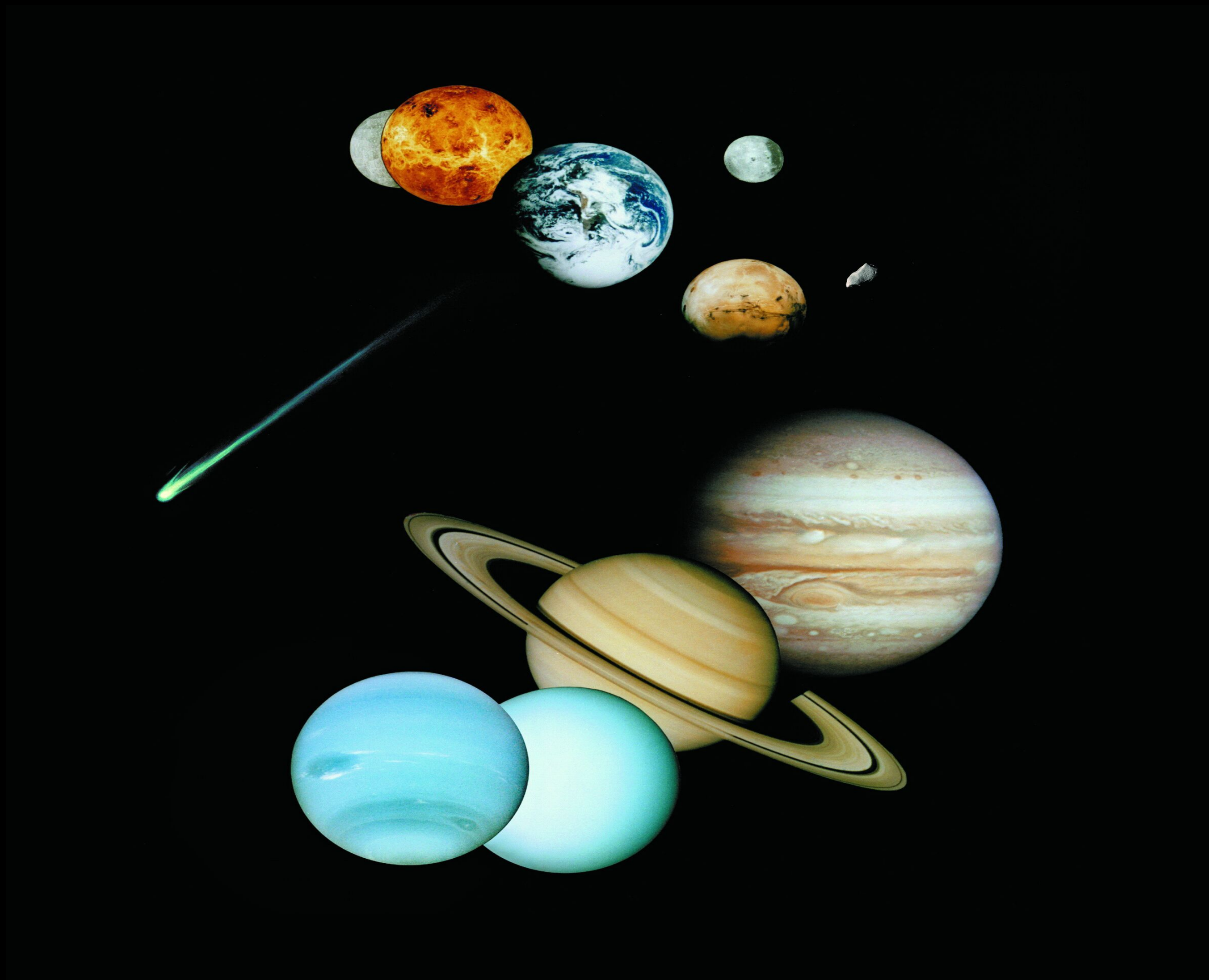
- LPF measures distance variations between test masses, whereas here we need to sense shear motion.
- Spacecraft pointing needs to be monitored to high precision as reference direction (TRL too low!)
- Signal to noise ratio a worry!
- Signal frequency is $1/T_{orbit}$, separation from disturbances is hard and requires more study.
- Separation from Earth's J_2.



