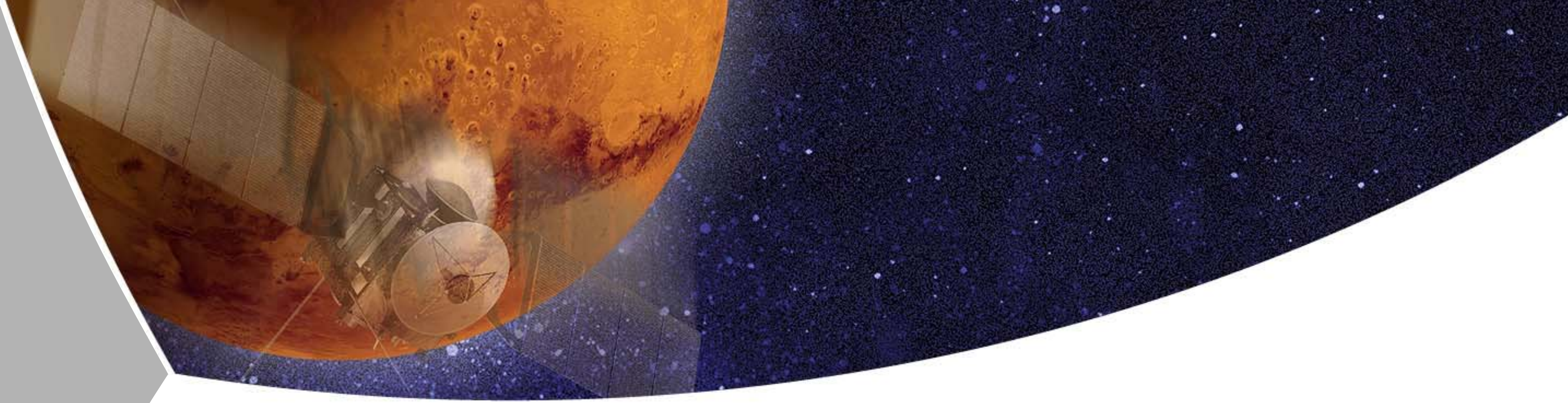

Tests of Gravity in the Solar System

Hansjörg Dittus
German Aerospace Center (DLR), Institute of Space Systems, Bremen

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Durham, 16.7. 2009

Outline

- Introduction / Motivation
- Experimental confirmation of GR with space tests
- Space tests for gravitational physics – an overview
- Unexplained phenomena / Observations in the solar system
- Anomalies from satellite tracking
  - Pioneer Anomaly
    - Present status of analysis
    - Thermal models
    - Other attempts for explanation
  - Fly-by Anomaly
  - GRACE Anomaly
- Outlook

Motivation

Theoretical Background

- Standard Model of Quantum Physics
- Special Relativity
- General Relativity
- Statistical Physics

But:

- Incompatibility of Quantum Theory and Gravitation

Experimental proofs

- Experimental confirmation of the Standard Model makes quantization of space and time a likely approach
- Gravitational theory well confirmed by experiments and observations
- Precision Cosmology (COBE, W-MAP, etc.)

Unexplained phenomena ?

- Space – a unique laboratory
- Do we see effects on satellites in deep space orbits?
- Is gravity modified on larger scales?

Experimental confirmation of GR

Foundations:

- Universality of Free Fall
- Local Lorentz Invariance
- Universality of Gravitational Redshift

Tests in the Post-Newtonian frame

$$g_{00} = -1 + 2\alpha \frac{U}{c^2} - 2\beta \frac{U^2}{c^4}$$

$$g_{0i} = 4\mu \frac{\left(\vec{J} \times \vec{r}\right)_i}{c^3 r^3}$$

$$g_{ij} = \left(1 + 2\gamma\right) \frac{U}{c^2}$$

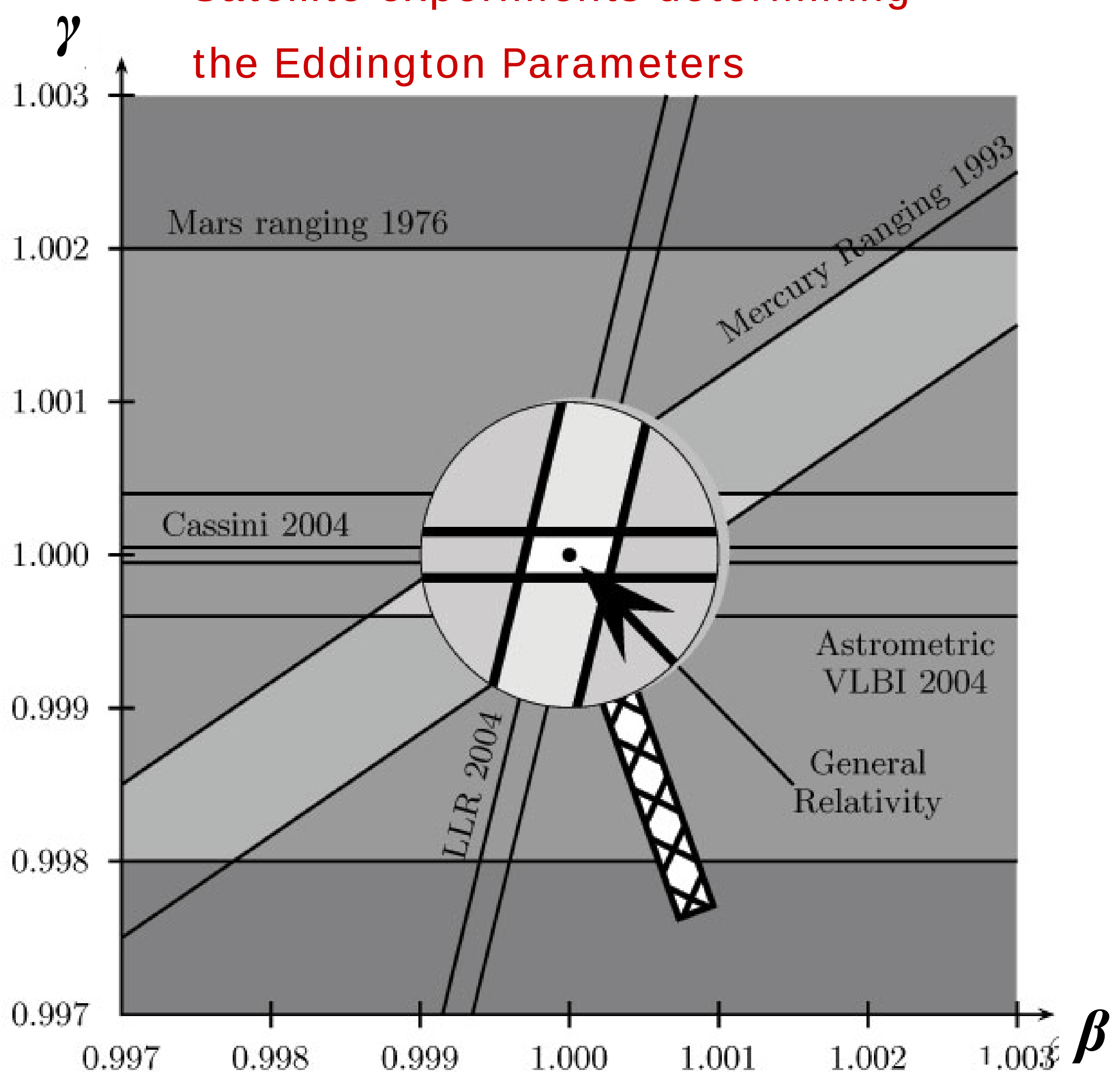
Predictions:

- Solar System Effects
  - Perihelion shift
  - Gravitational Redshift
  - Light deflection
  - Time delay
  - Gravitomagnetic effects
- Strong field observations
  - Binary systems
  - Black holes
- Gravitational waves
- Cosmology

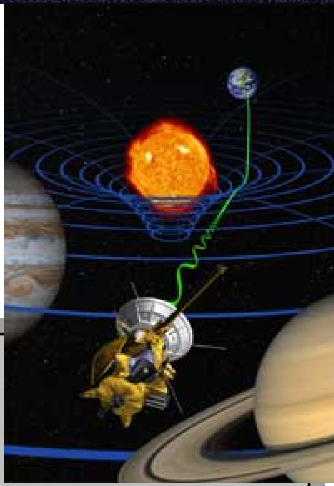
perihelion shift	astronomical observations	$\left\|\tfrac{2}{3}(\alpha+\gamma) - \tfrac{1}{3}\beta - 1\right\| \leq 10^{-4}$
light deflection	Very Long Baseline Interference	$\left\|\gamma - 1\right\| \leq 10^{-4}$
time delay	Cassini S/C	$\left\|\gamma - 1\right\| \leq 2 \cdot 10^{-5}$
gravitational redshift	Gravity Probe A	$\left\|\alpha - 1\right\| \leq 1.4 \cdot 10^{-4}$
Lense-Thirring effect	LAGEOS satellites	≤ 0.1
Schiff effect	Gravity Probe B	$\leq 5 \cdot 10^{-3}$ (not yet confirmed)

Space Tests for GR

Satellite experiments determining the Eddington Parameters



Shapiro Time Delay



Einstein-Infeld-Hoffmann Equation

- Numerical models based on an isotropic PPN - n-body metric
- Planets and asteroids considered to be point masses
- Accelerations calculated wrt the barycentre of the solar system.

$$\ddot{\vec{r}}_i = \sum_{j\neq i} \frac{Gm_j\left(\vec{r}_j - \vec{r}_i\right)}{\left|\vec{r}_j-\vec{r}_i\right|^3}$$

$$\cdot\left[1-\frac{2(\beta+\gamma)}{c^2}\sum_{k\neq i}\frac{Gm_j}{\left|\vec{r}_i-\vec{r}_k\right|} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{Gm_j}{\left|\vec{r}_j-\vec{r}_k\right|} + \gamma\frac{\left|\dot{\vec{r}}_i\right|^2}{c^2} + (1+\gamma)\frac{\left|\dot{\vec{r}}_j\right|^2}{c^2} - \frac{2+2\gamma}{c^2}\dot{\vec{r}}_i\cdot\dot{\vec{r}}_j - \frac{3}{2c^2}\left(\frac{\left(\vec{r}_i-\vec{r}_j\right)\cdot\dot{\vec{r}}_j}{\left|\vec{r}_j-\vec{r}_i\right|}\right)^2 + \frac{1}{c^2}\left(\vec{r}_j-\vec{r}_i\right)\cdot\ddot{\vec{r}}_j\right]$$

$$+\frac{1}{c^2}\sum_{j\neq i}\frac{Gm_j}{\left|\vec{r}_j-\vec{r}_i\right|^3}\left(\left(\vec{r}_j-\vec{r}_i\right)\cdot\left((2+2\gamma)\dot{\vec{r}}_i-(1+2\gamma)\dot{\vec{r}}_j\right)\right) + \frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{Gm_j}{\left|\vec{r}_j-\vec{r}_i\right|}$$

