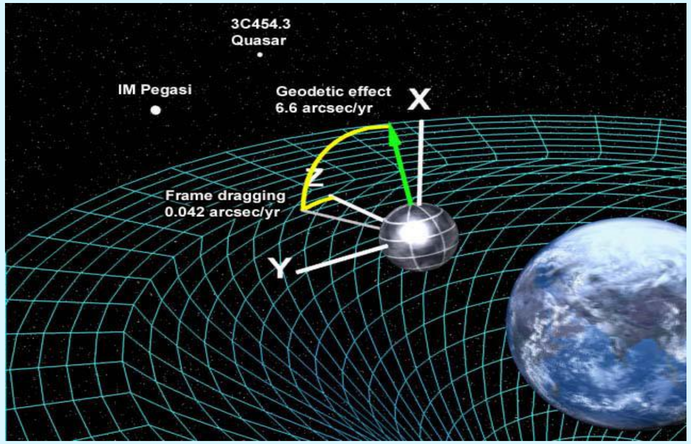
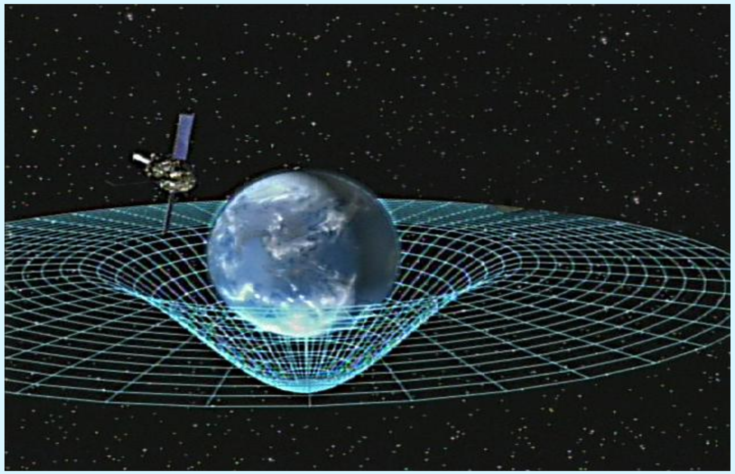
2ème Ecole d'été GRGS

"Géodésie spatiale, physique de la mesure et physique fondamentale".

30 août - 4 sept 2004 - Forcalquier (France)



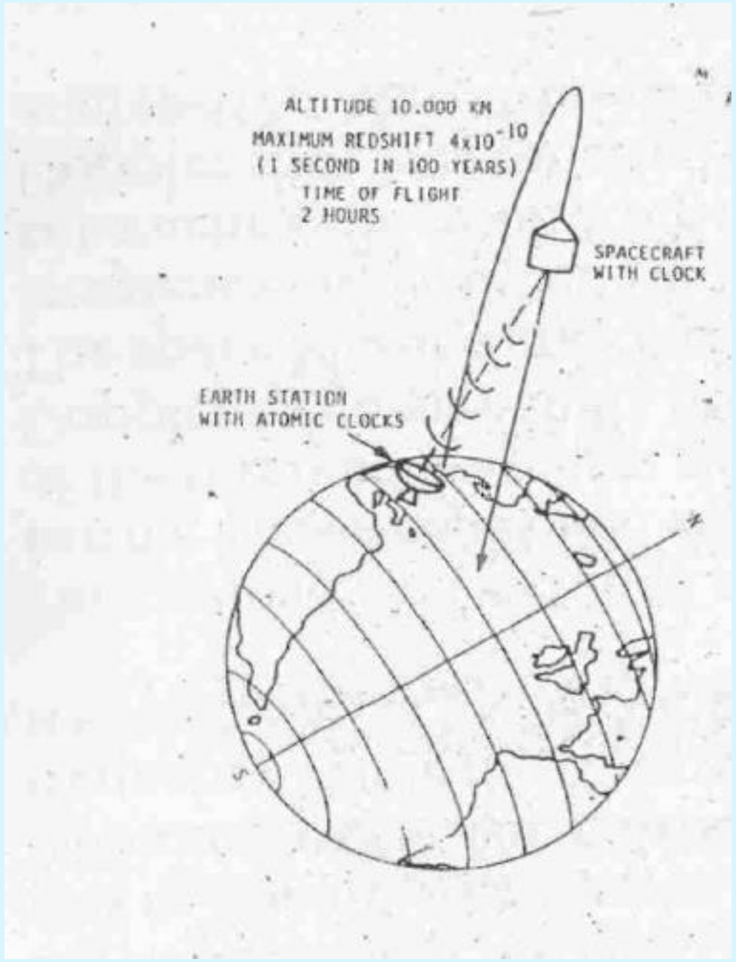
Pierre Touboul
ONERA - Physics and Instrumentation Department
BP 72 F-92322 Châtillon
Pierre.Touboul@onera.fr



Gravity probe B experiment, Superconducting gyro & atomic gyros

Precision Clocks in Space and GPA H-maser (1976)

- **Gravity Probe A (1976)**
  Vessot *et al, PRL 45, 2081 (1980)*
  - *Comparison of two clocks at different gravity potential*
  - *On ground and on board a rocket with parabolic trajectory (10 000 km max. altitude)*
  - *Redshift of $4x10^{-10}$ measured with a 10^{-14} clock frequency stability*
  - *70 ppm confirmation of combined redshift and 2nd order Doppler*
- **ACES/PHARAO (ISS : 2008 ? Or other S/C : ?)**
  expected accuracy : 25 better



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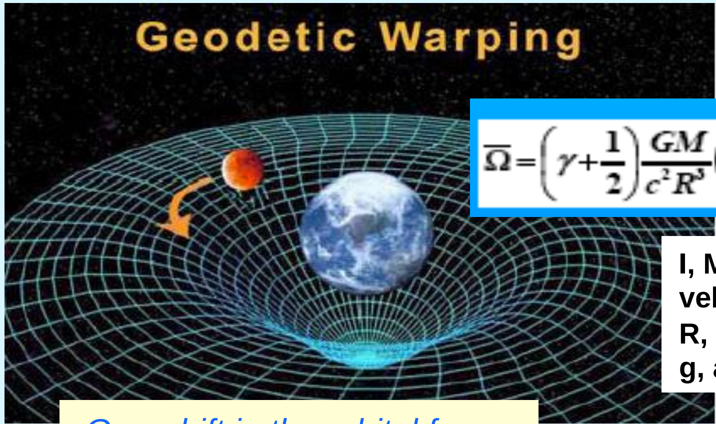
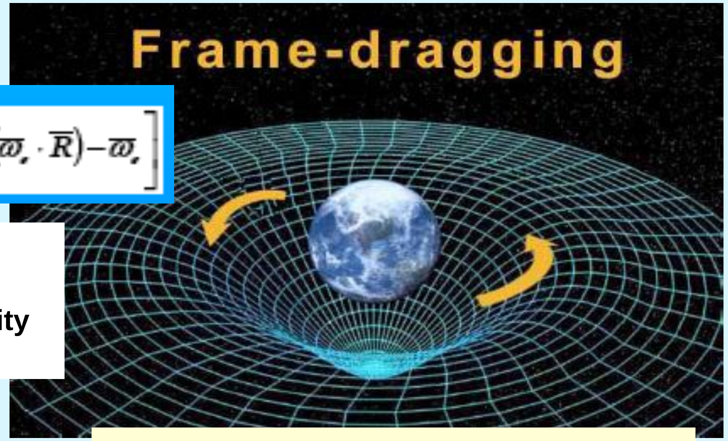
GRAVITY PROBE B Scientific Objectives

Earth gravity field as a curvature of space time



Gyro drift in the orbital frame

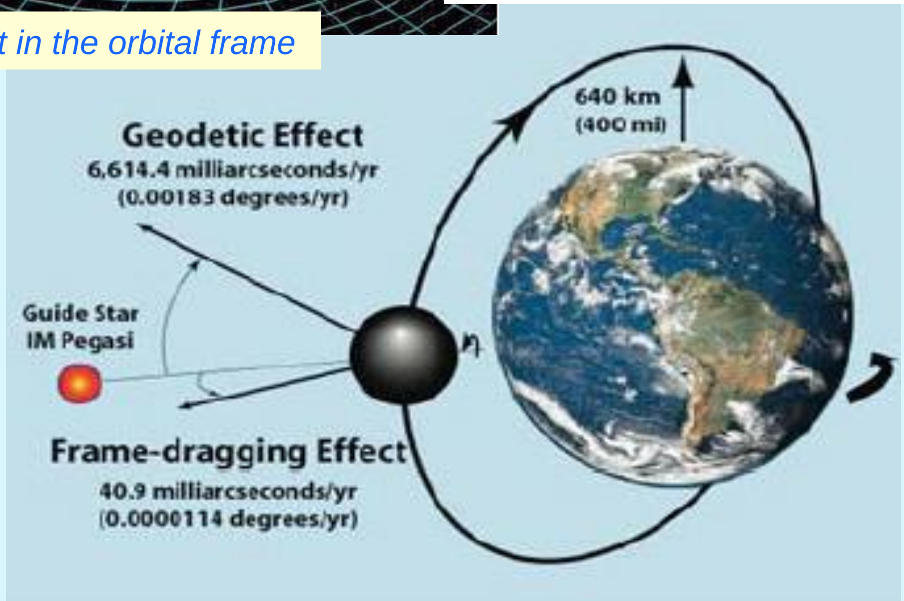
Earth rotation drags local space time



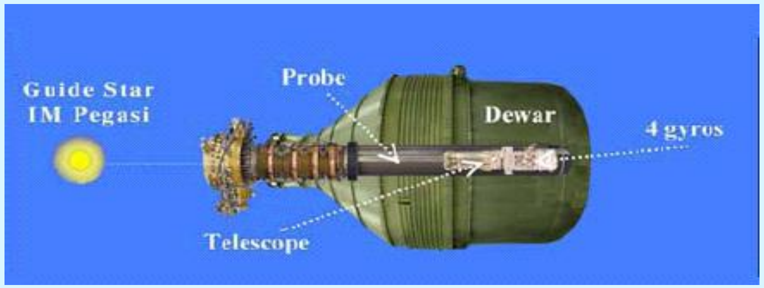
Gyro drift normal to the orbital frame

$$\overline{\Omega} = \left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}(\overline{R}\times\overline{v}) + \left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}(\overline{\varpi}_e\cdot\overline{R})-\overline{\varpi}_e\right]$$

I, M, w Earth Inertia, Mass, angular velocity
R, v Gyroscope position and velocity
g, a, PN parameters (GR : 1,0)



Gravito-magnetic effect



In orbit configuration

Circular Polar Orbit :

- Altitude : 640 km
- Eccentricity : 1-2 10^{-3}
- Inclination : 90.007 °

18 months operation
(16 months present evaluation)

1 telescope
4 gyros (0.3 marcsec/year resolution)
1 GPS receiver
Mass trim mechanism
12 thrusters

Needs of:

- **Star reference frame**
- **Ultra-sensitive gyros**
- **No disturbation**
- **Integration of the signal**

→

CONTROLLED SPACE ENVIRONMENT
with drag-free satellite orbit
and cryogenic experiment :

- **Magnetic shielding**
- **Squid rotation detection**
- **Low thermal noise**
- **He thrust**

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Project Timeline : The basis

1893 **Mach's Principal -The Science of Mechanics- acceleration relative to distant stars.**

1887 **Michelson & Morley Experiment : speed of light remains constant**

1905 **Einstein Special Relativity : propagation of matter and light at high speeds.**

1915 **Einstein General Relativity : gravitational forces in terms of space curvature caused by the presence of mass.**
Fundamental principle : accelerated frames and in gravitation fields frames are equivalent.
General Relativity predicts : clocks evolution in gravitational fields (or accelerated frames), gravitational redshift, existence of gravitational lensing, gravitational waves, gravitomagnetism, Lense-Thirring effect, and relativistic precession of orbiting bodies.

1924 **J. Lense and H. Thirring**
calculated effect : a rotating object will slowly drag space and time around with it! A moon orbiting a rotating planet undergoes a relativistic advance of its ascending node. Frame Drag.

1929 **A. S. Eddington : proposed an Earth based gyroscope or pendulum experiment of general relativity.**
If the earth's rotation could be accurately measured by Foucault's pendulum or by gyrostatic experiments, the result would differ from the rotation relative to the fixed stars by this amount of 19 milliarcsecond/year precession.

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Project Timeline : The Fondation

1961 First formal NASA contact : Fairbank writes Dr Abe Siberstein describing an instrument that would measure the geodetic precession to a few percent.

1962 Francis Everitt joins William Fairbank and Leonard Shiff at Stanford on the Gravity ProbeB.

1965 1st fused quartz telescope built.

1971 NASA begins examining feasibility of a flight experiment.
Ball Aerospace completed a Mission Definition Study.

1973 Dan Debra's successful flight of a drag-free satellite (the Transit navigation satellite).

1976 Gravity Probe A launch. 1 hour 55 minute flight of a MASER atomic clock demonstrating time change as weaker levels of gravity : test of redshift to an accuracy of 2.10^{-4} .

1977 End of longest single continuous research NASA grant ever awarded (63-77).

1980-82 Phase A at MSFC leading to larger dewar and satellite.

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Project Timeline : The mission happens

1983 **Stanford restructured program : science instrument within the dewar to be integrated and launched in 1991 on the shuttle : STORE (Shuttle Test of the Relativity Experiment)**

1985 **Gyro production throws out Beryllium, Hollowed Beryllium, Hollow Quartz spheres and focuses on Quartz rotors...**

1986 **Challenger explodes.**

1989 **Stanford's first prolonged levitation of a quartz sphere.**

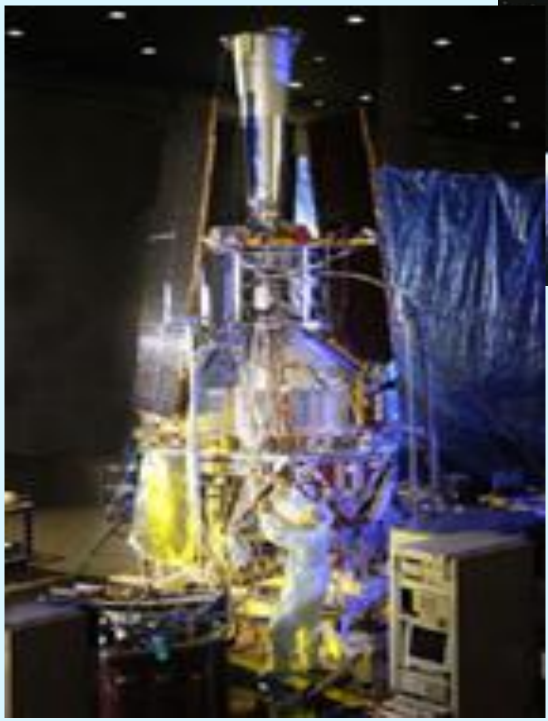
1992 **First Flight Hardware within the Science Mission starts to be built : Dewar...**

1995 **NASA cancels Shuttle Test and directs Stanford to go directly to flight.**

2001 **Integrate Payload with Spacecraft.**

April 20th 2004 **Gravity Probe B successfull launch out of Vandenburg Air Force Base at 9:55am.**

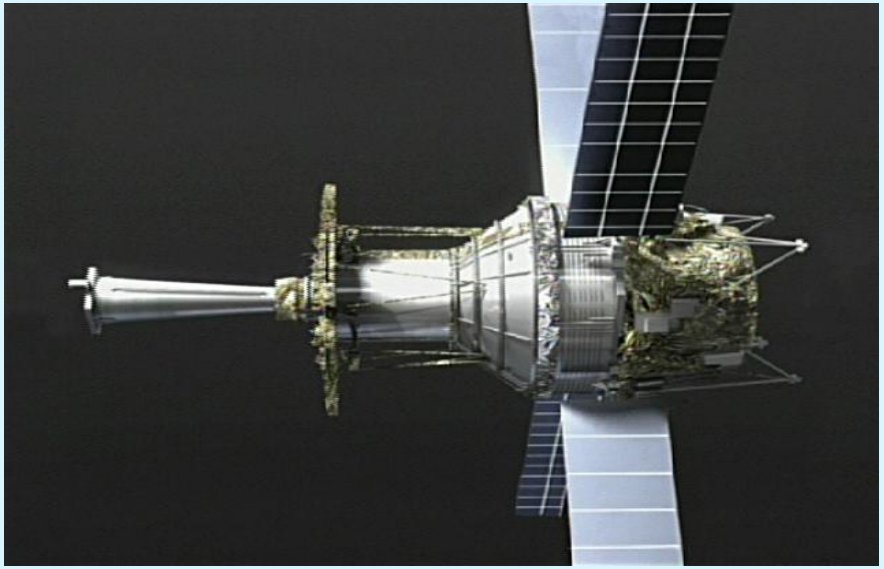
The Satellite



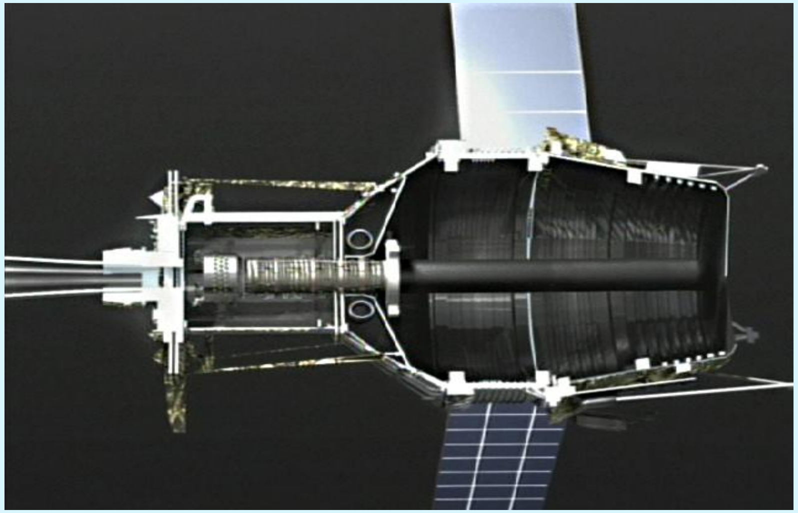
VEHICLE
- Length 6.43 meters
- Diameter 2.64 meters
- Weight 3,100 kg
- Spacecraft Power: 293 Watts

