New high precision tests of General Relativity

Claus Lämmerzahl
4. November 2021

ICRANet-Isfahan astronomy meeting
online, 5. - 5. November 2021

DFG
Research Training Group
Graduiertenkolleg
Models of Gravity

Universität Bremen*

CENTER OF
APPLIED SPACE TECHNOLOGY
AND MICROGRAVITY
ZARM

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

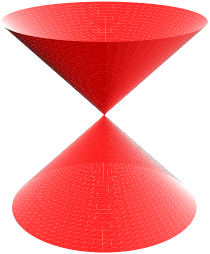
Unresolved questions

Summary and outlook

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation $\rightarrow$ metrics, local Special Relativity



$c = const$

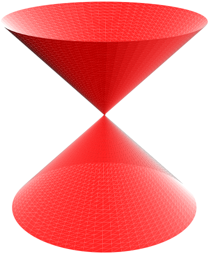
Minkowski metrics η_{ab}

many Tests $10^{-15} - 10^{-30}$

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation $\rightarrow$ metrics, local Special Relativity



- independence of c from velocity of source: $\leq 10^{-11}$
- isotropy of c: $\leq 10^{-17}$
- Kennedy-Thorndike: $\leq 10^{-17}$
- time dilation: $\leq 10^{-8}$

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation → metrics, local Special Relativity
- **Universality of Free Fall**

$\exists$ coordinate system so that $\forall$ freely falling particles

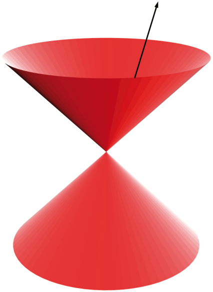
$$\frac{d^2 x^\mu}{dt^2} \overset{*}{=} 0$$

- bulk matter Schlamminger et al, 2003: $\eta \leq 10^{-13}$, MICROSCOPE $\eta \leq 10^{-14}$
- particles with spin
- charged particles
- anti-particles

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation → metrics, local Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity



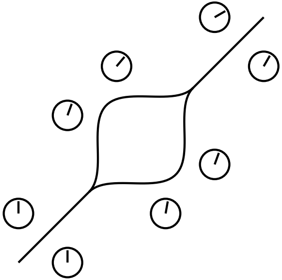
$v < c$

- laboratory: $\leq 10^{-6}$
- astroparticles: $\leq 10^{-21}$

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation → metrics, local Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of clocks** or uniqueness of quantum mechanics or **Local Position Invariance**



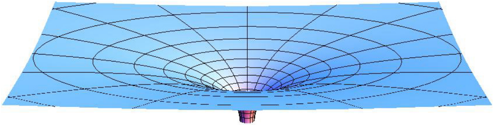
clocks show twin paradox but same ticking rate

comparison of different clocks Ashby et al, 2018: $\alpha \leq 5 \cdot 10^{-7}$
anti-clocks, Galileo

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation → metrics, local Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of clocks** or uniqueness of quantum mechanics or **Local Position Invariance**

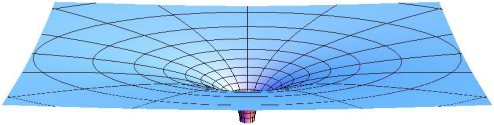


Einstein Equivalence Principle

Gravitation

Foundation of space-time geometry (Ehlers, Pirani, Schild 1972; Will 1993)

- **Licht** Uniqueness of light propagation $\rightarrow$ metrics, local Special Relativity
- **Universality of Free Fall**
- **Compatibility** no superluminal velocity
- **Uniqueness of clocks** or uniqueness of quantum mechanics or **Local Position Invariance**



Einstein Equivalence Principle

Result: Gravity is described by a curved Riemannian space-time $g_{\mu\nu}$

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

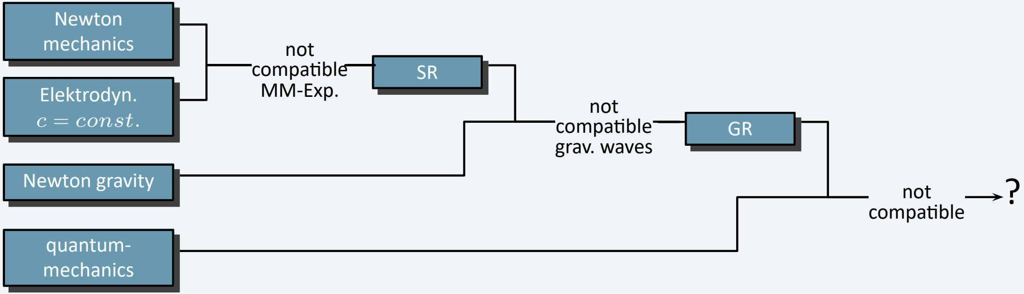
Unresolved questions

Summary and outlook

The Einstein field equations

History of space-time theories

Historical context



Implications of GR

- tiny Solar system effects: perihelion shift., deviation of light, redshift, grav. time delay., ...
- take field equations serious: Black Holes → triumph of theory !!!
- then perhaps also: time travel, worm holes, ... ?

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

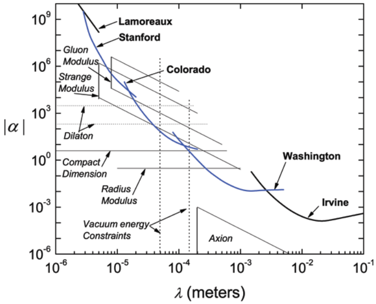
Outlook: Measurement of a new clock effect?

Unresolved questions

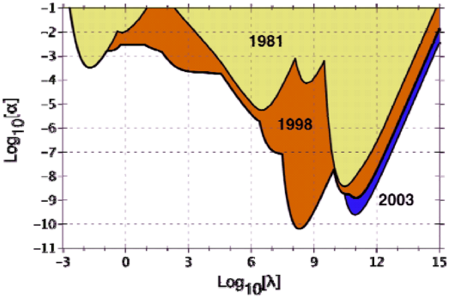
Summary and outlook

Test of Newton potential

$$U = \frac{GM}{r}\left(1 + \alpha e^{-r/\lambda}\right) = \text{Newton} + \text{Yukawa deviation}$$



small scales



large scales (LLR, ephemerides, ...)

Test of Newton potential

SME (Kostelecky, PRD 2005): anisotrope Newton potential

$$U = \frac{MG}{r}\left(1 + \frac{r^i c_{ij} r^j}{r^2}\right) = \text{Newton} + \text{anisotropy}$$

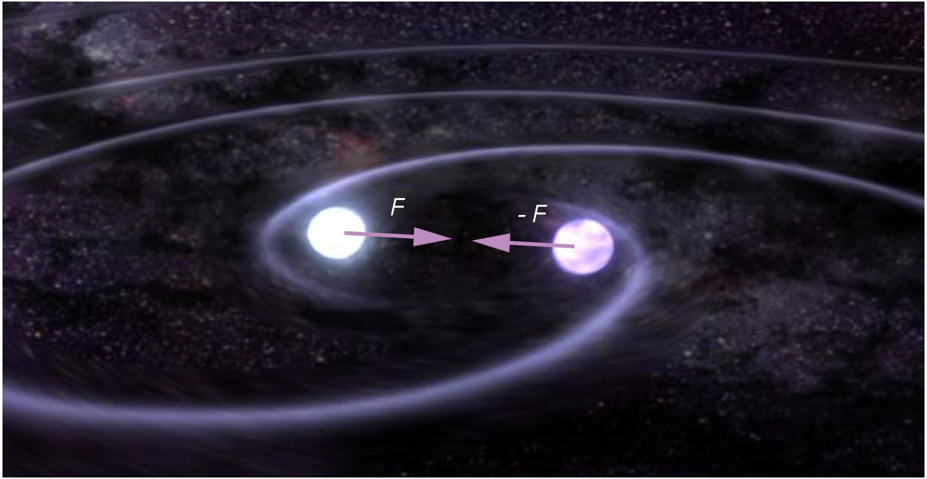
Experiment

- atom interferometry (Müller et al, PRL 2007)
- LLR (Battat, Chandler & Stubbs, PRL 2007)

result

$$|c_{ij}| \leq 10^{-5} \ldots 10^{-9}$$

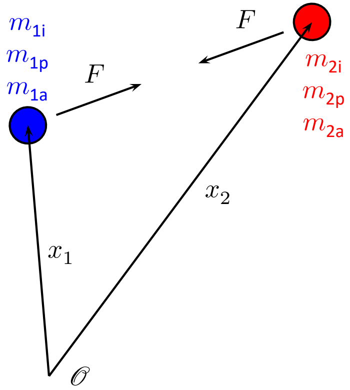
actio = reactio ?



