17 – 24 April 2005, Baksan School “Particles & Cosmology”

Equivalence Principle
and
A new phase of GR test

V.N.Rudenko (SAI MSU)

Contents

EP Û GR mutual relation

EP – “free fall universality”

$\Downarrow$

Geometrization of Gravity

$j \rightarrow g_{ik}$; $c \neq \infty$

$\Downarrow$

$$R_{ik} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^2} T_{ik}$$

$\Uparrow$

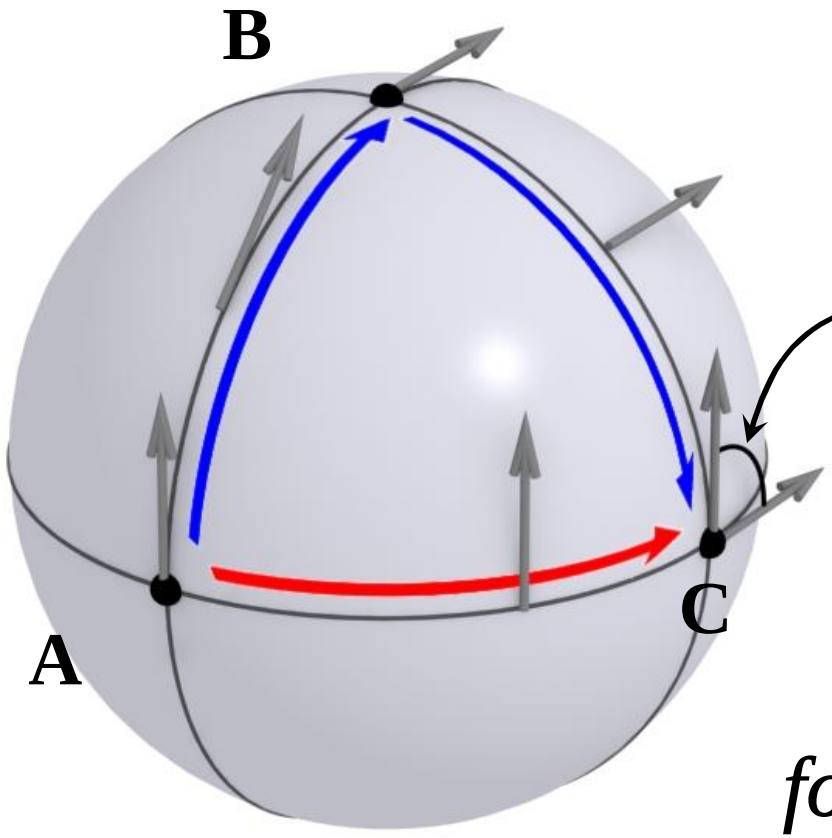
Λg_{ik}

Experimental Proves of GR

- gravitational red shift + 0.01% GP-A
- light beam deflection +
- planet orbit precession +
- EM-signals delay +
- relativistic precession of gyro ?

- gravitational waves .....?
- black holes (+) ! ?-
- cosmological expansion (+) ! ?

$$dS^2 = (1 - (r_g/r) + \gamma(r_g/r)^2 + ...)\, dt^2 - (1 + (r_g/r) + \beta\,(r_g/r)^2 + ...)\, dl^2$$



for closed loop:

$$dj = \int_S k(p)\,ds$$

for sphere $k(p) \equiv k$ *then:*

$$dj = kS = \frac{p}{2} \qquad S = \frac{4pR^2}{8} \equiv \frac{1}{2}pR^2$$

$$k = 1/R^2$$

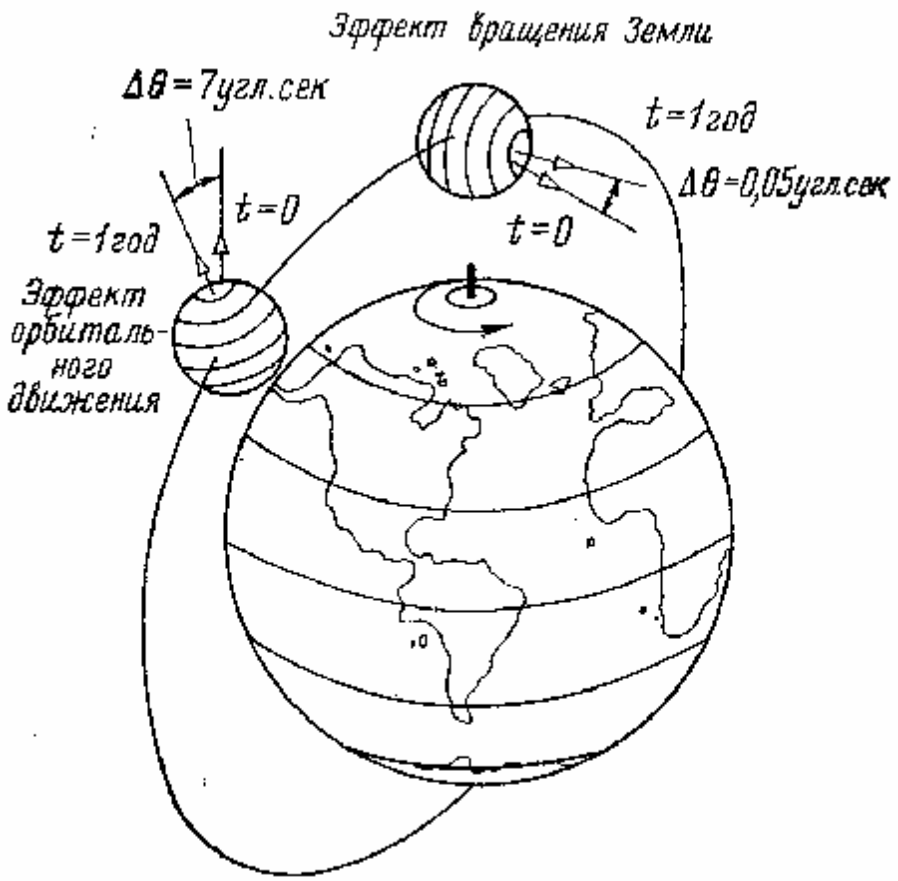
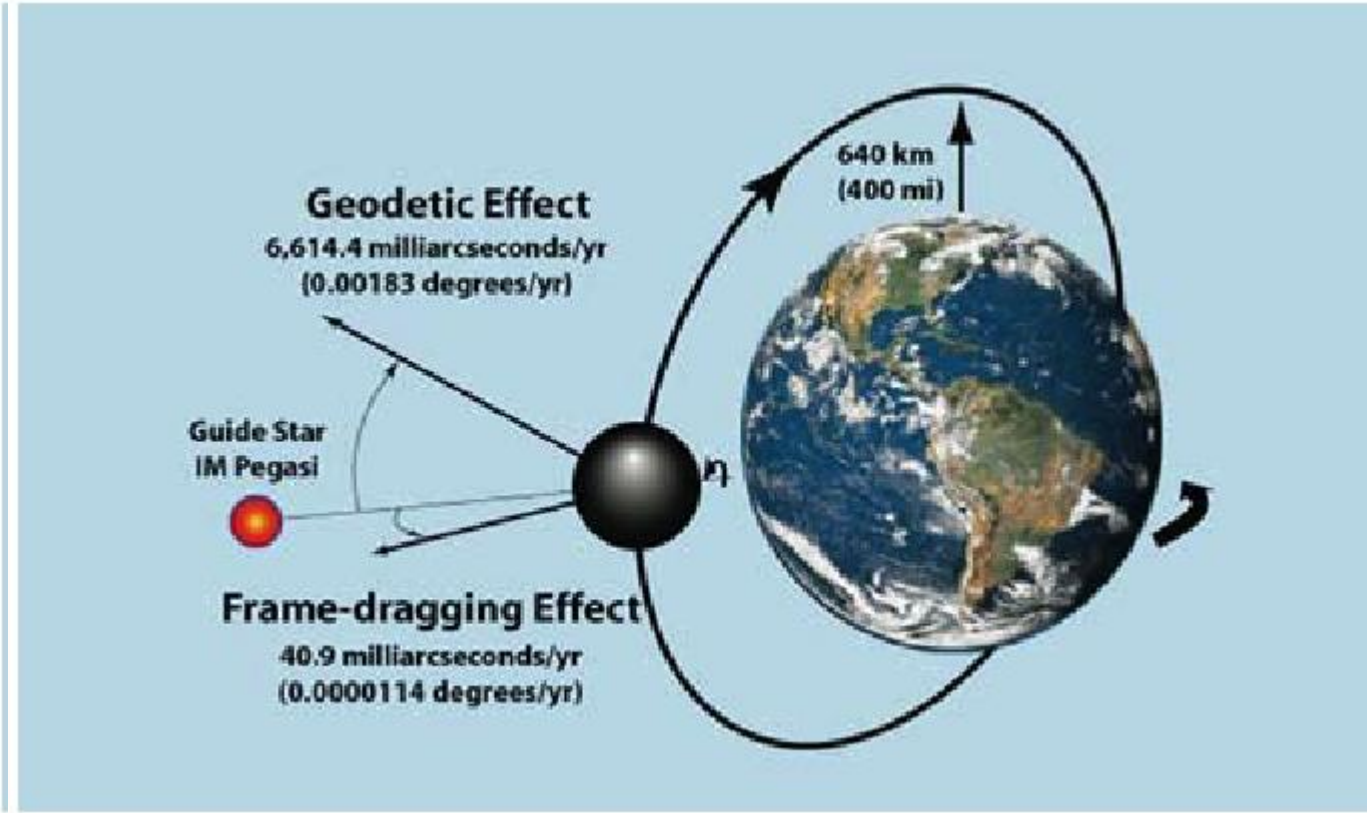


Рис. 6.