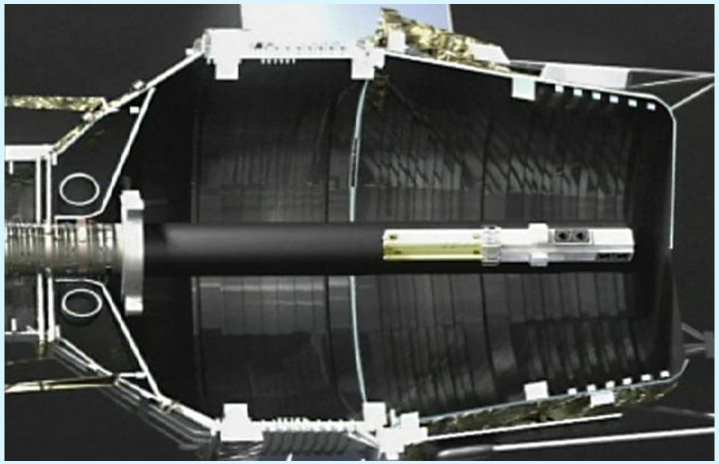
LAUNCH 20 April 2004

Payload general configuration



- From cryogenic (He liq. 1.8 K) to room temperature
- Alignment : Telescope, Gyros, S/C spin axis
- Drag free satellite : 10^{-9} g
- S/C mass centring
- Satellite rotation : ~ 10^{-2} Hz (period : 1 to 3 mn)

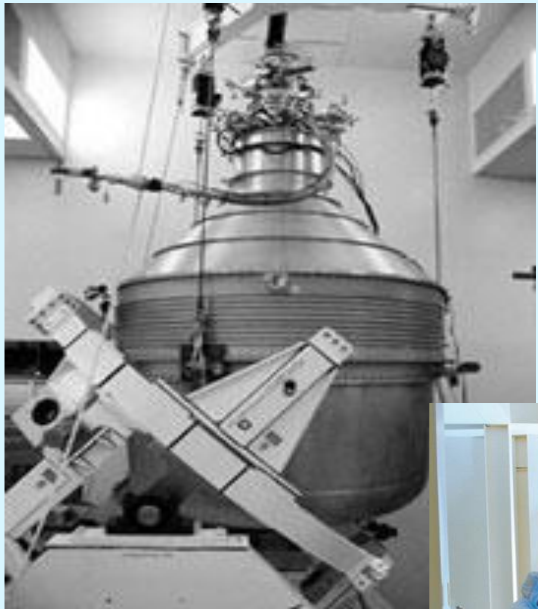




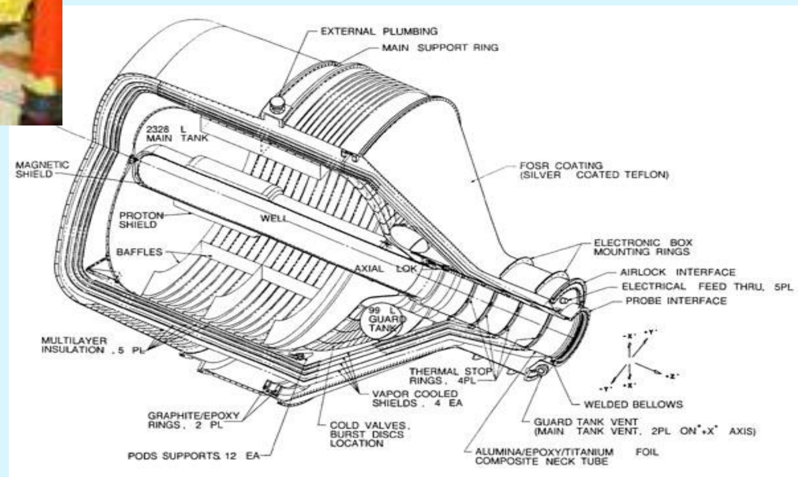
4 gyros for redundancy and performance improvement
drift rate : 0.25 marsec/year
leads to accuracy $\gamma \approx 2.10^{-5}$ $\alpha \approx 3\ 10^{-3}$

The Payload with the Dewar

PAYLOAD and DEWAR
- 2 441 liters of supercooled helium at 1.8 Kelvin (-271.4 C)
- 2.74 m tall / 2.64 m diameter
- Porous plug at the top : as the internal liquid helium heats up, it evaporates and the gas is vented out taking heat with it.
- Payload Power Usage: 313 Watts



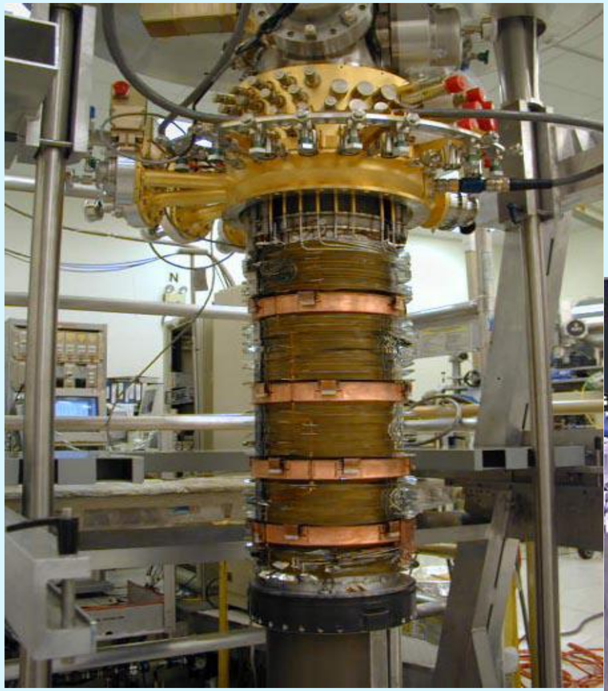
High structural stability
Low temperature
Fine management of He behaviour
Fine magnetic shielding
Fine mass centering

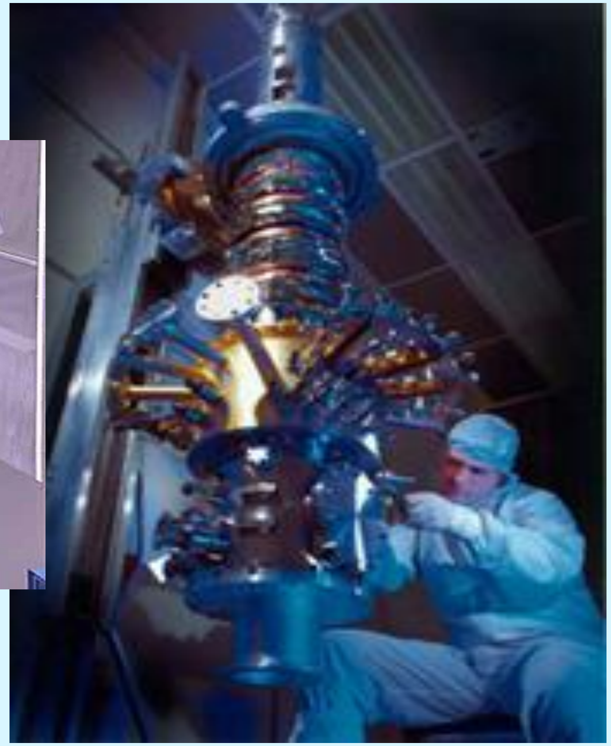


The Probe

PROBE

- Length- 2.74m (9 feet).
- Working temperature- 1.8 Kelvin (-271.4 C).
- The probe contains 450 plumbing lines and electrical wires.
- The entire probe was assembled in a class-10 cleanroom.

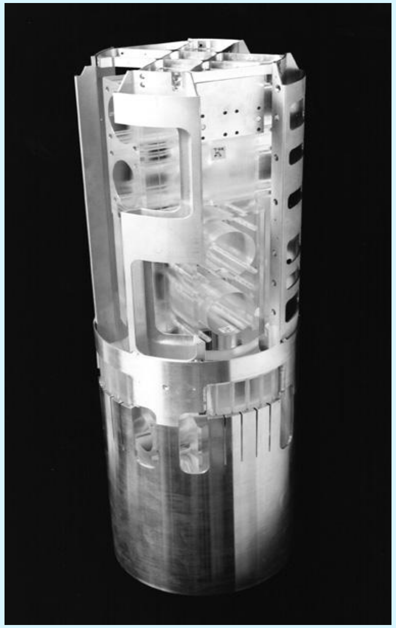




The Quartz Block

QUARTZ BLOCK

- Weight : 34 kg
- Length : 55 cm
- Diameter : 18.5 cm
- Block lapped and polished (14 months to hand-polish)
- Telescope mounting surface of the block had to be polished to within 0.01 µm



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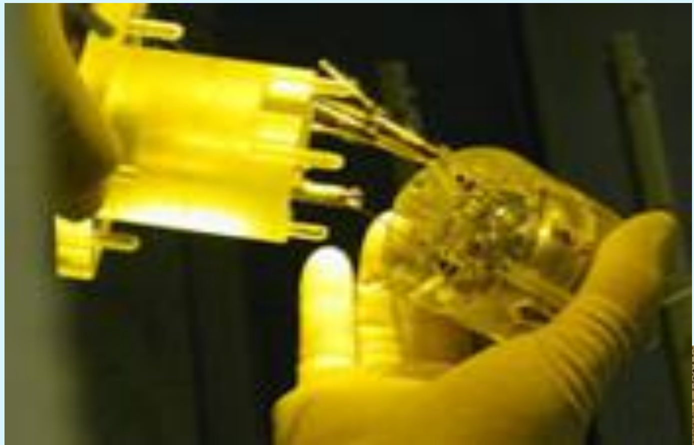
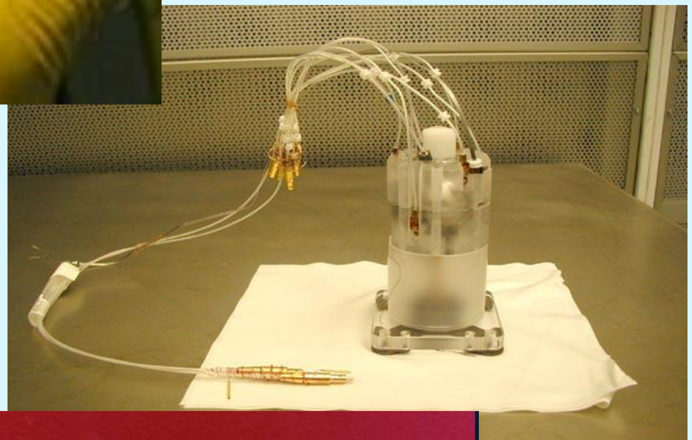
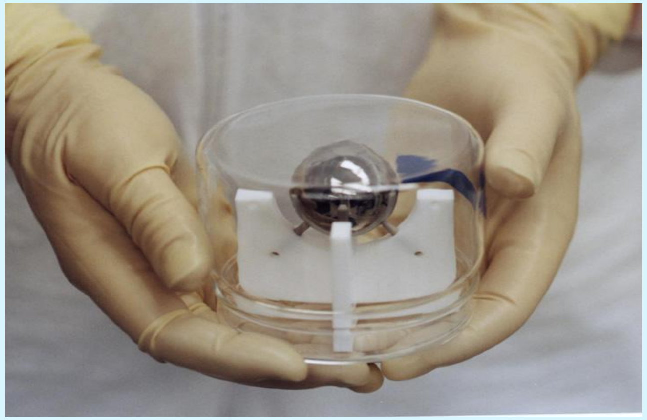
The Gyroscopes

GYROSCOPE

- Ball (rotor) size- 3.81 centimeter diameter (1.5-inch)
- Homogeneous fused quartz : 2 10^{-6}
- Sphericity : less than 40 atomic layers from perfect (1nm)
- Coating- Niobium (uniform layer 1,270 nanometers thick)
- *Electrostaticaly suspended (25 µm gap).*
- *Spin Rate- Between 5,000 and 10,000 RPM (obtained once by He flow)*
- Accuracy : 0.25 marcsec/year drift (0.5 10^{-16} rd/s)







Major deffects :

- Non sphericiy
- Unballanced mass
- Friction

The SQUID's rotation measurement

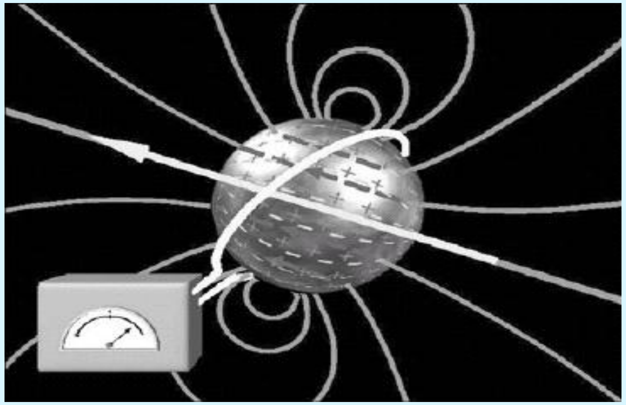
SQUID's

- Cryogenic magnetic field variation sensor.
- Superconducting loop with 2 Josephson junctions
- Sensitivity : 5×10^{-14} gauss (5×10^{-18} Tesla) 10^{-13} of the Earth's magnetic field.

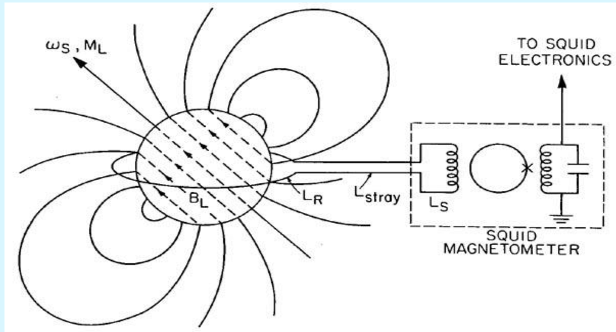
Rotation Measurement :

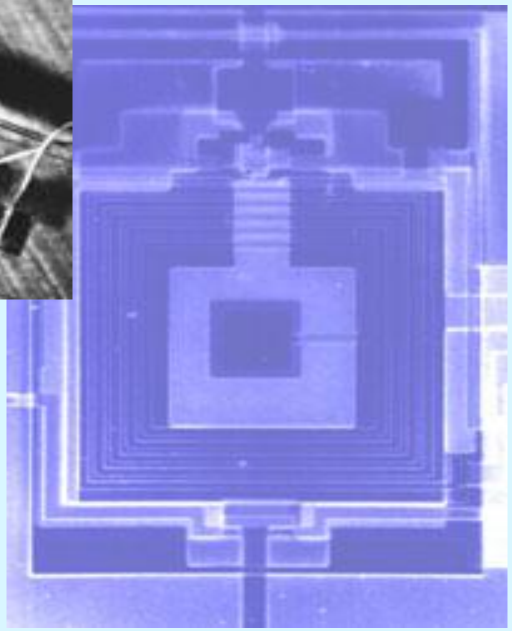
London Effect

6.10^{-12}°/ hour (< 10^{-6} best nav. gyro performance)



London effect induces magnetic moment the variation of orientation is detected by SQUID

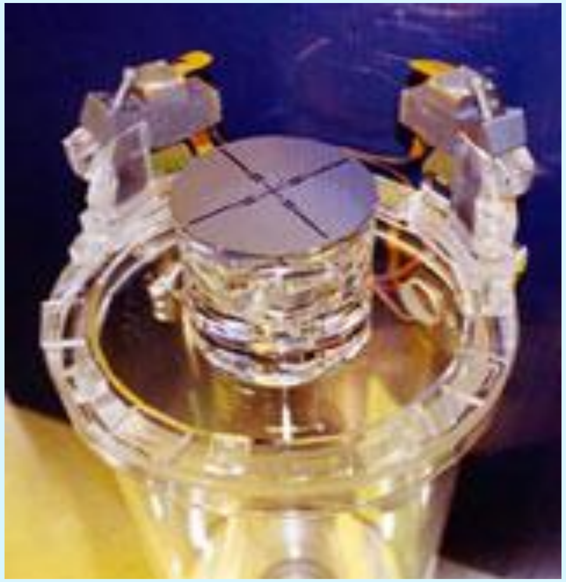


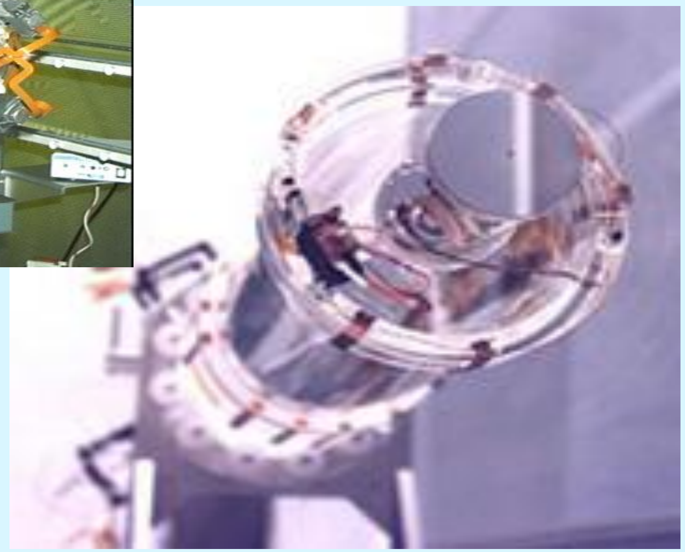


The Telescope

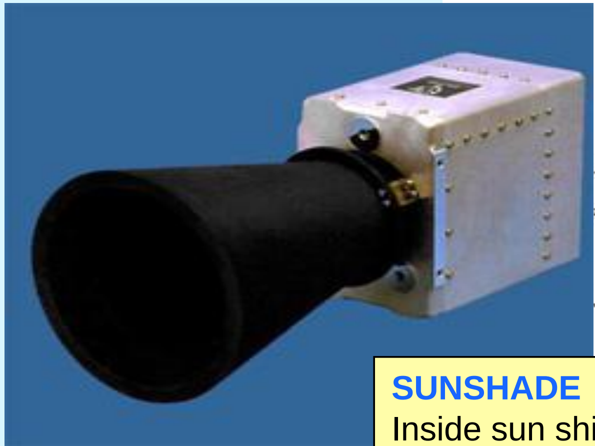
CASSEGRAIN TELESCOPE

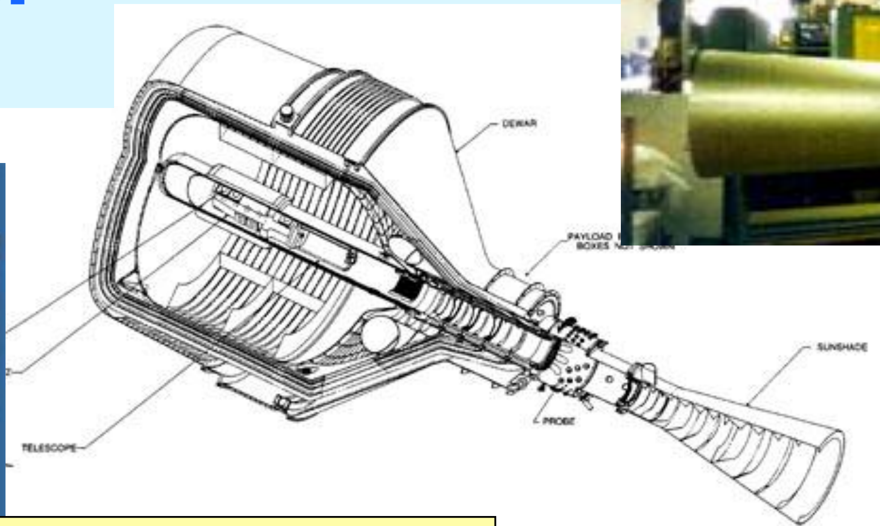
- Composition- Homogeneous fused quartz
- Length 35.56 centimeters (14 inches)
- Aperture 13.97 centimeter (5.5-inch)
- Focal length 3.81 meters (12.5 feet)
- Mirror diameter 14.2 centimeters (5.6 inches)
- Guide Star HR 8703 (IM Pegasi : Mag 5.6)
- Accuracy : 0 .1 milliarcsecond i.e. 5.10^{-10} rd





The star tracker
& Sunshade





SUNSHADE

Inside sun shield : series of black, metal baffles to absorb incoming stray light before it can reach the telescope.