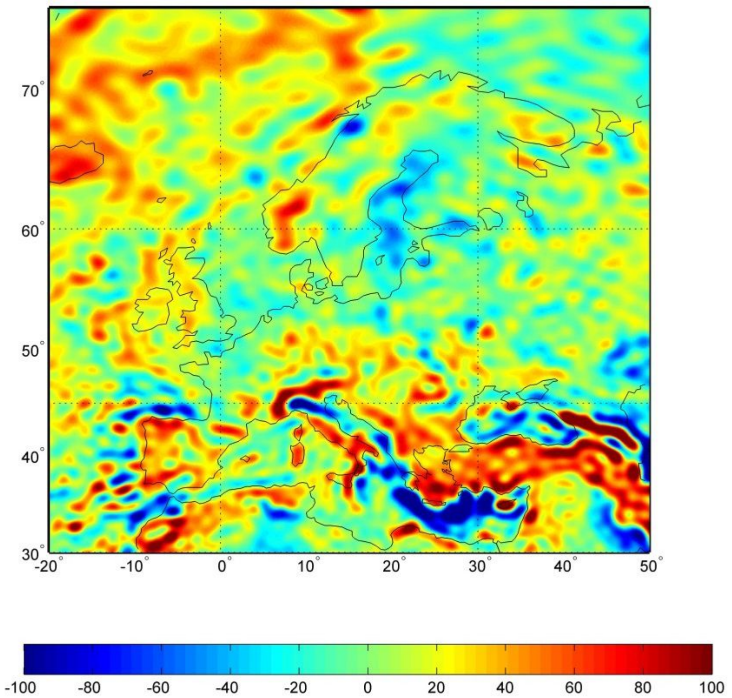


Gravitomagnetic Effect

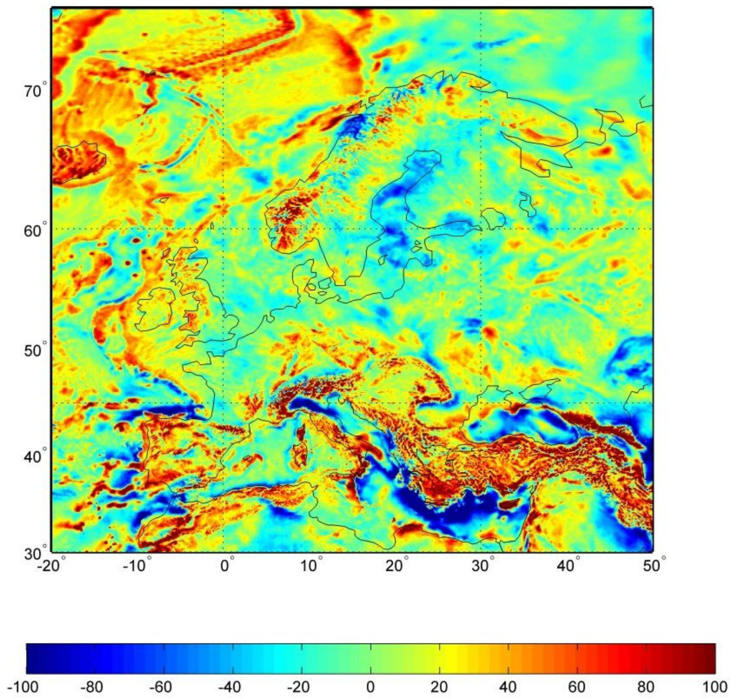
Planetary gravity field measurement and satellite gradiometry



Earth gravity field from satellite gradiometry



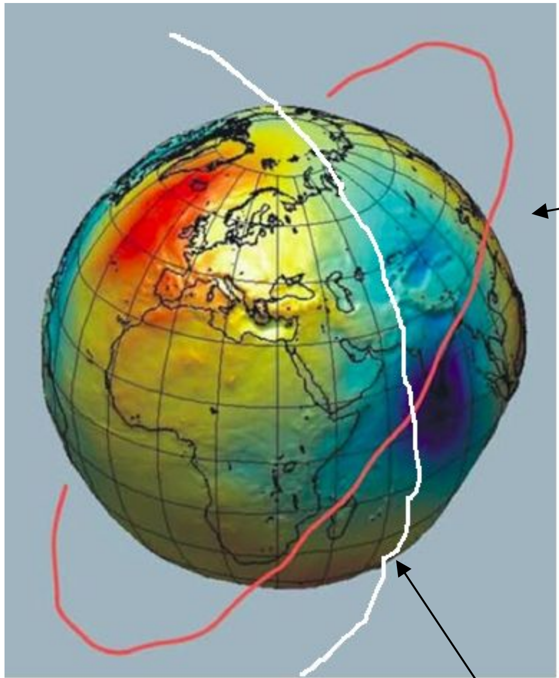
GOCE: global, gravity only



EGM2008: not globally same resolution, combining with local measurements, altimetry, modelling.