Time delay in space time curved by sun and earth

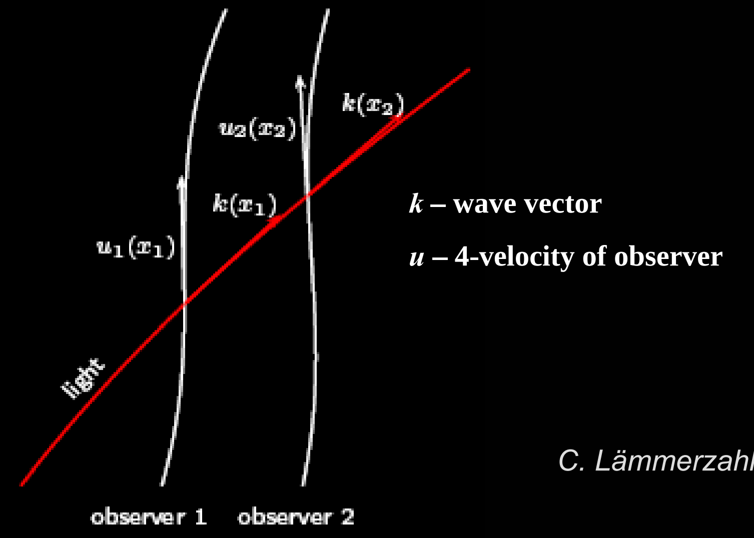
$$\Delta t = \frac{\left|\vec{r}_t^{\,C} - \vec{r}_s^{\,C}\right|}{c} + \frac{(1+\gamma)Gm_S}{c^3}\ln\left(\frac{r_s^S + r_t^S + \left|\vec{r}_t^{\,S} - \vec{r}_s^{\,S}\right| + (1+\gamma)Gm_S/c^2}{r_s^S + r_t^S - \left|\vec{r}_t^{\,S} - \vec{r}_s^{\,S}\right| + (1+\gamma)Gm_S/c^2}\right) + \frac{(1+\gamma)Gm_E}{c^3}\ln\left(\frac{r_s^E + r_t^E + \left|\vec{r}_t^{\,E} - \vec{r}_s^{\,E}\right|}{r_s^E + r_t^E - \left|\vec{r}_t^{\,E} - \vec{r}_s^{\,E}\right|}\right)$$

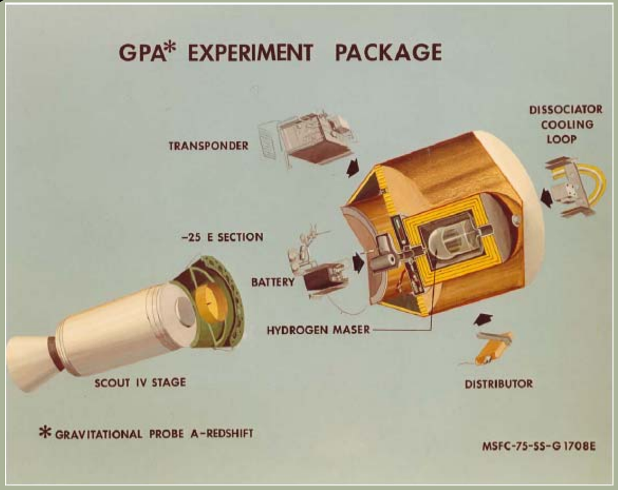
Cassini Conjunction Experiment (*Bertotti* et al. 2002):

- Satellite – Earth distance: > 10^9 km
- Ranging: X~7.14GHz & Ka~34.1GHz (dual band)
- Result: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

Gravitational redshift

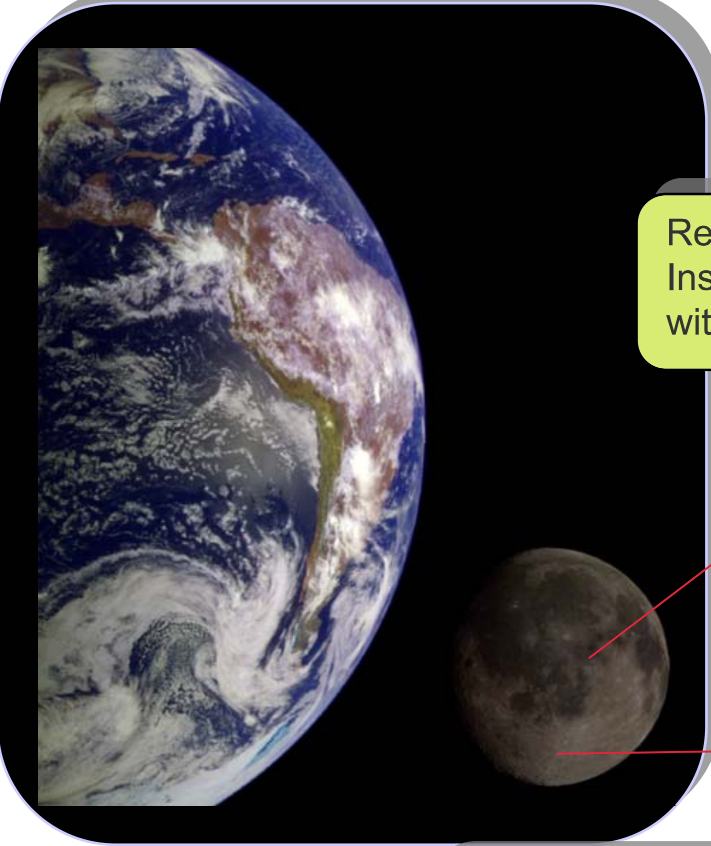
- Gravity Probe A experiment (*Vessot* et al., 1974): ballistic rocket flight
- Confirmation of the Universaliy of the Gravitational Redshift:
All clocks run the same and experience the same frequency shift in gravitational fields– independent of their physical characteristics
- GP-A: comparison of H-masers on earth and in a capsule on a ballistic flight path
- Accuracy $\delta\left(\frac{f_1}{f_2}\right) \leq 10^{-4}$



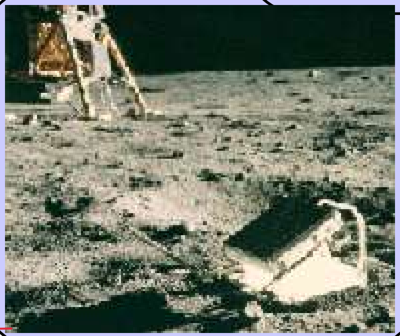


$$\frac{f_1}{f_2} = \frac{k(u_1)}{k(u_2)} = \sqrt{\frac{g_{00}(x_1)}{g_{00}(x_2)}}\left(1 - \frac{U(x_1) - U(x_2)}{c^2}\right)$$

Lunar Laser Ranging

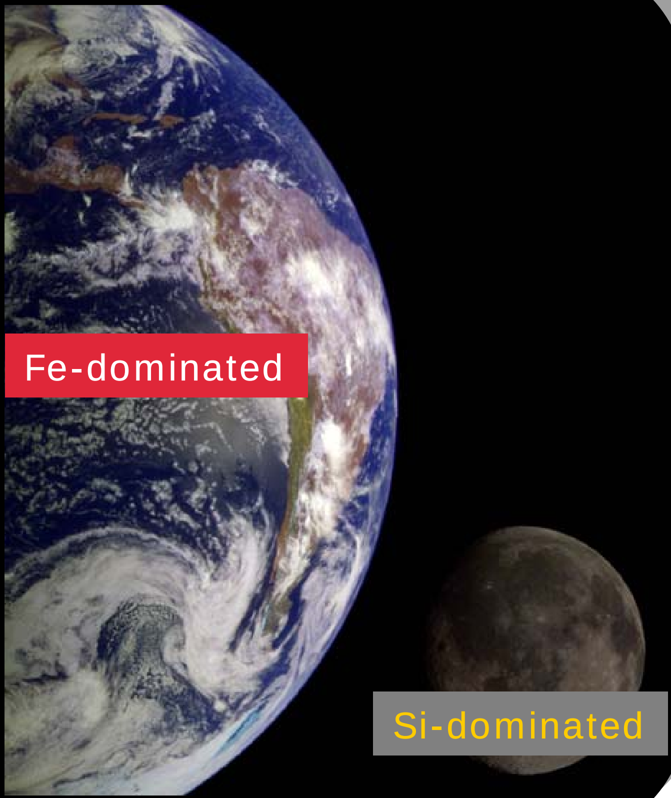


Retroreflectors on moon surface:
Installed between 1969 and 1973
with Apollo 11,14,15 and Luna 17,21



Resolution: ca. 2 cm (< 1 cm)
Laser pulse width: 150 – 300 ps
Pulse frequency: 10 Hz
Illuminated area on moon surface: 20 km^2
1 of 10^{19} photons observed (1 photonper 10 pulses)

Lunar Laser Ranging



Earth and moon are of different chemical composition and freely falling in the sun´s gravitational field. This enables to perform tests of the Weak Equivalence Principle by ranging between earth and moon.

$\eta_E \leq 10^{-13}$ for $a_d = \eta_E \frac{Gm_S}{r_{ES}^2}$

Dependent on the validity of the Strong Equivalence Principle:

Does self-gravitation Ω contributes the same to inertial and gravitational mass?

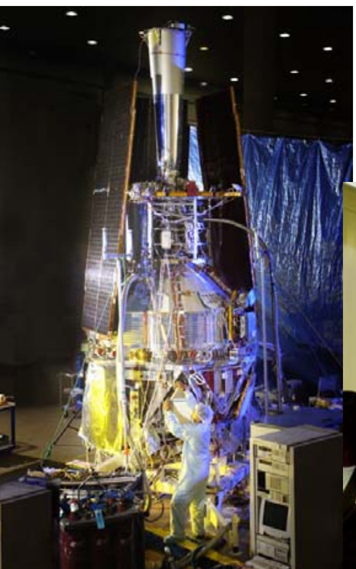
$$\mathbf{a}_d = \frac{-m'_{total}\mathbf{r}_{EM}}{r_{EM}^3} + \eta\left(\left(\frac{\Omega}{m}\right)_E - \left(\frac{\Omega}{m}\right)_M\right)\frac{m_S \mathbf{r}_{ES}}{r_{ES}^3} + \left(\frac{m_{passive}}{m}\right)_M m_S\left(\frac{\mathbf{r}_{ES}}{r_{ES}^3} - \frac{\mathbf{r}_{MS}}{r_{MS}^3}\right)$$

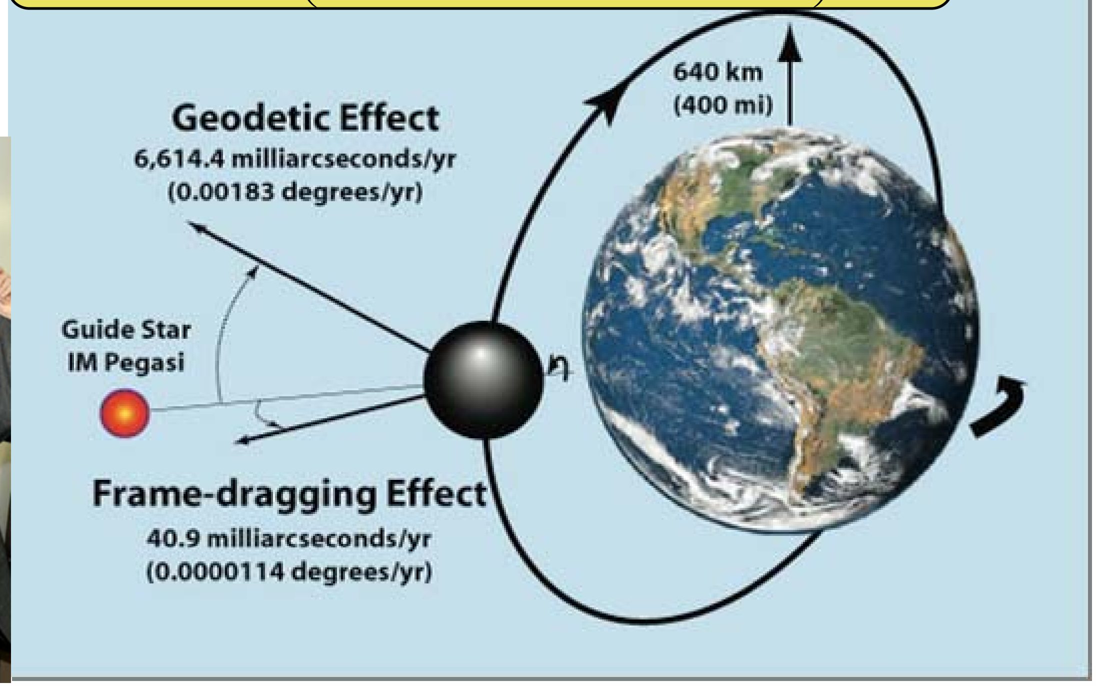
Nordtvedt parameter $\eta \leq 4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2 \leq 10^{-3}$