STAR TRACKER

Two star trackers : wide field and narrow field (star sensor).

Star sensor : field of view ~ 1° (1.7 10^{-2} rd)
resolution ~ 1 arcminute (3 10^{-4} rd)
in GP-B telescope field of view,
-> Guide star's position to 1 milliarcsecond (5 10^{-9} rd).

The GMA

The Gas Management Assembly

GMA FACTS

- Helium gas (99.999% pure) used to spin up the gyroscope ball.
- Helium gas used for thrusters of the drag free control.
- Fine distribution and management of the evaporated He to be ejected from the dewar

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The Thrusters

THRUSTER

- 12 pairs of thrusters on the vehicle.
- Use of the evaporated liquid helium from the dewar as a propellant linear thruster independent of the inlet pressure

Objective :

- Fine control of the satellite attitude and orbit
- Satellite rotates to modulate the SQUID output (reduction of noise)

DMPH

GPB Mission Present Status (Cospar july 04)

- **Satellite in nominal orbit and nominal operation**
- **Drag free and attitude control being optimised : telescope pointing not yet stabilized along reference star**
- **2 gyros rotates at nominal frequency**
- **He Dewar : 14 months mission evaluated**
- **Calibration phase running : no scientific results before 6 months**

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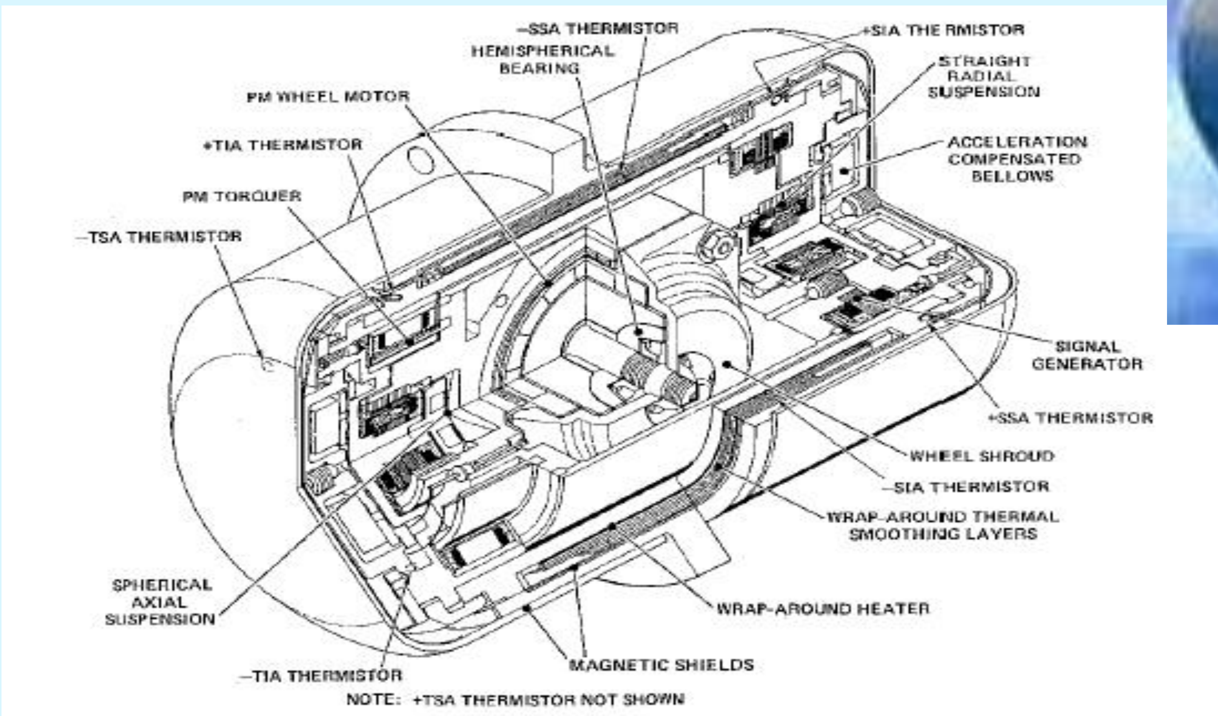
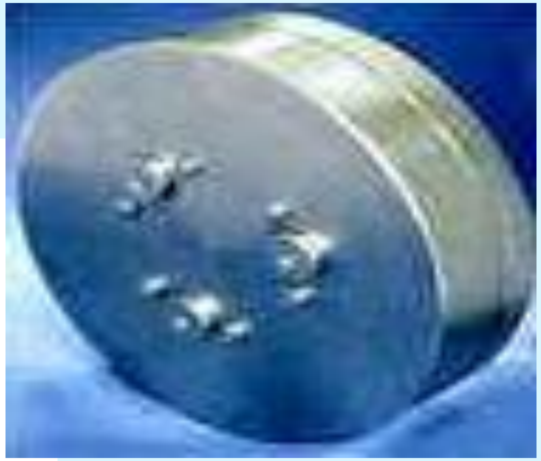
Existing gyroscope technology for craft attitude motion application

- ESGN (submarine navigation)
- Draper LN-TGG gyro
- Litton/Northrop Hemispherical Resonator





Fibersense IFOG

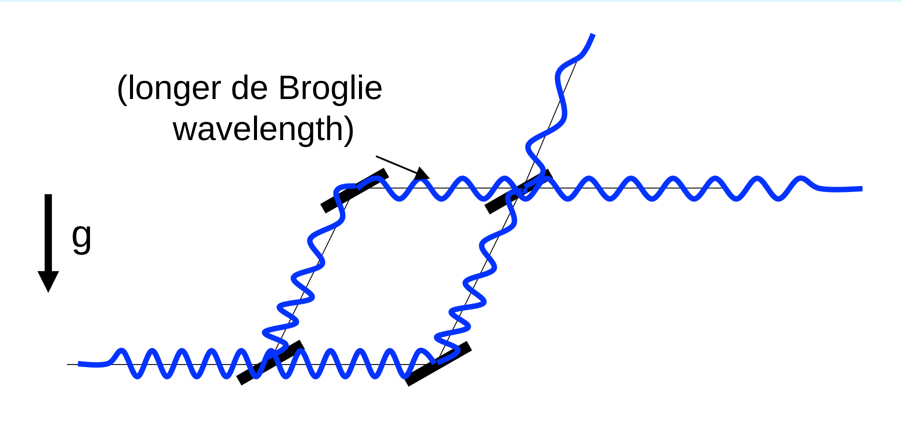
LN-TGG; 1 nrad 0.1-100 Hz
Source: SPIE 4632-15

Atom interferometer force sensors

The quantum mechanical wave-like properties of atoms can be used to sense inertial forces.

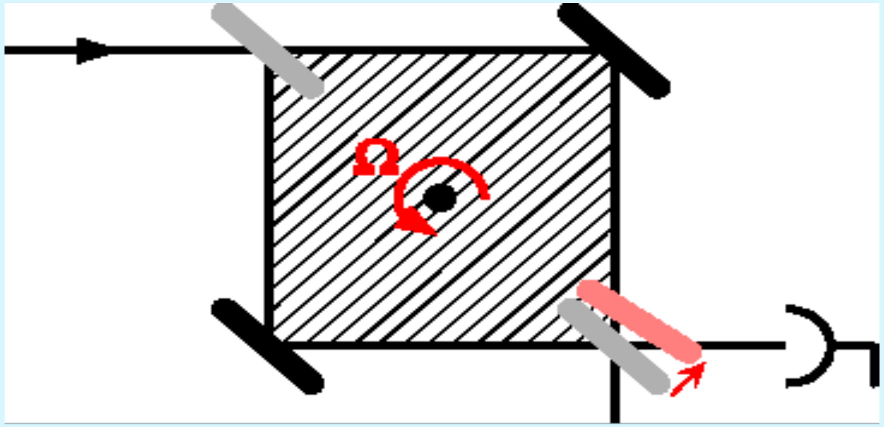
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

Rotations induce path length differences by shifting the positions of beam splitting optics



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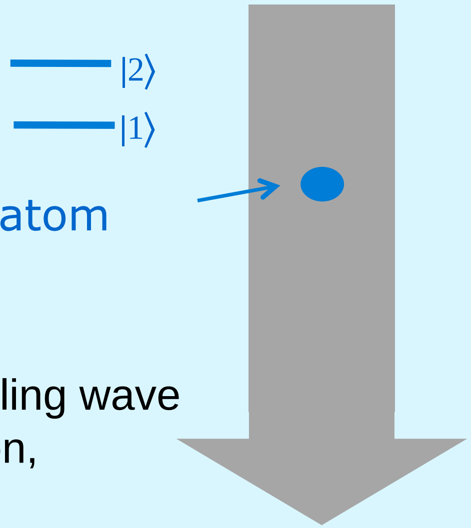
(Light-pulse) atom interferometry

Resonant optical interaction

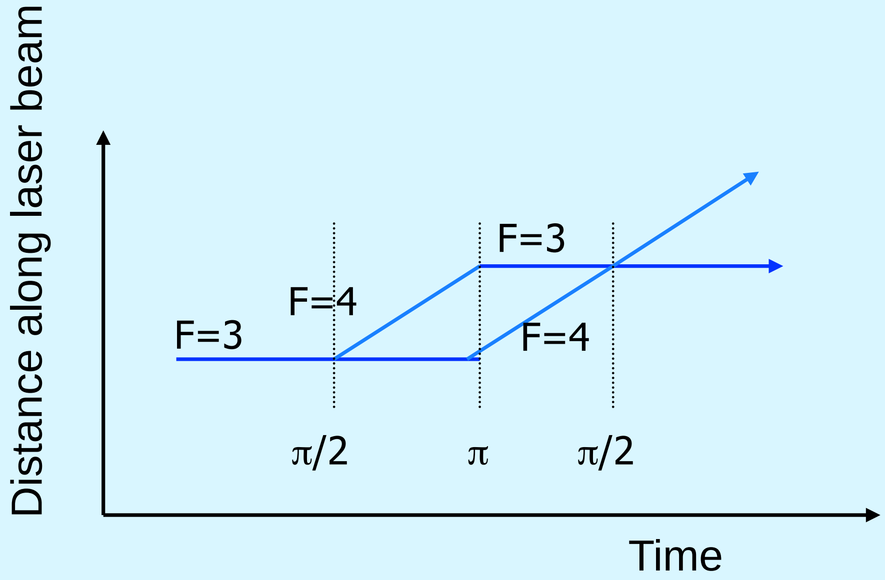
2-level atom



Resonant traveling wave
optical excitation,
(wavelength l)

Recoil diagram

Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.

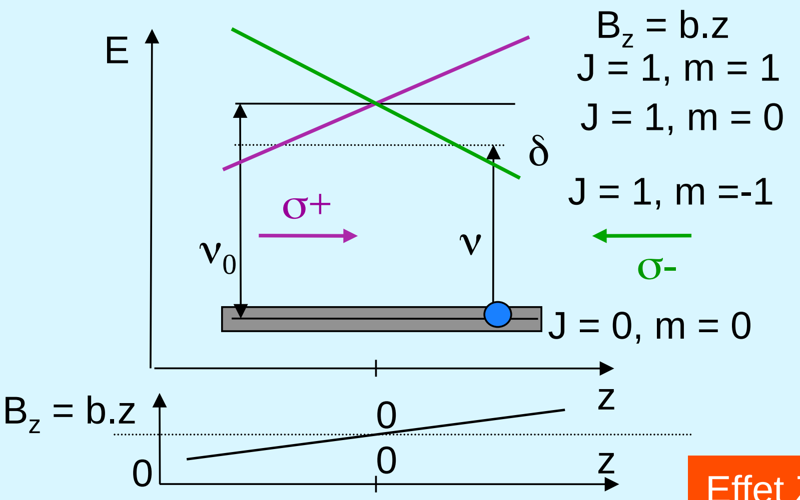


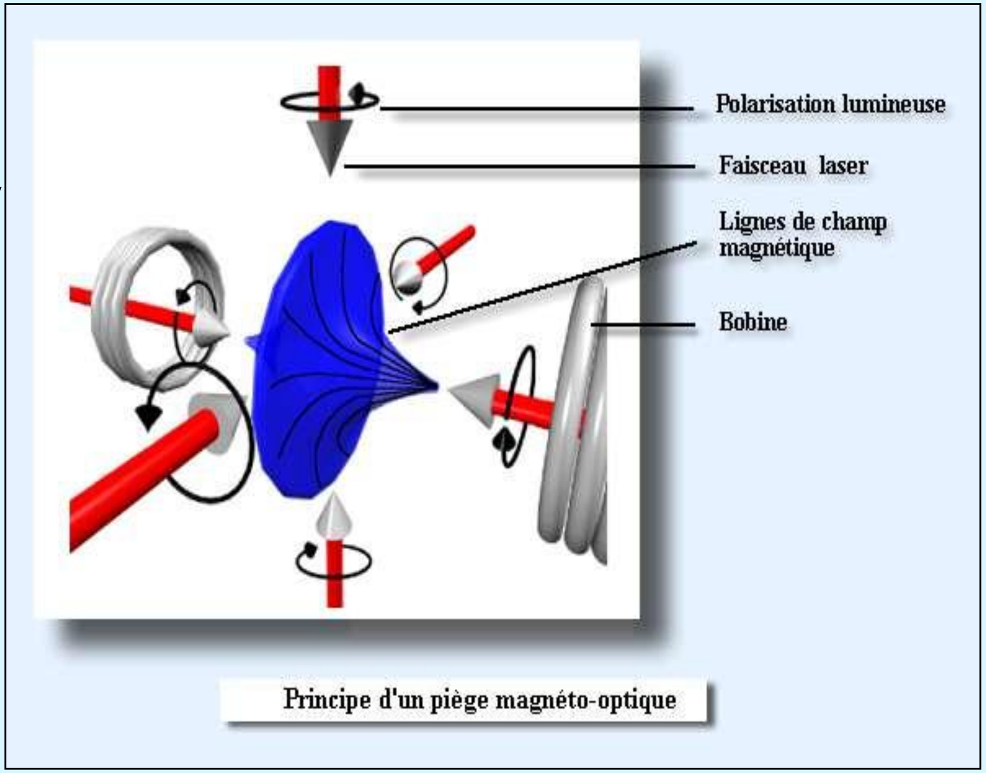
Refroidissement et positionnement des atomes :
piège magnéto-optique (avec gradient de champs magnétiques)

Faisceau de droite :
$\nu_{app} = \nu_L + kv$
$= \nu_0 - kv + kv = \nu_0$
Résonance

Faisceau de gauche :
$\nu_{app} = \nu - kv$
$= \nu_0 - kv - kv = \nu_0 - 2kv$
Hors résonance