Active and passive gravitational mass

Gravitationally bound 2-body system (Bondi, RMP 1957)

$$\begin{aligned} m_{1\mathrm{i}}\ddot{x}_1 &= m_{1\mathrm{p}} m_{2\mathrm{a}} \frac{x_2 - x_1}{|x_2 - x_1|^3} \\ m_{2\mathrm{i}}\ddot{x}_2 &= m_{2\mathrm{p}} m_{1\mathrm{a}} \frac{x_1 - x_2}{|x_1 - x_2|^3} \end{aligned}$$



⇒ self-acceleration of center-of-mass if

$$C_{21} = \frac{m_{2\mathrm{a}}}{m_{2\mathrm{p}}} - \frac{m_{1\mathrm{a}}}{m_{1\mathrm{p}}} \neq 0$$

- violation of *actio = reactio* for gravity
- $C_{12} = 0 \Rightarrow$ masses of same weight create the same gravitational field, independent of their composition ↔ another equivalence principle

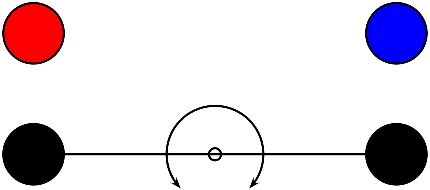
Experiment for testing $m_{\mathsf{a}} = m_{\mathsf{p}}$

measurement of gravitational attraction

Schritt 1: two masses with equal weight $m_{\mathsf{p1}} = m_{\mathsf{p2}}$

Schritt 2: test of equality of active gravitating masses with torsion balance

experimental setup: torsion balance with identical test masses is sensitive to $m_{\mathsf{a1}} \neq m_{\mathsf{a2}}$



no effect has been observed: $C_{12} \leq 5 \cdot 10^{-5}$ (Kreuzer, PR 1868)

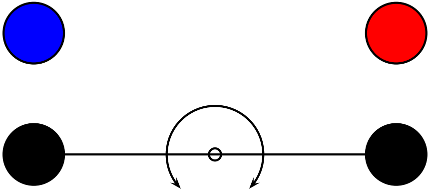
Experiment for testing $m_\mathsf{a} = m_\mathsf{p}$

measurement of gravitational attraction

Schritt 1: two masses with equal weight $m_{\mathsf{p1}} = m_{\mathsf{p2}}$

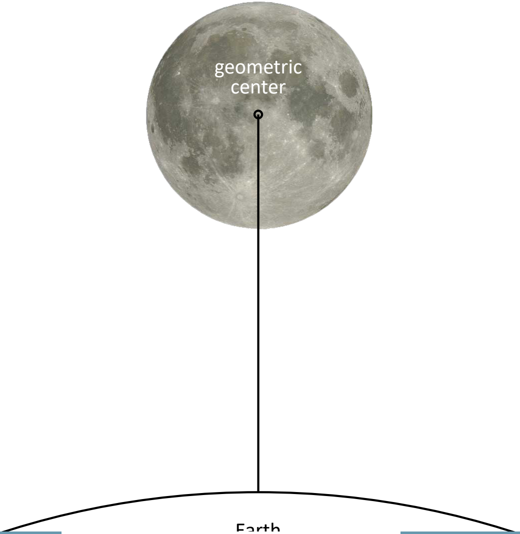
Schritt 2: test of equality of active gravitating masses with torsion balance

experimental setup: torsion balance with identical test masses is sensitive to $m_{\mathsf{a1}} \neq m_{\mathsf{a2}}$

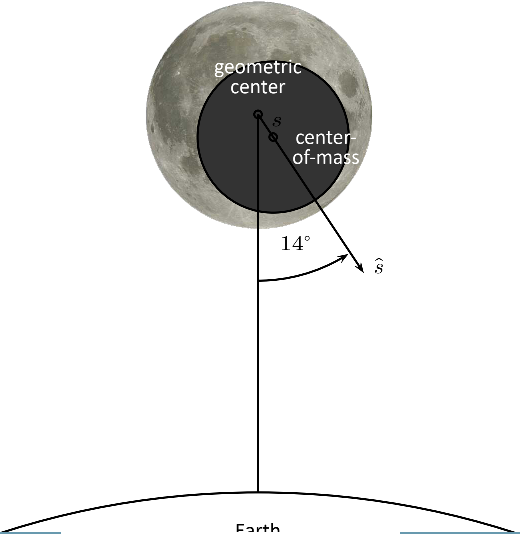


no effect has been observed: $C_{12} \leq 5 \cdot 10^{-5}$ (Kreuzer, PR 1868)

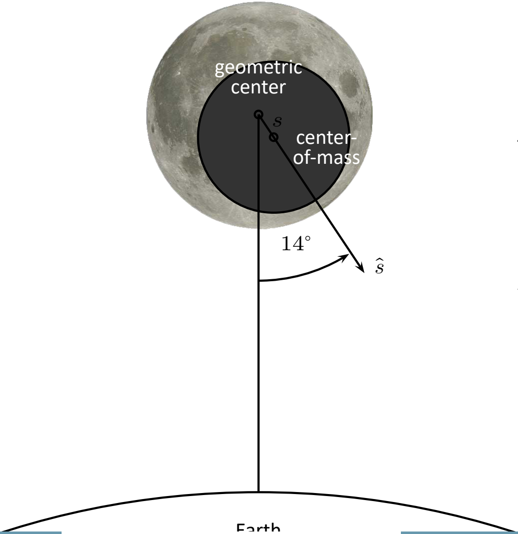
Experiment for testing $m_\mathsf{a} = m_\mathsf{p}$



Experiment for testing $m_{\mathsf{a}} = m_{\mathsf{p}}$



Experiment for testing $m_\mathsf{a} = m_\mathsf{p}$



measurement of self-acceleration of center-of-mass

$$\frac{F_\text{self}}{F_\text{EM}} = C_\text{Al-Fe} \frac{M_\text{M}}{M_\oplus} \frac{r^2_\text{EM}}{r^2_\text{M}} \frac{s}{r_\text{M}} \frac{\rho}{\Delta\rho} \hat{s}$$

tangential component of force increases orbital velocity

$$\frac{\Delta\omega}{\omega} = 6\pi \frac{F_\text{self}}{F_\text{EM}} \sin 14^\circ \text{ per month}$$

with LLR $\frac{\Delta\omega}{\omega} \leq 10^{-12}$ per month

$$\Rightarrow \qquad C_\text{Al-Fe} \leq 7 \cdot 10^{-13}$$

Bartlett & van Buren, PRL 1986

possible improvement with new LLR- and Moon Orbiter data

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

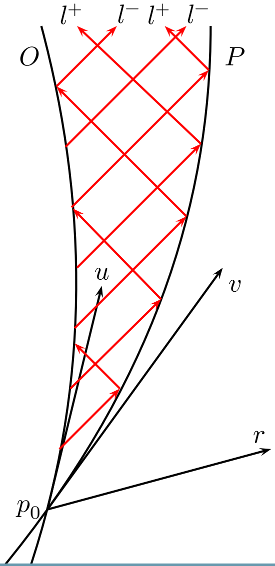
Unresolved questions

Summary and outlook

Standard clock, distance, and rotation

based on (freely falling) particles and light rays (unique)

- Standard clock
  GR defines what is a good clock
  (Perlick, GRG 1987)
  atomic clocks are good clocks

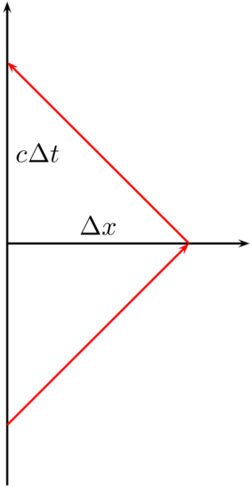


Standard clock, distance, and rotation

based on (freely falling) particles and light rays (unique)

- Standard clock
  GR defines what is a good clock
  (Perlick, GRG 1987)
  atomic clocks are good clocks
- unique determination of distance

$$\Delta x = c\,\Delta\tau$$



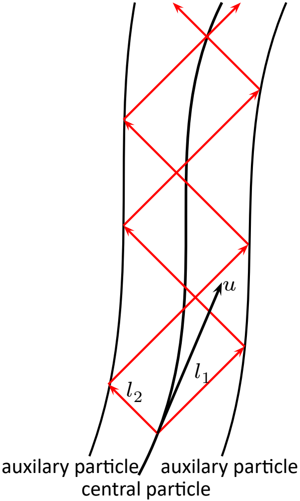
Standard clock, distance, and rotation

based on (freely falling) particles and light rays (unique)

- Standard clock
  GR defines what is a good clock
  (Perlick, GRG 1987)
  atomic clocks are good clocks
- unique determination of distance

$$\Delta x = c\,\Delta\tau$$

- rotation
  GR defines rotation
  (Pirani, BAP 1965)
  gyroscopes show exactly this rotation

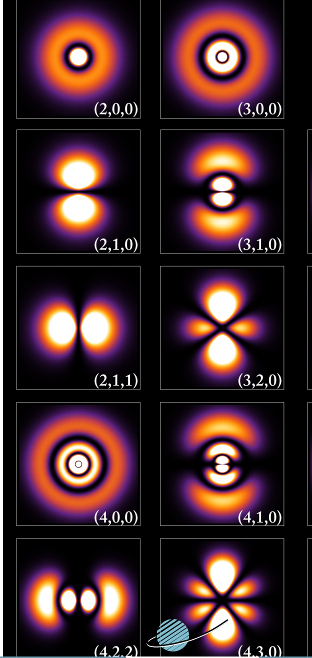


What is a good clock?

definition: a freely falling observer measures vanishing relative acceleration for freely falling particles

one can show: with very high precision an atomic clock is a standard clock:

- only in the vicinity of Black Holes space-time curvature may become so large that it influences the energy levels of atoms according to Ra_B^2 (a_B is the Bohr radius, Parker, Pimentel, PRD 1982) $\longrightarrow$ then atomic clocks are no standard clocks
- space-time curvature on Earth is very small $\Rightarrow$ leads to modification of the order $\frac{\delta\nu}{\nu} \sim 10^{-42}$ – far beyond experimental reach



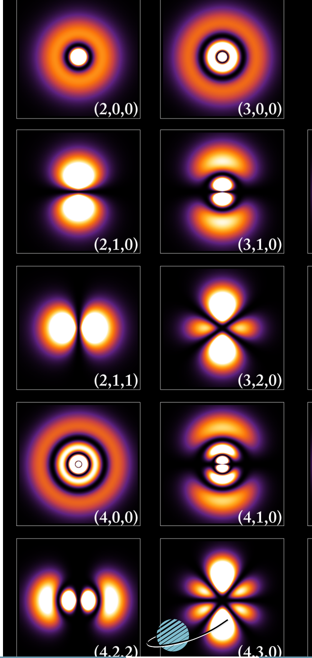
What is a good clock?

definition: a freely falling observer measures vanishing relative acceleration for freely falling particles

one can show: with very high precision an atomic clock is a standard clock:

- only in the vicinity of Black Holes space-time curvature may become so large that it influences the energy levels of atoms according to Ra_B^2 (a_B is the Bohr radius, Parker, Pimentel, PRD 1982) → then atomic clocks are no standard clocks
- space-time curvature on Earth is very small $\Rightarrow$ leads to modification of the order $\frac{\delta\nu}{\nu} \sim 10^{-42}$ – far beyond experimental reach

based on such standard clocks we define the gravitational redshift, gravitational time delay, gravitomagnetic clock effect, ...



Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

Summary GR

- equation for the **gravitational field**: Einstein field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **equations of motion** of pointlike particles in the gravitational file: geodesic equation

$$0 = \frac{d^2 x^\mu}{ds^2} + \left\{ {\mu \atop \rho\sigma} \right\} \frac{dx^\rho}{ds} \frac{dx^\sigma}{ds}$$

  $\left\{ {\mu \atop \rho\sigma} \right\}$ is the Christoffel symbol, and $ds = \sqrt{g_{\mu\nu} dx^\mu dx^\nu}$
  for extended objects: Mathisson-Papapetrou-Dixon equation

- **time keeping with standard clock** = proper time, defined through space-time geometry

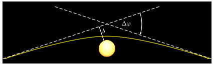
$$s = \int ds$$

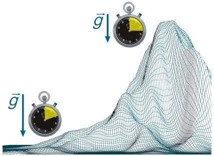
  kann operational definiert werden als Standarduhr (Perlick, GRG 1987), mit großer Genauigkeit realisiert durch Atomuhren

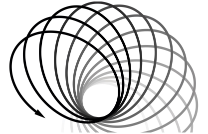
Summary tests of GR

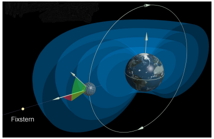
- effects on **light rays**
  - deviation of light (VLBI, Gaia) Eddington
  - gravitational lensing Twin Quasar Q0957+561
  - shadow of Black Holes (EHT) EHT-Kollaboration 2019
- **orbital effects**
  - perihelion shift (Mercury) Le Verrier
  - Lense-Thirring effect: spin-orbit-coupling (LAGEOS) Ciufolini
  - back reaction (binary systems) Hulse-Taylor, gravitational waves
- effects on **extended bodies**
  - Schiff effect: spin-spin-coupling (GP-B) Everitt
- effects on **clocks** / effects on frequencies
  - gravitational redshift Pound-Rebka, GP-A, Galileo
  - gravitational time delay Cassini
  - gravitomagnetic clock effect
- **gravitational waves** Abbott et al 2016

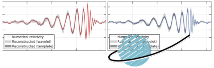
+ all SR effects: time dilation, Doppler effect, Sagnac effect, length











Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

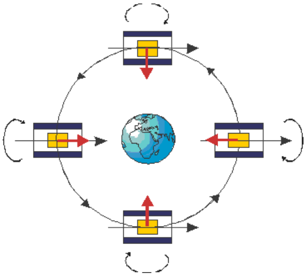
Outlook: Measurement of a new clock effect?

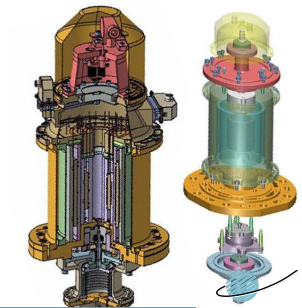
Unresolved questions

Summary and outlook

MICROSCOPE: The Mission

- French space mission with participation of CNES, ESA, ZARM and PTB
- Mission goal: Test of Equivalence Principle with an accurary of $\eta = 5 \cdot 10^{-16}$
- Mission overview:
  - Micro-satellite of CNES Myriade series
  - Drag–free satellite
  - Sun–synchronous orbit
  - Altitude about 800 km
  - Mission lifetime of 1 year
- Payload:
  - Two high–precision capacitive differential accelerometers
  - Science sensor: Ti and Pt test mass
  - Reference sensor: two Pt test masses
- Test of accelerometers at ZARM drop tower
- modeling

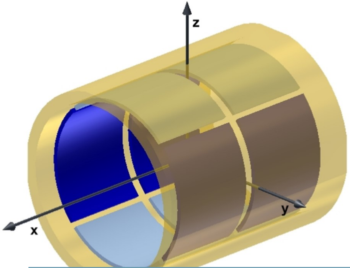


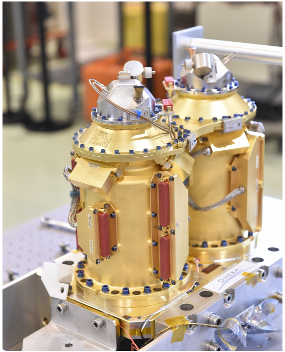


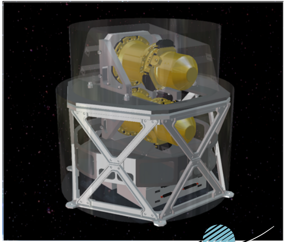
Main payload T-SAGE

T-SAGE = Twin-Space Accelerometer for Gravity Experiment

- developed and built by ONERA
- two differential acceleromters, each containing two test masses
- test mass made by PTP
- each test mass is controlled by 18 electrodes



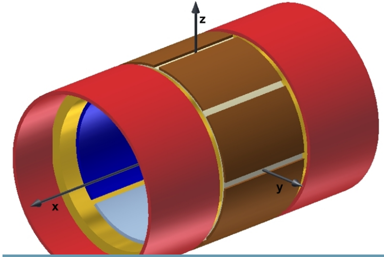


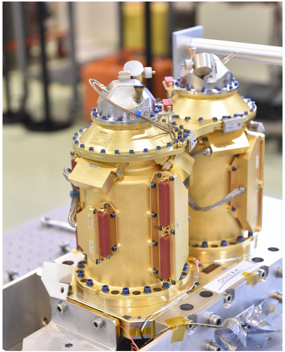


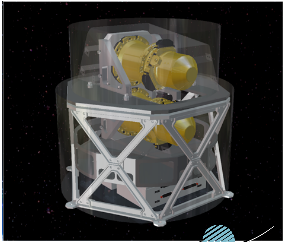
Main payload T-SAGE

T-SAGE = Twin-Space Accelerometer for Gravity Experiment

- developed and built by ONERA
- two differential acceleromters, each containing two test masses
- test mass made by PTP
- each test mass is controlled by 18 electrodes



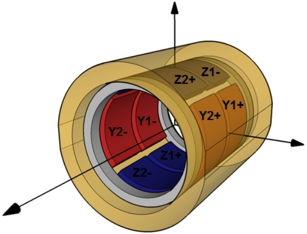


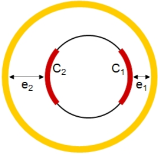


Main payload T-SAGE

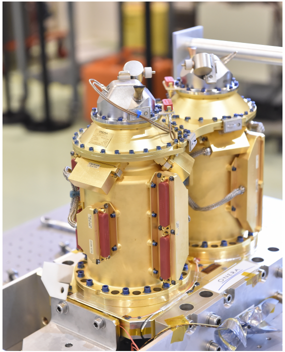
T-SAGE = Twin-Space Accelerometer for Gravity Experiment

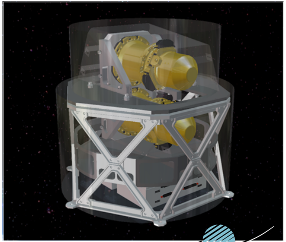
- developed and built by ONERA
- two differential acceleromters, each containing two test masses
- test mass made by PTP
- each test mass is controlled by 18 electrodes





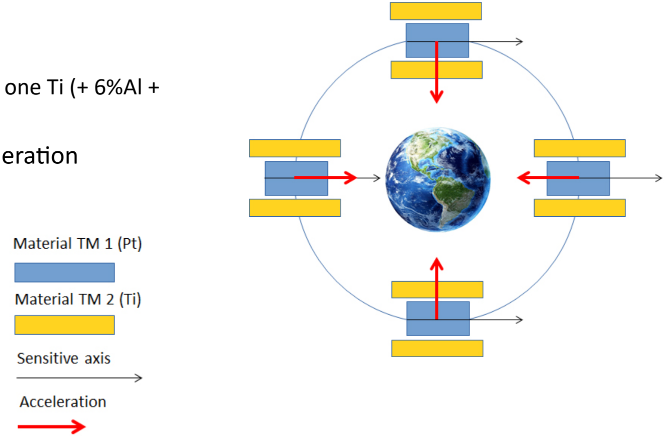
$$C_i = f\left(\frac{1}{e_i}\right)$$





MICROSCOPE – mission scenario

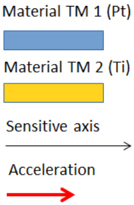
- servo-controlled test masses with identical centers of gravity
- two pairs of test masses
  - SUREF = 2 test masses of Pt
  - SUEP = 1 test mass Pt (+ 10% Rh), one Ti (+ 6%Al + 1% V)
- measurement of differential acceleration between test masses
- AOCS: drag free motion