Gravity Probe B

- Precise measurement of gyro prececcions due to space-time curvature of the rotating earth.
- Geodetic Precession: 6,6 arcsec per year
- Lense-Thirring precession (frame dragging, Schiff effect):
  0,042 arcsec pro Jahr für die Lense-Thirring-Präzession
- Experiment already proposed 1959 (!) (*G. Pugh*)
- Carried out: April 2004 to Au

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \left(-\frac{1}{2}\vec{v} \times \vec{a} + \frac{3}{2}\vec{v} \times \nabla U + \nabla \times \vec{h} \right) \times \vec{S}$$

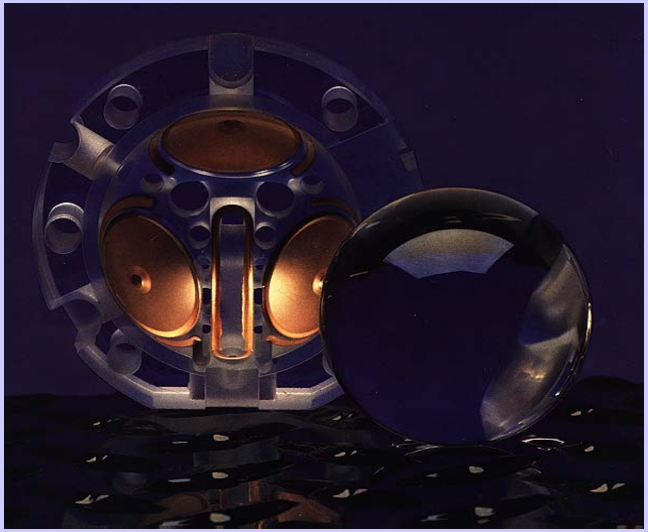


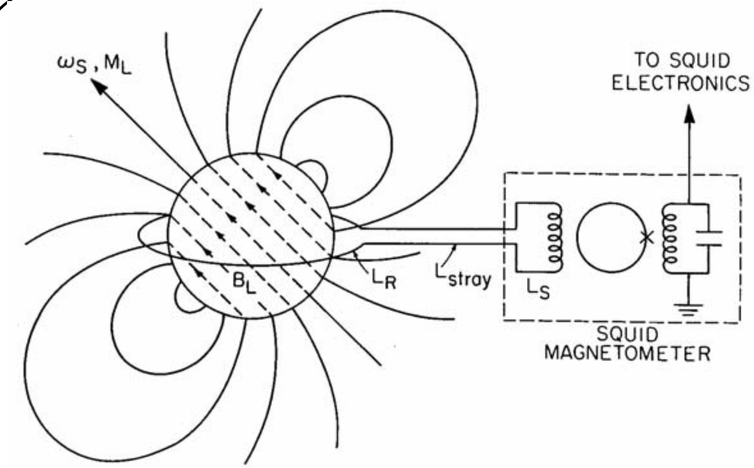


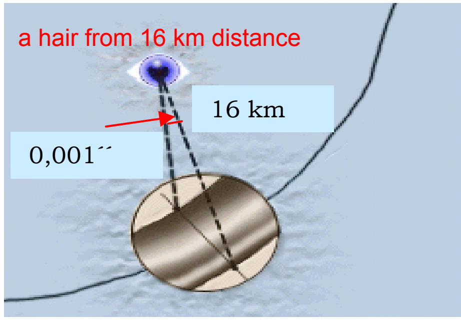
F. Everitt, Stanford University

Precise gyroscopes

- Ideally round spheres made from fused silica, Nb-coated for supercondcutivity:
  deviation from sphericity max. 5 nm
- Electrostatic levitation, frictionless bearing:
  spin-rate change: 1 % in 1000 years
- Accuracy:
  10^{-11}° /h^{-1}
  (1 revolution in 11,5 billion years)

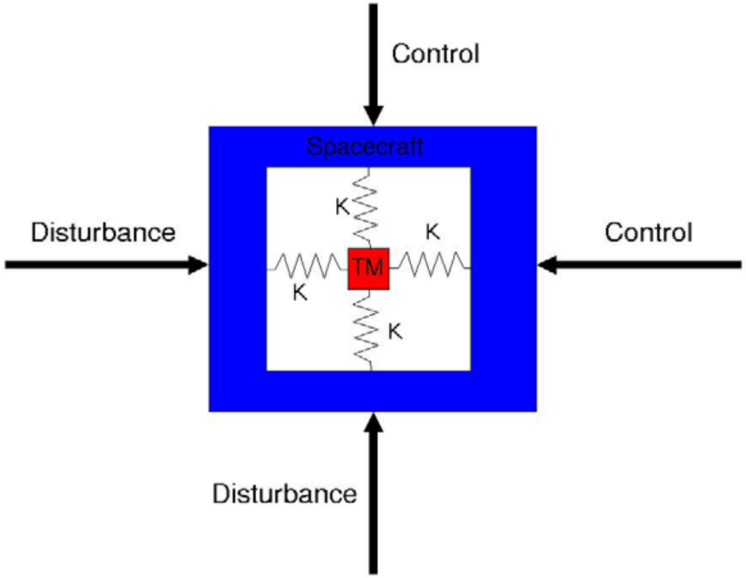


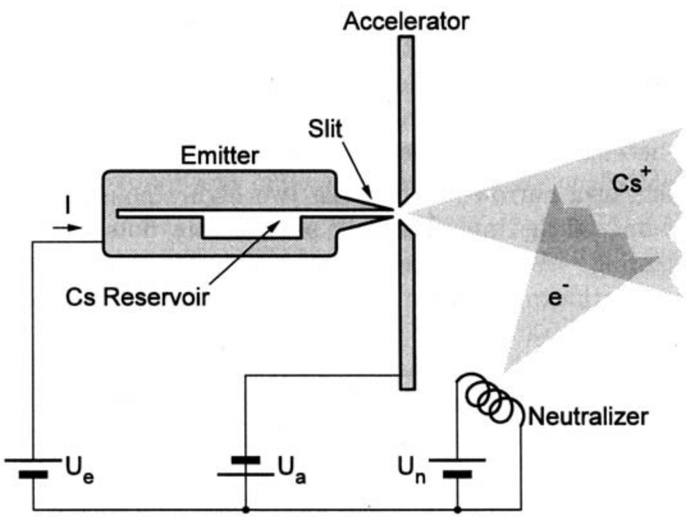




Precision-thruster for satellites

- Drag free control: Satellit follows a freely falling test mass on a geodetic
- Closed-loop control of test mass movement
- Micropropulsion thrusters guide the satellite
- Field Emission Electrical Propulsion (FEEP)

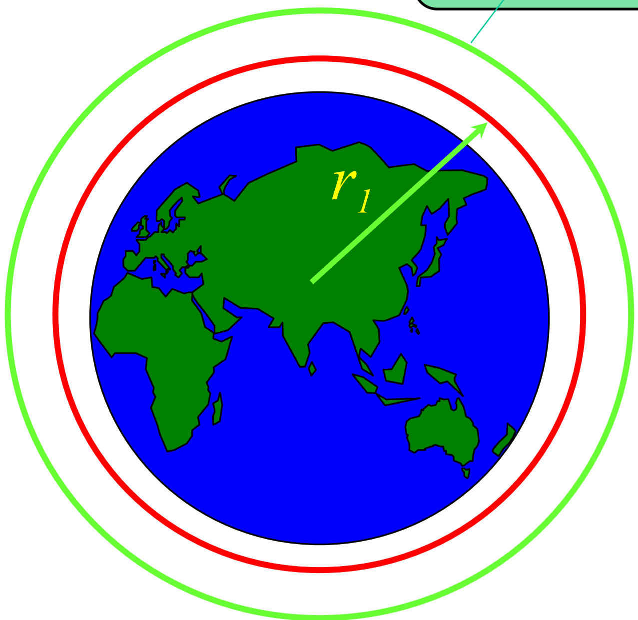


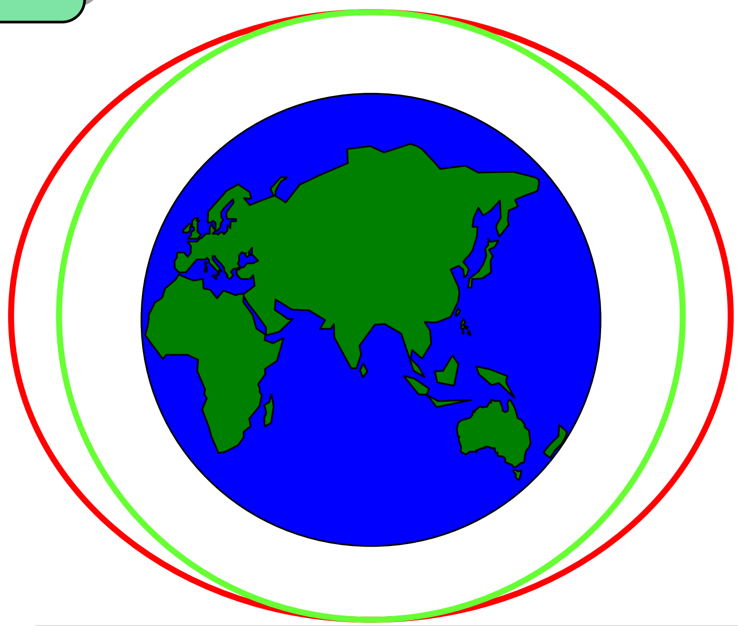


Residual acceleration: ca. 10^{-14} m / s^2
Thrust-increment resolution: ca. 0.1 µN
Specific impuls: > 10,000 s

WEP tests on satellites

$$dr = \frac{1}{3} r_1 \eta_E \approx 10^{-12}\,\mathrm{m}$$





Orbit radius difference too small for direct measurment

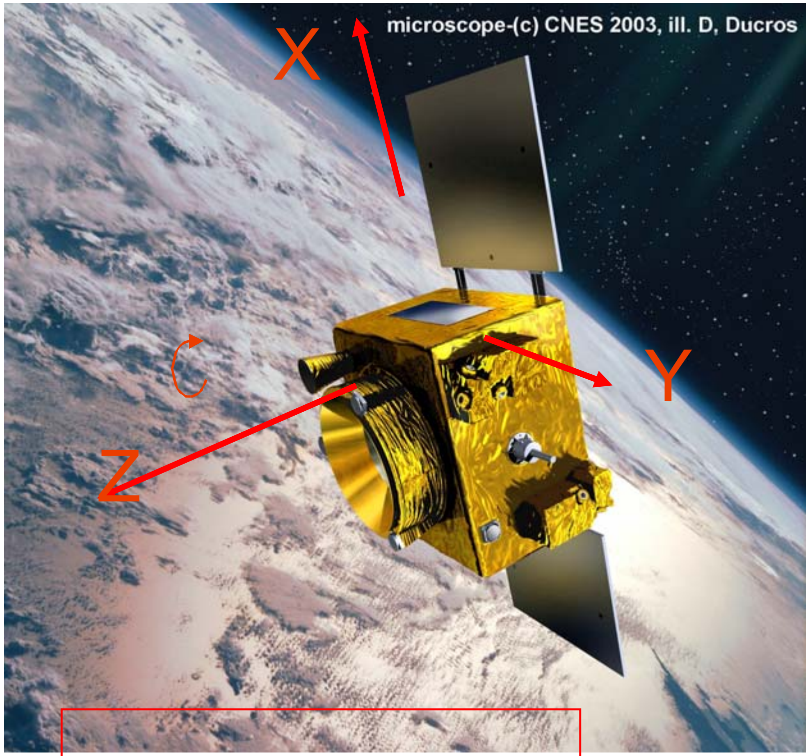
For weak mechanical coupling both test masses as well as the satellite form a spring-mass system, which amplitude varies periodically with orbit frequency. Can be measured with high precision..