La force résultante s'oppose au mouvement de l'atome : refroidissement

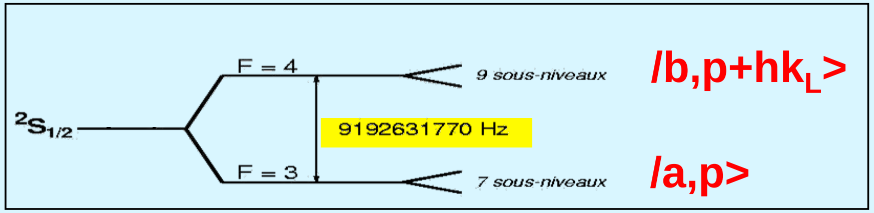




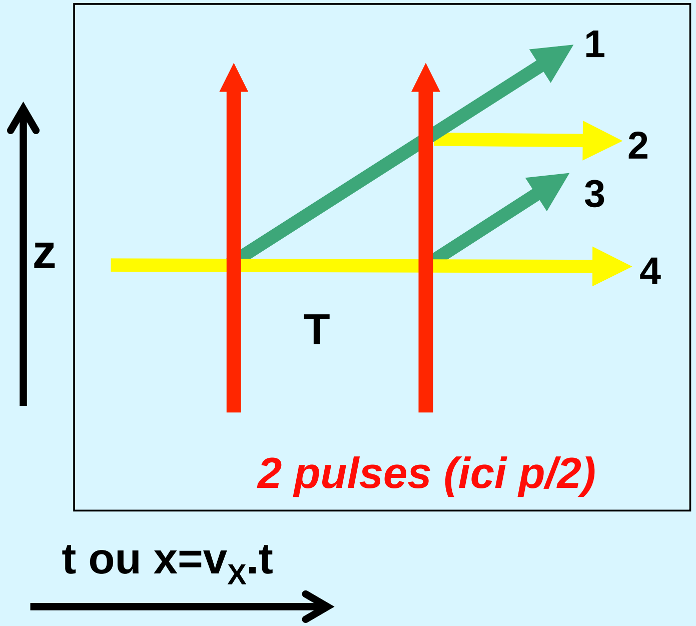
Effet Zeeman + Gradient de B --> Force de rappel

Au total : $F = -\alpha v - \beta r$ = friction + rappel

Interférométrie à onde de matière



La probabilité d'obtenir des atomes dans l'état /b,…> résulte des interférences des probabilités des différents chemins possibles : 1 et 3



Calcul du déphasage

3 termes :

- **' *Evolution* ' des états internes**
- **' *Propagation* '**
- **' *Interaction* ' avec la lumière**

- ' *Evolution* ' des états internes : Exp(-i.w.t)
Onde de matière à la pulsation w=E/ h

- ' *Propagation* ' sur la trajectoire réelle : Exp(-i.S/h)

$$S_{A\to B} = \int_{t_A}^{t_B} L_{agrangien}\,dt = \int_{t_A}^{t_B}\left(\frac{m\dot{z}^2}{2} - V(z)\right)dt$$

et la formulation donne en référentiel tournant :

$$S_{A\to B} = \int_{t_A}^{t_B}\left(\frac{m\dot{r}^2}{2} + \frac{m\left(\vec{\Omega}\times\vec{r}\right)^2}{2} + m\vec{\Omega}.\left(\vec{r}\times\vec{v}\right) - V(r)\right)dt$$

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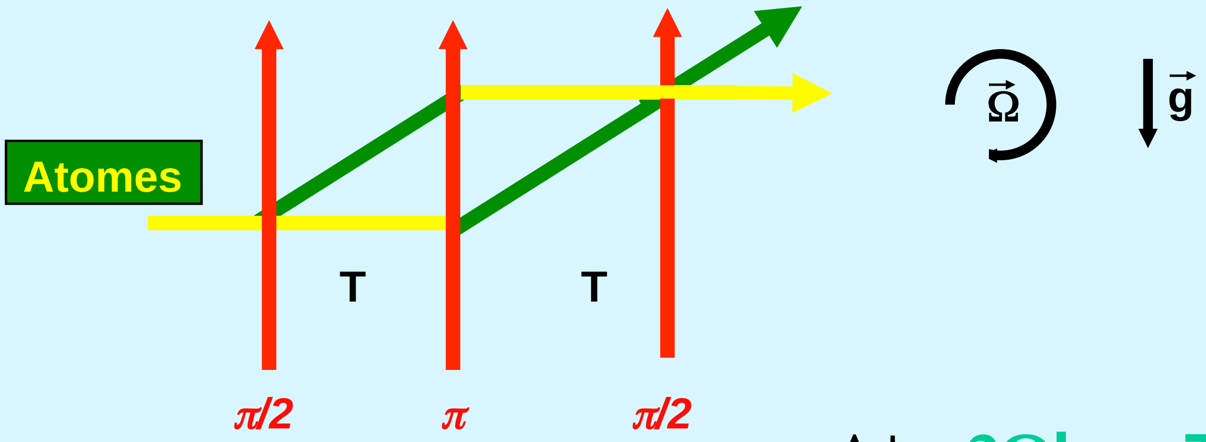
Capteurs inertiels à ondes de matière

Interférométrie atomique : (ici le plus simple : MACH - ZENDER)



$$\Delta\phi = 2T\,(\omega_L - \omega_0 - \omega_R - \omega_D + \ldots)$$

Detuning — *Recul, Doppler* — *Rotation, g, gradients, déphasage ...*

$$\Delta\phi = 2\Omega k_L v_X T^2$$

Gyromètre (Sagnac)

$$\Delta\Phi = \frac{2m\vec{\Omega}.\vec{A}}{\hbar}$$

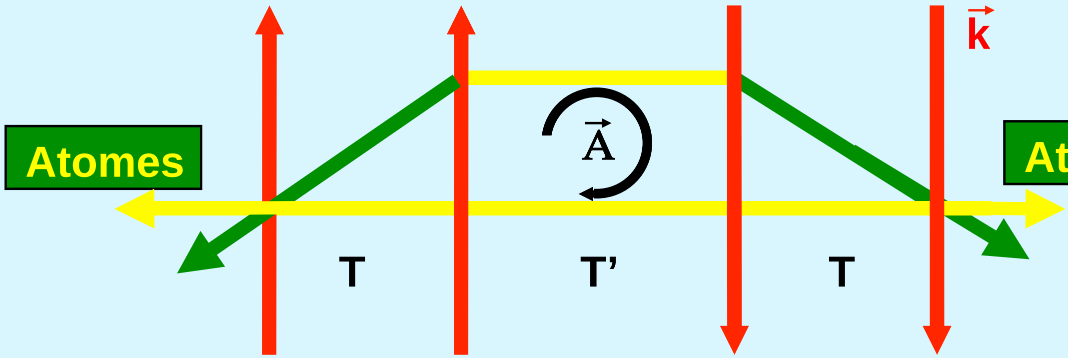
$$\Delta\phi = -k_L g T^2$$

Accéléromètre (Red-Shift)

$$\vec{g} \sim 200\,\omega_{Terre}$$

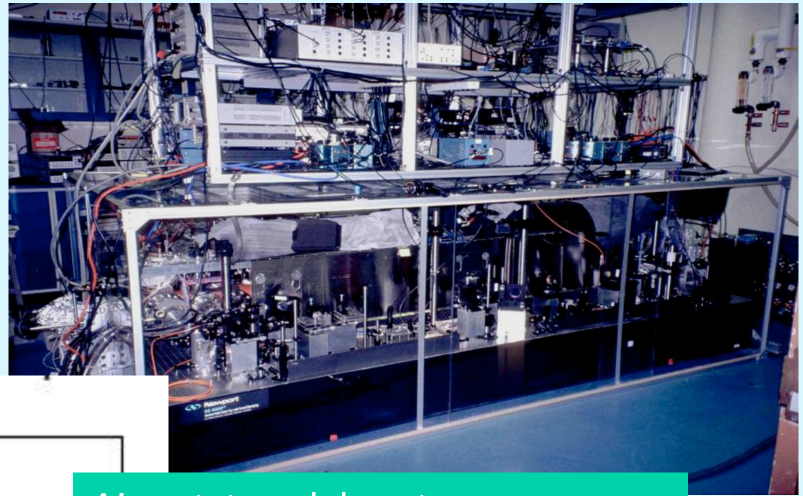
DMPH

Double Interférométrie atomique : Gyromètre



(ici RAMSEY-BORDE)

Kasevich 91-92

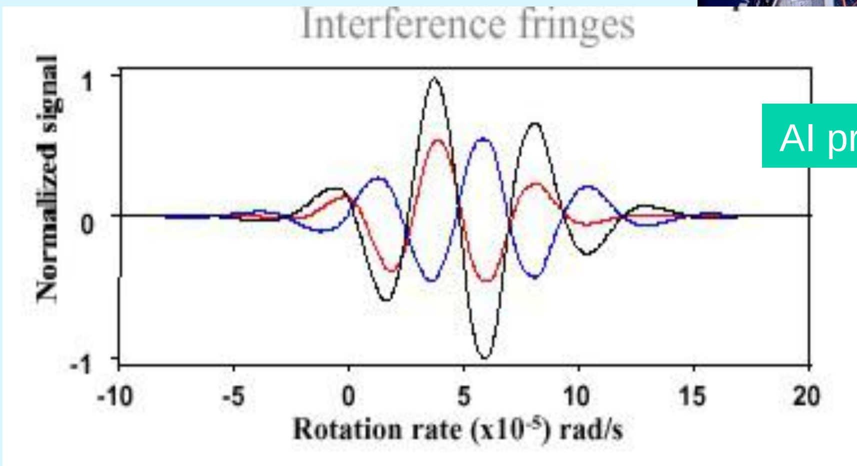


AI prototype laboratory gyroscope

Interféromètre n°1

Interféromètre n°2

Différence

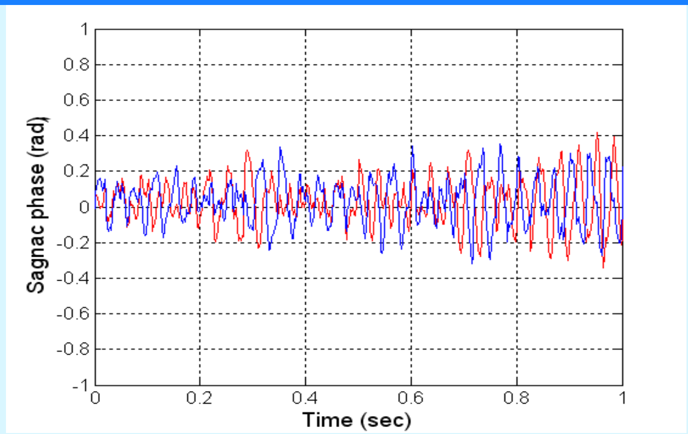


Sensitivity:

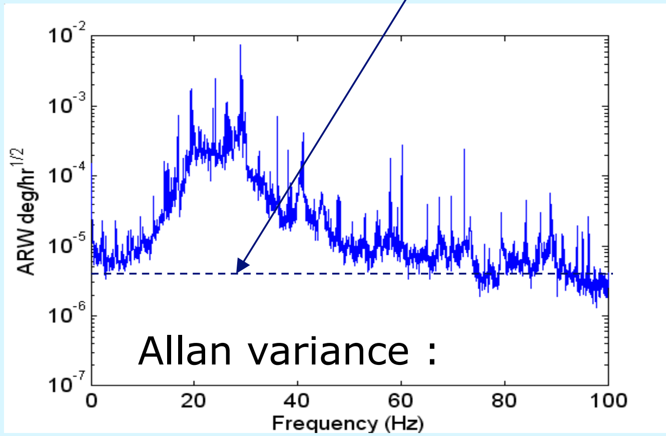
6.10^{-10} rad.s^{-1}/√Hz

Gyroscope performance

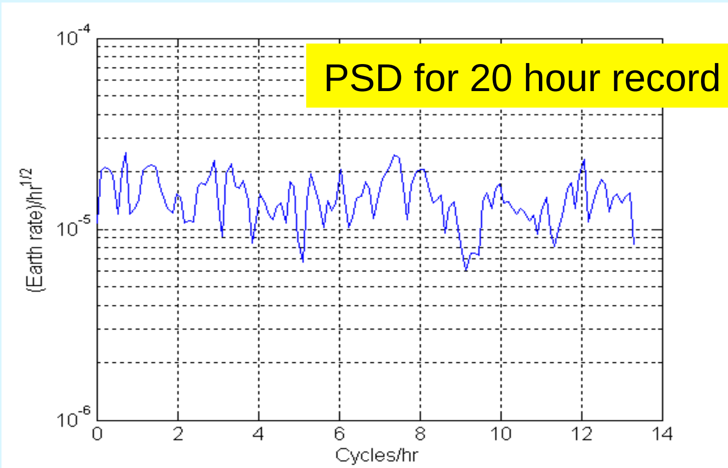
Raw signals for floor mounted unit (cultural noise of laboratory):



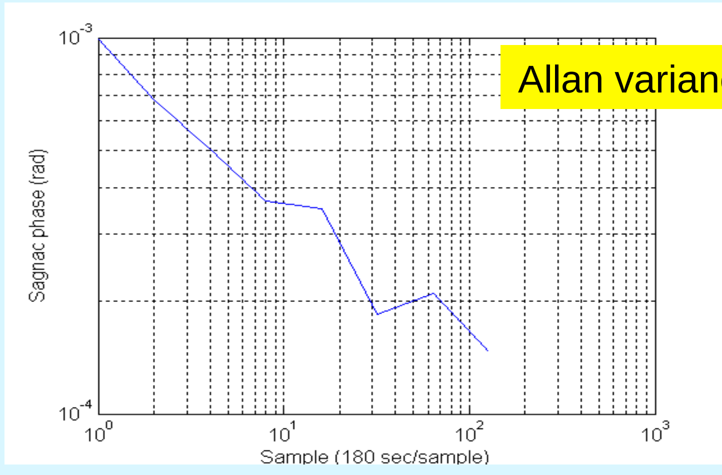
Inferred noise floor from independent tests



PSD for 20 hour record



Allan variance



Bias stability: < 60 mdeg/hr
Scale factor stability: < 5 ppm

Capteurs inertiels à ondes de matière

Interférométrie atomique

Historique

- 1923 : Louis de Broglie
- 1927 : interférence sur e⁻ (Davisson- Germer)
- 1974 : expérience COW (neutron lent)
- 1980 : écho de photon (Mossberg)
- 1991 : Sodium (Kasevich / Chu)
- 2001 : Formalisme ABCD abouti (Bordé)

Résultats

- Gyromètre (à jet thermique) : Kasevich 1991 :	$6.10^{-10}\ rad/s/\sqrt{Hz}$
- Gravimètre (à atomes froids) : Chu 1999 :	$5.10^{-9}\ g$ ou $2.10^{-8}\ g$ $3.10^{-9}\ g$ sur $60s$
- Gradiomètre : Kasevich 2000 :	$4.10^{-9}\ s^{-2}/\sqrt{Hz}$

En France, développements au SYRTE, IOTA, LPL, ONERA

AI inertial sensors: performance summary

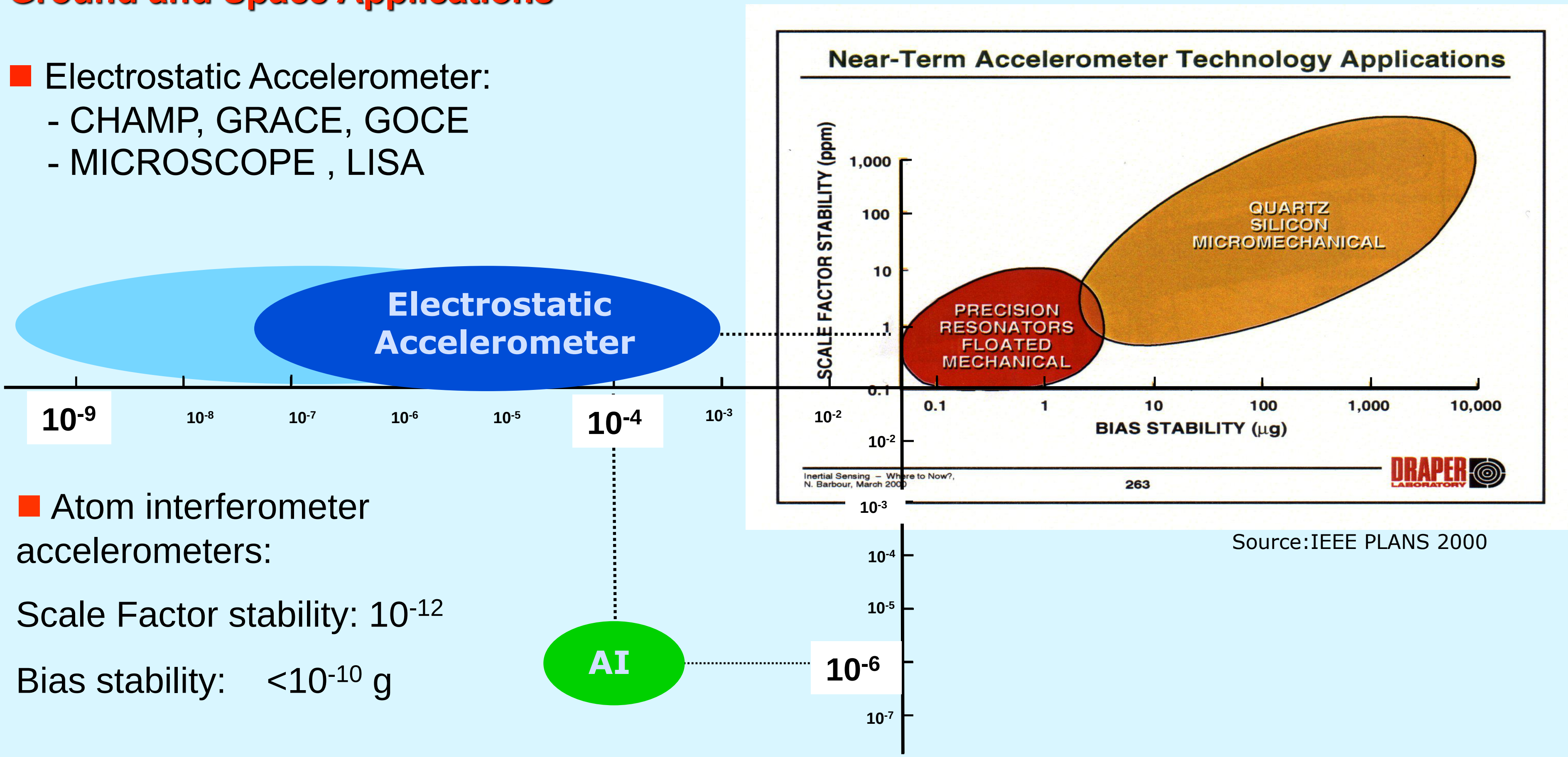
	Demonstrated ground	Anticipated ground	Projected space
Gyroscope ARW Bias stability Scale factor	2×10^{-6} deg/hr$^{1/2}$ 6×10^{-5} deg/hr 5 ppm	$<1 \times 10^{-6}$ deg/hr$^{1/2}$ $<10^{-5}$ deg/hr <1 ppm	$<10^{-8}$ deg/hr$^{1/2}$ $<10^{-7}$ deg/hr <1 ppm
Accelerometer Sensitivity Bias stability Scale factor	10^{-9} g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	$<10^{-10}$ g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	$<10^{-13}$ g/Hz$^{1/2}$ $<10^{-16}$ g ? $<10^{-12}$