Long-term aim: globally high resolution from gravity alone

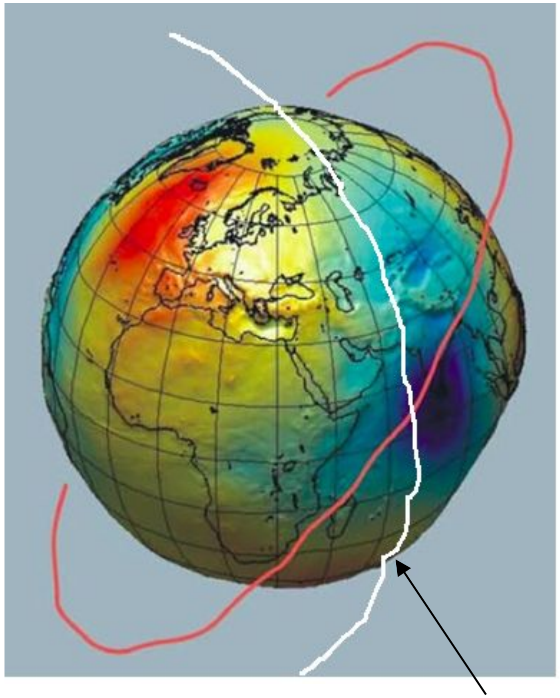
Enhanced earth gravity field recovery



orbit with constant inclination for the gradiometer, 450-650km in altitude