УФН, 1970, т.100, в.3, с.395. «Релятивистские гравитационные эксперименты»
В.Брагинский, В.Руденко

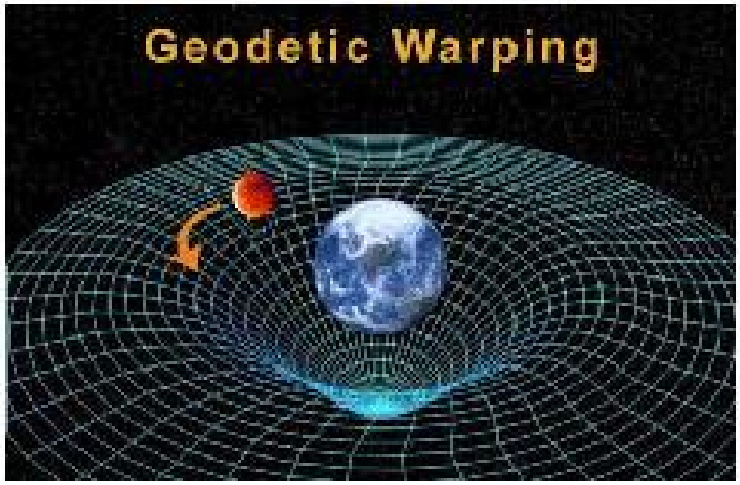
Gyroscope at the Earth's orbit



L.Schiff , 1960 (just NASA was launched its 1st satellite)

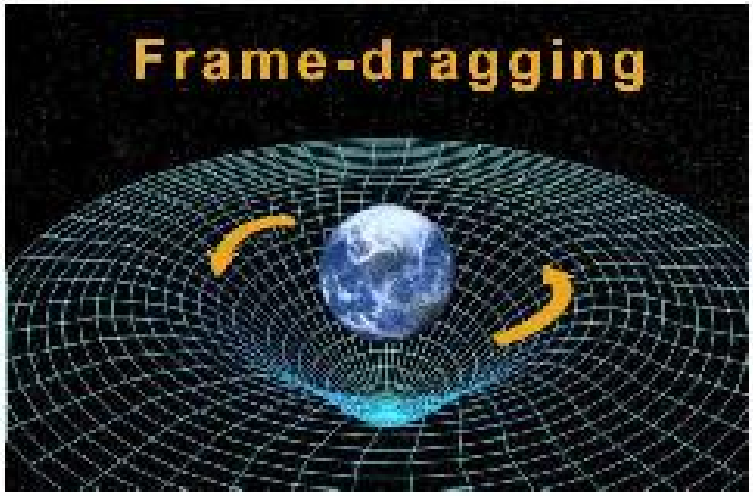
W.Fairbank, L.Schiff , 1961, first conceptual proposal

for NASA gyroscope experiment



Geodesic precession

6.6 arcsec/y;
m.accuracy (+-) 0.01%

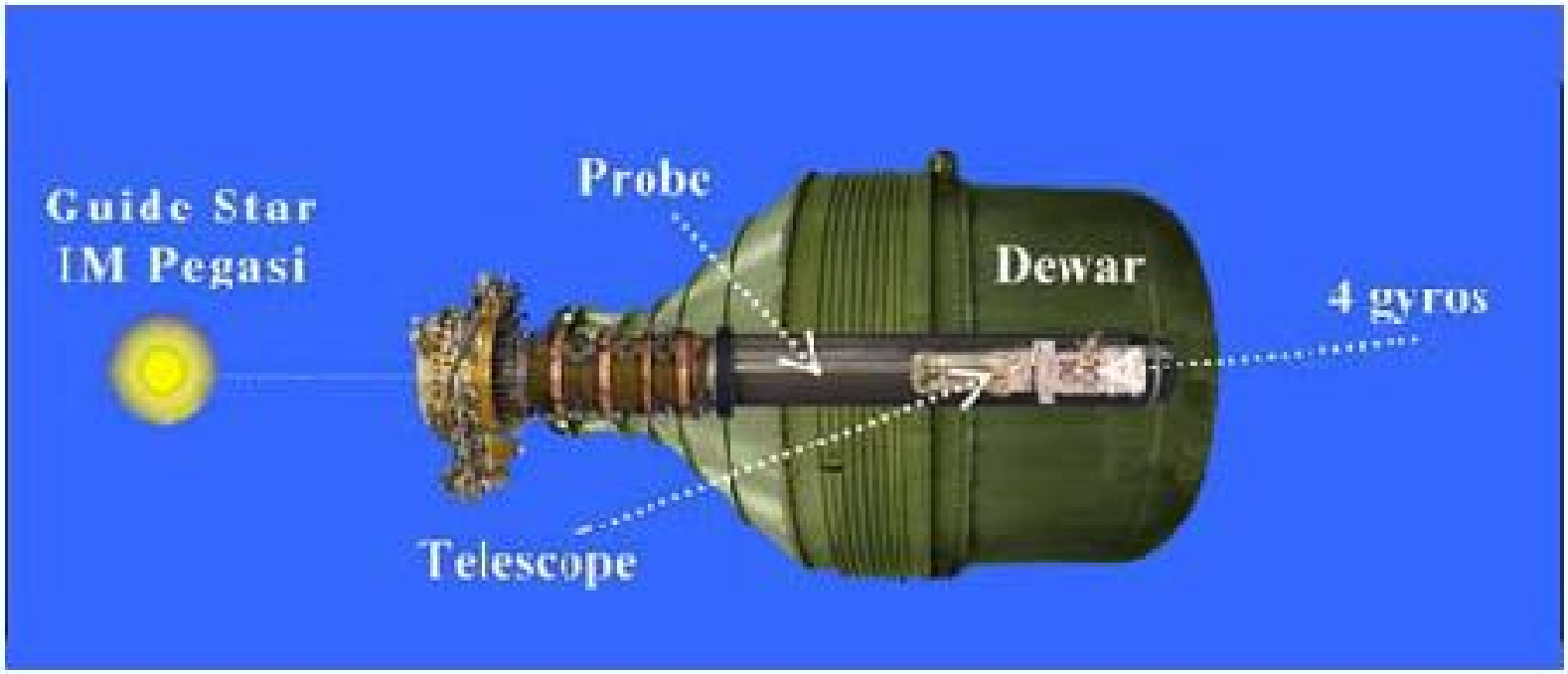


LT-precession

0.04 arcsec/y;