Kasevitvh 2003

Accelerometer Technology

Ground and Space Applications

- Electrostatic Accelerometer:
  - CHAMP, GRACE, GOCE
  - MICROSCOPE , LISA



Source:IEEE PLANS 2000

- Atom interferometer accelerometers:

Scale Factor stability: 10^{-12}

Bias stability: $<10^{-10}$ g

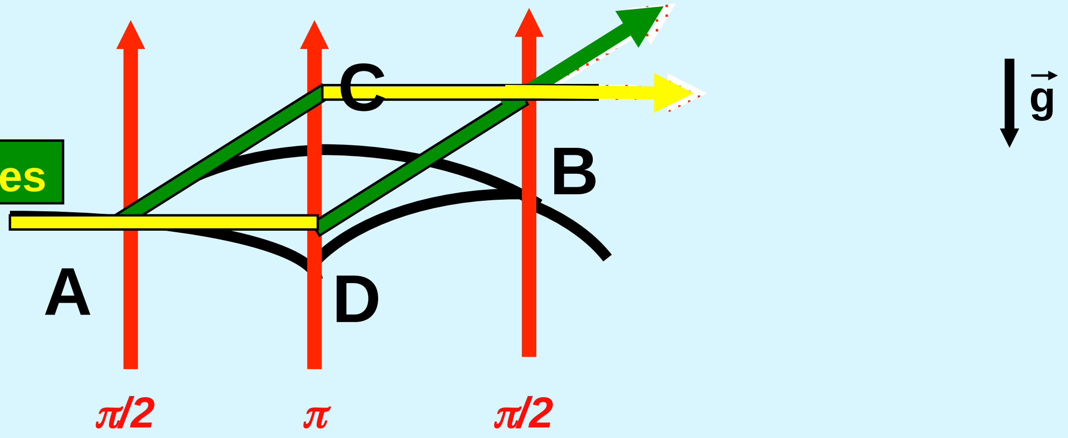
Excellent bias stability is required

Scale factor stability too, depending on s/c environment

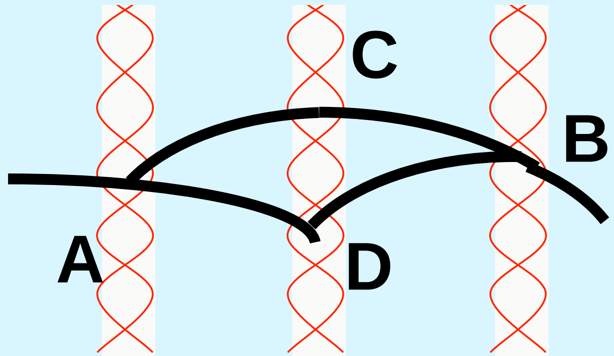
Other aspects : Absolute accuracy & frequency bandwidth

Capteurs inertiels à ondes de matière

Interférométrie atomique : Gravimètre

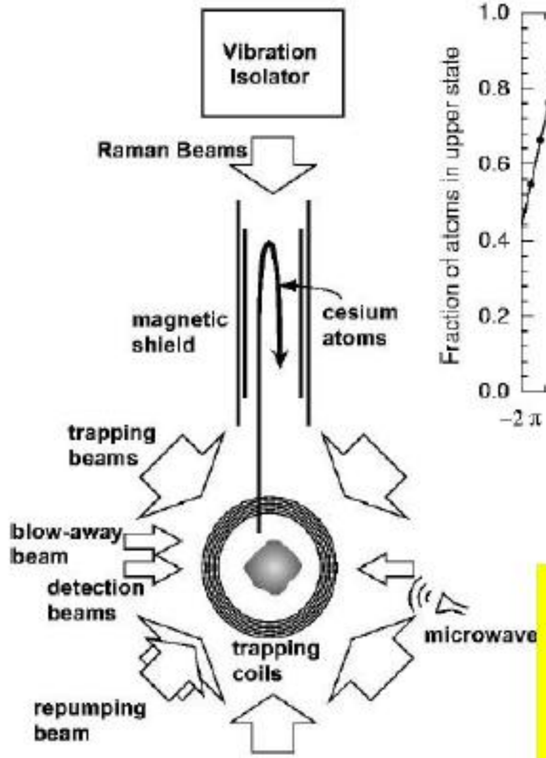


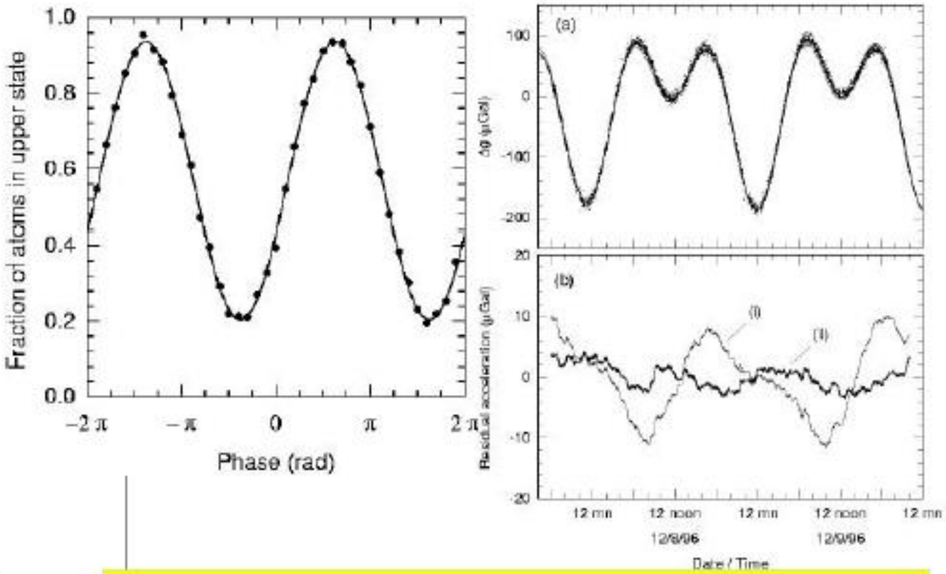
$\Delta\phi = -(k_L g T^2)$ provient du terme d'interaction $= k_L.(z_A - z_D + z_B - z_C)$



3 règles absolues à mesurer sont imprimées dans l'espace par les lasers, pour être lues 4 fois par les atomes

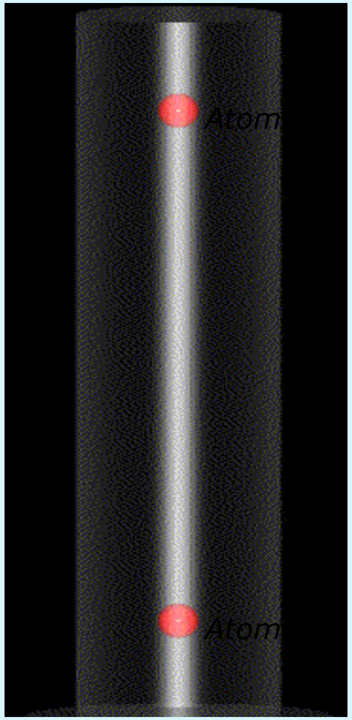
Gravimètre

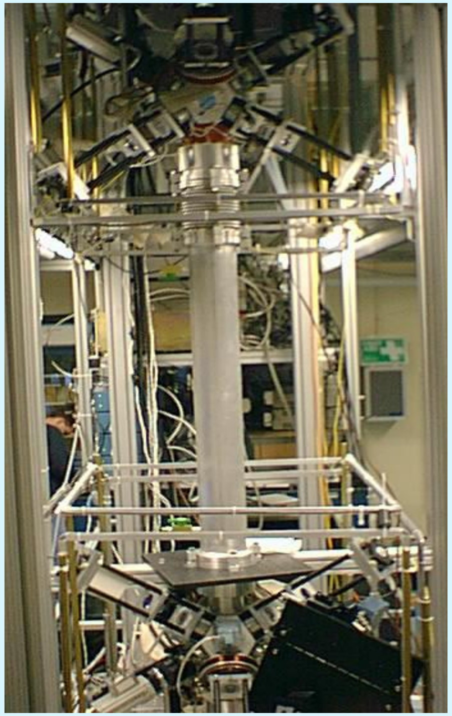




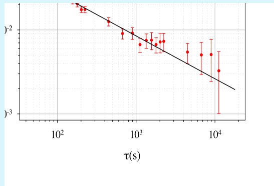
- **Performances:**
  - Resolution: $3x10^{-9}$ g after 1 minute
  - Absolute accuracy: $\Delta g/g<3x10^{-9}$
    - From A. Peters, K.Y. Chung and S. Chu

Stanford/Yale laboratory gravity gradiometer





1.4 m



Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

Demonstrated diffential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

Gravimètre

Calcul général et exact du déphasage ...

Formules disponibles :
- pour les gradients
- général en T et T '
- ...

which can be written to first-order in γ, with T=T':

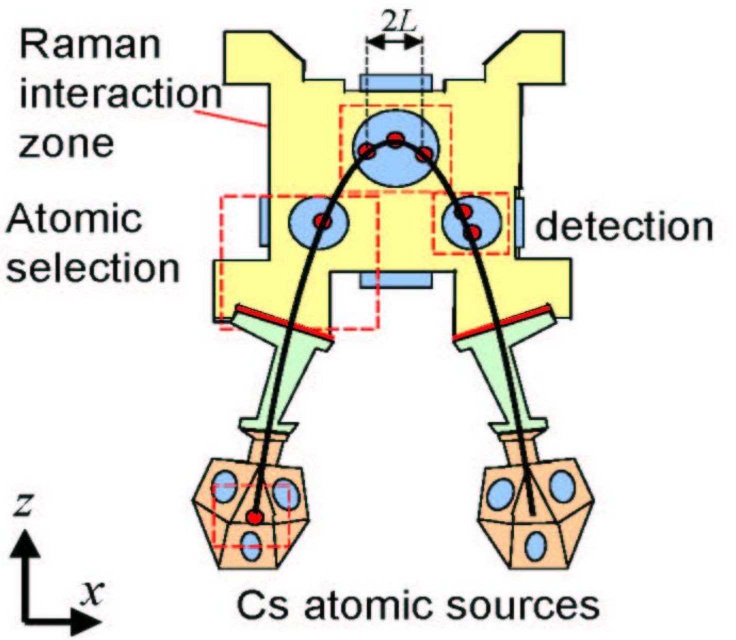
$$\delta\varphi = kgT^2 + k\gamma T^2\left[\frac{7}{12}gT^2 - \left(v_0 + \frac{\hbar k}{2M}\right)T - z_0\right]$$

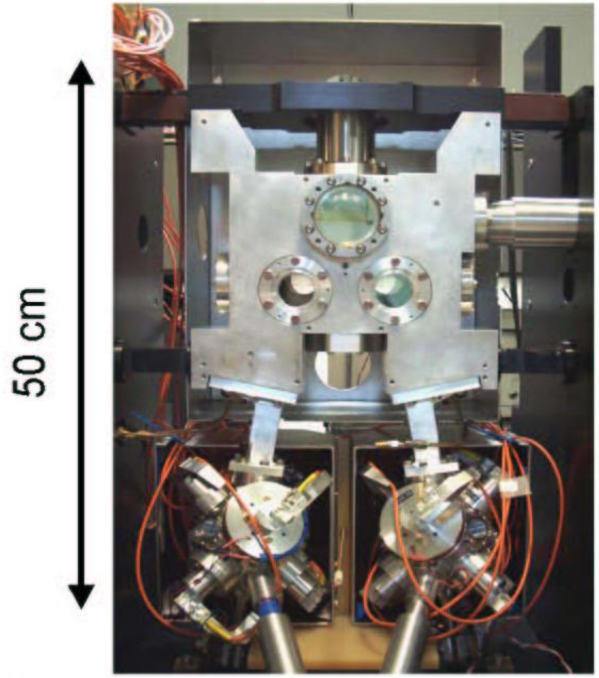
Reference: Ch. J. B., Theoretical tools for atom optics and interferometry, C.R. Acad. Sci. Paris, 2, Série IV, p. 509-530, 2001

Cold Atom Inertial Base

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

Courtesy of A. Landragin (Paris)





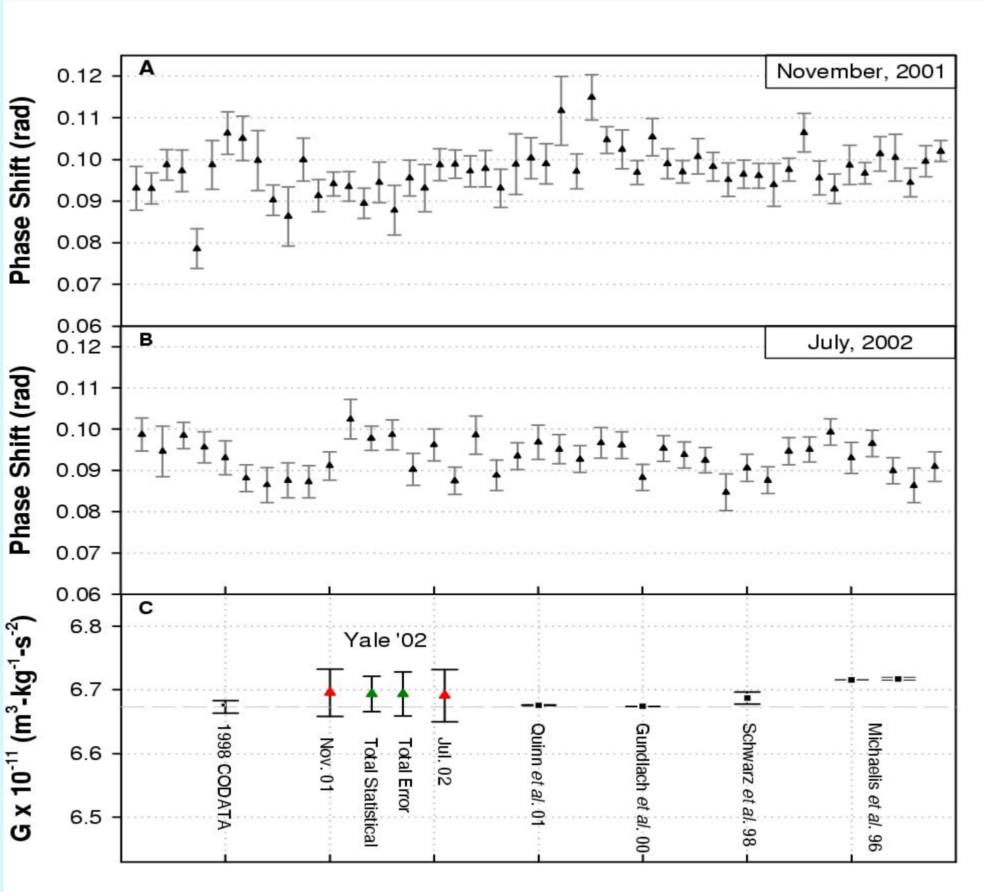
Launching velocity :
V = 2,6 m.s^{-1}
θ = 8°

Interrogation zone :
$2L$ = 30 mm
$2T$ = 100 ms
V_x = 30 cm.s^{-1}
area = 6 mm^2

Expected sensitivity of 30 nrad.s^{-1}.Hz$^{-1/2}$

Theoretical model (include. relativity) by C. Bordé

Measurement of G



Systematic	$\frac{\delta G}{G}$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

Present sensitivity/accuracy:

dG = 3 x 10^{-3} G

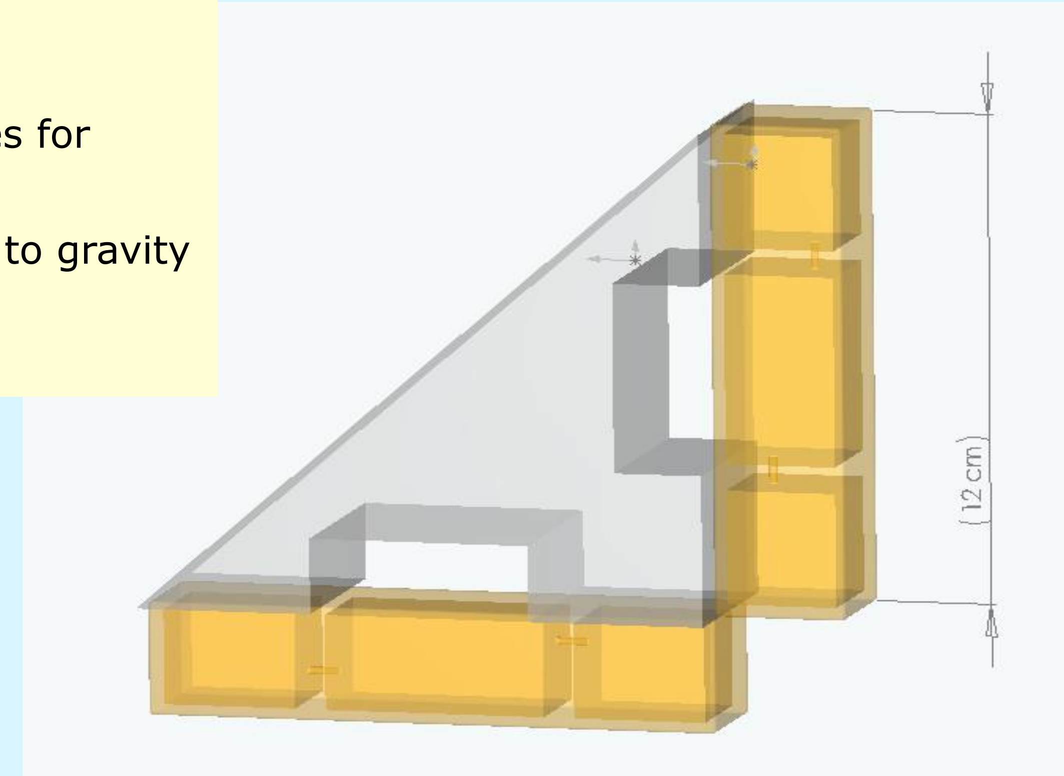
Measurement consistent with accepted value

IMU

DARPA PINS PRECISION INERTIAL NAVIGATION SYSTEMS

Full IMU/compact sensor arrangement:

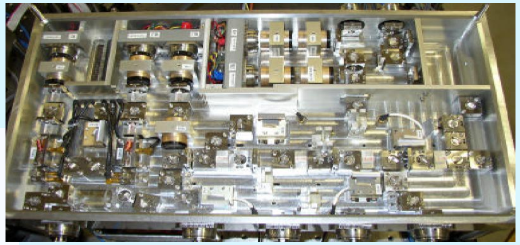
- 10 μdeg/hr$^{1/2}$ ARW (2.5 10^{-9} rd/s$^{1/2}$)
- 10^{-8} g/Hz$^{1/2}$ accel noise
- 100 Hz bandwidth
- Expected excellent bias stabilities for accel/gyro
- Laser/control electronics similar to gravity gradient sensor
- Robust



3 axes rotation + 3 acceleration

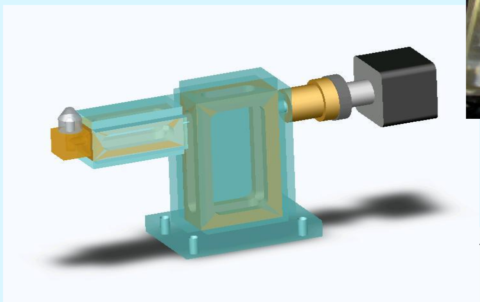
Gravity gradient sensor :

planar configuration developed by Stanford U.