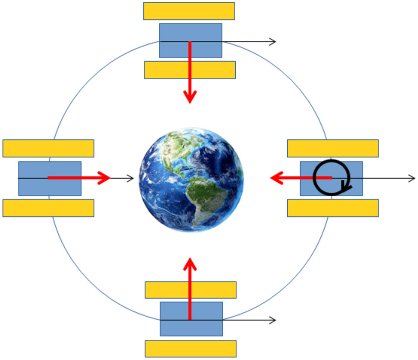


MICROSCOPE – mission scenario

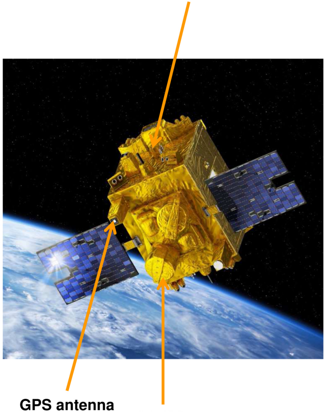
- servo-controlled test masses with identical centers of gravity
- two pairs of test masses
  - SUREF = 2 test masses of Pt
  - SUEP = 1 test mass Pt (+ 10% Rh), one Ti (+ 6%Al + 1% V)
- measurement of differential acceleration between test masses
- AOCS: drag free motion
- spinning mode

$$\omega_\eta = \omega_{\text{orbit}} + \omega_{\text{spin}}$$





MICROSCOPE - the satellite

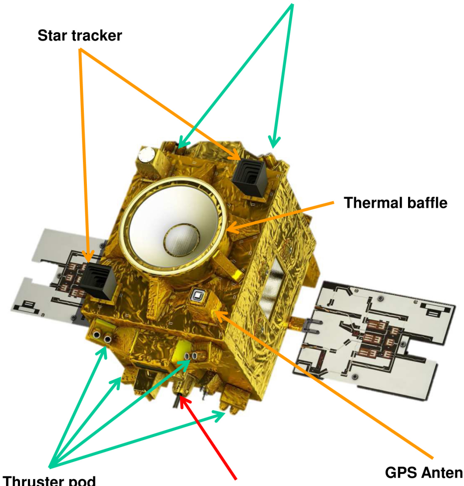


4 pods of redundant thrusters
Propulsion Wall System (reservoir+electronics)

GPS antenna

IDEAS
De-orbitation system

© CNES/ill./DUCROS David, 2016



Thruster pods

Star tracker

Thermal baffle

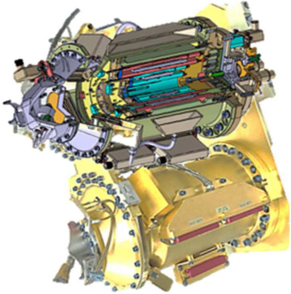
Thruster pod

TM antenna

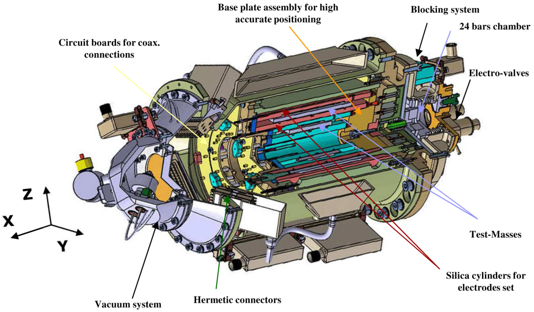
GPS Antenna

MICROSCOPE - main payload

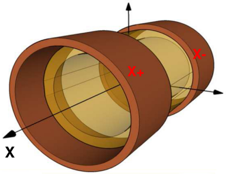
ICU : digital control laws, data conditioning



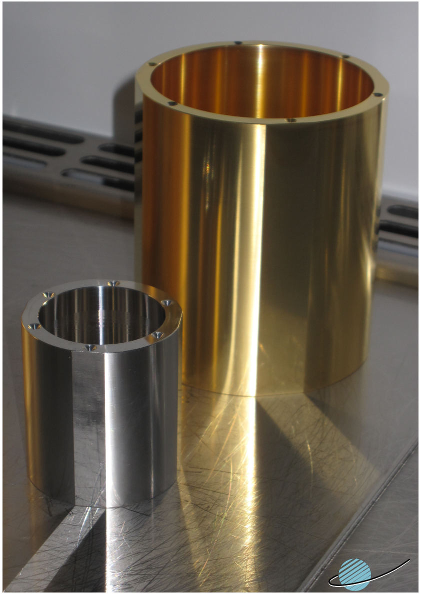
SU: 2 Sensor units REF + EP



FEEU : 2 low noise Electronics units

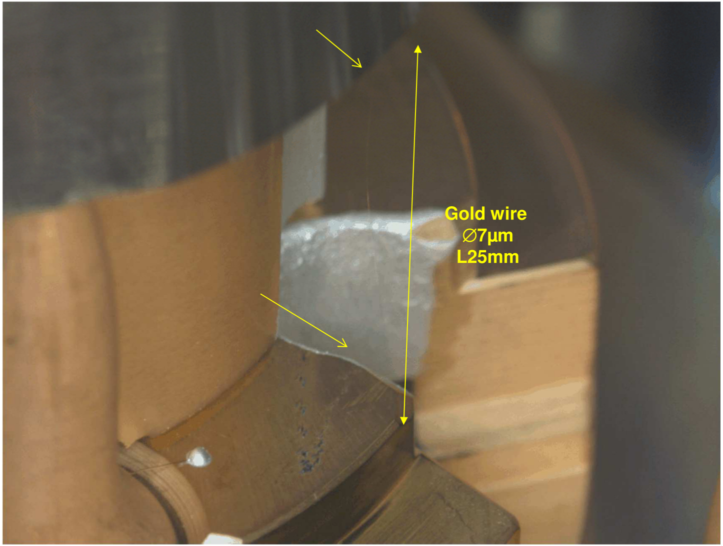


MICROSCOPE - the test masses



- μm machining precision
- material (Pt, Ti) very expensive
- manufactured by PTB

MICROSCOPE - the Gold wire



Gold wire needed for discharging

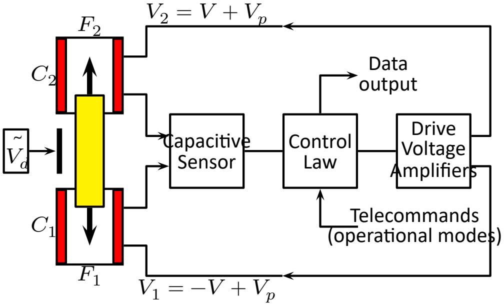
induces damping

all instrument photos
from ONERA

MICROSCOPE - the

MICROSCOPE - the capacitive sensor

Scheme of one servo–loop channel



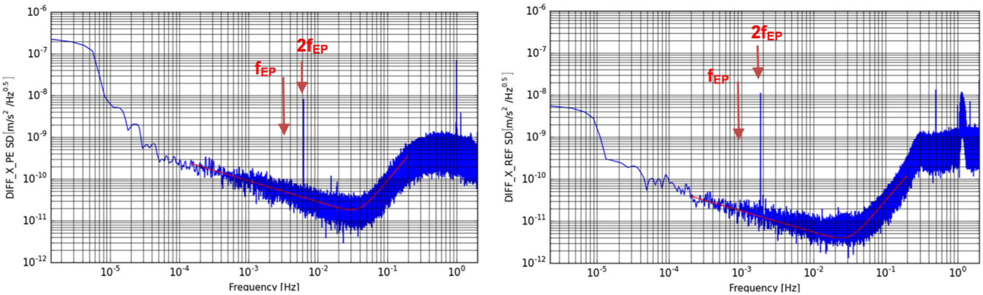
The resulting force

$$F = F_1 + F_2 = \frac{1}{2}\left(\nabla C_2\left(V_2 - V_p\right)^2 + \nabla C_1\left(V_1 - V_p\right)^2\right) = m\Gamma_{\text{elec}}$$

the resultant force F is proportional to V:

$$m\Gamma_{\text{elec}} = F = 2\,m\,\nabla C\,V_p\,V$$

MICROSCOPE - the measurement

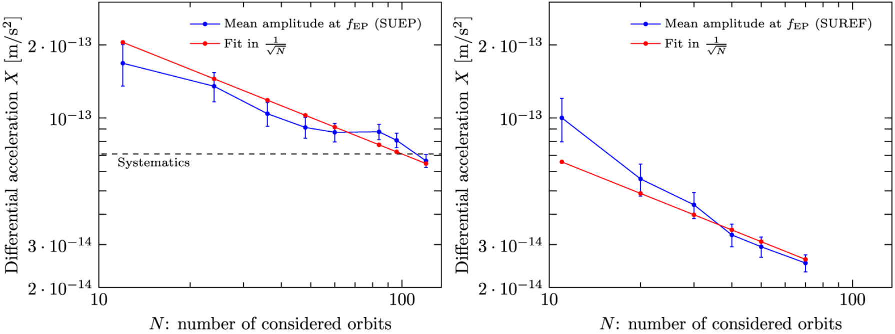


SUEP

SUREF

power spectral density of differential accelerometer along sensitive axis for two different spin periods
gravity gradient signal appears at $2f_{\mathrm{EP}}$

MICROSCOPE - the measurement



Evolution of the mean amplitude of the FFT of the differential signal along sensitive axis at ω_η as a function of integrating times.