m.accuracy (+-) 1 %

GP-B spacecraft design



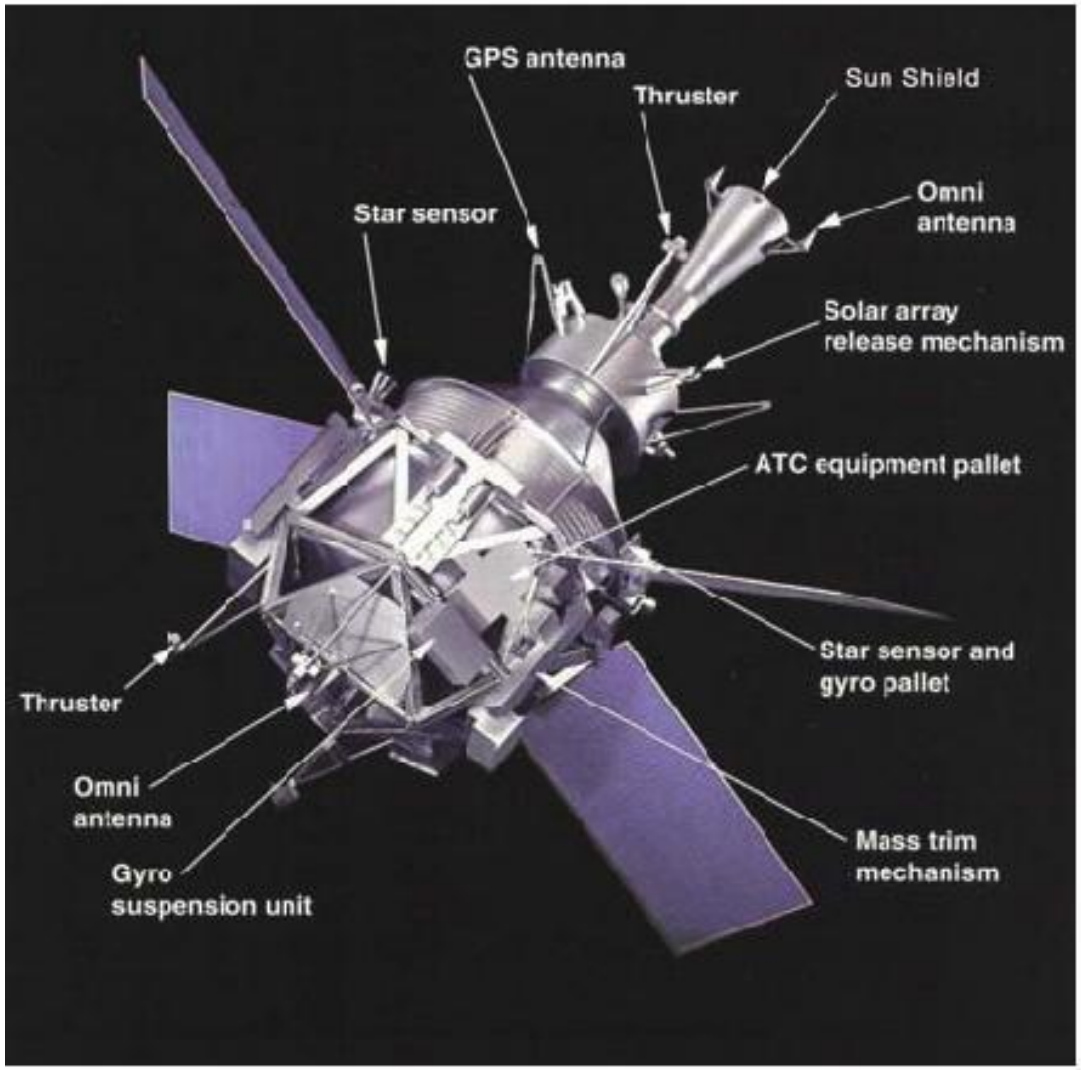
Polar-orbiting satellite with four ultra-precise spherical gyroscopes and a telescope aligned with a distant «guide» star; all instruments are located inside the helium dewar along its main axis

Launch, Monday 20 April, 2004, Vandenberg Air Force Base, CA.

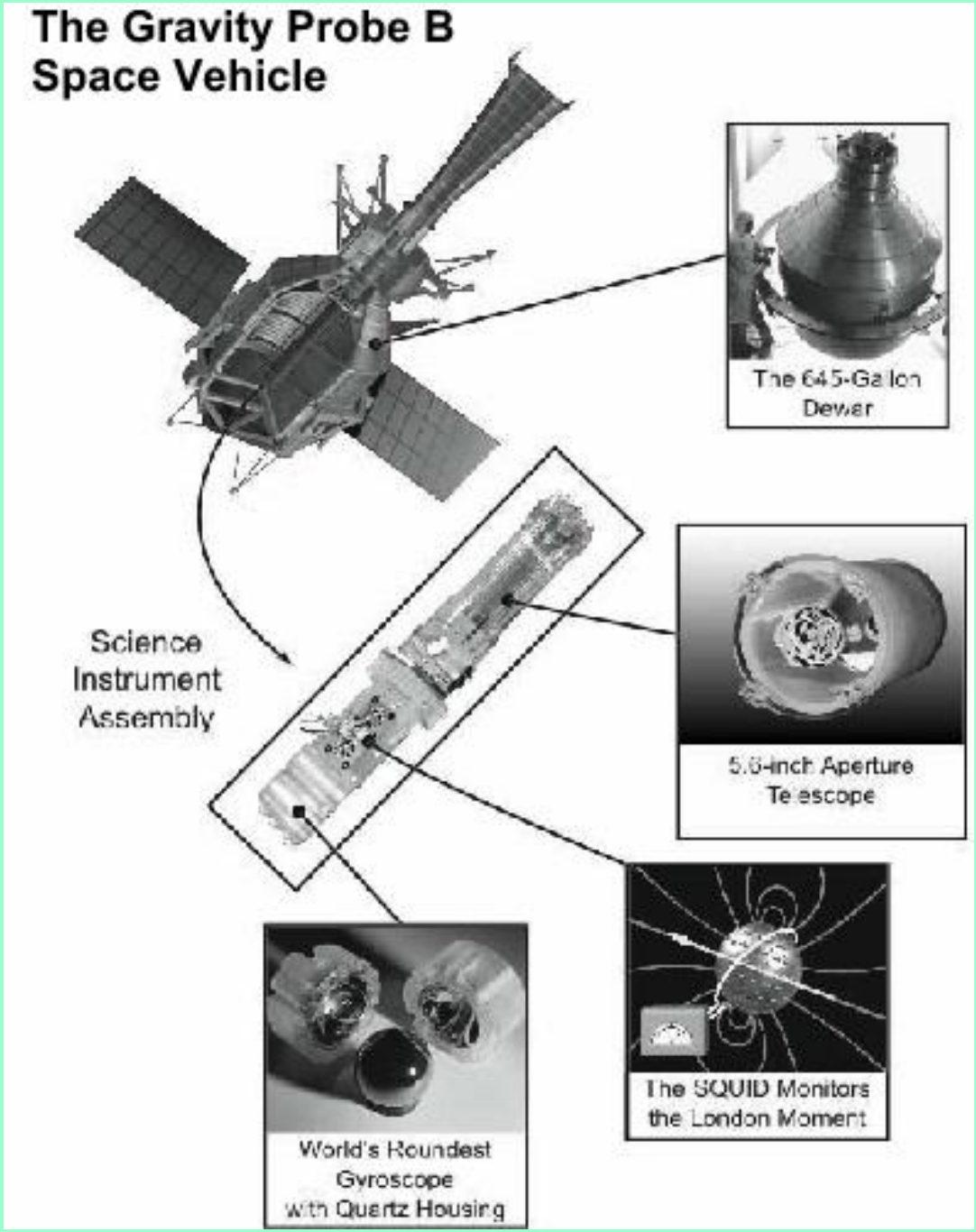
Photos: (Left) Russ Underwood, Lockheed Martin Corporation; (Right) Boeing Corporation

Dealta II 7920-10 Launch Vehicle, 38.6 m, 250 tons; Spacecraft 6.3 m, 3.1 tons, 2.64 d

General GP-B layout



L.C.


The Gravity Probe B
Space Vehicle
The 645-Gallon
Dewar
Science
Instrument
Assembly
5.8-inch Aperture
Telescope
The SQUID Monitors
the London Moment
World's Roundest
Gyroscope
with Quartz Housing

Gravity Probe-B in a Nutshell

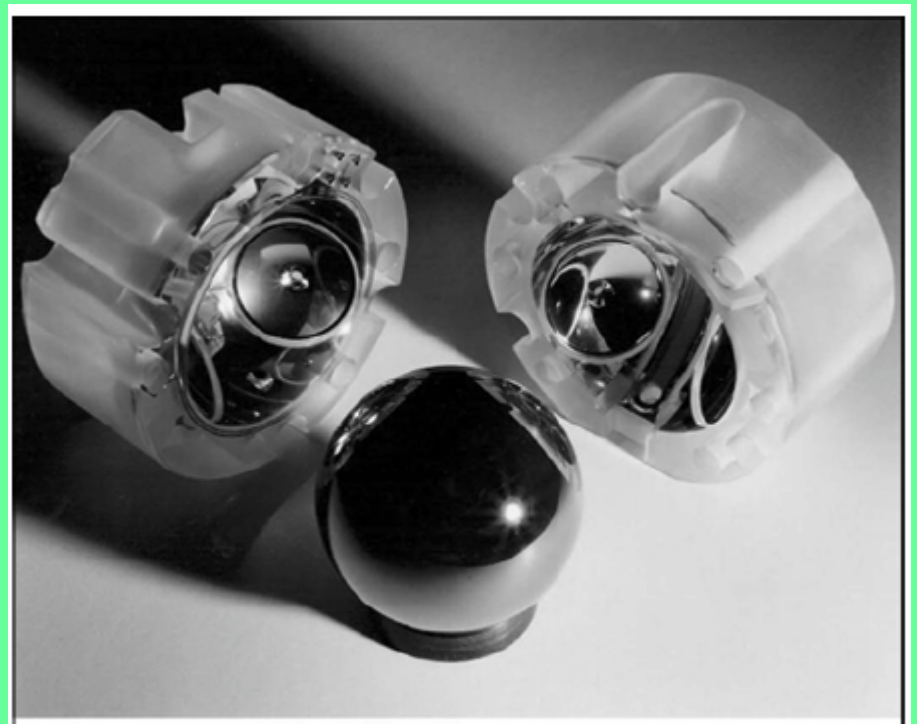
Quartz giro

Size 3.81 cm

Composition:
homogenous
fused quatrz
~2 ppm

$\Delta r/r \sim 3\ 10^{-7}$

in 100 times
smaller then
CD $\rightarrow$ 1 ppm



Gravity Probe B gyroscope (rotor), with quartz housing halves.