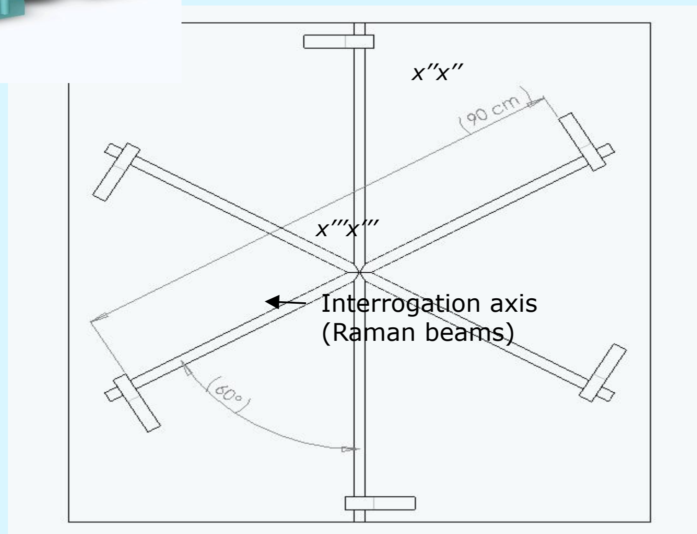


Laser system

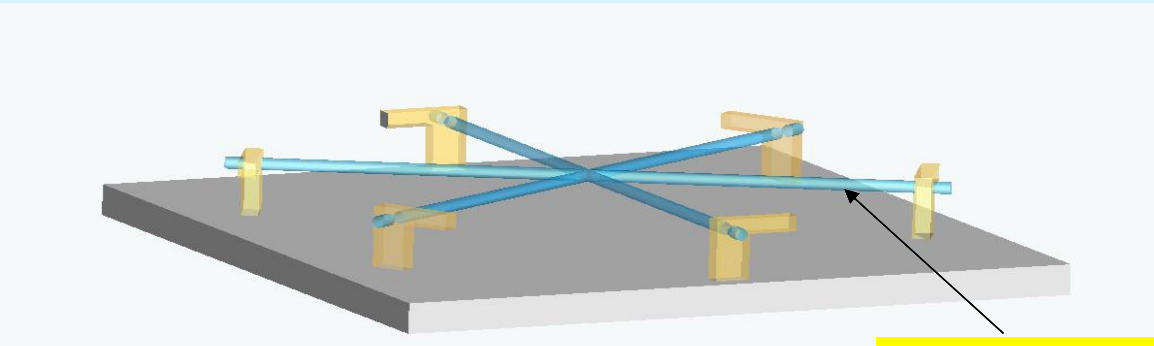
POC sensor: equilateral configuration minimizes sensor head count to achieve required gg tensors components



x′x′



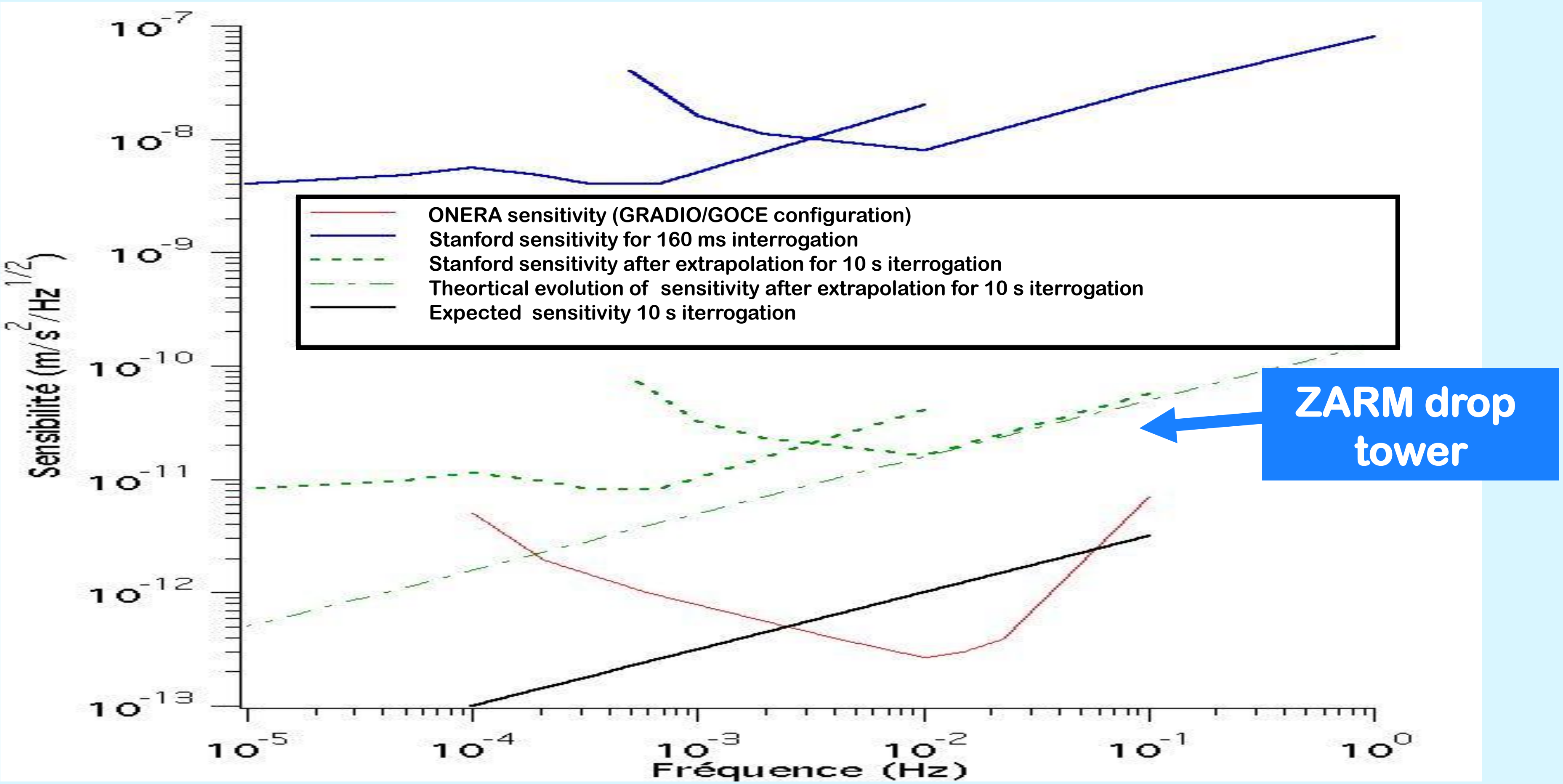
$$\begin{pmatrix} T_{xx} \\ T_{xy} \\ T_{yy} \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ -\frac{1}{3} & \frac{2}{3} & \frac{2}{3} \end{bmatrix} \begin{pmatrix} T_{x'x'}(0) \\ T_{x''x''}(\pi/3) \\ T_{x'''x'''}(2\pi/3) \end{pmatrix}$$



Laser beams for atom cooling not shown

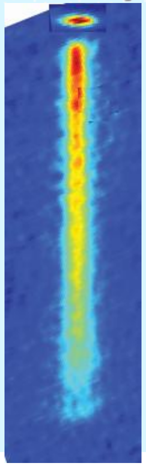
Raman laser beam for acceleration measurements

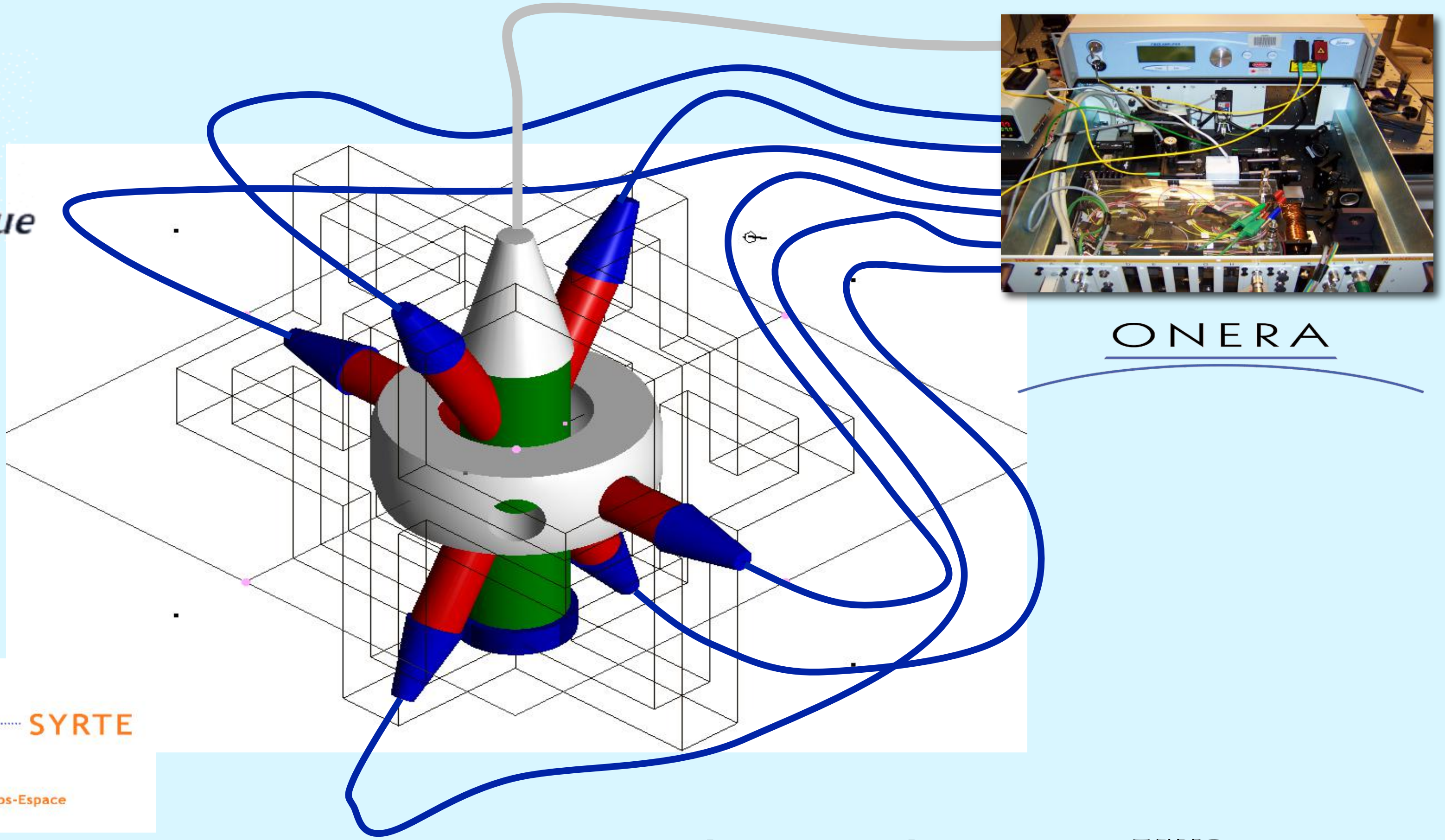
Accelerometry



DMPH

ICE : interferometry in 0-g with BEC





Proposed to Cnes in 2003

THE END

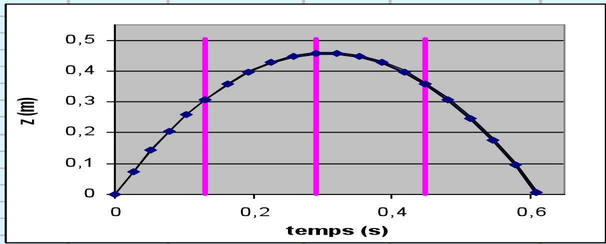
Gravimètre

Perfo - calcul simpliste … (exemple du cas A. Peters/ S. Chu)

Lbda =	852	nm	→	keff =	14749261,3 m-1
masse atome =	133	uma	→	masse =	2,21E-25 kg
N =	?	atomes		Vrecul =	7,05E-03 m/s
T =	1,5	µK	→	δv thermique =	0,0096829 m/s
T lancement =	0,13	s		δx en fin =	11,8131342 mm
T entre Raman =	0,16	s			
T détection =	0,16	s			
g =	9,8	m/s/s	→	dphi(g)=	3700294,67
v lancement =	3	m/s		hmax =	0,45918367 m
detection monocoup a la frange sur	**85**				

uma	1,66E-27	kg
k	1,38E-23	J/K
h	6,63E-34	J.s
pi	3,14E+00	

dg/g = 2,00E-08
20,0 µGal



	temps	Pulses	Vz	z	z-	z+
Lancement	0		3	0	0	0
	0,026		2,7452	0,07	0,074435845	0,07493936
	0,052		2,4904	0,14	0,142246889	0,14325391
	0,078		2,2356	0,2	0,203433134	0,20494367
	0,104		1,9808	0,26	0,257994579	0,26000862
	0,13	0	1,726	0,31	0,305931223	0,30844878
Pulse π/2	0,13	0,505102	1,726	0,31	0,305931223	0,30844878
	0,162		1,4124	0,36	0,355835771	0,35897303
	0,194		1,0988	0,4	0,395705118	0,39946208
	0,226		0,7852	0,43	0,425539265	0,42991593
	0,258		0,4716	0,45	0,445338213	0,45033459
	0,29	0	0,158	0,46	0,45510196	0,46071804
pulse π	0,29	0,505102	0,158	0,46	0,45510196	0,46071804
	0,322		-0,1556	0,46	0,454830507	0,46106629
	0,354		-0,4692	0,45	0,444523854	0,45137935
	0,386		-0,7828	0,43	0,424182002	0,4316572
	0,418		-1,0964	0,4	0,393804949	0,40189985
	0,45	0	-1,41	0,36	0,353392696	0,3621073
pulse π/2	0,45	0,505102	-1,41	0,36	0,353392696	0,3621073
	0,482		-1,7236	0,31	0,302945244	0,31227956
	0,514		-2,0372	0,25	0,242462591	0,25241661
	0,546		-2,3508	0,18	0,171944738	0,18251846
	0,578		-2,6644	0,1	0,091391686	0,10258511
	0,61		-2,978	0,01	0,000803433	0,01261657
Détection	0,61		-2,978	0,01	0,000803433	0,01261657

Gravimètre

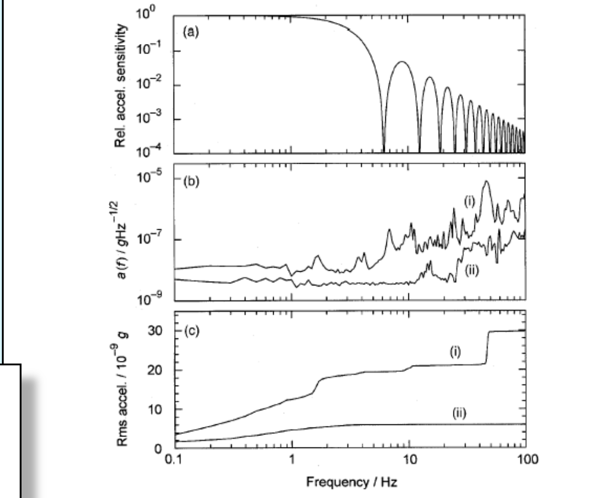
Points importants non abordés :

- déplacements lumineux
  (effet Stark AC/DC)

- asservissement du miroir Raman

- sources de bruit :
  bruit de phase haute fréquence,
  vibration, rotation, intensité laser, …

Noise source	S/N	σ_g/µGal
Atom shot noise (3×10^6 atoms)	1700	0.16
Detection noise	300	0.9
Loran-C frequency stability	95	3.0
Raman laser intensity noise	75	3.5
Residual vibrations and rotations	55	5
Background fluctuations	40	7
High-frequency phase noise	25	11
Overall known noise sources	**18**	**15**
Observed noise	**14**	**19**



...igure 20. Effect of vibrations. (a) Relative sensitivity to different vibrational frequencies for an interferometer pulse ...acing of T = 160 ms. (b) Vibration-isolator error signal: $a(f)$ is the acceleration noise spectral density (i) before ...d (ii) after implementing improvements. (c) Predicted noise of interferometer signal due to vibrations (weighted) ...tegrated up to a certain frequency (i) before and (ii) after the improvements.