MICROSCOPE

Micro-satellite à Trainée Componsée pour l´Observation du Principe d´Equivalence

Missions parameter:

- Sunsynchronous orbit: 660 km
- Orbit exzentricity: $< 5 \cdot 10^{-3}$
- Spin rate: varying for modulation of the orbit-frequency
- Signal frequenz: $(\pi + 1/2)\, f_{orb}$ und $(\pi + 3/2)\, f_{orb}$
- Missions duration: 6 to 12 months
- Satellite mass: < 120 kg



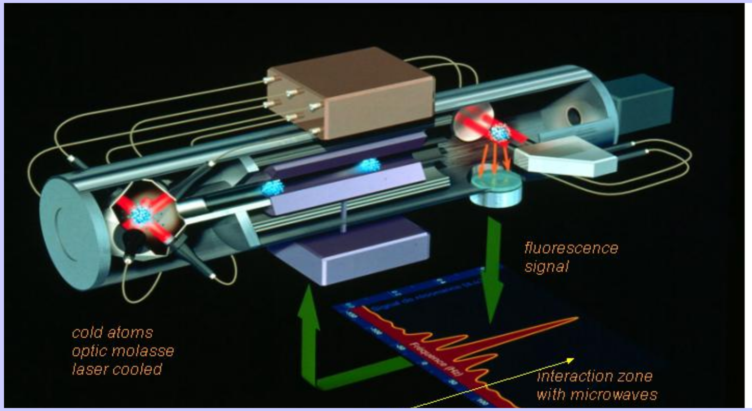
x-axis: sensitive axis
z-axis: satellite spin axis

ONERA

Clocks in space: ACES / PHARAO

- PHARAO most precise clock in space
- Allan-Variance: 10^{-16}
- ACES enables Phase and Frequency comparison between a Cs-atomic clock and earth bound clocks:
  - 0.3 ps during ISS pass (~5min.)
  - 7 ps during 1 day
  - 23 ps during 10 days

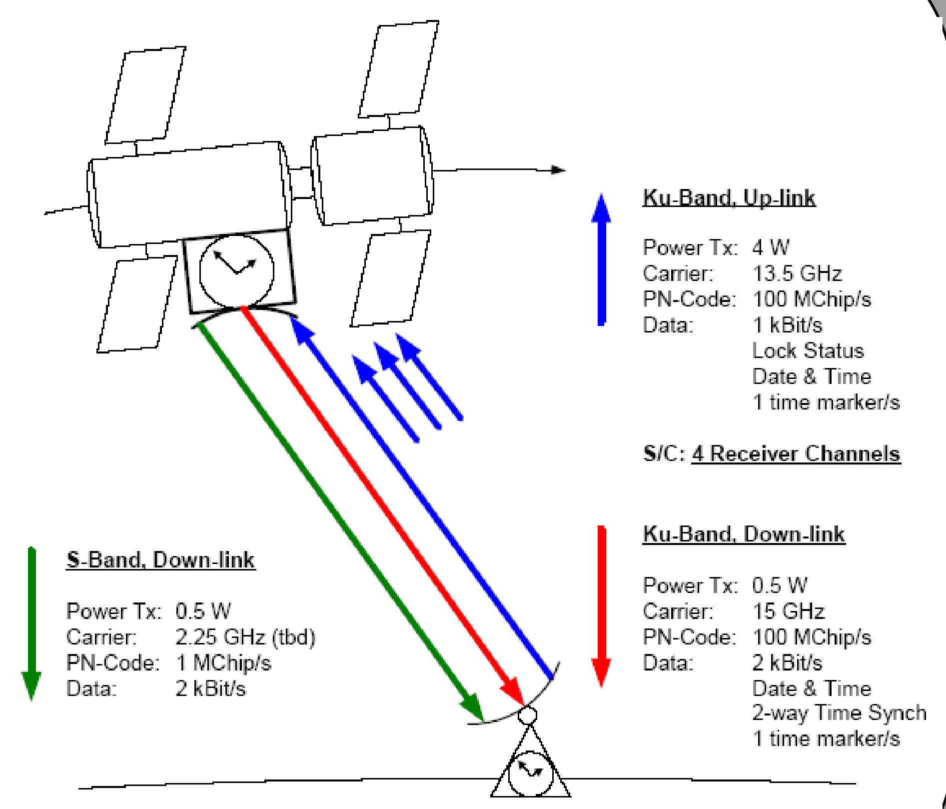
	in GNSS Orbits
Longitudinal Doppler effect	10^{-2} s per day
Transversal Doppler effekt	10^{-5} s per day
Sagnac effekt	$3 \cdot 10^{-7}$ s per orbit
1st ord. Gravitational redshift	$8 \cdot 10^{-5}$ s per day
2nd ord. Gravitational redshift	10^{-13} s per day
Gravitational time delay	$4 \cdot 10^{-11}$ s
Gravitomagentic clock effect	10^{-7} s per orbit



- Resolution of the time-link:
  - common view: 1 ps
  - non-common view:
    3 ps for Δt < 1,000 s
    10 ps for Δt < 10,000 s

Time transfer (MWL)

- MWL (Microwave link to ISS) developed for transfers of time signals between ISS and earth
- Frequency comparison with a relative accuracy of 10^{-16} (230 fs per pass, 5 ps per orbit)
- 2 symmetric 1-way links for ein continuly pseudo-noise coded signal
- High Ku-band chip rate (100 MChip/s) to improve the resolution and to depress possible multipath signals
- 1 W power (S- and Ku-band)
- Enables additional ranging with λ/1,000 = 24 µm accuracy.

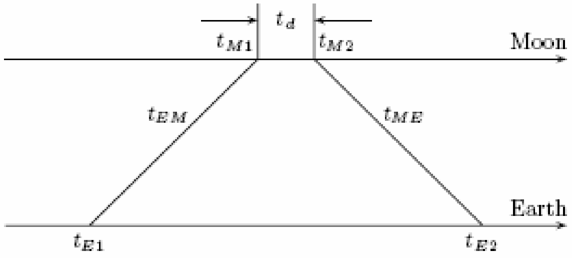


Optical links for tracking

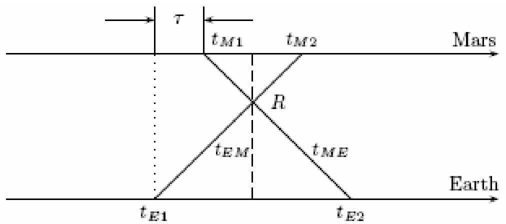
- Optical transponder (On-board-laser, telescope, on-board.clock)
- Successfully demonstrated over 0,17 AU (24 million km) with Messenger S/C (2-way link) and Mars Global Surveyor S/C(1-way link)
- Nd:YAG-Laser, pulse frequency 8 Hz
- Atmospheric correction; calibration via ranging to near-earth satellites (e.g. LAGEOS) from different stations

	Messenger S/C	MOLA on Mars Global Surveyor (1-way)
Distance	$2.4\cdot10^7$ km	$8\cdot10^7$ km
Pulse-width	10 ns (up), 6 ns (down)	5 ns
Pulse-energy	16 mJ (up), 20 mJ (down)	150 mJ
Repetition rate	240 Hz (up), 8 Hz (down)	56 Hz
Laser energy	3.84 W (up), 0.16 W (down)	8.4 W
Beam divergence	60 µrad (up), 100 µrad (down)	50 µrad
Mirror area	0.042 m^2(up), 1.003 m^2 down)	0.196 m^2

John J. Degnan, in Lasers, Clocks, and Drag Free…



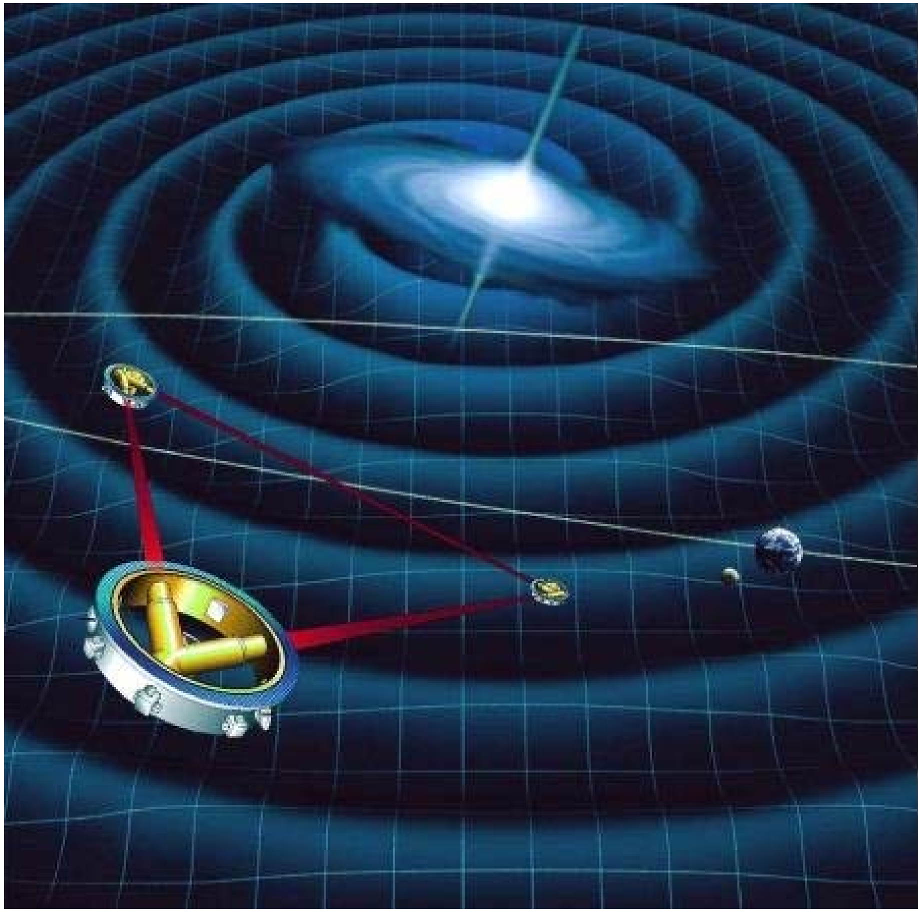
Echo transponder
Time delay must be known.



Asynchronous transponder für satellite laser ranging
Repetition rate must be known.

LISA: gravitational waves obs.

- Cluster of 3 S/C in heliocentric orbits at 1 AU
- S/C form an equilateral triangle with
  5 mio km arm length
- Earth trailing orbit:20 ° behind the Earth
- Leaned 60° with respect to the ecliptic
- S/C contain laser and inertial test masses
- System forms a Michelson Interferometer
- Designed for galactic and cosmological sources



K.Danzmann, MPI-AEI

Unexplained phenomena within GR

Cosmological phenomena

Dark Energy (*Turner* 1999):
to describe the accelerated expansion of the universe seen from supernovae observations and CMB anisotropy measurements

Dark Matter (*Zwicky* 1933):
to describe galactic rotation curves, gravitational lensing effects and early structure formation in cosmological models

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Astronomical observations

Increase of the Astronomical Unit (*Pitjeva* 2005, *Krasinski* 2005):
length scale related to the earth-sun distance increases
by 7 ± 1 m per 100 years (confirmed by astronomical observations);
solar mass loss only explains ca. 1 m per century

Quadrupole/Octopole Anomaly (*Tegmark et al*. 2005, *Schwarz et al.* 2005):
Quadrupole and octopole of CMB are correlated with solar system ecliptic

Increase of the Astronomical Unit

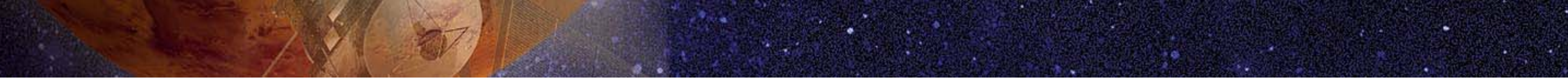
Observations

Krasinsky and Blumberg (2005): 15 ± 4 m / 100 a

Pitjeva (in *Standish* (2005)): 7± 1 m / 100 a

Remarks and questions

- $dG/dt \neq 0$ exluded by Lunar Laser Ranging
- Mass loss of Sun causes only 1 m / 100 a
- Influence by cosmic expansion many orders of magnitude too small
- Increase of solar wind plasma on long time scales ?
- Drift of clocks $t \to t + \alpha t^2$ with $\alpha \approx 3 \cdot 10^{-20}\ s^{-1}$?