polar orbit to be occupied by the GRACE Follow on mission

Enhanced earth gravity field recovery



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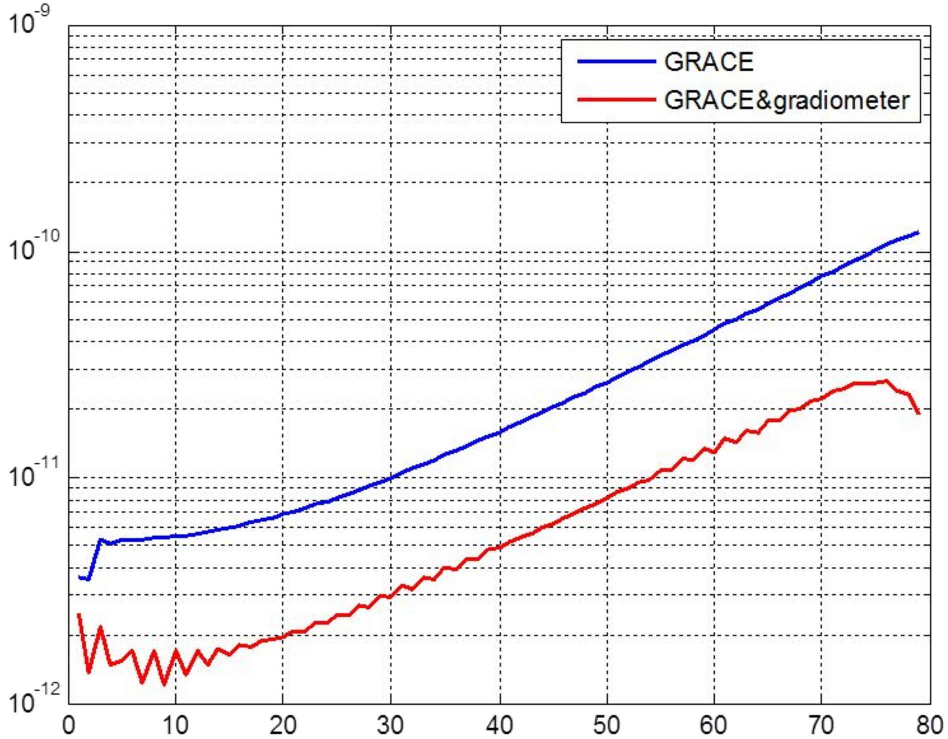
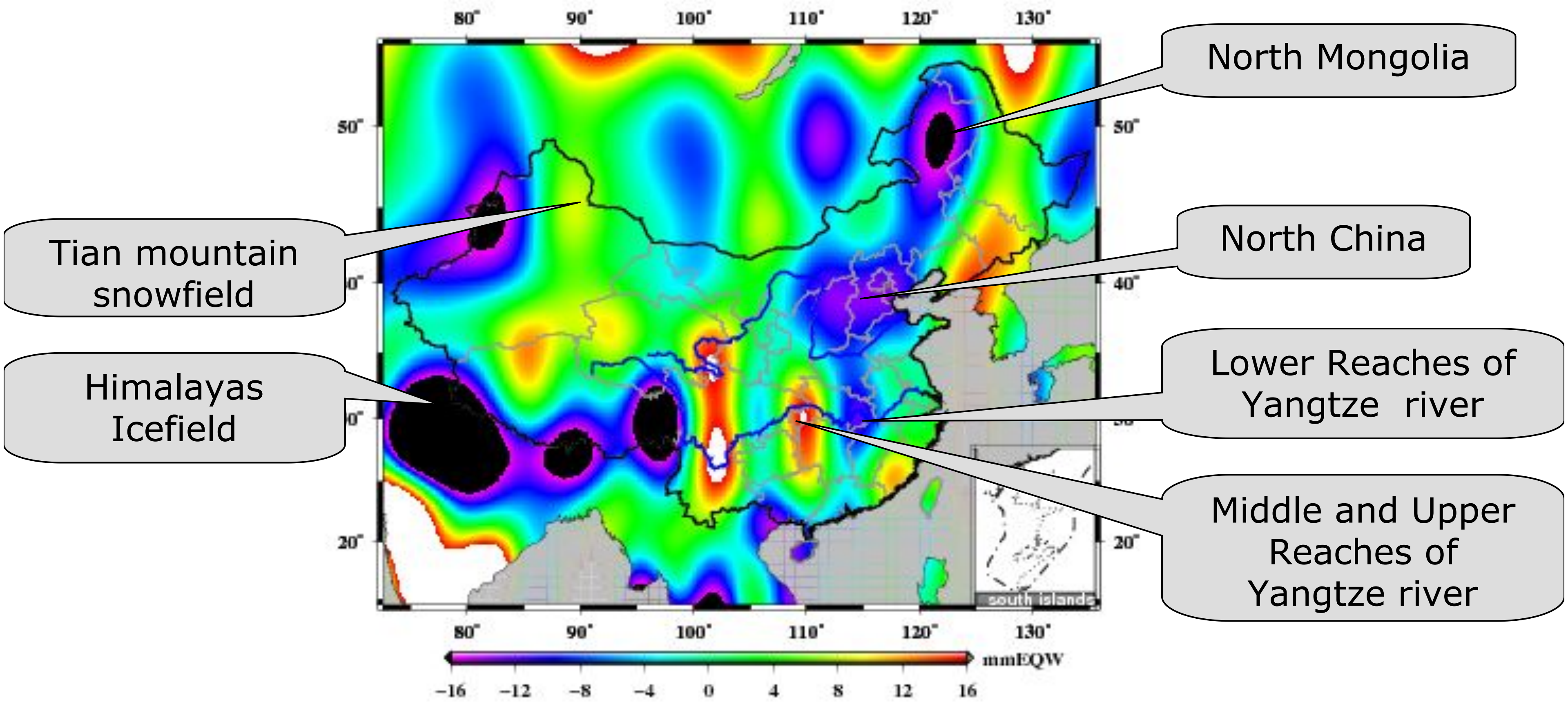
Follow on mission