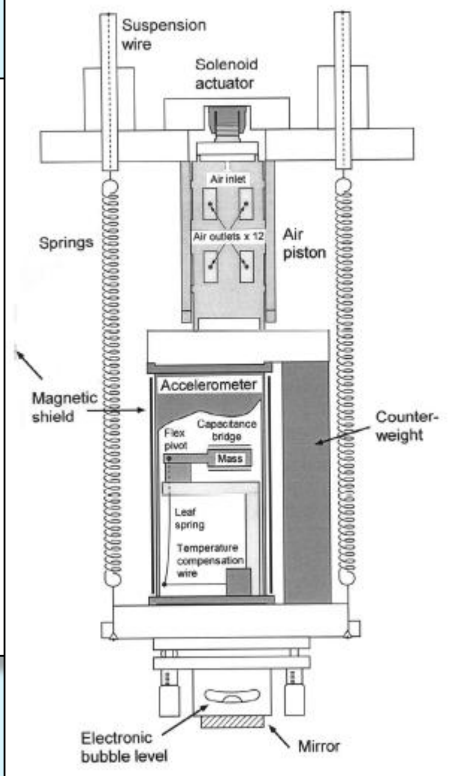
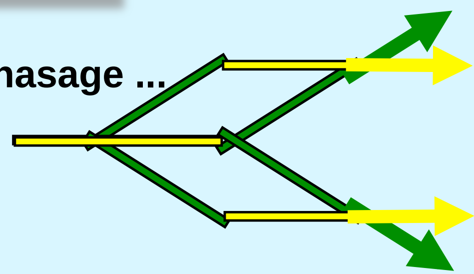


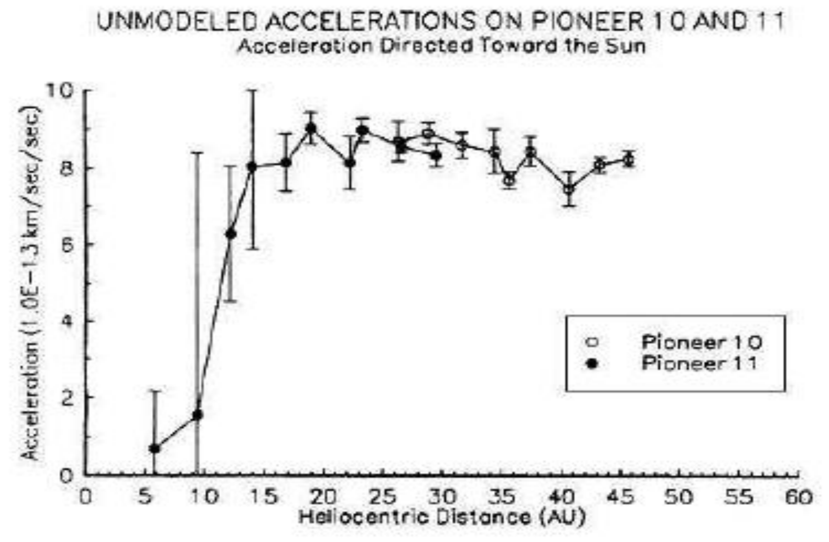
Figure 16. Mechanical system of the vibration isolator.

Metrologia, 2001, **38**, 25-61

- double interféromètre : même déphasage …



Long distance acceleration measurement :
« Pionner effect »



$A \approx 8 \times 10^{-10}\ m/s^2$

FIG. 1: Unmodelled acceleration as a function of distance from the sun, by Anderson *et al.* [3].

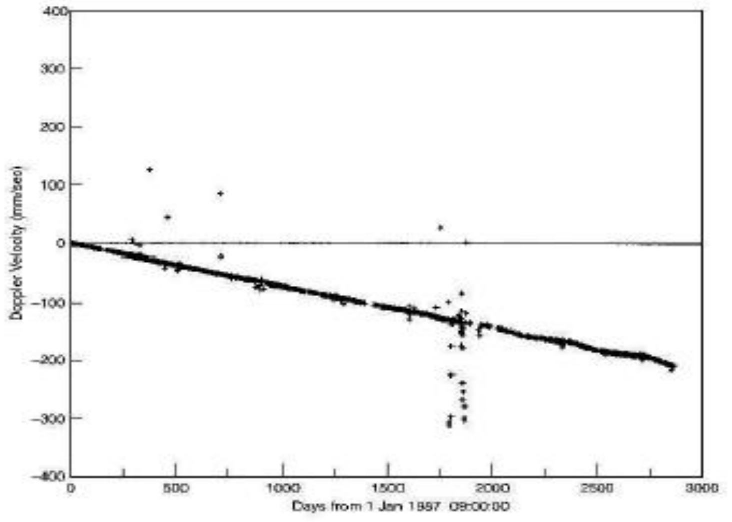
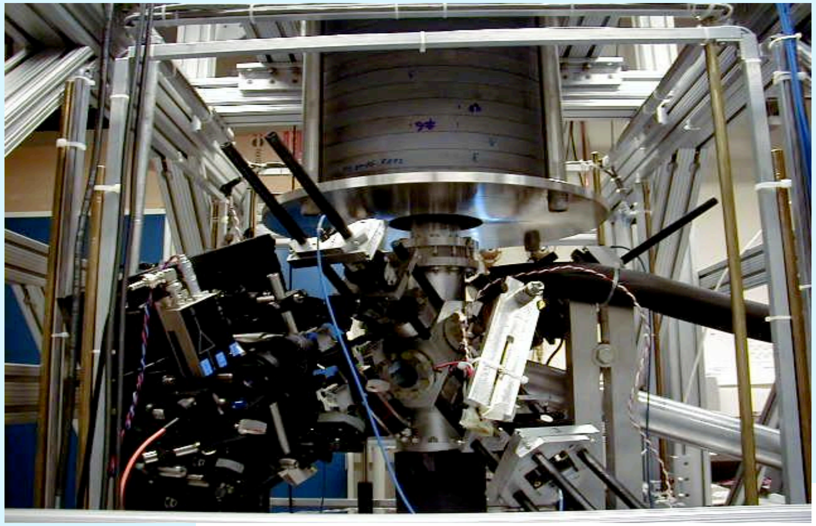


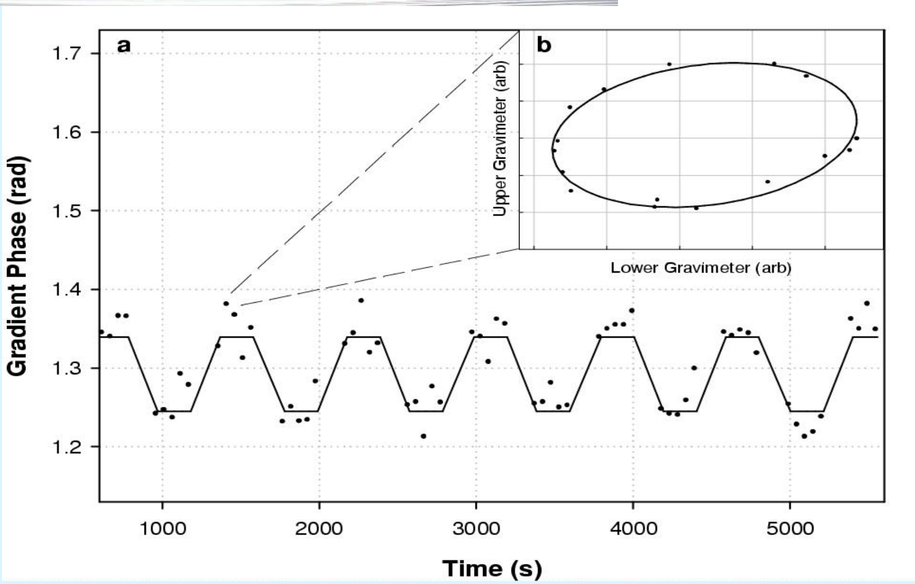
FIG. 8: CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs. time. 1 Hz is equal to 65 mm/s range change per second. The model is fully-relativistic. The solar system's gravitational field is represented by the Sun and its planetary systems [49].

DMPH

Gravity gradiometer: measurement of G



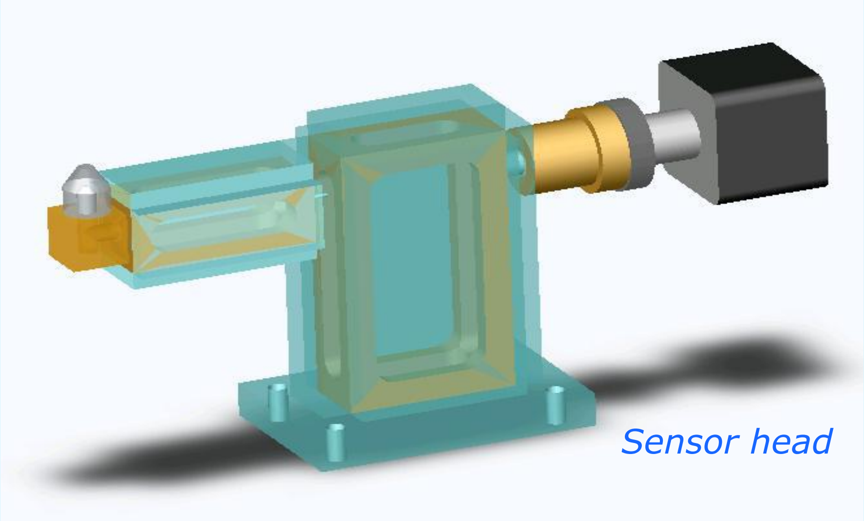
Pb mass translated vertically along gradient measurement axis.



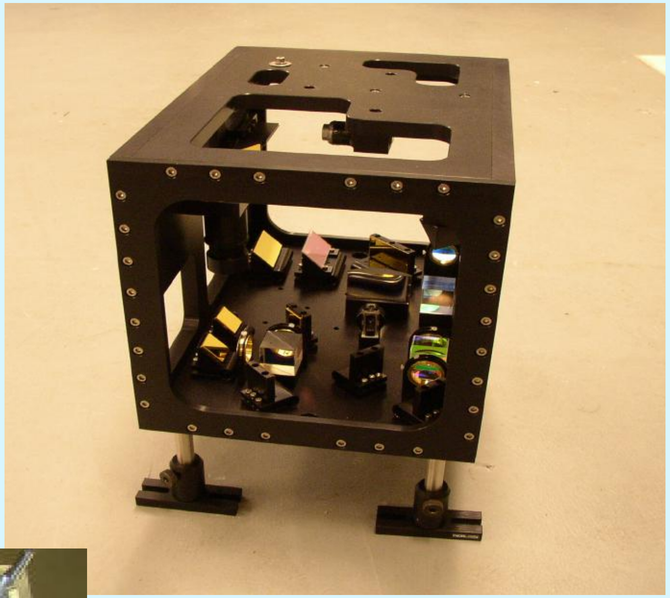
Typical data:

~1x10^{-8} g change in acceleration due to gravitational forces for different Pb positions

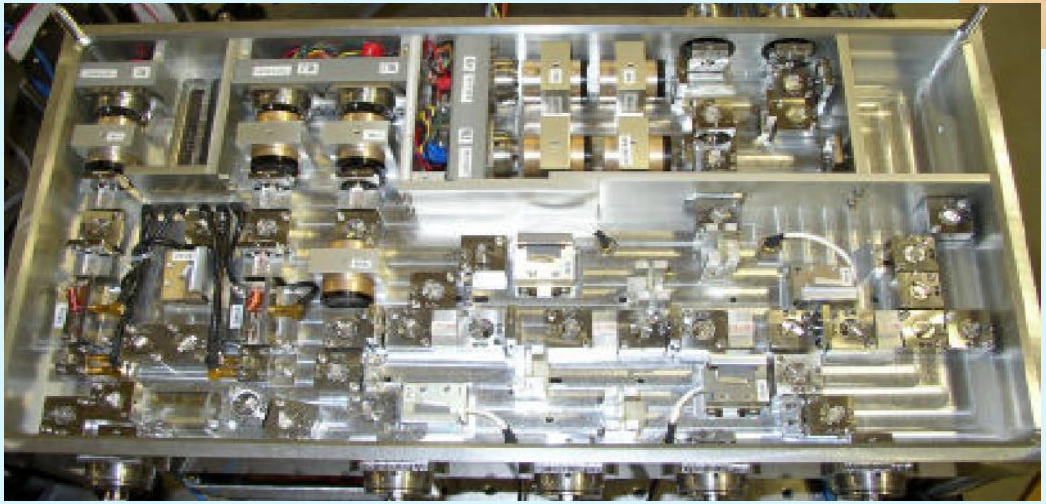
Prototype field ready sensor



Sensor head



Sensor optomechanics



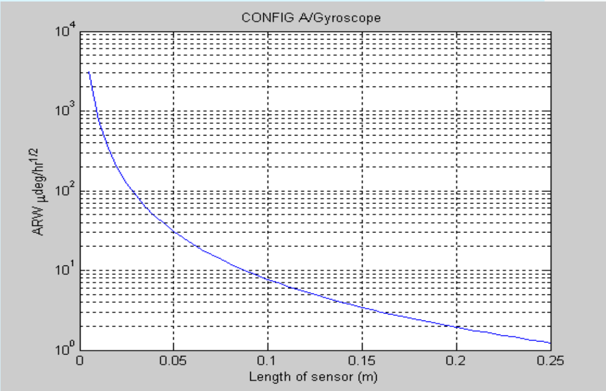
Laser system

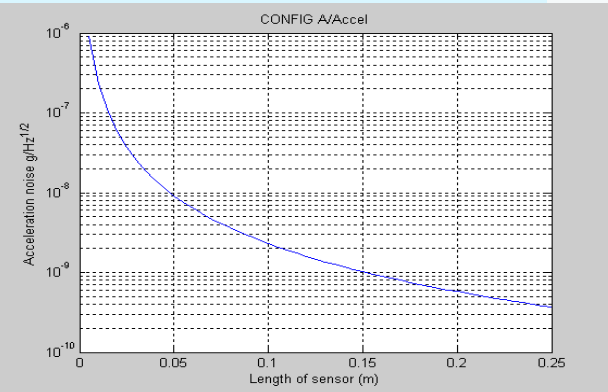
DMPH

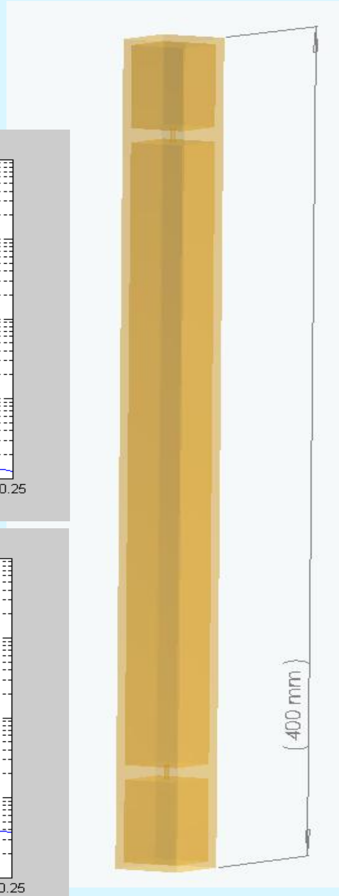
Gyroscope

PRECISION INERTIAL NAVIGATION SYSTEMS

High sensitivity 2 axis gyro + 2 axis accelerometer:





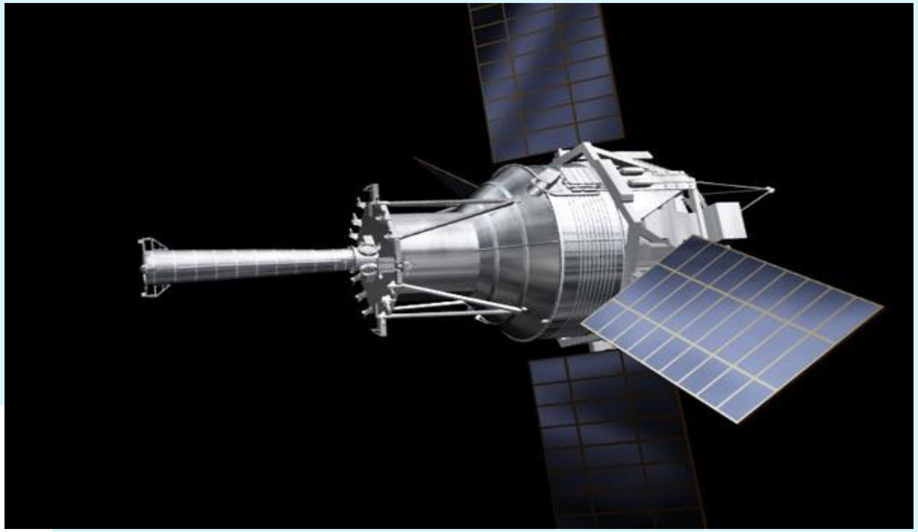


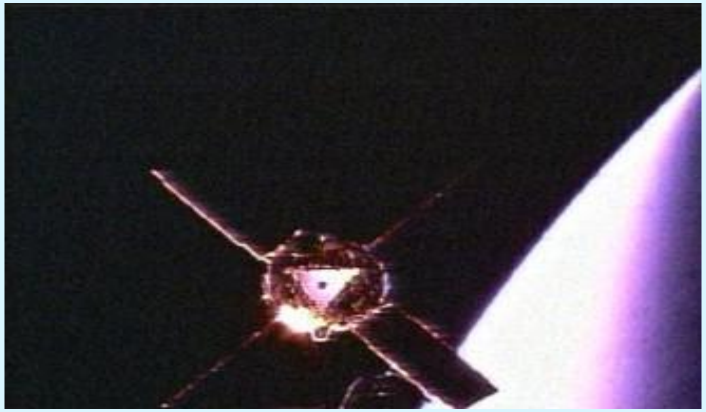
Gyroscope (~30 cm length, vertically oriented)
ARW = 0.88 microdeg/hr1/2
Bandwidth 10 Hz