Nutshell gap

~25 mkm

niobium film

~ 12 A

B ~ 10{-13}
Earth field
$\Delta\alpha$~ 0.1 miliarcsec
τ ~ two days

The Probe,- central cigar-shaped canister

Class-10 clean room; speck of dust < 1 mkm

8 pairs of micro thrusters driven by the helium gas: at the rate 1/100th of a human «puff» to clean eyeglasses

Flow of helium keeps center-mass position ballanced around one of the gyroscopes- a proof mass of the dragg-free mechanics

Lockheed Martin Space System

GPS-position control 1 cm (commercial 1 m)

Cement Mixer-sized Thermos Bottle

2 441 litre of liquid helium

Amaizing Technology of GP-B

nine new technologies had to be invented to carry out GP-B exp.

1. GP-B gyro has a stability more then a million times better the inertial navigation gyros

2. SQUID magnetomers can detect - 1/ 40 000 000 th part of a degree an axis deflection

3. Dragg-free compensation of acceleration less 1/ billion part of the Gal

4. Space Dewar keeps 1.8 K during of 18 months (2.5 000 lit.) ;T-variations ~ 1p.p.m. K

5. Board Telescope keeps the orientation ~ 1 miliarcsec with aperture 1 arcmin

6. ……etc.

Scientific influence of GP-B project:

more then 100 PhD have been written on various aspects of the program;
carees were made by numerous graduated and high school students,
members of aerospace companies (including the first women astronaut),
professors of Harvard, Princeton, Stanford, and others…. and
a recent Nobel Laureate in Physics

Telescope & Guide Star

36 cm long Cassegrain reflector, f= 3.8 m, optically bonded to the end of quartz block that houses the gyroscopes (no any «glue»);

focussing ~ (+-) 20 miliarcsec for a very distant star.

Chossing and Mapping a Guide Star with VLBI

splitting the guide star image to keep a center (+-) 0.1 miliarcsec.
control of local movements with respect to a reference quasar
VLBI monitoring the quasar coordinates

1 400 stars were studied;

IMPegasi - HR8703, 300 light years , magnitude 5.85-5.6

From francis@relgyro.stanford.edu Wed Apr 6 20:11:46 2005
Date: Wed, **29 Dec 2004** 13:39:07 -0800
From: Francis Everitt <francis@relgyro.stanford.edu>
To: rvn@sai.msu.ru
Cc: mester@relgyro.stanford.edu, worden@step.stanford.edu, t.sumner@ic.ac
Subject: Rokot and Plesetsk

Dear Valentin,

Happy New Year to you also!

Our person at Stanford responsible for contacts with Eurockot and, therefore, the hoped-for use of a Rokot launch vehicle is Dr. John Mester. I forwarded your email to him and suggested that he and you be in touch.

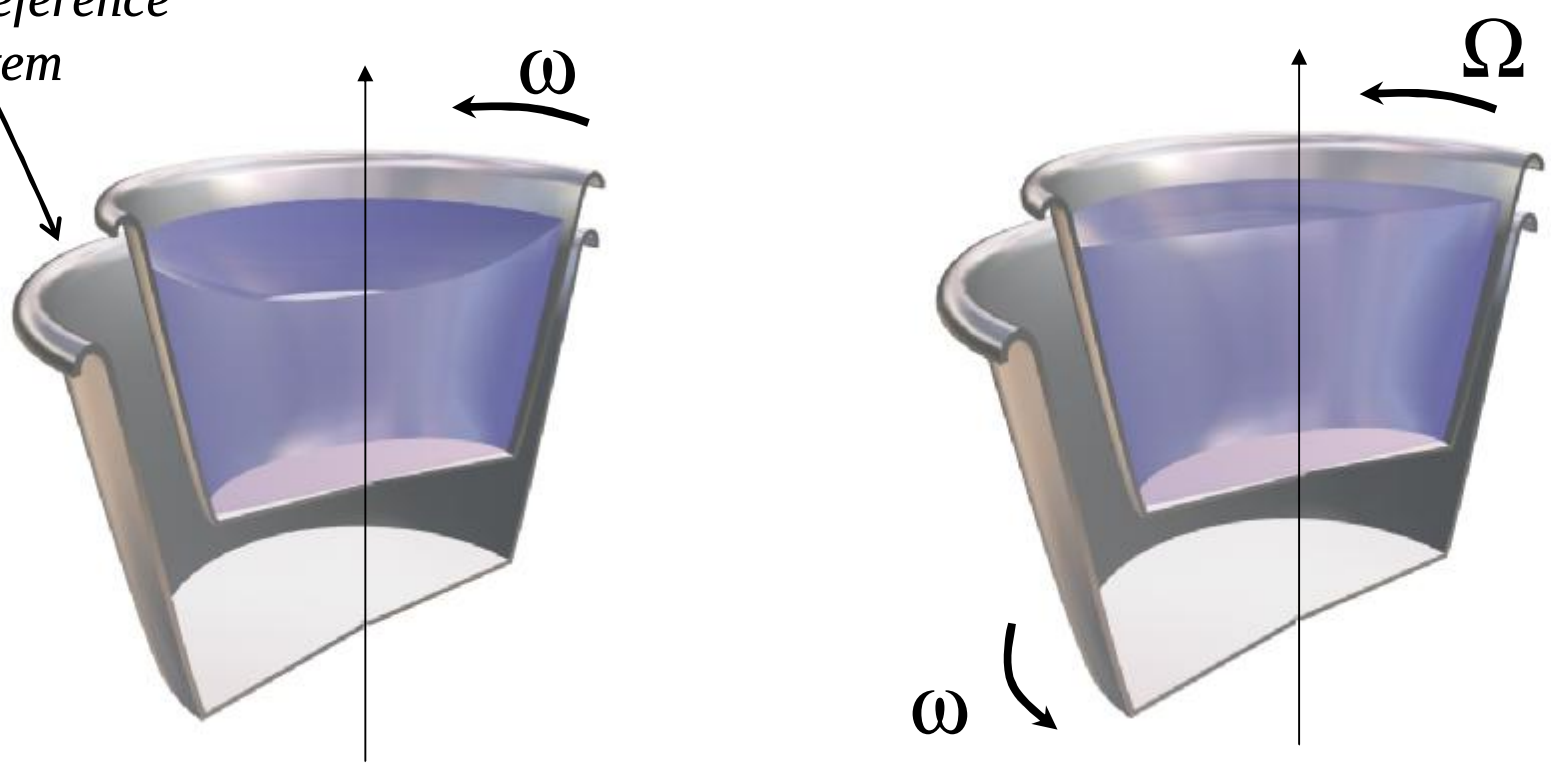
Today, GP-B is in Day 124 of science data collection.

Yours,
Francis

Newton's bucket

"absolute rotation proof"

outside reference system

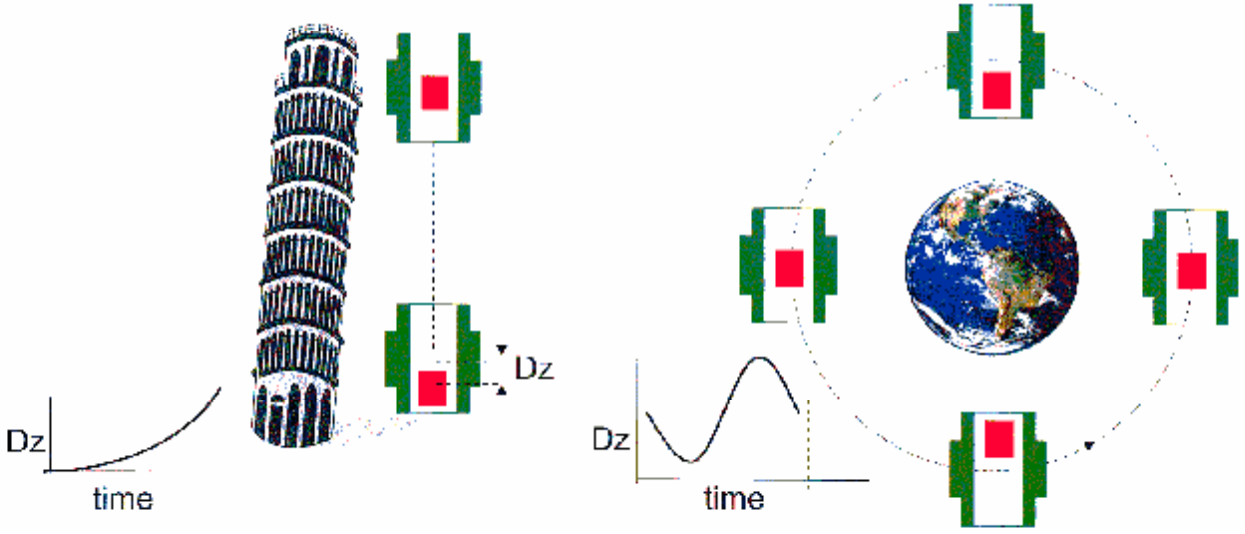


but in GR: $\Omega \approx \frac{r_g}{R} w$

frame dragging

STEP (Satillite Test of Equivalence Principle)