First result

PRL 119, 231101 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

[1]*ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau Cedex, France*
[2]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur,*
250 Avenue Albert Einstein, F-06560 Valbonne, France
[3]*CNES, 18 Avenue Edouard Belin, F-31401 Toulouse, France*
[4]*ZARM, Center of Applied Space Technology and Microgravity, University of Bremen,*
Am Fallturm, D-28359 Bremen, Germany
[5]*IHES, Institut des Hautes Études Scientifiques, 35 route de Chartres, F-91440 Bures-sur-Yvette, France*
[6]*DLR, Köln Headquarters, Linder Höhe, 51147 Köln, Germany*
[7]*LPTENS, École Normale Supérieure (PSL Research University), 24 Rue Lhomond, 75231 Paris Cedex 05, France*
[8]*PTB, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[9]*IGN, Institut Géographique National, 73 Avenue de Paris, F-94160 Saint Mandé, France*
[10]*Laboratoire Kastler Brossel, UPMC-Sorbonne Université, CNRS,*
ENS-PSL Research University, Collège de France, F-75005 Paris, France
[11]*Blackett Laboratory, Imperial College London, United Kingdom*
[12]*Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands*

(Received 12 May 2017; revised manuscript received 20 September 2017; published 4 December 2017)

According to the weak equivalence principle, all bodies should fall at the same rate in a gravitational field. The *MICROSCOPE* satellite, launched in April 2016, aims to test its validity at the 10^{-15} precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A nonvanishing result would correspond to a violation of the equivalence principle, or to the discovery of a new long-range force. Analysis of the first data gives $\delta(\mathrm{Ti,Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$ (1σ statistical uncertainty) for the titanium-platinum Eötvös parameter characterizing the

First result

$$\eta(\mathrm{Ti,Pt}) \leq (-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})) \cdot 10^{-15}$$

PRL **119,** 231101 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

[1]*ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau Cedex, France*
[2]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur,*
250 Avenue Albert Einstein, F-06560 Valbonne, France
[3]*CNES, 18 Avenue Edouard Belin, F-31401 Toulouse, France*
ity, University of Bremen,
any
F-91440 Bures-sur-Yvette, France
öln, Germany
LPTENS, Ecole Normale Supérieure (PSL Research University), 24 Rue Lhomond, 75231 Paris Cedex 05, France
[8]*PTB, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[9]*IGN, Institut Géographique National, 73 Avenue de Paris, F-94160 Saint Mandé, France*
[10]*Laboratoire Kastler Brossel, UPMC-Sorbonne Université, CNRS,*
ENS-PSL Research University, Collège de France, F-75005 Paris, France
[11]*Blackett Laboratory, Imperial College London, United Kingdom*
[12]*Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands*

(Received 12 May 2017; revised manuscript received 20 September 2017; published 4 December 2017)

According to the weak equivalence principle, all bodies should fall at the same rate in a gravitational field. The *MICROSCOPE* satellite, launched in April 2016, aims to test its validity at the 10^{-15} precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A nonvanishing result would correspond to a violation of the equivalence principle, or to the discovery of a new long-range force. Analysis of the first data gives $\delta(\mathrm{Ti,Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$ (1σ statistical uncertainty) for the titanium-platinum Eötvös parameter characterizing the

First result

PRL **119,** 231101 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

[1] *ONERA, chemin de la Hunière, BP 80100, F-91123 Palaiseau Cedex, France*

[2] *Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, 250 Avenue Albert Einstein, F-06560 Valbonne, France*

[3] *CNES, 18 Avenue Edouard Belin, F-31401 Toulouse, France*

ity, University of Bremen,

any

F-91440 Bures-sur-Yvette, France

öln, Germany

homond, 75231 Paris Cedex 05, France

[8] *PTB, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

[9] *IGN, Institut Géographique National, 73 Avenue de Paris, F-94160 Saint Mandé, France*

[10] *Laboratoire Kastler Brossel, UPMC-Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France*

[11] *Blackett Laboratory, Imperial College London, United Kingdom*

[12] *Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands*

(Received 12 May 2017; revised manuscript received 20 September 2017; published 4 December 2017)

According to the weak equivalence principle, all bodies should fall at the same rate in a gravitational field. The *MICROSCOPE* satellite, launched in April 2016, aims to test its validity at the 10^{-15} precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A nonvanishing result would correspond to a violation of the equivalence principle, or to the discovery of a new long-range force. Analysis of the first data gives $\delta(\mathrm{Ti,Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$ (1σ statistical uncertainty) for the titanium-platinum Eötvös parameter characterizing the

$$\eta(\mathrm{Ti,Pt}) \leq (-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})) \cdot 10^{-15}$$

result of new analysis will be published

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

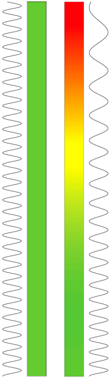
Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

1st laboratory test

- Mössbauer effect
- 22.5 m height difference at Jefferson “Tower” at Harvard
- Pound & Rebka, 1960, accuracy $\sim 1\%$



Space test: The mission Gravity Probe A

first order gravitational effect

$$\nu(x_1) = \left(1 - \frac{U(x_1) - U(x_0)}{c^2}\right) \nu(x_0)$$

or

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta U}{c^2}$$

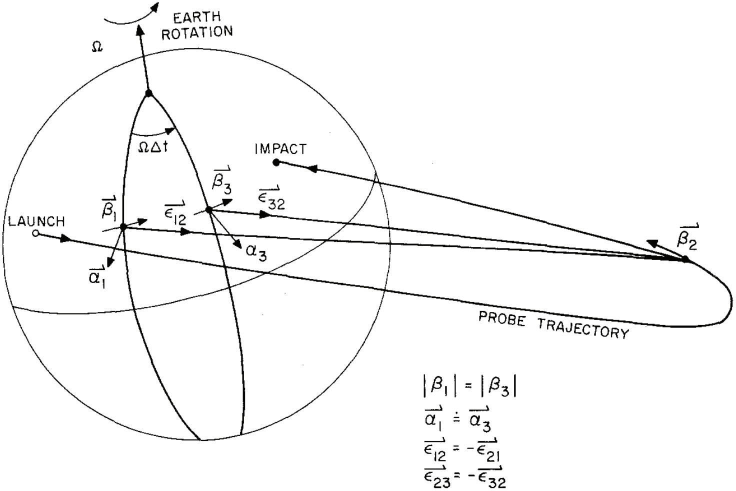
hypothetical deviation or hypothetic dependence on clock

$$\frac{\Delta\nu}{\nu} = -(1 + \alpha)\frac{\Delta U}{c^2}$$

- precise measurement of gravitational redshift: $|\alpha| \leq 10^{-4}$ (Vessot, Levine, et al, GRG 1978, PRL 1980)
- precise test of Doppler effect

GP A H-maser

The mission Gravity Probe A



$$|\beta_1| = |\beta_3|$$

$$\vec{\alpha}_1 \doteq \vec{\alpha}_3$$

$$\vec{\epsilon}_{12} = -\vec{\epsilon}_{21}$$

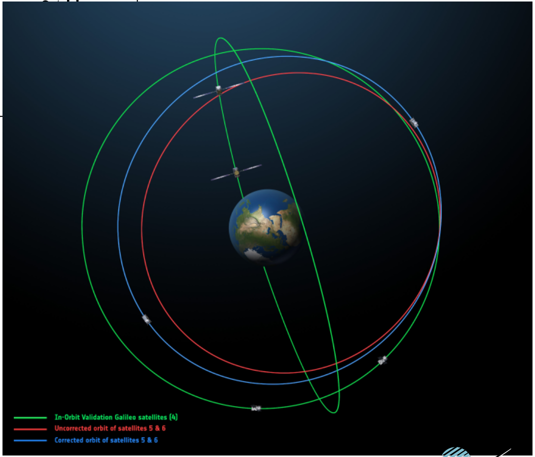
$$\vec{\epsilon}_{23} = -\vec{\epsilon}_{32}$$

Galileo 5 and 6

	after launch	after correction	target orbit
e	0.233	0.1561	~ 0
a [km]	26,192	27,977	29,900
i	49.774	49.7212	55
$r_a - r_p$ [km]	11,681	8,730	~ 0

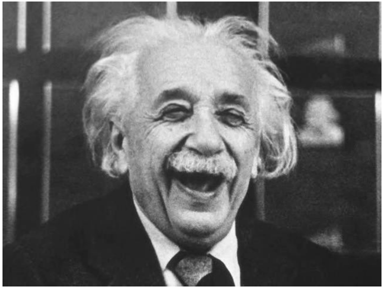
Galileo 5 and 6

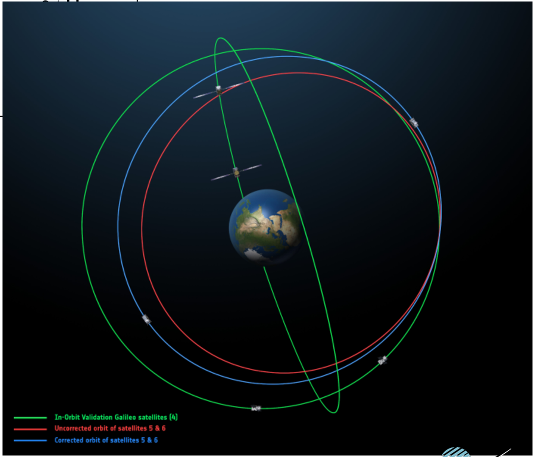
	after launch	after correction	target orbit
e	0.233	0.1561	0
a [km]	26,192	27,977	
i	49.774	49.7212	
$r_a - r_p$ [km]	11,681	8,730	



Galileo 5 and 6

	after launch	after correction	target orbit
e	0.233	0.1561	0
a [km]	26,192	27,977	
i	49.774	49.7212	
$r_a - r_p$ [km]	11,681	8,730	