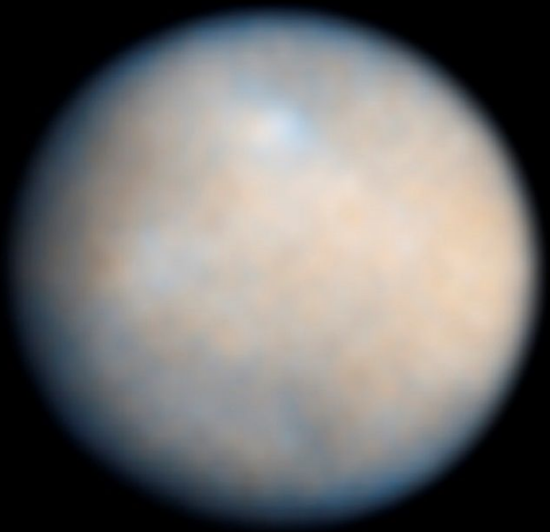
Water Storage Changes over China



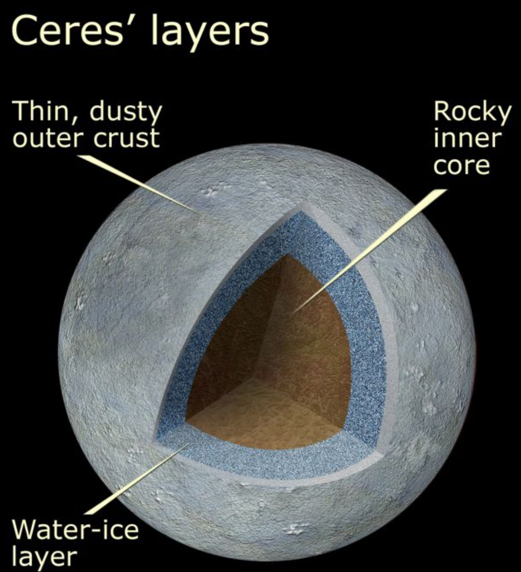
North Niemeng region (-), North China(-), Lower Reaches of Yangtze river (-), Middle and Upper Reaches of Yangtze river (+), Tian mountain snowfield (-), Himalayas Icefield (-). (GRACE data inversion by IGG, CAS)

Planetary gravity field

- Explore gravity of Ceres, an „embryonic planet“ with water



谷神星



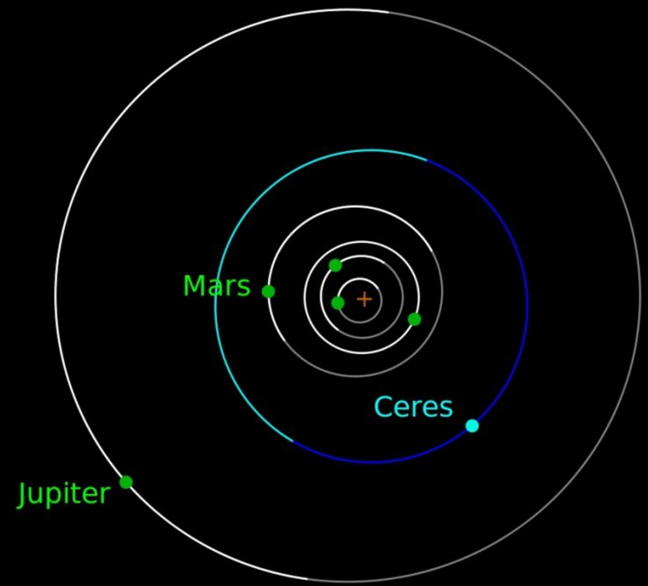


Image credits: NASA

Ceres 谷神星

- Most important parameters
  - Radius: 455-487 km
  - Low orbiter velocity: 0.36 km/s
  - Low orbiter period: 2h 12min
  - Proper rotation: 9 h
- DAWN mission (NASA)
  - Launched 2007, Vesta 2011, Ceres 2015
  - 1240 kg wet mass, 450 Mio US$ (2007)
  - 90 mN Xe Ion thrusters
  - 1.3 kW solar panels, no RTG

New Sciences with realistic technologies

- Potential applications of LISA Pathfinder and GRACE Follow-On inherited technologies to other gravity experiments
- Adaptations are necessary for different dynamic range, different orbits or possibly new sensing axes
- Goals are very different:
  - New results in fundamental physics: feasibility yet to be established
  - Gravity map of planets interplanetary operation not yet studied
  - Better Earth gravity map Very realistic and useful but not in the scope of the current call
- Huge potential for joint technology development
- Well established collaboration on both sides

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