Equivalence & History, Experimental V



Orbiting drop tower experiment { * More time for separation to build
* Periodic signal

Equivalence & History

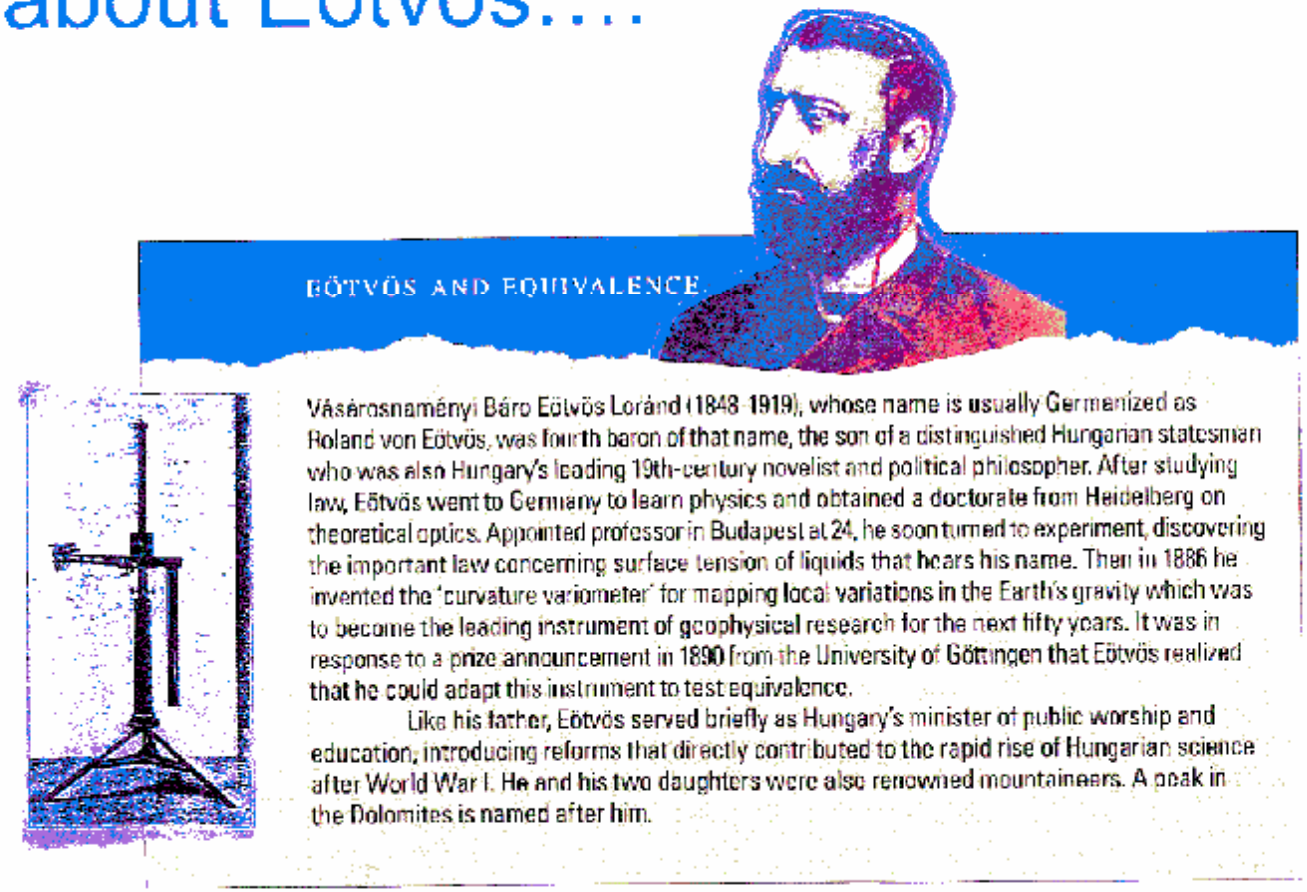



Pescara Meeting, *20 - 23 September, 2004*

Francis Everitt

Equivalence & History, Experimental - II

A Little about Eötvös….



EÖTVÖS AND EQUIVALENCE

Vásárosnaményi Báró Eötvös Loránd (1848–1919), whose name is usually Germanized as Roland von Eötvös, was fourth baron of that name, the son of a distinguished Hungarian statesman who was also Hungary's leading 19th-century novelist and political philosopher. After studying law, Eötvös went to Germany to learn physics and obtained a doctorate from Heidelberg on theoretical optics. Appointed professor in Budapest at 24, he soon turned to experiment, discovering the important law concerning surface tension of liquids that bears his name. Then in 1886 he invented the 'curvature variometer' for mapping local variations in the Earth's gravity which was to become the leading instrument of geophysical research for the next fifty years. It was in response to a prize announcement in 1890 from the University of Göttingen that Eötvös realized that he could adapt this instrument to test equivalence.

Like his father, Eötvös served briefly as Hungary's minister of public worship and education, introducing reforms that directly contributed to the rapid rise of Hungarian science after World War I. He and his two daughters were also renowned mountaineers. A peak in the Dolomites is named after him.

Equivalence & History, Conceptual - IV

- Eötvös on Einstein, a *psychological* impact
- Einstein

  *(a) Equivalence, a 'principle' * 1907, 1911*

  (b) redshift, a gravitational deflection of light

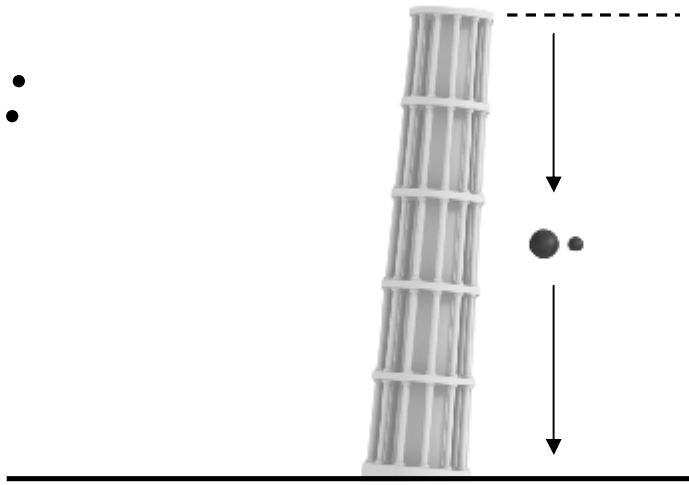
  * ***Principle*** *= something physicists believe but don't understand*
- 'Weak' & 'Strong' Equivalence

  (a) Schiff vs. Dicke (Am. J. Phys., 1960)

  (b) the evil influence of loaded language

"When I am weak, then I am strong." – St. Paul

1. Galileo:



free fall

$t \approx 3\text{sec}$

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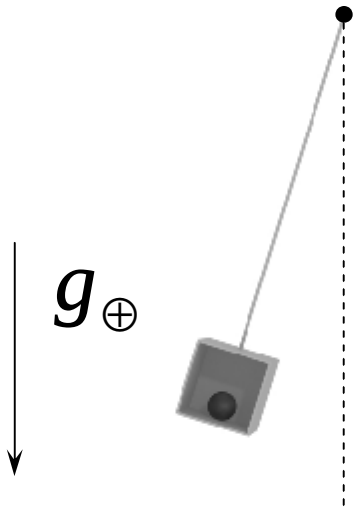
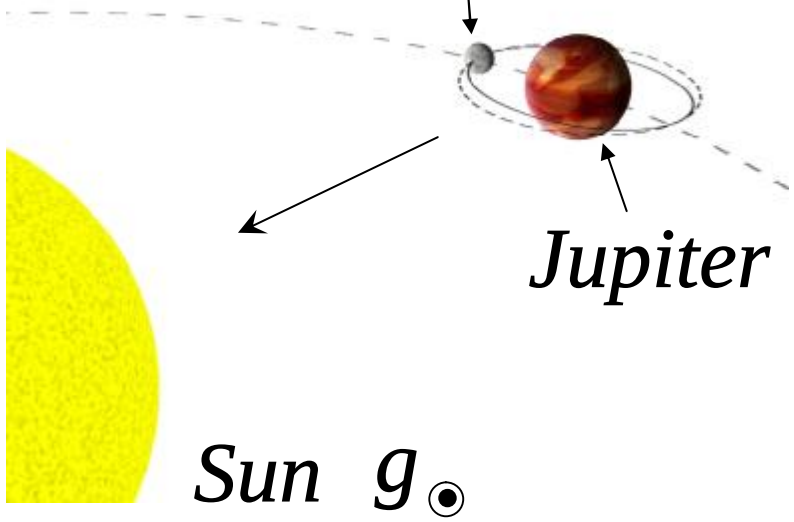
2. Newton: *pendulum*