Galileo clocks: Passive Hydrogen Maser

- Ground Performance: 7×10^{-15} flicker floor @ > 10000 s
- Actively Temperature Stabilized to $\Delta T < 0.5$ K
- T-sensitivity: $\Delta\nu/\nu = 2 \times 10^{-14}/$K
- Passive magnetic shielding
- B-sensitivity: $\Delta\nu/\nu = 3 \times 10^{-13}/$G

PHM: Passive Hydrogen Maser by *SpectraTime*
mass = 18 kg

Galileo clocks: Rubidium Atomic Frequency Standaed

- Ground Performance: 2×10^{-14} flicker floor @ > 10000 s
- used as secondary clock only

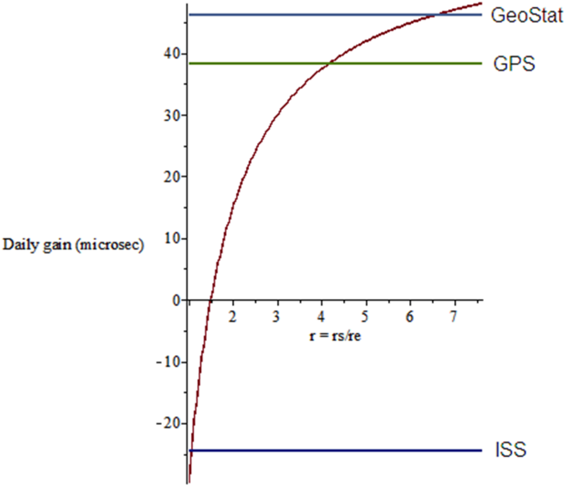
RAFS: Rubidium Atomic Frequency Standard
mass = 3.3 kg

Galileo clock effects

Dominant effects:

- gravitational redshift
  → clocks tick faster
- special relativistic time dilation
  → clocks tick slower

$$d\tau = \left(1 + \frac{U}{c^2} - \frac{1}{2}\frac{v^2}{c^2}\right) dt$$



Galileo redshift

Redshift

- redshift between perigeum and apogeum

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{GM}{c^2}\left(\frac{1}{r_\mathrm{p}} - \frac{1}{r_\mathrm{a}}\right) \quad \Rightarrow \quad \Delta t = 2(1+\alpha)\frac{\vec{r}\cdot\vec{v}}{c^2}$$

- experimental parameter: α
- with the maximum difference of radius of ~ 8730 km one gets the maximum redshift $\frac{\Delta\nu}{\nu} \approx 5 \cdot 10^{-11}$
- corresponds to 370 ns time gain per revolution (nominal ~ 0.5 ns)

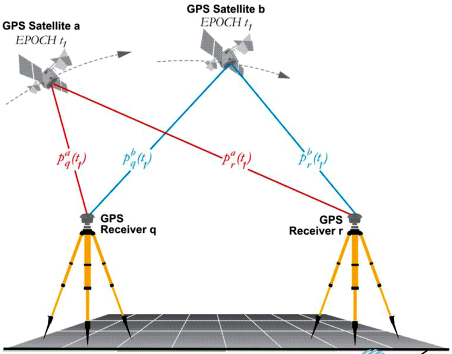
Clock data

Pseudo range for measured times (similar for carrier phase)

$$\begin{aligned} P^s_{r,f}(t) &= \left\|\vec{r}_r(t) - \vec{r}^s(t-T)\right\| + c\left(\Delta t_r(t) - \Delta t^s(t-T)\right) \\ &\quad + c\left(d_{r,f}(t) - d^s_r(t-T)\right) + I^s_{r,f} + T^s_{r,f} - m^s_{r,P,f}(t) + \epsilon^s_{r,P,f}(t) \end{aligned}$$

$\vec{r}^s$, $\vec{r}_r$ satellite and receiver position
Δt_r, Δt^s clock bias; $d_{r,f}$, d^s_f instrument delays
$I^s_{r,f}$, T^s_r iono- & tropospheric corrections
$m^s_{P,r,f}$ multipath errors; $\epsilon^s_{P,r,f}$ noise

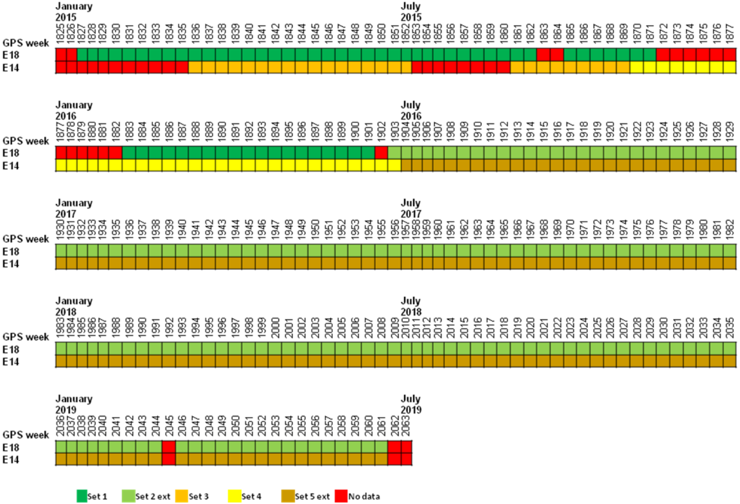
- Measurement of signal travel times = pseudo range
- one has to determine satellite clock corrections Δt^s
- clock corrections depend, among others, on orbit information: 30 cm → 1 ns



Clock data

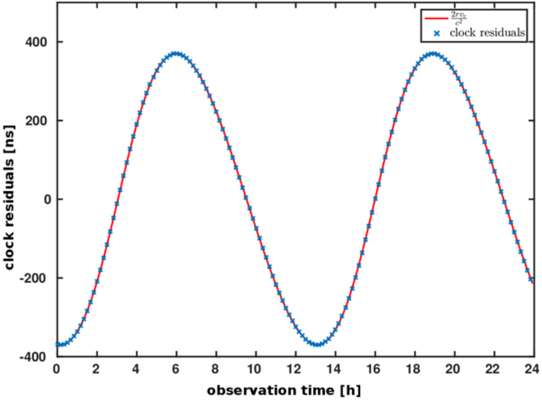
Clock and orbit products from 2015 on are made available to us by ESOC

- 30 s sampling on clock $\leftrightarrow i$ / 300 s sampling on orbit
- Customized reprocessing to needs of data analysis (E. Schönemann, F. Dillsner, T. Springer from ESOC)



Data without relativistic “correction”

GPS week 1870; day 0



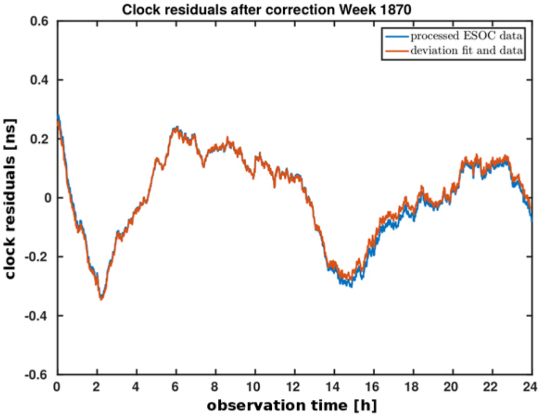
- relativistic effects included
- gravitational redshift + Doppler

$$\Delta t = 2\frac{\vec{r}\cdot\vec{v}}{c^2}$$

- $\sim$ 370 ns modulation amplitude

Data without relativistic "correction"

GPS week 1870; day 0



- relativistic effects modeled and removed by ZARM
- comparison to final ESOC products
- provides a check of basic common understanding

- variations of $\sim$ 0.5 ns due to systematic effects

Least squares fit model

$$S = \sum_{i=1}^{n} \left(\epsilon_i - \alpha \left(\int_{\text{path}} \left(\frac{GM_\oplus}{rc^2} \left(1 - \frac{J_2 a_\oplus}{2r^2} \left(\frac{3z^2}{r^2} - 1 \right) \right) + \frac{v^2}{2c^2} \right) dt_i \right) - a_0 - a_1 t_i \right)$$

with

ϵ_i clock residuals

J_2 axially symmetric quadruple moment of Earth (flattening)

a_0 clock offset parameter

a_1 clock drift parameter

to be determined α

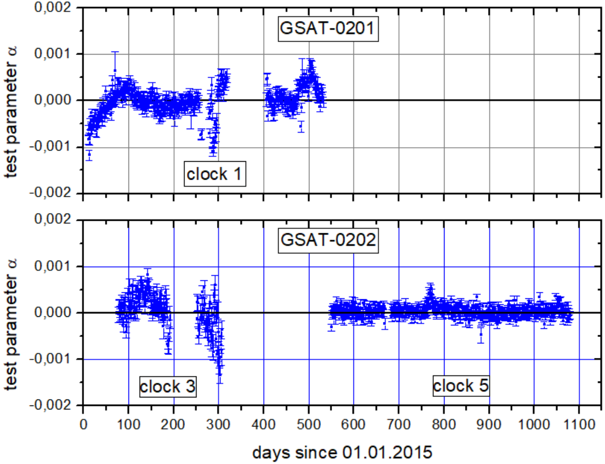
working on Bayesian data analysis

Availability of clock and orbit data

- 5 different transmitting clockd: 4 PHM and 1 RAFS
- only data from 3 PHM included in analysis