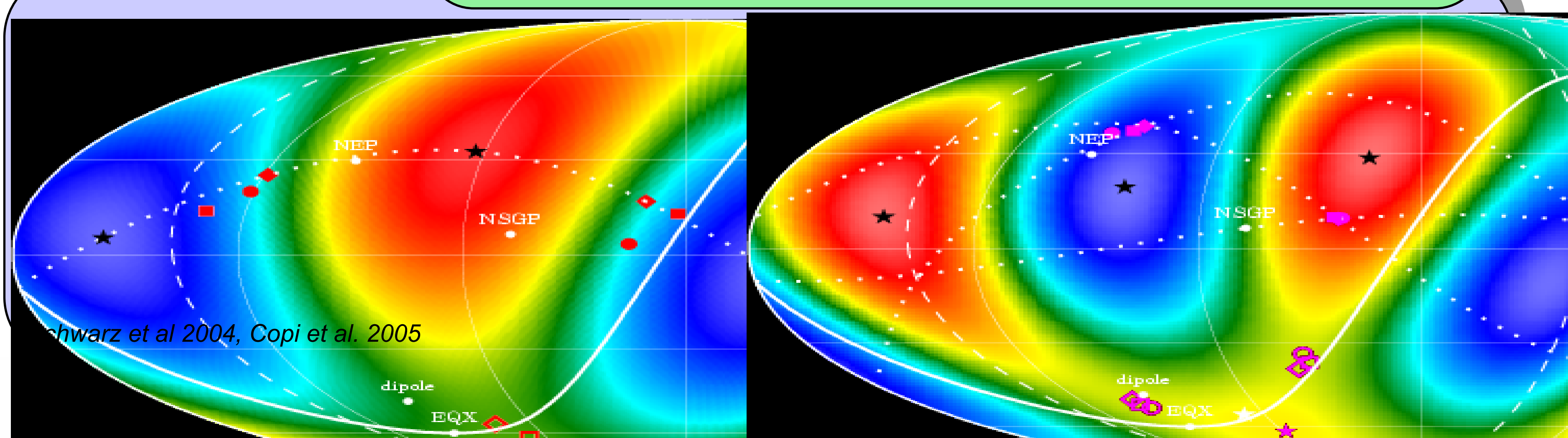
Quadropole / octopole anomaly

Observations

- Anomalous behaviour of low ℓ contributions to CMB quadupole and octopole aligned to > 99.87 %
- Quadrupole and octopole aligned to ecliptic to > 99 %
- No correlation with the galactic plane
  (*Oliveira* et al (2004), *Schwarz* et al (2005))

Remarks and questions

- Influence of solar system on CMB observations ?
- Systematics ?



chwarz et al 2004, Copi et al. 2005

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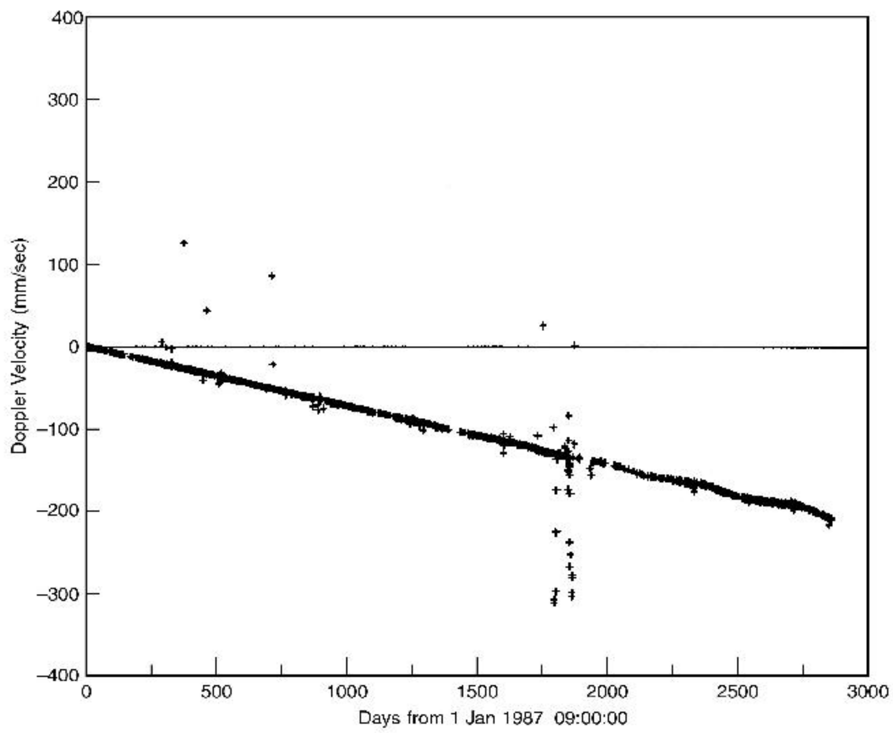
Satellite tracking effects

Pioneer Anomaly (*Anderson et al.* 1998,2002/04)

Fly-by Anomalies (*Antresian and Guinn* 1998, *Anderson and Williams* 2001, *Morley* 2005, *Campbell* 2006, *Anderson* et al., 2008)

GRACE-Anomaly (*Bertiger* et al 2003)

(1) Pioneer Anomaly



- Acceleration has been observed as *constant* for more than 16 years
- Temporal and spatial variantions < 3%
- Analyzed in detail with data from 1987 to 1998 for distances *between 20 and 70 AU* by JPL
- Effect observed when satellites had set from elliptic (bound) to *hyperbolic (escape) orbits*
- No indication about range in space

- Doppler tracking of the Pioneer 10 and 11 satellites showed a blue- shifted, anomalous frequency shift

$$\dot{f}_p = (5.99 \pm 0.01) \cdot 10^{-9}\ \mathrm{Hz/s}$$

- Drift can be interpreted as an acceleration directed toward the sun of

$$a_p = (8.74 \pm 1.33) \cdot 10^{-10}\ \mathrm{m/s^2}$$

(*Anderson* et al. 1998, 2002)

Reasons for Speculations

- Surprising coincidence of PA acceleration and cosmic expansion rate

$$a_p \approx cH$$

- Extremely constant acceleration in space and time
  Cancels out nearly all systematics
- Largest size experiment ever carried out
  Failed to proof Newton´s $1/r^2$-law on large distances
- Not the only anomaly observed in our solar system

Doppler Tracking in the expanding Universe

- Observer at rest in cosmic substrate
- S/C moves on geodesics and is slowed down
- Cosmic redshift of frequency
- Resulting Doppler effect (velocity of points of constant distance wrt cosmic substrate

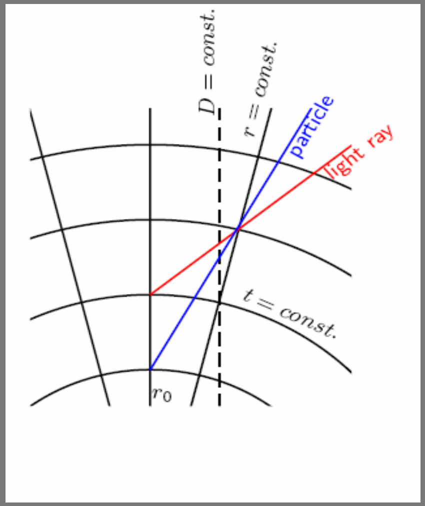
$$\nu_2(t_2) = \left(1 - H(t_2 - t_1) - V_2^{tot}\right)\nu_0(t_1)$$

$$V_2^{tot}(t_2) = H(t_2 - t_1) - V_2^{tot} H(t_2 - t_1)$$

Red shift and Doppler cancel

- Only the satellite´s slow down ist left over.

$$a = HV = \frac{V}{c} cH << cH$$



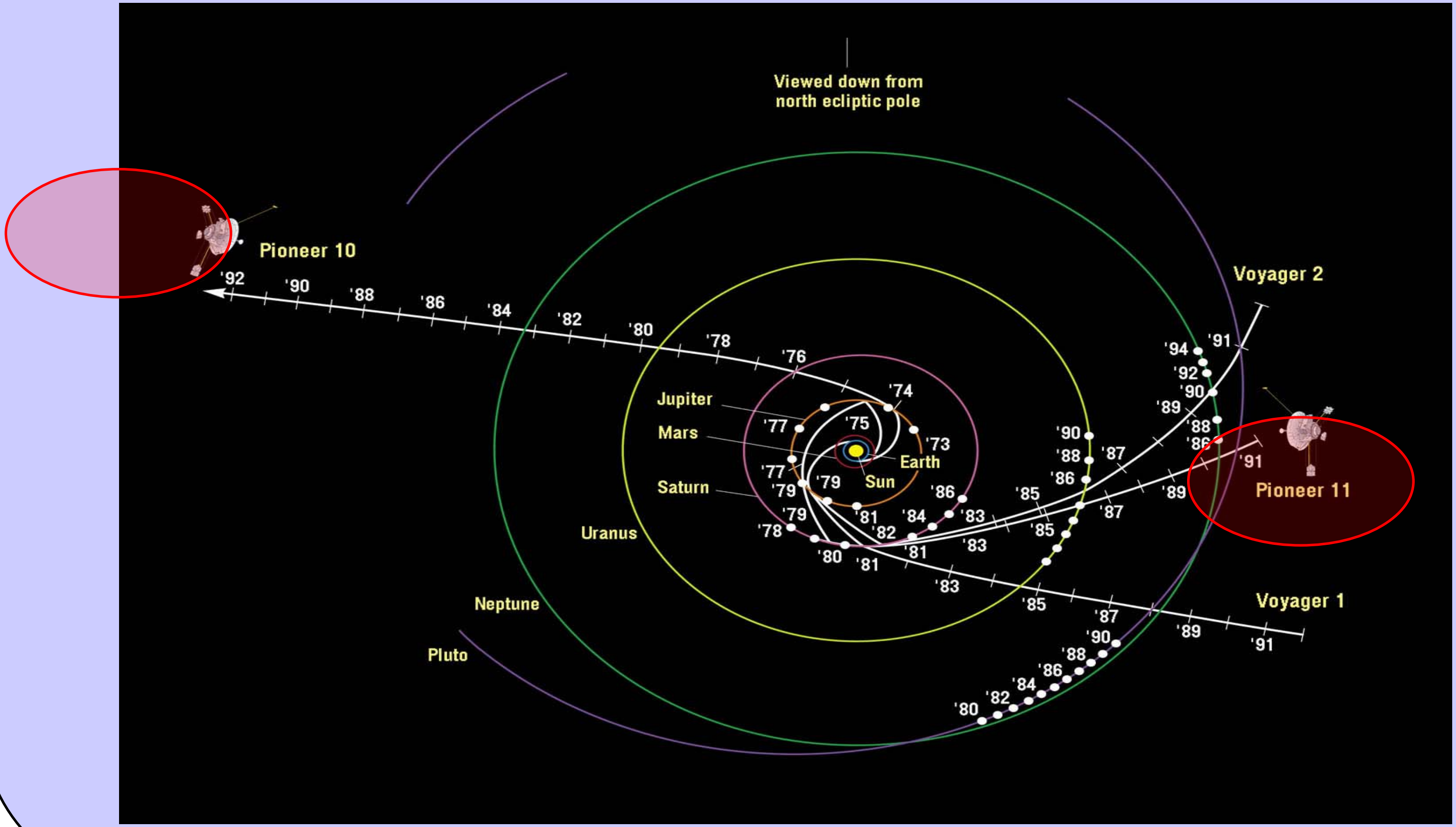
Pioneer 10 and 11 satellites

	Pioneer 10	Pioneer 11
Launch	2.3.1972	5.4.1973
Planetary fly-bys	Jupiter: 4.12.1973	Jupiter: 2.12.1974 Saturn: 1. 9.1979
Last data received	27.4.2002 (after 30 years of operation) @ 80.2 AU	1.10.1990 @ ca. 30 AU
Direction of orbit line	Aldebaran	Aquila constellation

Satellite mass	259 kg
Power: SNAP-19 RTGs	boom 3 m / mass 13.6 kg
Magnetometer	boom 6 m / mass 5 kg
High-gain antenna Ø	2.74 m
Maximum cross section	5.914 m^2
Spin rate	4.28 rpm
Maximum moment of inertia	588.3 $kg \cdot m^2$
Up-link frequency	2.110 GHz (S-band)
Down-link frequency	2.292 GHz (S-band)
Radio link wavelength	ca. 13 cm
Transmission power	8 W

Slava Turyshev, JPL.