$$T = 2p\sqrt{\frac{l}{g_\oplus}} = const$$

Pb, Si…

orbiting

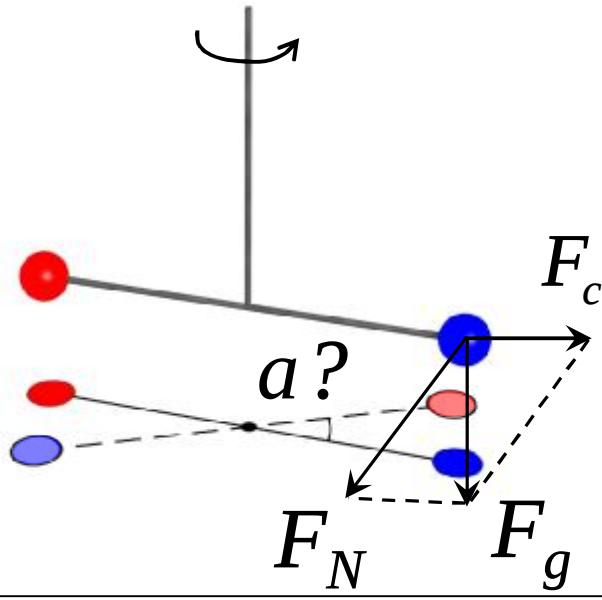


3. Eötvös

torsion balance

static

$N_N \sim \frac{1}{f^g}$



$F_c \equiv m_i \Omega^2 r$

~~$g_\oplus$~~ *compensated*

---

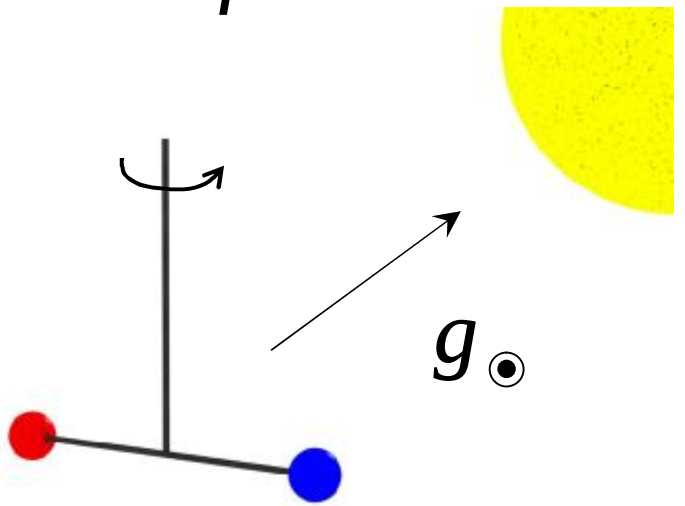
4. Dikki et al.

Sun's field

$g_\odot \sim 10^{-3} g_\oplus$

~~$g_\oplus$~~

compensated



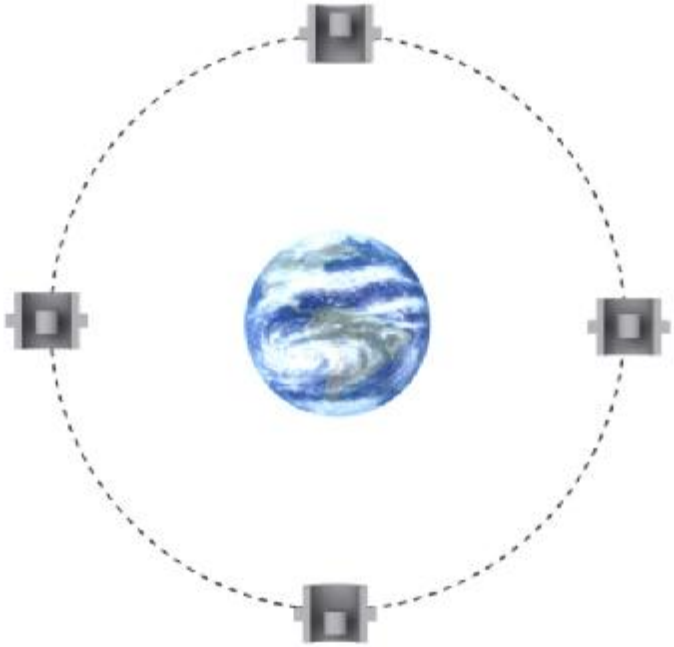
period

$t_0 = 24h$

5. Stanford University

unlimited "free fall"

P. Worden, F. Everitt, 1976



$\underline{\underline{g_{\oplus}}}$

$t_0 \sim 1h$

~~*seismics*~~

T~2K

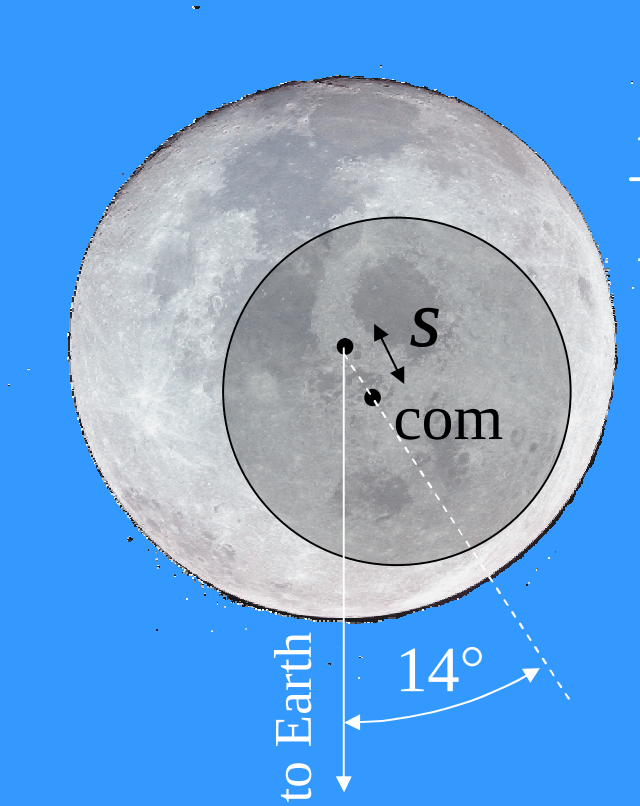
Equivalence & History, Experimental - I

The 4 approaches

	Original	Later Limits
Galileo 1592, *Free Fall*	10^{-2}?	~ 3 X 10^{-10} (Polacco, 1996)
Newton I, 1686 *Pendulum*	$<10^{-3}$	~2 x 10^{-6} (Potter, 1923)
Newton II, 1687 *Earth-Moon system* *Jupiter's moons*	~ 10^{-3}	5 x 10^{-13} (LLR, 2000)
Eötövos 1890 *Torsion Balance*	5 x 10^{-8}	2 x 10^{-12} (Adelberger, et al. 2000)

Equivalence of passive and active Gravitational Mass

Observation of Moon-orbit (Bartlett and van Buren 1986)



$$\frac{\dot{F}_{self}}{F_{EM}} = C_{ab}\frac{M_M}{M_E}\frac{r_{EM}^2}{r_M^2}\frac{s}{r_M}\frac{r}{\Delta r}\hat{s} \approx 5C_{ab}\hat{s}$$

Effect of tangential force is dominant: increase of orbital angular velocity

$$\frac{\Delta w}{w} = 6p\,\frac{F_{self}\,\sin 14^\circ}{F_{EM}} \quad \text{per month}$$

$$\frac{\Delta w}{w} \le 10^{-12}/\text{month} \quad \Rightarrow \quad C_{\text{Al-Fe}} \le 7\cdot 10^{-13}$$

Equivalence & History, Experimental - III

Some Limitations of 4 Methods

- Free Fall on Earth

  (a) release (b) short (3 - 4 sec) time [readout accuracy]

- Pendulum, $T = 2\pi\sqrt{l/g}$

  (a) l, temperature dependent (b) g, seismic effects

- Torsion Balance on Earth

  (a) gravity gradient (b) seismic effects [dominant]

- Earth-Moon System

  (a) ranging (b) 150-km Newtonian effect of same signature

Space brings one full circle back to free fall method….