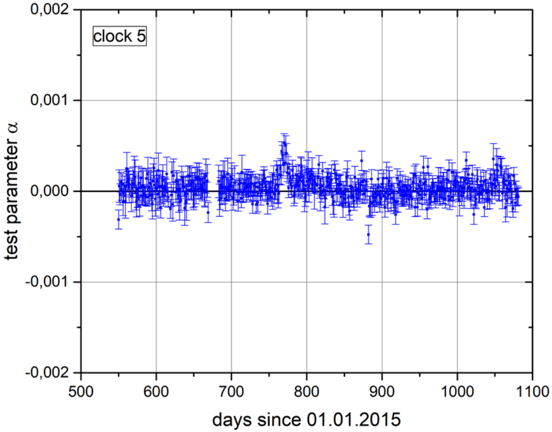
Clock no.	Sat	Clock	Start	End	Length [days]	Gaps [days]	performance
clock 1	E18	PHM B	11 Jan 15	15 Jun 16	521	101	ok
clock 2	E18	PHM A	02 Jul 16	16 Dec 17	533	11	not nominal
clock 3	E14	PHM B	19 Mar 15	04 Nov 15	231	59	ok
clock 4	E14	RAFS	05 Nov 15	02 Jul 16	241	0	no PHM
clock 5	E14	PHM A	03 Jul 16	16 Dec 17	532	15	ok

Daily results for α from all clocks



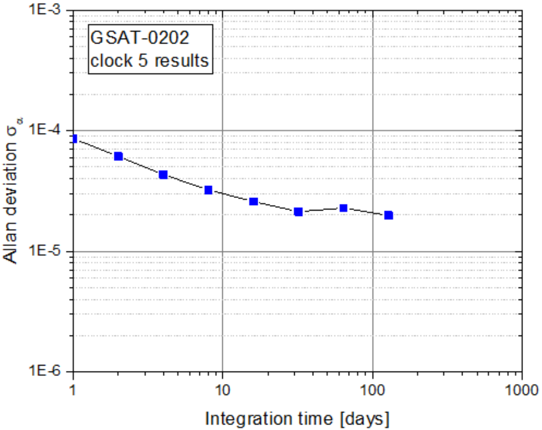
Clock 5 results

- E14 / PHM A
- $n = 510$ days
- constant positive bias
- systematics better behaved than for clock 1 and 3



Clock 5 results

- E14 / PHM A
- $n = 510$ days
- constant positive bias
- systematics better behaved than for clock 1 and 3

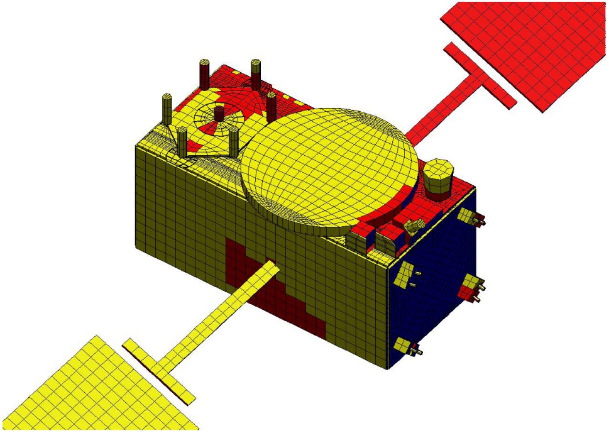


Cause of systematic bias ?

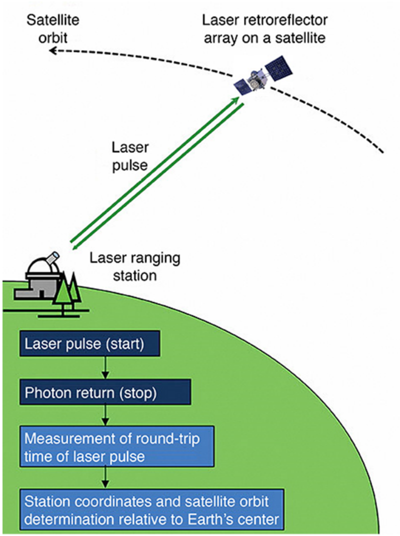
- Possible direct systematics on satellite clock
  - temperature effects
  - magnetic fields
- Possible indirect systematics on orbit/clock solution
  - orbit error by mismodelling solar radiation pressure SRP
  - inclusion of tidal potentials of Sun and Moon
- Possible systematics on ground clocks ?
  - daily modulation possible, to be spectrally separated from orbital period + averaging over many ground clocks

Satellite model

finite surface element model of Galileo with shadow



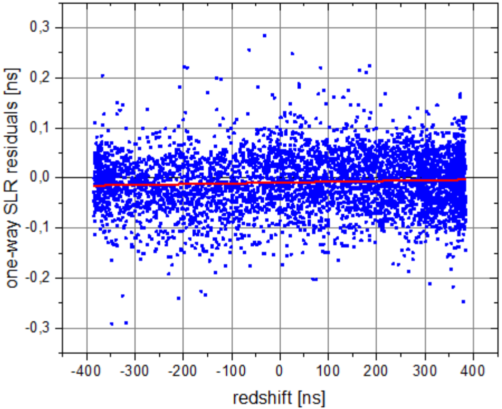
Satellite model, SRP, and SLR



- independent orbit information from SLR
- reprocessings of orbit
- clock with improved SRP models
- reduction of SLR residuals
- orbit understood within ± 2 mm

Correction of remaining orbit systematics

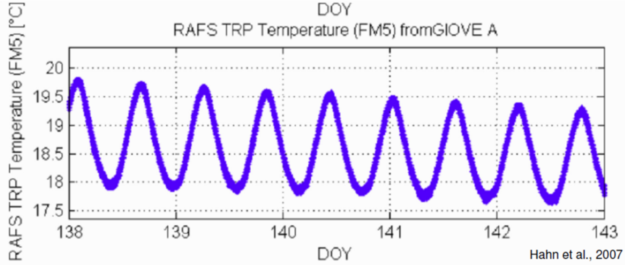
- convert SLR residuals to clock bias
- fit redshift model to SLR data to determine systematic contribution
- correct alpha result accordingly



global estimate for clock 5: non vanishing small correlation: 1.5×10^{-5}

Temperature systematics

- temperature variation for RAFS on GIOVE A
- temperature data for PHMs on Doresa + Milena not available



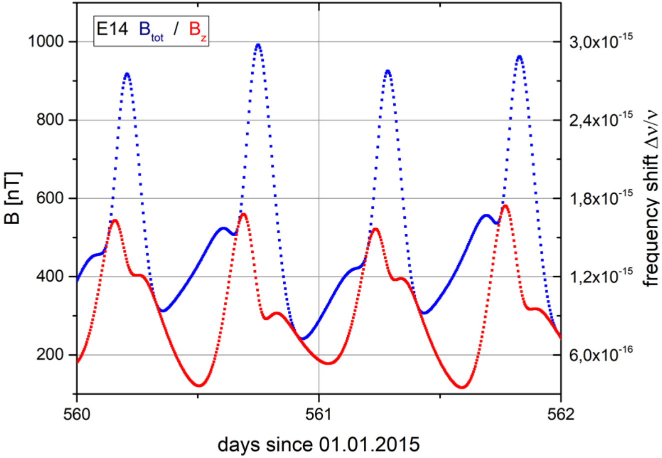
Hahn et al., 2007

- PHM clocks on FOC actively stabilized to $\Delta T = \pm 0.5$ K
- temperature sensitivity of PHM: $\Delta\nu/\nu = 2 \times 10^{-14}$ /K (Rochat et al., 2012)
- temperature driven by solar illumination $\rightarrow$ disentangling from redshift signal over one year
- uncertainty estimate: $\Delta\alpha = \pm 2 \times 10^{-5}$

Magnetic fields

- no magnetometers on board of satellites
- adopt IGRF model of Earth's magnetic field

- clock sensitivity: $\Delta\nu/\nu = 3 \times 10^{-13}$ /G (Rochat et al., 2012)
- ambiguity in sign / clock bias field orientation
- rerun analysis for worst case: total amplitude, both signs
- $\Delta\alpha = \pm 8 \times 10^{-6}$ systematic uncertainty in α

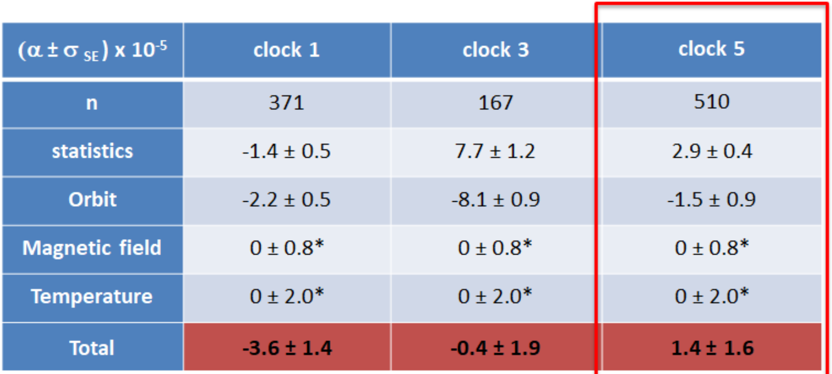


Other possible systematics considered

- Ground clocks ?
  - potential 24 h or 12 h systematics
  - decorrelate from orbit signal (13 h) within days
- Phase wind-up ?
  - considered not critical using nominal satellite attitude
- Atmospheric effects ?
  - ionosphere free combination, but maybe higher order corrections

Error budget and systematic uncertainties

- combining all systematic uncertainties for each clock (* = max/min interval)
- final result taken only from clock 5
- combined error derived from posterior of a Bayesian approach
- redshift only: $\alpha = (2.8 \pm 3.2) \cdot 10^{-5}$, factor 5 improvement



$(\alpha \pm \sigma_{SE})$ x 10^{-5}	clock 1	clock 3	clock 5
n	371	167	510
statistics	-1.4 ± 0.5	7.7 ± 1.2	2.9 ± 0.4
Orbit	-2.2 ± 0.5	-8.1 ± 0.9	-1.5 ± 0.9
Magnetic field	0 ± 0.8*	0 ± 0.8*	0 ± 0.8*
Temperature	0 ± 2.0*	0 ± 2.0*	0 ± 2.0*
Total	**-3.6 ± 1.4**	**-0.4 ± 1.9**	**1.4 ± 1.6**