The orbits of Pioneer 10 and 11



- Elliptic (bound) orbits befor the last fly-by
- Hyperbolic (escape) orbits after the last fly-by

Observed Anomalous Doppler Drift

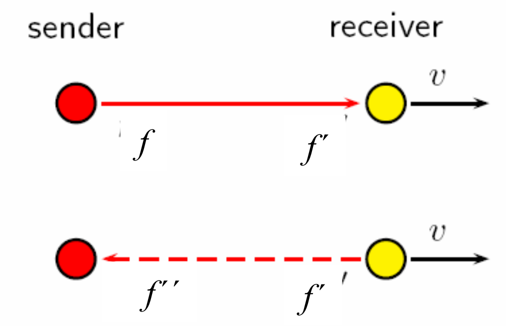
frequency received at S/C:

$$f' = \frac{1}{\sqrt{1-v^2/c^2}}\left(1-\frac{v}{c}\right)\cdot f$$

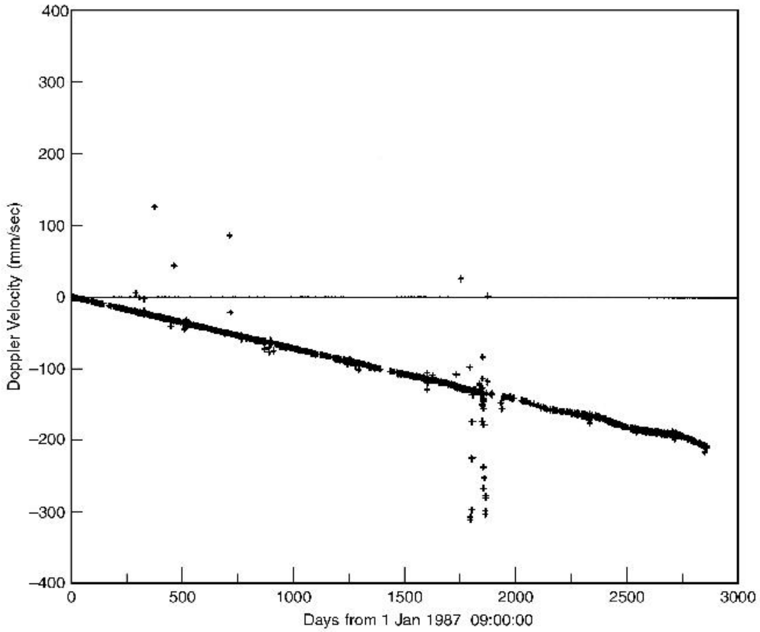
frequency sent back and received on earth:
(neglecting the transponder shift)

$$f'' = \frac{1}{\sqrt{1-v^2/c^2}}\left(1-\frac{v}{c}\right)\cdot f'$$

$$\frac{f''-f}{f} = -2\frac{v/c}{1+v/c} \approx -2\frac{v}{c}$$



$$v_{observed} - v_{modelled} = -2a_p t$$



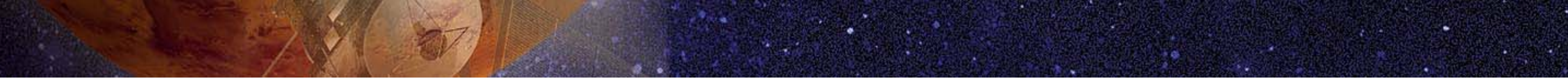
Anderson et al.

The two-way Doppler residuals for Pioneer 10 vs time

[1 Hz is equal to 65 mm/s range change per second].

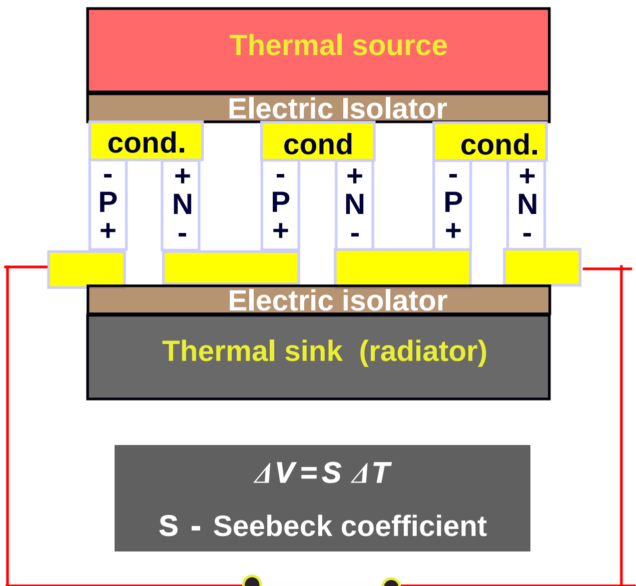
Error budget of external effects

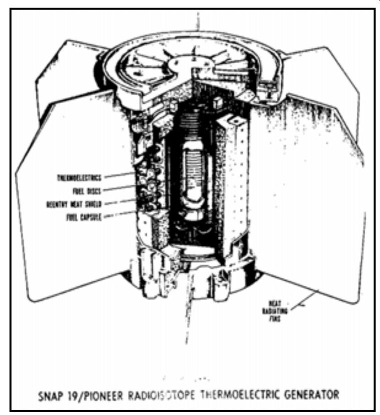
error budget constituents	bias $[10^{-10} m/s^2]$	uncertainty $[10^{-10} m/s^2]$
sources of external systematics		
solar radiation pressure		**± 0.001**
→ sol. rad. press. from mass uncertainties	**+ 0.03**	**± 0.01**
solar wind		**± 0.00001**
solar corona effects		**± 0.02**
Lorentz force (em-effects)		**± 0.0001**
Kuiper belt´s gravity		**± 0.03**
earth rotation		**± 0.001**
mechanical / phase stability of DSN antenna		**± 0.001**
clock effects on phase stability		**± 0.001**
DSN station location		**± 0.00001**
tropospheric and ionospheric effects		**± 0.001**
computational systematics		
numerical stability of least-square estimation		**± 0.02**
accuracy of consistency / model tests		**± 0.13**
→ mismodelling of manoeuvers		**± 0.01**
→ mismodelling of solar corona		**± 0.02**
annual / diurnal terms		**± 0.32**



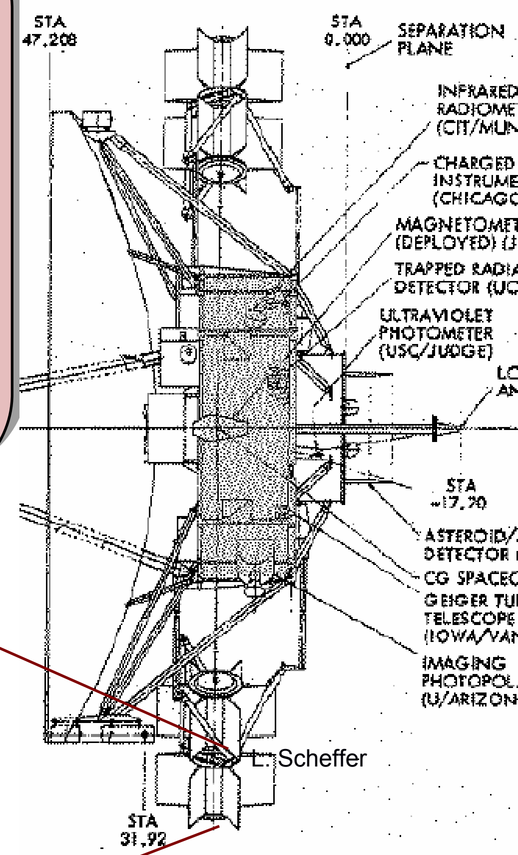
Sources of internal systematic error

error budget constituents	bias [10^{-10} m/s^2]	uncertainty [10^{-10} m/s^2]
radio beam reaction force	+ 1.10	± 0.11
thermal and propulsion effects from RTGs		
→ RTG heat reflected off the S/C	-0.55	± 0.55
→ differential emissivity of the RTGs		± 0.85
→ non-isotropic radiative cooling of S/C		± 0.16
→ expelled He produced within the RTGs	+0.15	± 0.16
mass expulsion / gas leakage		± 0.56
variation between S/C determinations	+0.17	± 0.17





Radioisotope Thermoelectrical Generator (SNAP-19)



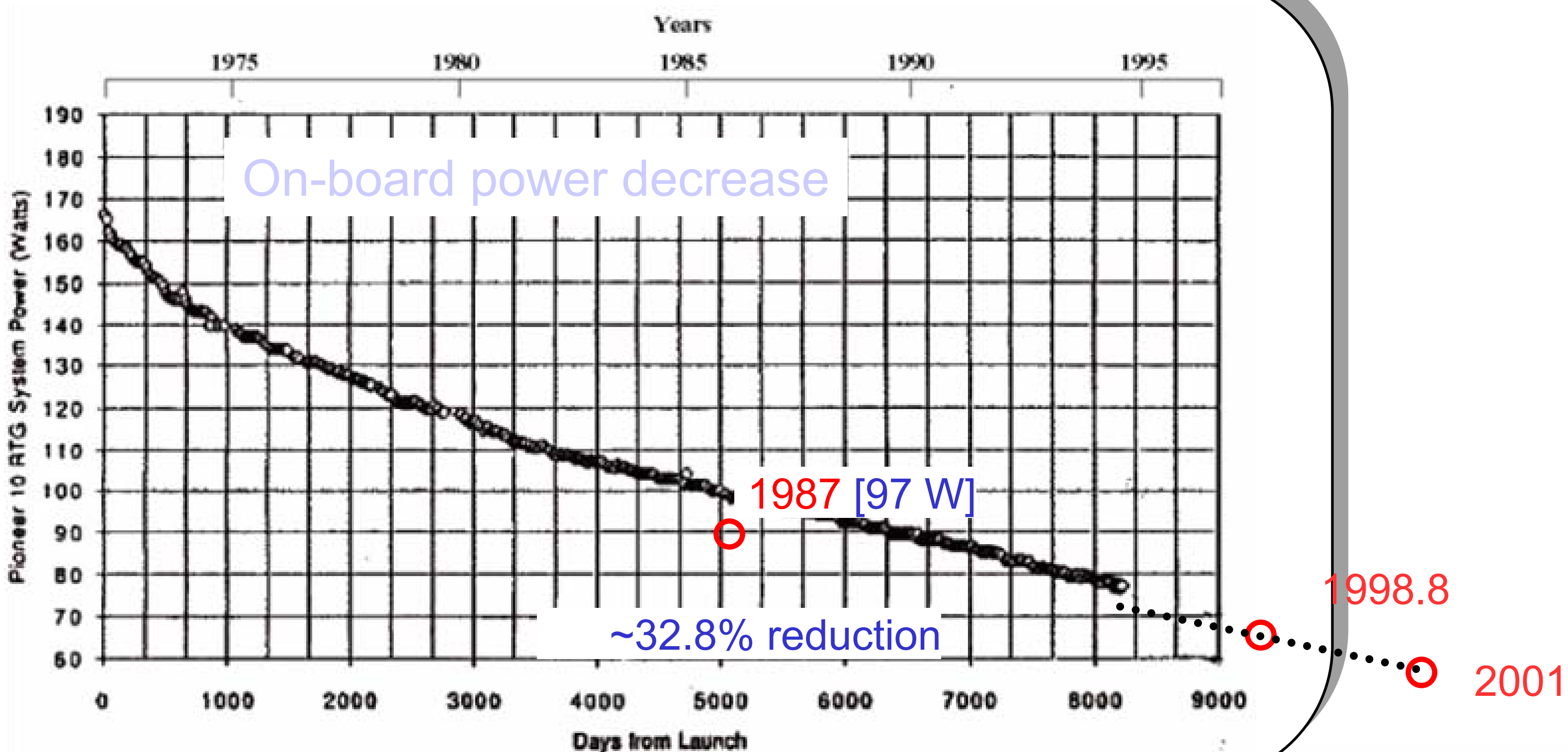
$$_{94}Pu^{238} \rightarrow {}_{92}U^{234} + {}_{2}He^{4}$$