Equivalence & History, Experimental - IV

- Two Initial Merits of Space Test
  - *Larger 'driving acceleration'*
    [850 cm/s^2 vs. two ground-based options, 0.6 cm/s^2 (Sun), 1.3 cm/s^2 (Eötvös)]
  - *Quieter, seismic environmental (drag-free)*
- Initial Difficulty
  - *EP effect varies as GM/r^2, and gravity gradient effect as $GM\,\delta r/r^3$*
  - *In space with torsion balance, gg effect ~ 10^8 > EP effect*
- Solution: Back Full Circle to Free Fall Method!
  - *Gravity gradient, being doubly-periodic, allows centering adjustment*

Chapman-Hanson:	1970
Worden-Everitt:	1973 - on
STEP:	10^{-17}, 10^{-18} (NASA, ESA)
MICROSCOPE:	10^{-15} (CNES, ESA)

10^3 greater driving acceleration x 10^3 'seismically' quieter
➡ 10^6 advance in accuracy

Layout of the STEP probe

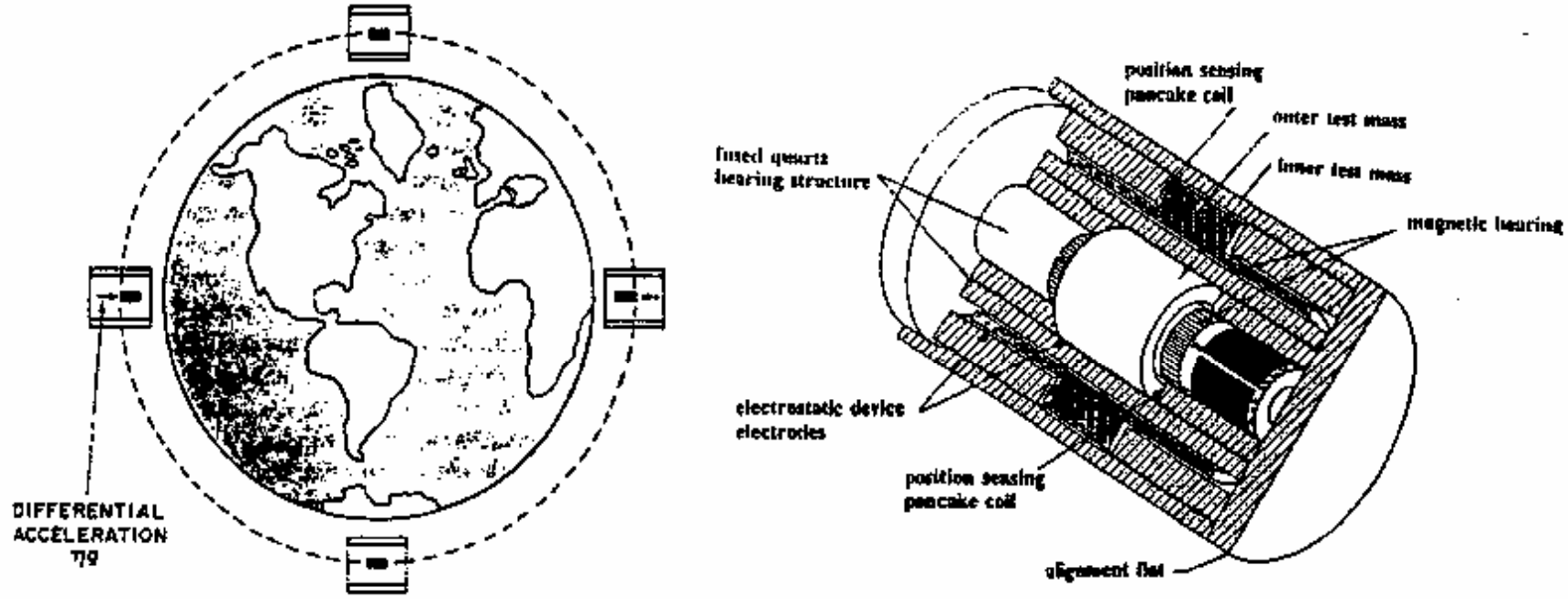
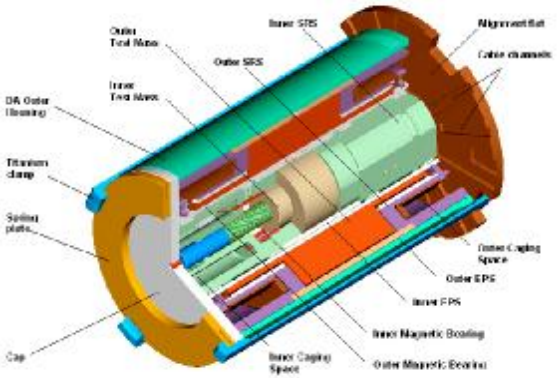
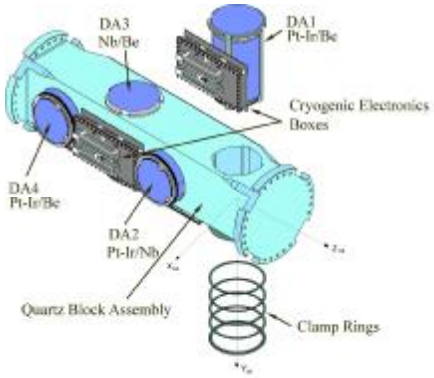


Fig. 3.1. *MiniSTEP mission concept (left); and accelerometer cross-section (right)*

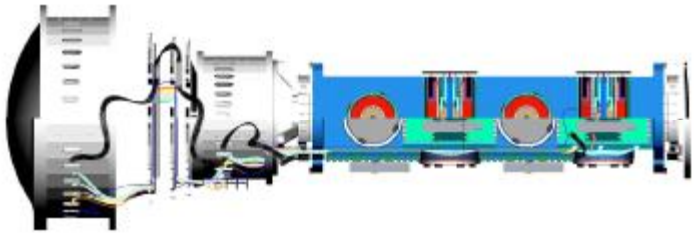
Main STEP Systems
Significant technology advances from SCR/RDR 1999 to SMEX 2002