Summary

- Improvement of GB-A by a factor 5 with Galileo Satellites 5 and 6
  Herrmann et al, PRL 2018, Delva et al, PRL 2018
- Accuracy is limited by systematic effects: Temperature, magnetic fields, orbit model
- Main systematic due to mismodeling of solar radiation pressure SRP, could be improved
- Ongoing: study of SLR systematics, refinement of analysis
- Test case for future GNSS + Fundamental Physics missions

121

PHYSICAL
REVIEW
LETTERS

Articles published week ending 7 DECEMBER 2018

PRL 121 (23), 230401–238102, 7 December 2018 (318 total pages)

23

Published by
American Physical Society

APS physics

Volume 121, Number 23

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

The gravitomagnetic clock effect on satellites

special cases

- for counterpropagating circular motion: $\alpha = -1$
  effect to first order in J (Cohen and Mashhoon 1993)

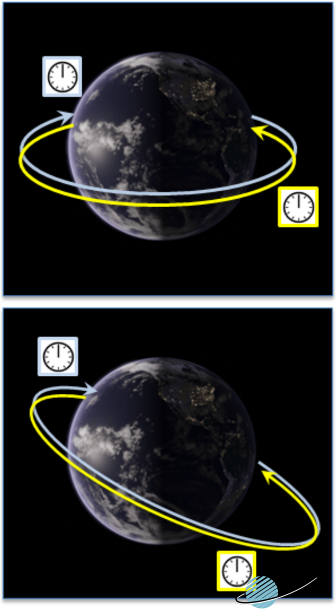
$$\Delta s_{\text{gm}} = 4\pi \frac{J}{Mc^2}\sqrt{\frac{r}{r-3}} + \mathcal{O}(J^2) \approx 4\pi \frac{J}{Mc^2}$$

  for large r

- general but identical Keplerian orbits (Mashhoon et al 2001)

$$\Delta s_{\text{gm}} = 4\pi \frac{J}{Mc^2} \frac{(3e^2+2e+3)\cos i - 3e - 2}{(1-e^2)^{\frac{3}{2}}}$$

but we need different orbits



General gravitomagnetic clock effect

observable for the gravitomagnetic clock effect for arbitrary orbits

New observable (Hackmann & CL, PRD 2014)

for two geodesics in Kerr space-time: define a new observable

$$\Delta s_{\text{gm}}(J) := s_1(\pm 2\pi; J) + \alpha\, s_2(\pm 2\pi; J)$$

α is given such that the usual gravitoelectric effects cancel

- α can be calculated from orbital data: compute energies E_n, angular momenta $L_{z,n}$, Carter constants K_n (all depend on angular momentum J)
- determine $E_n(0)$, $L_{z,n}(0)$, and $K_n(0)$ by setting $J = 0$ and $s_n(2\pi; 0)$. α can be determined through $\Delta s_{\text{gm}} = 0$ for $J = 0$

$$0 = \Delta s_{\text{gm}}(J = 0) = s_1(\pm 2\pi; 0) + \alpha s_2(\pm 2\pi; 0)$$

and, therefore,

$$\alpha = -\frac{s_1(\pm 2\pi; 0)}{s_2(\pm 2\pi; 0)}$$

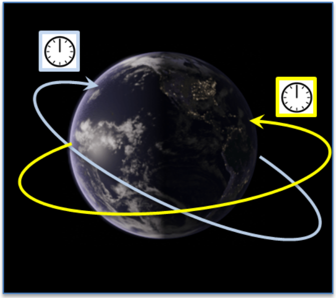
Application to GNSS satellites

it is possible to measure the gravitomagnetic clock effect using two satellites in arbitrary geodesic orbits with clocks with stabilities of about 10^{-14} over 10^4 s

- Galileo: circular orbit with radius $r_G = 29593$ km, inclination 56° from equatorial plane
- COMPASS: circular orbit with radius of $r_C = 42157$ km, inclination $\sim 0^\circ$ from equatorial plane

then

$$\alpha \approx -\sqrt{\left(\frac{a_1}{a_2}\right)^3} - \frac{3}{2}\sqrt{\frac{a_1}{a_2^5}}\left(\frac{a_1(1+e_2^2)}{1-e_2^2} - \frac{a_1 2(1+e_1^2)}{1-e_1^2}\right) \approx -0.588$$



gravitomagnetic clock effect

$$\Delta s_{\text{gm}} = s_G(2\pi; J_{\text{Earth}}) + \alpha s_C(2\pi; J_{\text{Earth}}) \approx -7.46 \times 10^{-8}\ \text{s}$$

- analysis should be generalized to real satellite orbits:
  complex gravitational field of Earth should be taken into account
- discussion of requirements on tracking of satellites
  and the deviation from ideal orbit (Mashhoon et al 1999)
- signals between satellites
- can also be applied to pulsar timing, with two pulsars orbiting a black hole

Clock requirements and magnitude of the effect

effects from analyical expressions

GNSS satellite pair	**inclination** $[^\circ]$	**eccentricity**	$\Delta\tau$ **[ns]**
Galileo vs Glonass	56 / 64.8	0 / 0	48
Gakileo vs geostationary	56 / 0	0 / 0	75
Glonass vs geostationary	64.8 / 0	0 / 0	99
Galieo: E11 vs E14	56 / 50	0 / 0.16	11

- measure absolute 10 - 100 ns difference in one orbit (~ 50000 s)
- current clocks show technical drifts of several μs per day
- clocks with improved frequency accuracy required + careful calibration (optical clocks, cold atom clocks, iodine ?)

Orbit requirements from analytical expessions

special cases

- exact solution for circular + equitorial orbit

$$\tau_{\pm} = \frac{2\pi}{\omega_0}\sqrt{1 - \frac{3GM}{r} \pm 2\frac{J}{Mc^2}\omega_0}$$

- derive from this the variation with respect to r and φ

$$\tau_+ - \tau_- = 4\pi\frac{J}{Mc^2} + \sqrt{\frac{r^3}{GM}}\Delta\varphi + \sqrt{\frac{r}{GM}}\Delta r$$

- similar results for the case of general Keplerian orbits

$\Rightarrow$ Δr uncertainty below 40 μm are required for 10 - 100 ns accuracy

currently under investigation

- how does this translate to required precision of orbit products (currently at few cm level)
- how does this change when integrating over 1000 s of orbits

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

Outlook: Measurement of a new clock effect?

Unresolved questions

Summary and outlook

Inconsistencies between GR and quantum mechanics

singularities: general prediction of GR – singularity theorems

- GR: pointlike singularities – Black Holes, Big Bang
- QM: uncertainty relation forbids pointlike phenomena

notion of time

- QM: time is an external parameter
- GR: time is dynamical

information paradox

- objects and information disappear in Black Holes
- Hawking radiation is thermal

zero point energy

- QM: zero point energy (Casimir effect)
- GR: all types of energy are sources for gravity
- problem of cosmological constant

conceptual inconsistency

- GR is local
- QM is global

Open questions

fundamental problems

- Übergang von Quantenmechanik zu klassischer Mechanik
- fundamentale Dekohärenz, Messprozess
- equivalence principles (inertia = passive gravitational mass (weight) = active gravitational mass)
- constancy of constants

“technical” problems

- renormalization
- self force
- quantum field theory in curved space-time

“smoking guns”

- Dark Matter
- Dark Energy

still to understand completely

- Black Holes
- Neutron Stars
- cosmic radiation

Outline

General Relativity

- The geometrical structure
- The gravitational field
- Further test: Newton potential
- Clocks, distances, and rotation

Consequences: GR and further tests

Improved test of the Universality of Free Fall with MICROSCOPE

Improved test of the gravitational redshift with Galileo

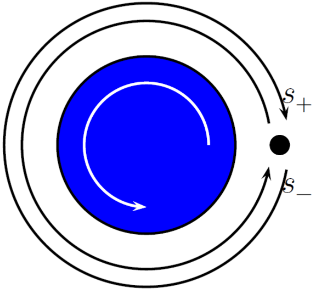
Outlook: Measurement of a new clock effect?

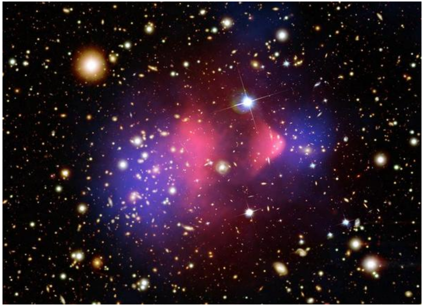
Unresolved questions

Summary and outlook

Take-home-messages

Experiments	thre is no single test contradicting SR or GR within the experimental errors
Missing	not yet measured: gravitomagnetic clock effect
Theory	big problem of theory: incompatibility of GR and QM
Observation	unknown: Dark Matter





Thank you for your attention

Thanks to

- Hansjörg Dittus
- Eva Hackmann
- Sven Herrmann
- Jutta Kunz
- Meike List
- Fritz Merkle
- Jürgen Müller
- Volker Perlick
- Ernst Rasel
- Piet Schmidt

- DFG Research Training Group ”Models of Gravity”
- Center of Excellence “Quantum Frontiers”
- DFG Collaborative Research Center ”Relativistic Geodesy” *geo*-Q
- German Research Foundation DFG
- German Space Agency DLR
- Center of Excellence QUEST
- German Israeli Foundation
- IRAP-PhD