Half-life time: 87.74 years

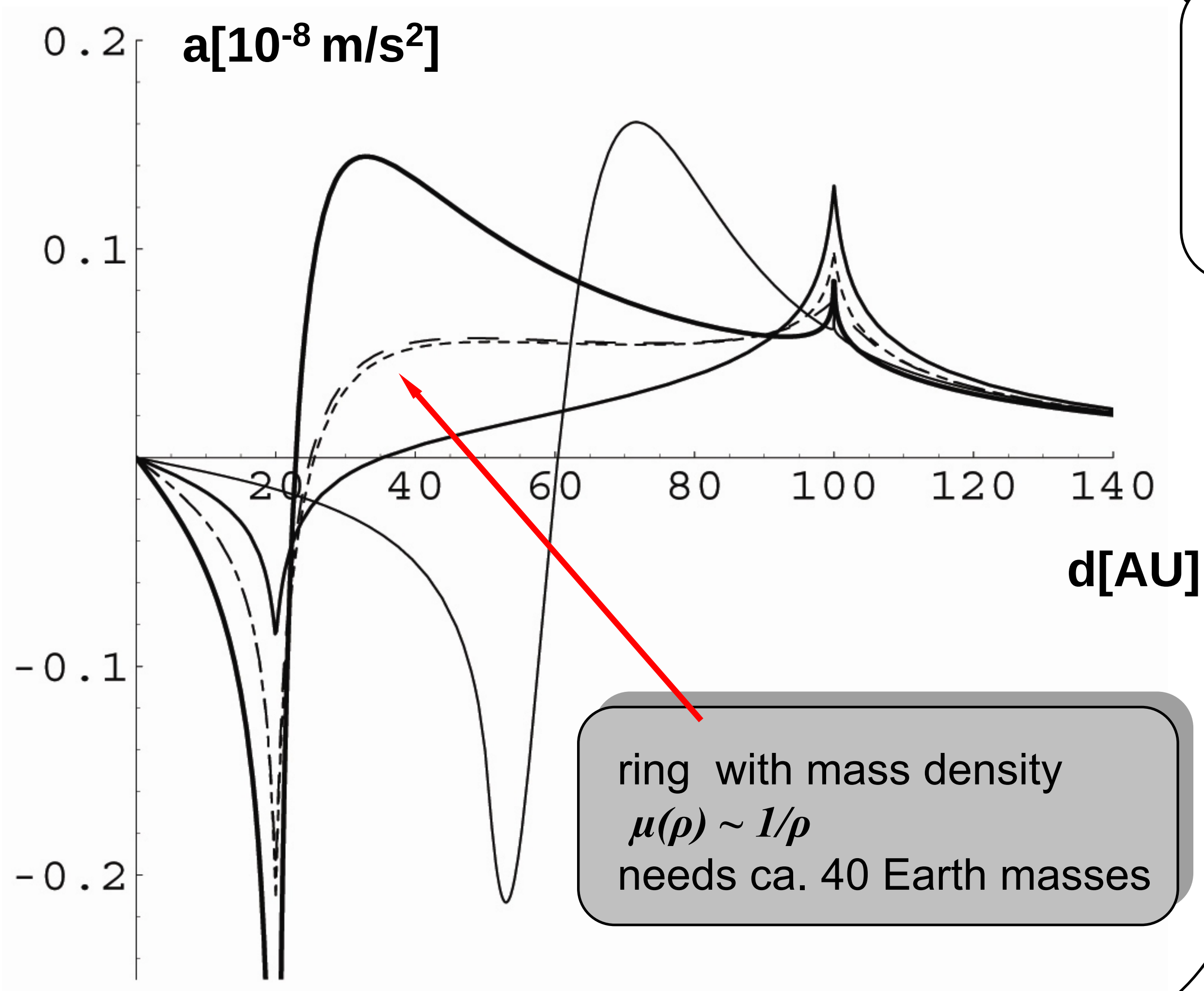
ca. 2000 W

Thermal history

- 60 W asymmetric IR-radiation (out of initial 2000 W) could explain the anomaly
- Symmetry breaking through high-gain antenna (Ø 2,3 m)
- Spin rate change of both satellites shows, that thermal models are consistent.
- Models include surface degradation effects (also worst-case scenarios)



Unexpected masses in the solar system



Acceleration vs. distance for different mass density distribution (*Nieto*, 2005)

ring with mass density
$\mu(\rho) \sim 1/\rho$
needs ca. 40 Earth masses

Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.

Drag through dust

Interplanetary Medium

- is a thinly scattered matter (neutral Hydrogen, microscopic particles) with two main contributions, IPD and ISD:
- Interplanetary Dust (IPD), modelled: $\rho_{IPD} \leq 10^{-24}$ g/cm^3
- Interstellar Dust (ISD), measured on Ulysses S/C: $\rho_{ISD} \leq 10^{-26}$ g/cm^3

Drag on a spacecraft

$$a_{drag} = -c_s \frac{\rho(r) v_s A_s}{m_s}$$

The Pioneer Anomaly (between 20 and 70 AU) could only be explained with an axially-symmetric dust distribution with a constant uniform density of

$$\rho(r) \leq \rho_0 = 3 \cdot 10^{-19} \text{ g/cm}^3 \approx 300.000(\rho_{IPD} + \rho_{ISD})$$

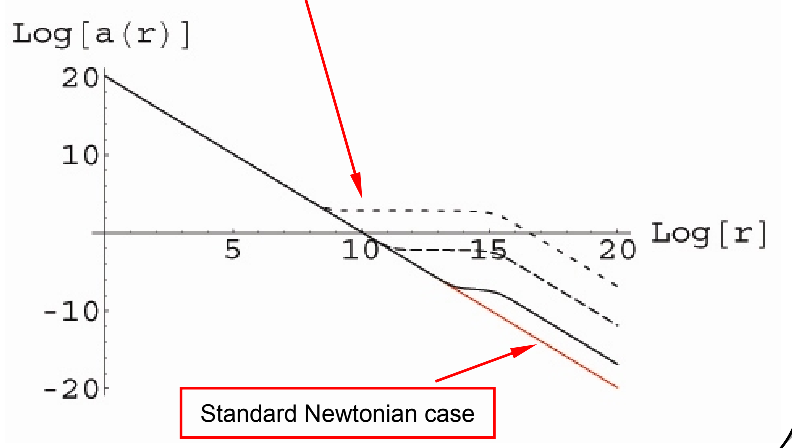
Yukawa modification

Ansatz $V(r) = G \frac{M_{Sun}}{r} \left(1 + \alpha \cdot e^{-r/\lambda}\right)$

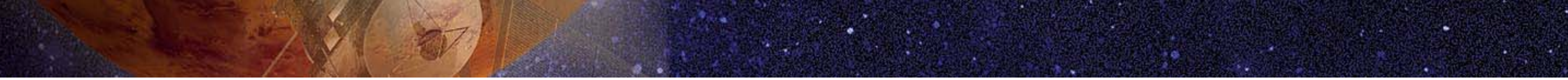
with Taylor extension and

$G_0 = (1 + \alpha)G$ as observed grav. constant for $r \to \infty$

$$a(r) = -G_0 \frac{M_{Sun}}{r^2} + \frac{\alpha}{1+\alpha} G_0 \frac{M_{Sun}}{2\lambda^2} - \frac{\alpha}{1+\alpha} G_0 \frac{M_{Sun}}{3\lambda^2} \frac{r}{\lambda} + \dots$$



- $\log_{10}(\lambda) > 16$ for $\log_{10}|\alpha| = 1$ compatible with present experimental results in the solar system (including planetary orbits)
- A viable model?
  - Pioneer Anomaly: $\log_{10}(\lambda) > 16$, $\alpha + 1 \leq 10^{-5}$
  - Galaxy rotation curves $\log_{10}(\lambda) > 16$, $\alpha + 1 \leq 10^{-1}$

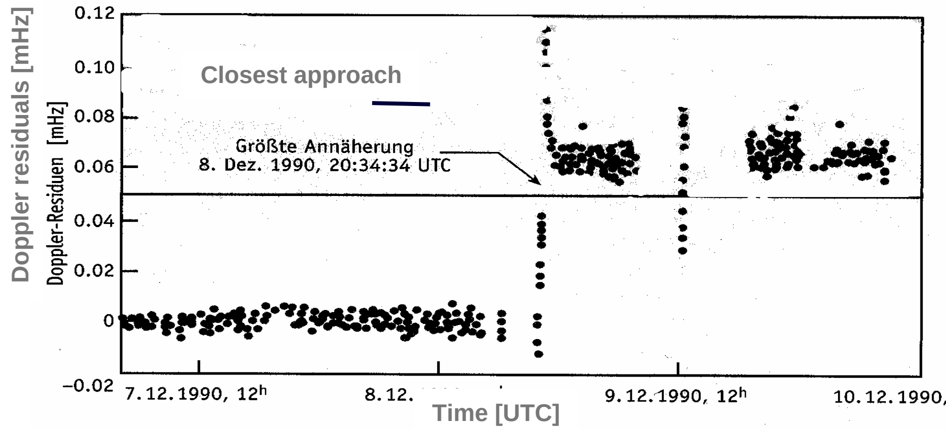


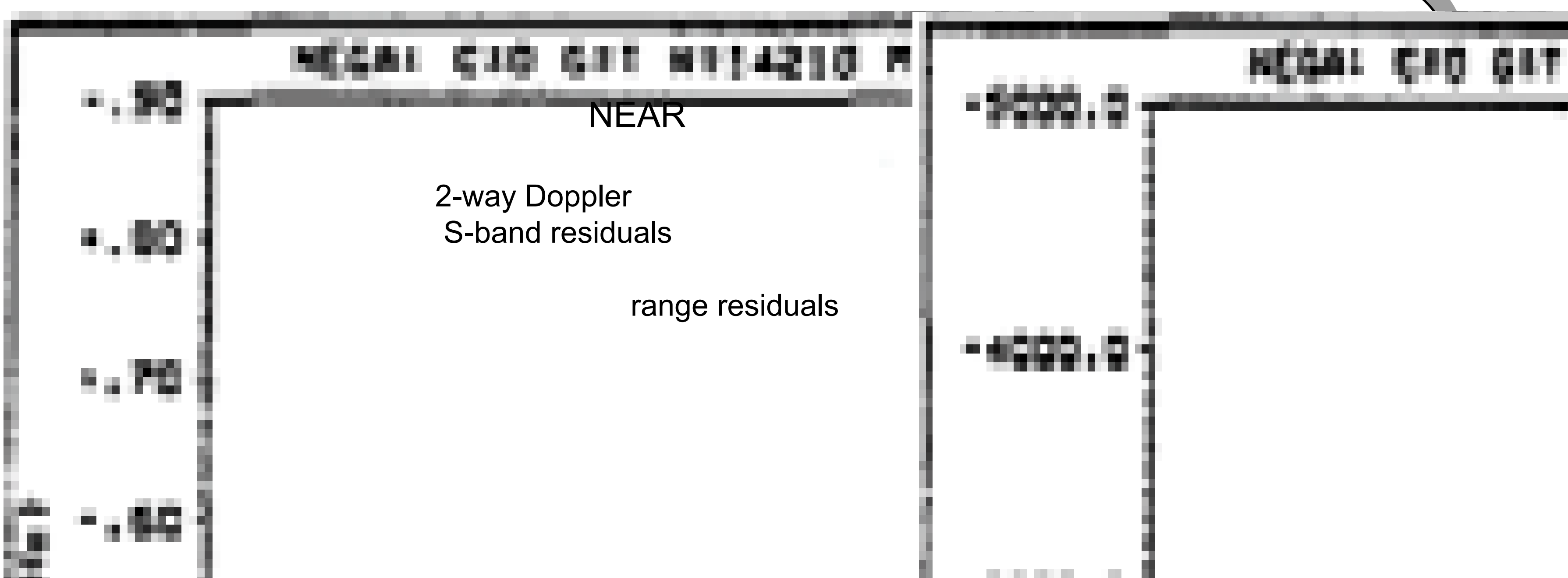
(2) Fly-by Anomaly

1st time measured Dec. 1990 during GALILIEO´s 1st gravity assist manouever at Earth:

unexplained 2-way S-band Doppler shift of 66 mHz which could be interpreted as anomalous velocity increase of 3.93 ± 0.08 mm/s