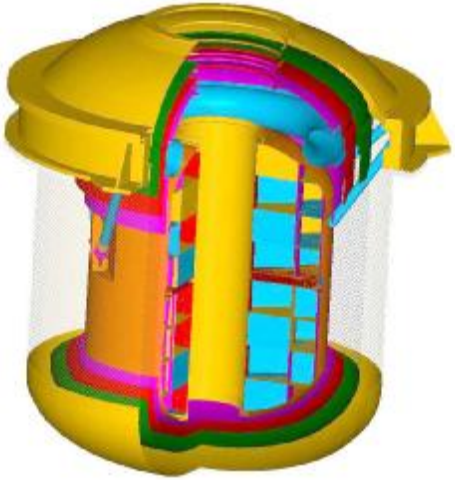
Differential Accelerometer



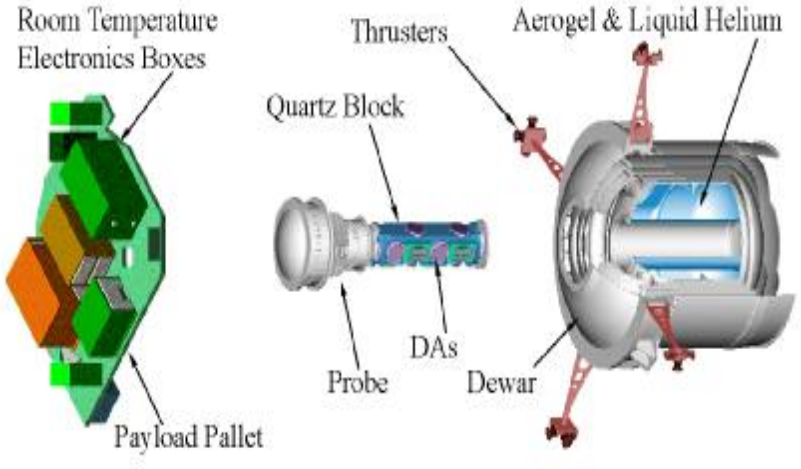
DA Package



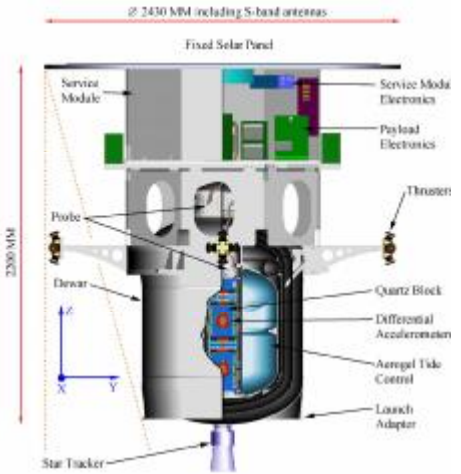
Science Instrument



Dewar

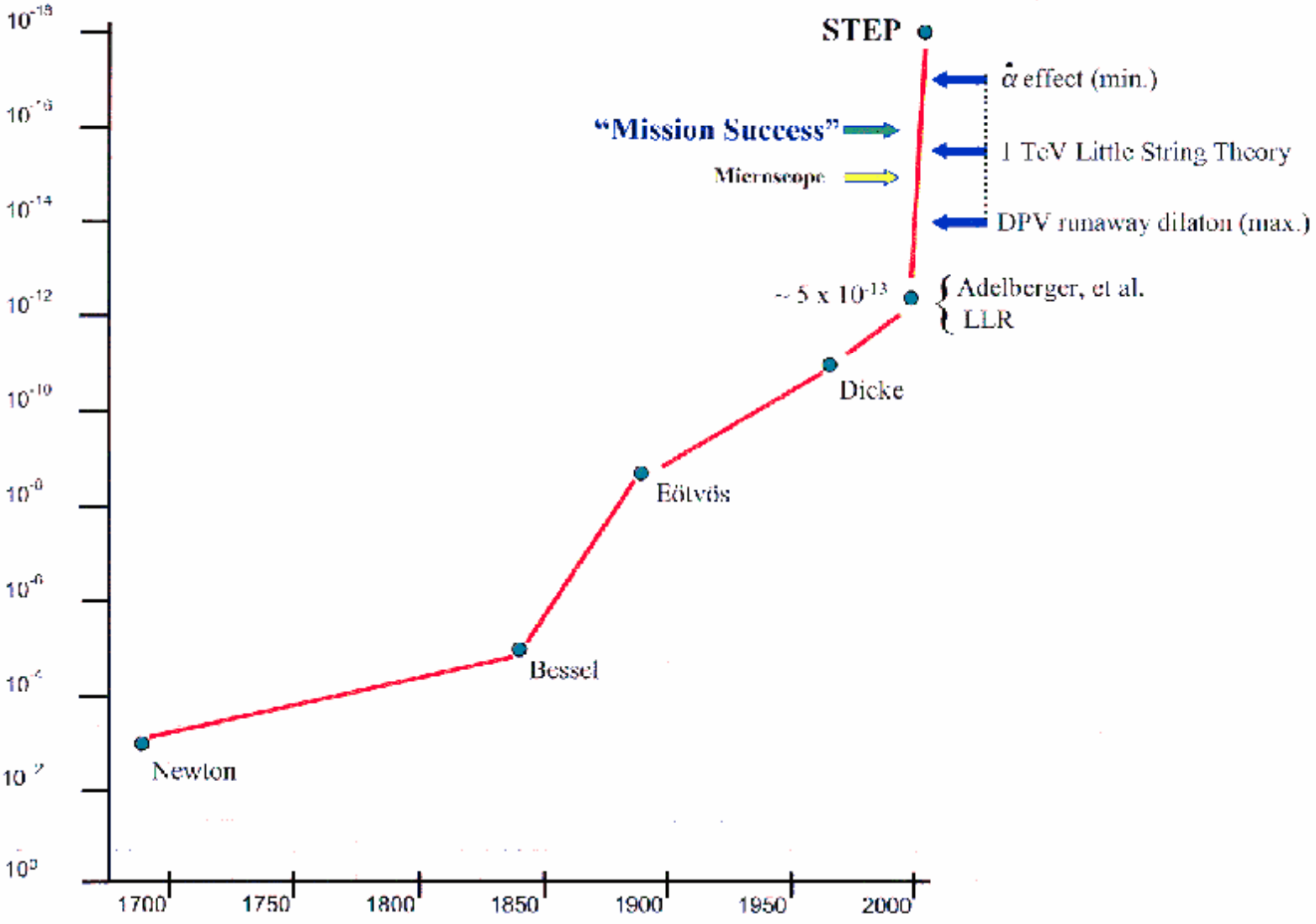


Payload



Space Vehicle

Equivalence & History, Experimental VI



A «new field» phenomenology

$$V(r) = -G\frac{m_1 m_2}{r}[1 + a e^{-(r/l)}]$$

$$strength \rightarrow a \propto |k_p|^2 \; ; \quad range. \propto l \quad ; \; boson..fields..m = (\mathbf{h}/cl)$$

extra dimensions: n → 1, 2, 3.. $F.. \propto .. \frac{1}{r^2} \rightarrow \frac{1}{r^{2+n}}; ...n = 2, ..R_* = l. \approx 0.3.mm$

$R_* = (M_p / M_*)^{2/n} (\mathbf{h} / 2pcM_*)$ $\qquad M_* \approx 1.Tev$

$$V(r) = -G\frac{m_1 m_2}{r}[1 + b_n (\frac{1_{mm}}{r})^{n-1}]$$

exchange by two massless particles: β - strength, n= 2, 3, 4, 5

ISL-test (recent results)

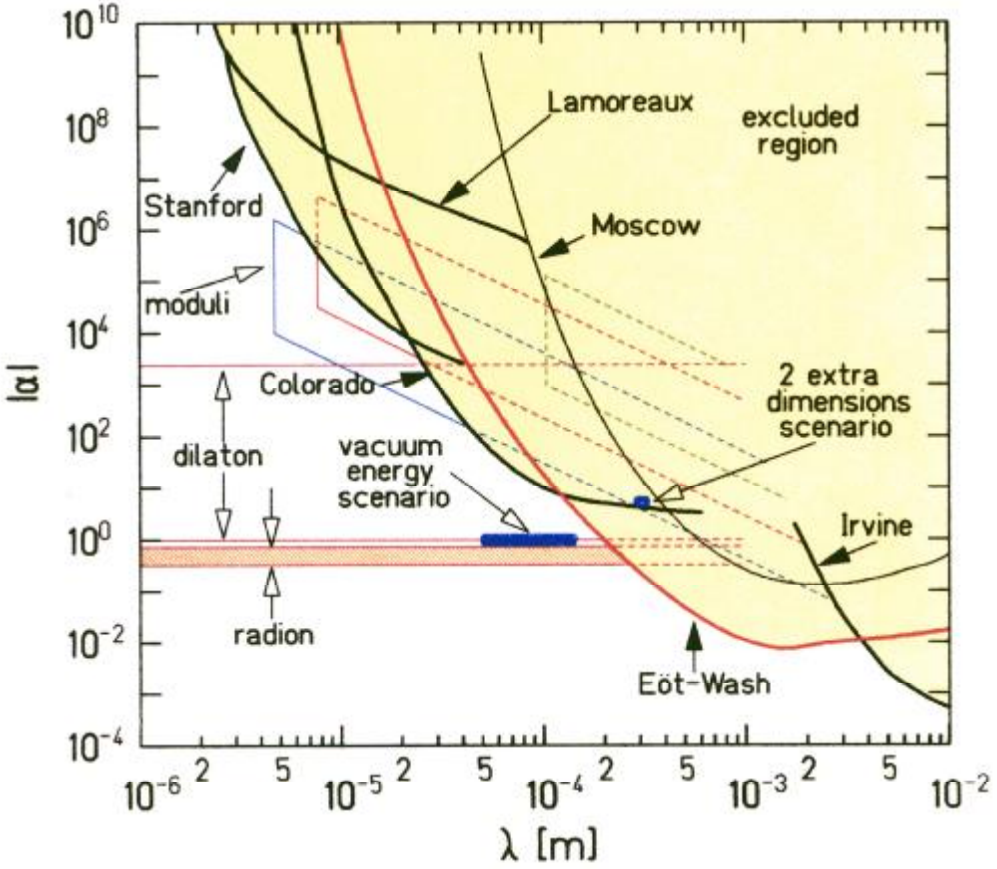
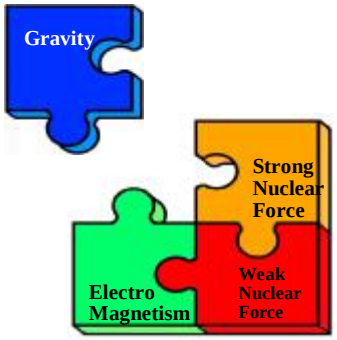


FIG. 34: [color online] Yukawa constraints from our combined data set as well as from other work[9–12, 32, 33]. The area above the heavy curves is excluded at the 95% confidence level. Predicted ISL violating effects from "extra dimensions"[1], from dilaton[15], moduli[16] and radion[18] exchange, and from a conjectured solution[4] of the cosmological constant (vacuum energy) problem are shown as fainter lines.

Can Gravity Be Made to Fit?

- Unification in physics – through fields (Maxwell), geometry (Einstein), symmetries and new particles (electroweak theory)….and now (?) supersymmetry and strings



- The problems of gravity – quantization; 10^{-42}; cosmological constant Λ ($10^{-120!}$); equivalence
- Partial steps toward Grand Unification
  - Strings/supersymmetry in early Universe $\Rightarrow$ scalar-tensor theory, not Einstein's
  - Damour - Polyakov: small Λ $\Rightarrow$ long range equivalence-violating dilaton
- EP violations inherent in all known GU theories
  - Runaway dilaton theories { (Witten) (Damour, Piazza, Veneziano) } η { >> 10^{-18} up to 10^{-14} }
  - 1 TeV Little String Theory (Antoniadis, Dimopoulos, Giveon) $\eta \sim 10^{-15}$

STEP's 5 orders of magnitude take physics into new theoretical territory

Equivalence & History, In Summary

The Mystery Remains; the History Continues….

The **power of gravity** is of a different nature from the **power of magnetism**; for the magnetic attraction is not as the matter attracted. Some bodies are attracted more by the magnet; others less; most bodies not at all. The power of magnetism in one and the same body may be increased and diminished; and is sometimes far stronger, for the quantity of matter, than the power of gravity…" – *Newton, 1687*

"Mass is defined by the resistance that a body opposes to its acceleration (inert mass). It is also measured by the weight of the body (heavy mass). That these two radically different definitions lead to the same value for the mass of a body is, in itself, ***an astonishing fact***." – *Einstein, 1950*

"…the existence of weak… long-range dilaton or moduli fields is an essential part of [string] theory and **a test of EP five-orders-of magnitude beyond the existing limit would be fantastically important**." – *David Gross, 2002*