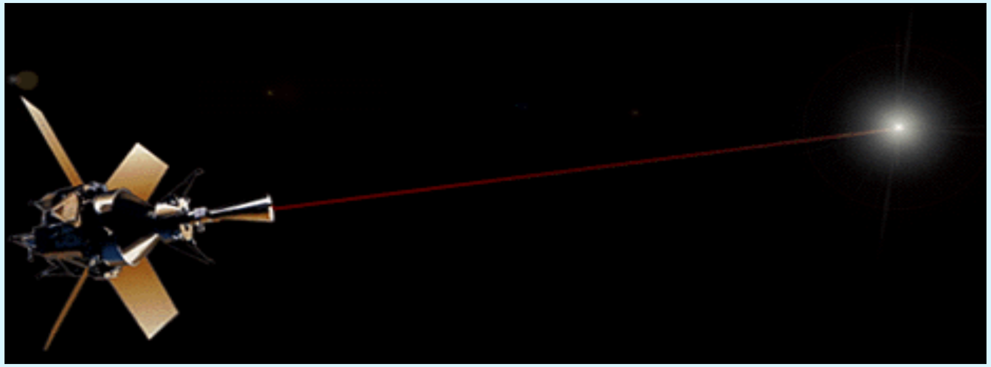
```
hbar = 1.054571596e-34;
m = 2.2085e-025;
k1 =   6*7.3833e+006;     Propagation vector
k2 =   6*7.3833e+006;
k3 =   6*7.3833e+006;
R = 6e6;
g3 = -9.8;
w2 = 7e-5;                Rotation rates (Earth rate for ref)
w3=7e-5;
T = 0.03;
v3 = 5;
Txx = 1.5e-6;             Gravity gradient
Tyy = 1.5e-6;
Tzz = -3.0e-6;
Txy = 1.5e-6;
Txz = 1.5e-6;
Tyz = 1.5e-6;
xg1 = .0001;              Position errors
xg2 = 1;
xg3 = .0001;
dv2 = .0001;              Velocity errors
dv3 = .0001;
dv1 = .0001;
dk1 = 1e-6*k1;            Alignment error
dk2 = 1e-6*k2;
dk3 = 1e-6*k3;
```

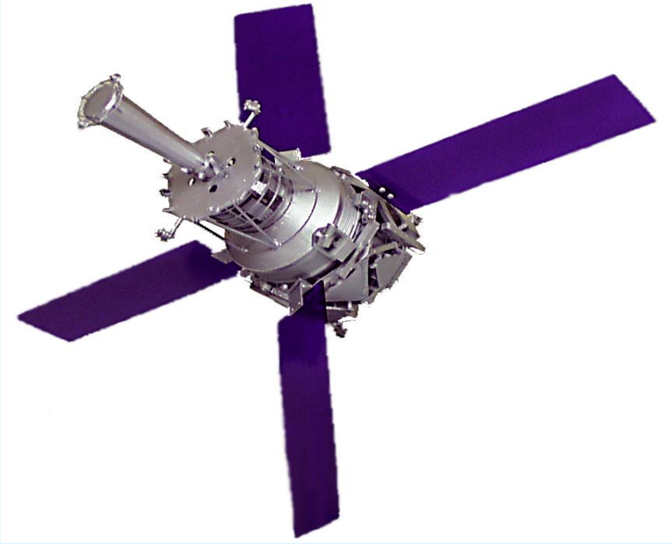
Term	Phase shift	Relative error
-2*T^2*w2*k1*v3	-2.791e+001	-1.000e+000
-2*T^3*w2*g3*k1	1.641e+000	5.880e-002
T^2*dk3*g3	-3.907e-001	-1.400e-002
T^3*Txz*v3*k1	8.971e-003	3.214e-004
-2*T^3*k1*w2*R*w3^2	-4.923e-003	-1.764e-004
-2*T^3*k1*w2^3*R	-4.923e-003	-1.764e-004
-T^2*w2*R*w3*dk2	-1.172e-003	-4.200e-005
T^2*w2^2*R*dk3	1.172e-003	4.200e-005
-2*T^2*w2*k1*dv3	-5.582e-004	-2.000e-005
2*T^2*w3*dv2*k1	5.582e-004	2.000e-005
7/12*T^4*Txz*g3*k1	-3.077e-004	-1.103e-005
1/2/m*T^3*Txx*hbar*k1^2	1.898e-005	6.799e-007
-7/12*T^4*Txy*w2*w3*R*k1	-9.231e-007	-3.307e-008
7/12*T^4*Txz*w2^2*R*k1	9.231e-007	3.307e-008
-3/2/m*T^3*w2^2*hbar*k1^2	-1.860e-007	-6.663e-009
-3/2/m*T^3*w3^2*hbar*k1^2	-1.860e-007	-6.663e-009
T^3*Txz*dv3*k1	1.794e-007	6.429e-009
T^3*Txx*dv1*k1	1.794e-007	6.429e-009
T^3*Txy*dv2*k1	1.794e-007	6.429e-009
17/6*T^4*Tzz*k1*w2*v3	-1.068e-007	-3.825e-009
-17/6*T^4*Tyz*w3*v3*k1	-5.338e-008	-1.912e-009
-7/6*T^4*Txx*k1*w2*v3	-2.198e-008	-7.875e-010
T^3*Tzz*v3*dk3	-1.794e-008	-6.429e-010

DMPH









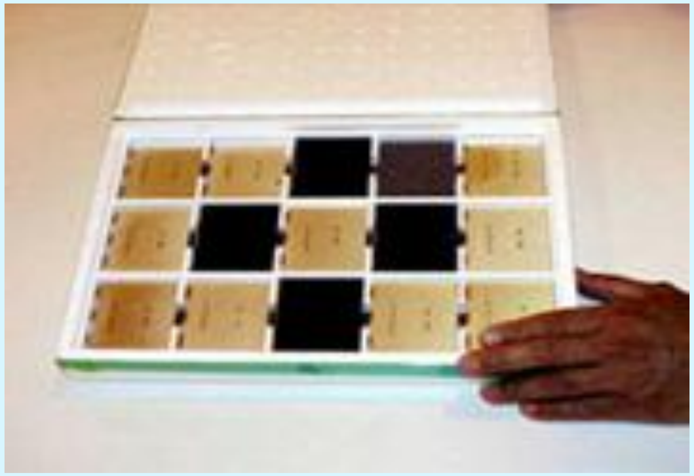
The Solar Arrays

so·lar cell

def: A semiconductor device that converts the energy of sunlight into electric energy. Also called a photovoltaic cell.

SOLAR ARRAYS FACTS

- Each panel is 3.5 meters long by 1.3 meters wide
- The release mechanism is made up of Nitinol rods, commonly called "memory metal". When the rods are heated, they change shape and release the panels.
- The 9,552 individual Gallium Arsinide solar cells have an effeciency of 18.5%
- The total power needed to run the entire satellite would barely power the average microwave.



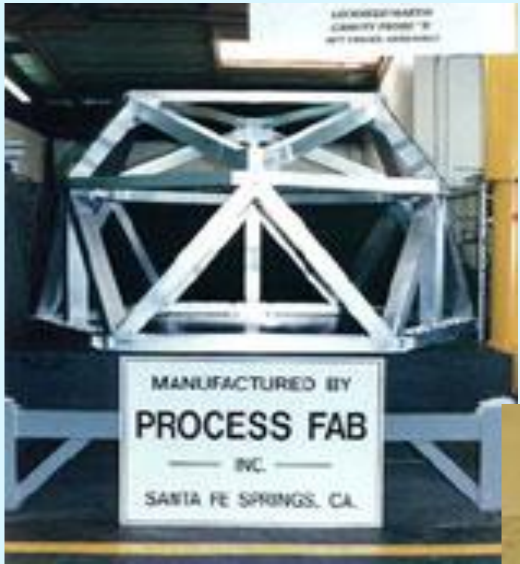
The Truss Structure

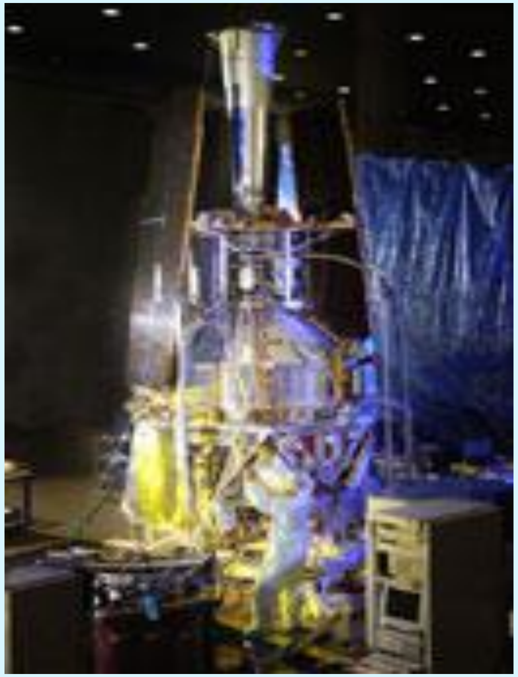
Truss

def: An engineered structure of short framing members, such as beams, chords, and diagonals, assembled into a rigid support structure.

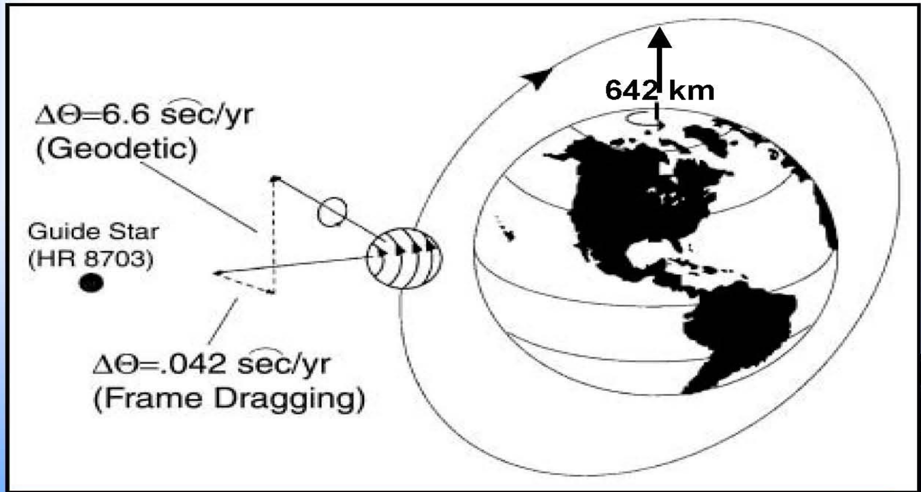
TRUSS STRUCTURE FACTS

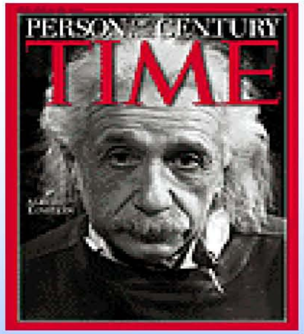
- The truss structure is made of aluminum alloy beams, heliarc welded at the joints. Mechanical joints were not stiff enough to maintain the satellite's critical geometry.
- The structure's "open" frame design exposes the dewar to space, improving heat radiation.
- Equipment is attached by self-integrated pallets. Individual subsystems can be removed without disassembling the entire space craft.





The Relativity Mission Concept
(Invented in 1959)

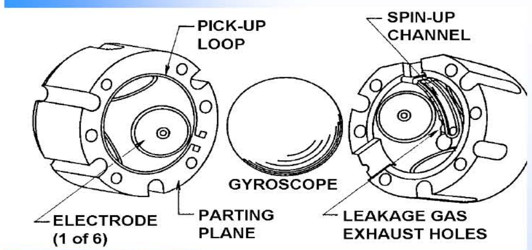




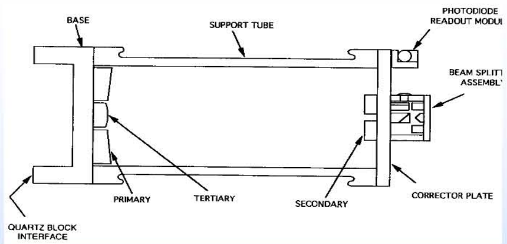
$$\overline{\Omega} = \left(\gamma+\frac{1}{2}\right)\frac{GM}{c^2R^3}(\overline{R}\times\overline{v}) + \left(\gamma+1+\frac{\alpha_1}{4}\right)\frac{GI}{2c^2R^3}\left[\frac{3\overline{R}}{R^2}\cdot(\overline{\omega}_e\cdot\overline{R})-\overline{\omega}_e\right]$$

DMPH

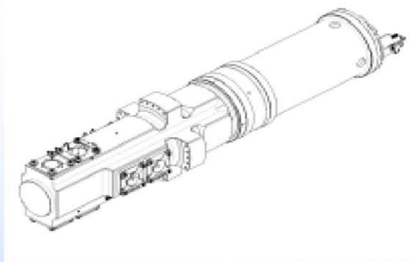
Main GP-B Systems



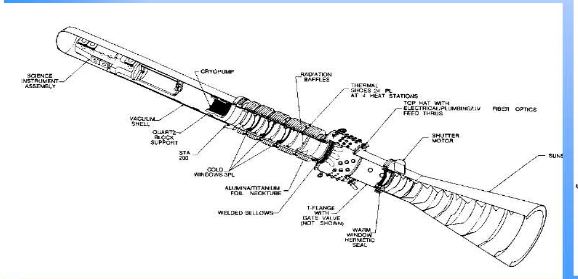
Gyroscope



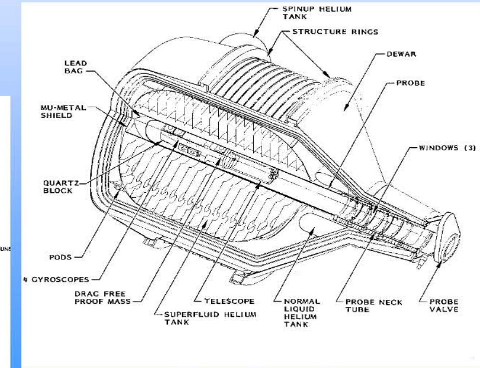
Telescope



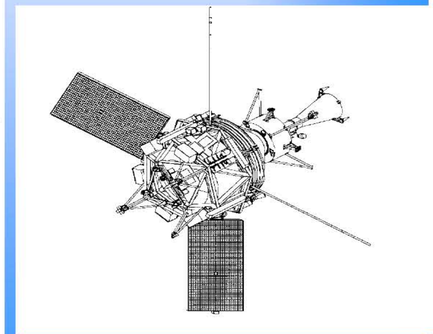
Science Instrument



Cryogenic Probe



Payload



Space Vehicle

20 MAR 2003

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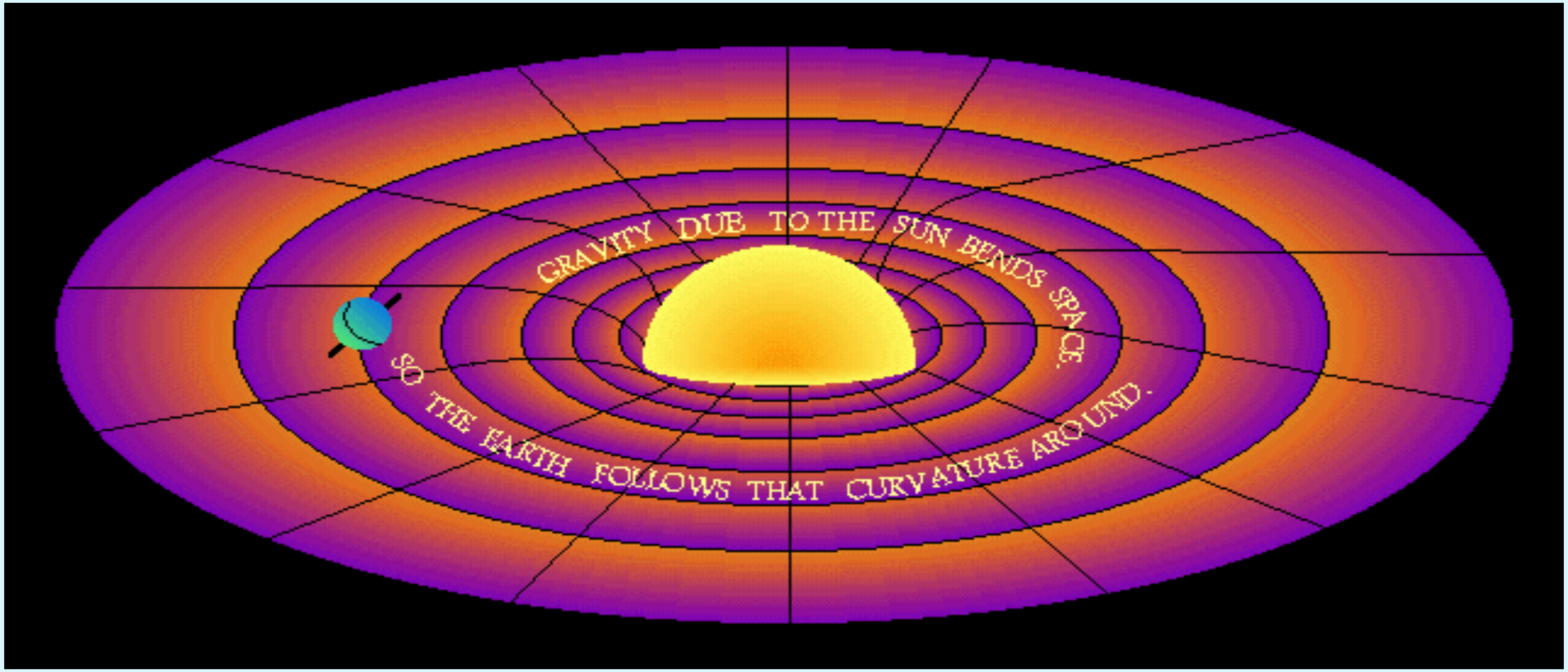
GRAVITY DUE TO THE SUN BENDS SPACE.
SO THE EARTH FOLLOWS THAT CURVATURE AROUND.

DMPH