Antreasian & Guinn 1998, *Anderson & Williams* 2001, *Morley* 2005, *Preuss* 2006



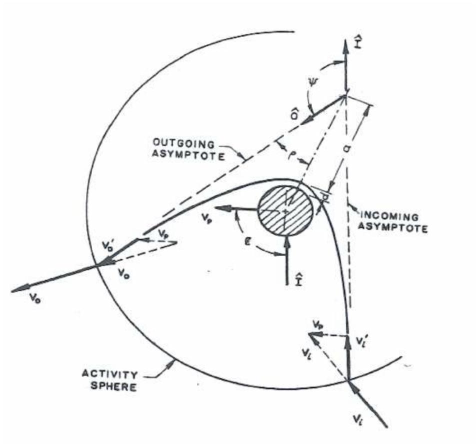


Earth Fly-bys analyzed so far

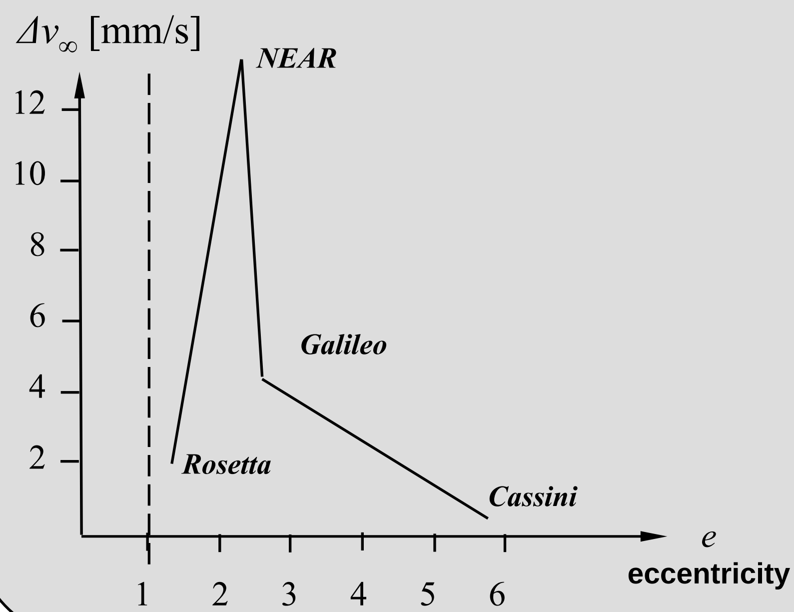
	Galileo (1st fly-by)	NEAR	Cassini	Rosetta	Messenger
v_∞ [km/s]	8.949	6.851	16.01	3.863	4.056
v_F [km/s]	13.738	12.739	19.03	10.517	10.389
h [km]	956	532	1,172	1,954	2,336
ε	2.47	1.81	5.86	1.31	1.13
Θ [°]	47.67	66.92	19.66	99.396	94.7
i [°]	142.9	108.0	25.4	144.9	133.1
Fly-by	8.12.1990	23.1.1998	18.8.1999	4.3.2005	2.8.2005
Δv_∞ [mm/s]	3.92 ± 0.08	13.46 ± 0.13	~ 1	1.82 ± 0.05	
Δv_F [mm/s]	2.56 ± 0.05	7.24 ±0.07	|-0.2| (?)	0.67 ± 0.02	O (0)

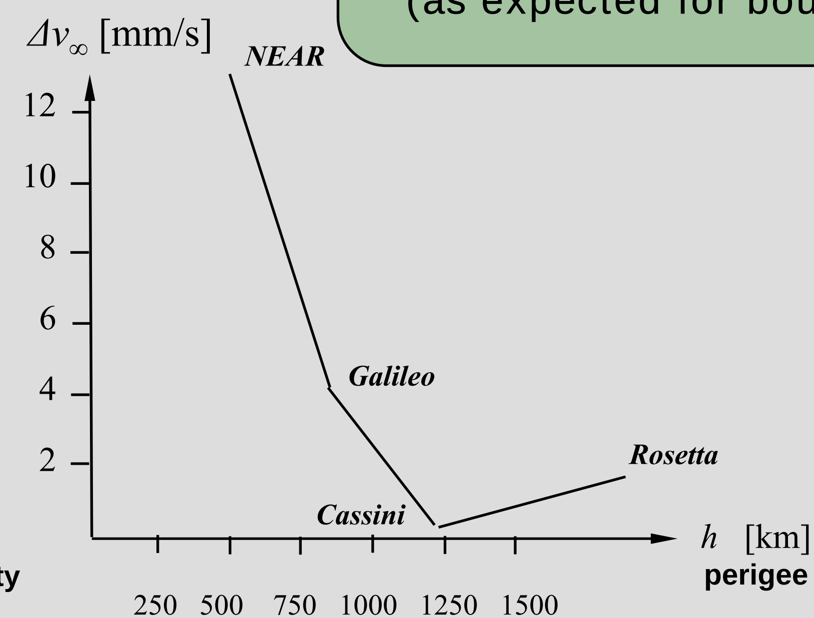
Observed phenomena

$$\Delta E_{kin} / m_{sat} = \left(v_0^2 - v_i^2\right)/2$$
$$= v_{earth}\left(v_0' - v_i'\right)$$



- Δv decreases with increasing eccentricity and perigee height
- Δv disappears at e = 1 (as expected for bound orbits)





Error analysis

error budget constituents	bias [10^{-5} m/s^2]
Atmospheric drag	- 0.0001
Ocean tides	± 0.1
Solid earth tides	« |0.15|
S/C charging (modeled / analyzed for LISA; for charging Q < 10^{-7} C	± 0.0001
Magnetic moments (< 2 · 10^{-7} G/m)	± 10^{-10}
Earth albedo (1 t S/C)	± 0.00024
Solar wind	± 0.0003
Relativistic corrections $U \cdot v^2 / c^2 \approx 10^{-20}$	not affecting
Spin rotation coupling (coupling of the helicity of radio waves with S/C spin and Earth rotation (only effective for 2-way Doppler ranging)	not affecting

Attempts to explain

- Explanations by systematics failed so far.
- Confirmed by different codes
- Real effect inherent to the tracking of S/C
- Source unknown

(*Anderson* et al., PRL, 2008)

Empirical prediction formula (*Anderson* et al., PRL, 2008)

$$V_\infty^2 = \vec{v}_{S/C} \cdot \vec{v}_{S/C} - \frac{2M_E G}{r}$$

↳ $$\frac{\Delta V_\infty}{V_\infty} = K\left(\cos\delta_{in} - \cos\delta_{out}\right) \quad \text{with} \quad K = \frac{2\omega_E R_E}{c}$$

(3) GRACE Anomaly

- Observed difference of a systematic time shifts of

  0.056 ps/ s → 45.6 ns/d

  independently determined by

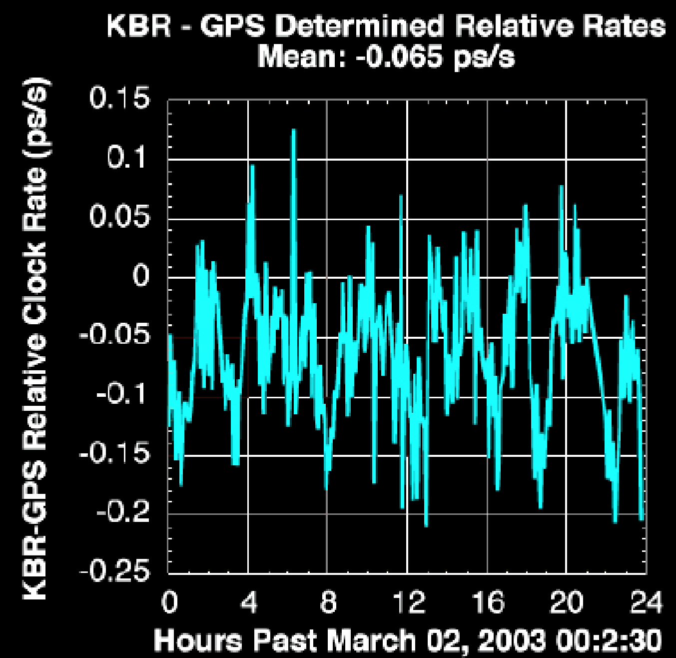
  (1) Ku-band ranging and

  (2) GPS (*Bertiger* et al. 2003)

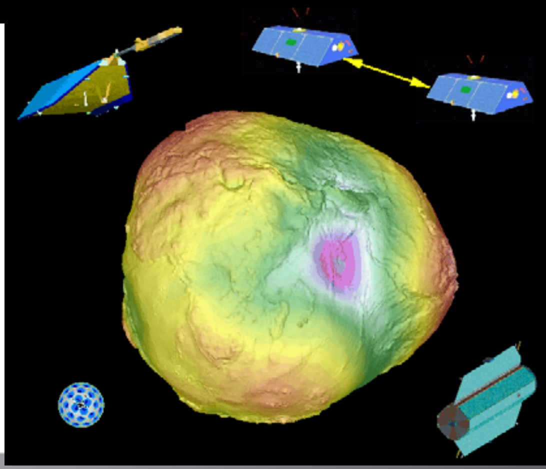
- Could be interpreted as a anomalous acceleration of the GRACE satellites:

  $0.2 \cdot 10^{-4}$ m/s^2

- Same order of magnitude than fly-by anomaly!



Difference of KBR and GPS determined clock rates



Take-home messages

- **Unexplained phenomena**
  - Dark matter (does it affect solar system physics?)
  - Dark energy
  - Increase of AU
  - Quadrupole / Octopole anomaly

„From Quantum to Cosmos 4“ (Q2C4)
Bremen (Germany) Sept. 21 – 24, 2009
www.zarm.uni-bremen.de/Q2C4
laemmerzahl@zarm.uni-bremen.de
hansjoerg.dittus@dlr.de

- **It´s**
  - probably are not
  - Are there similar effects in other gravitating systems?
  - What´s about hyperbolic orbits?
- **Observation of future fly-bys of satellites**
  - Rosetta Earth fly-by 11 / 2009 (orbital height: ca. 2,500 km)
  - New Horizon Jupiter fly-by in 2008 ?