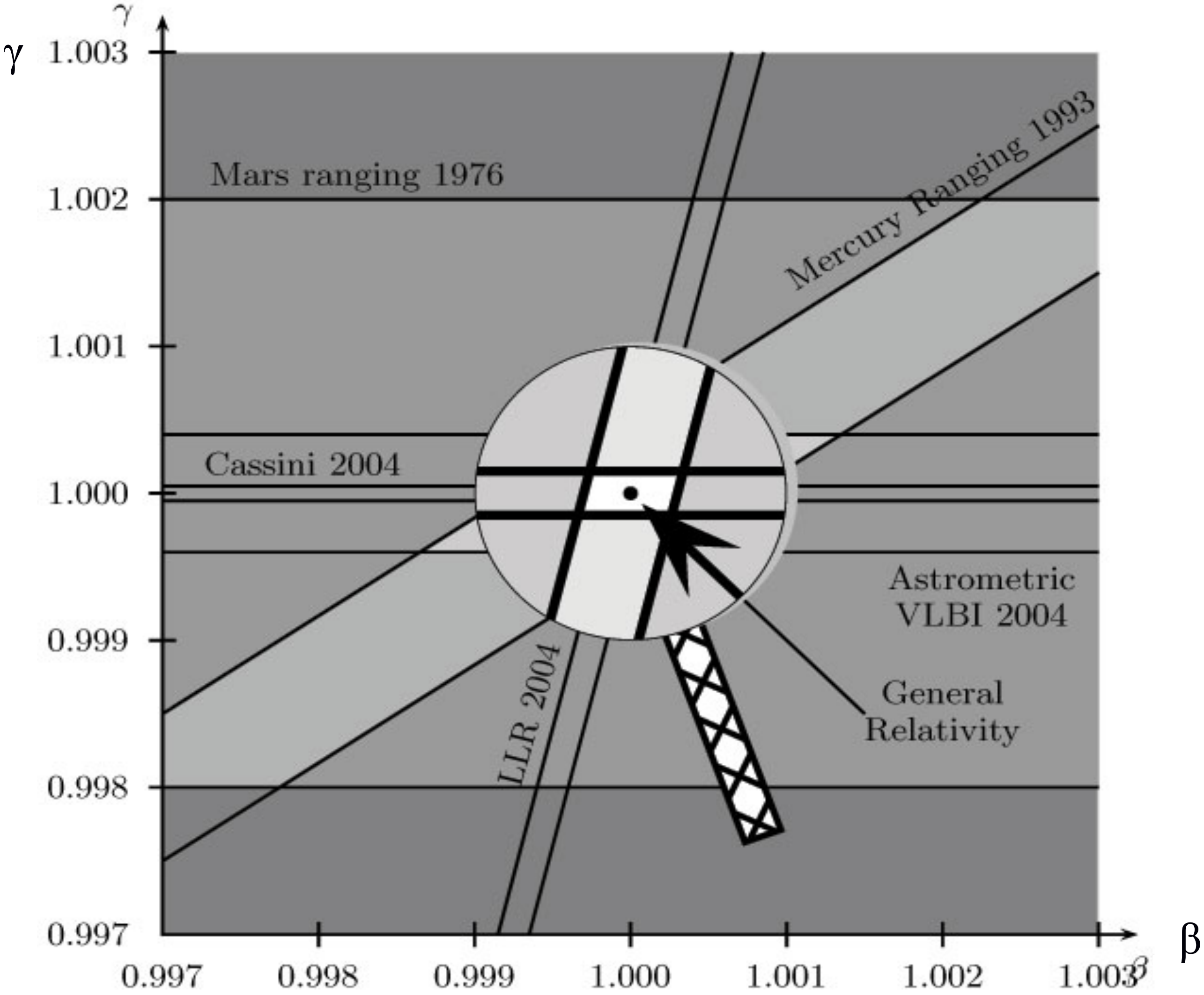
Fundamental Physics in the Framework of DLR´s Research and Technology Programme

Hansjörg Dittus
German Aerospace Center (DLR)

Knowledge for Tomorrow

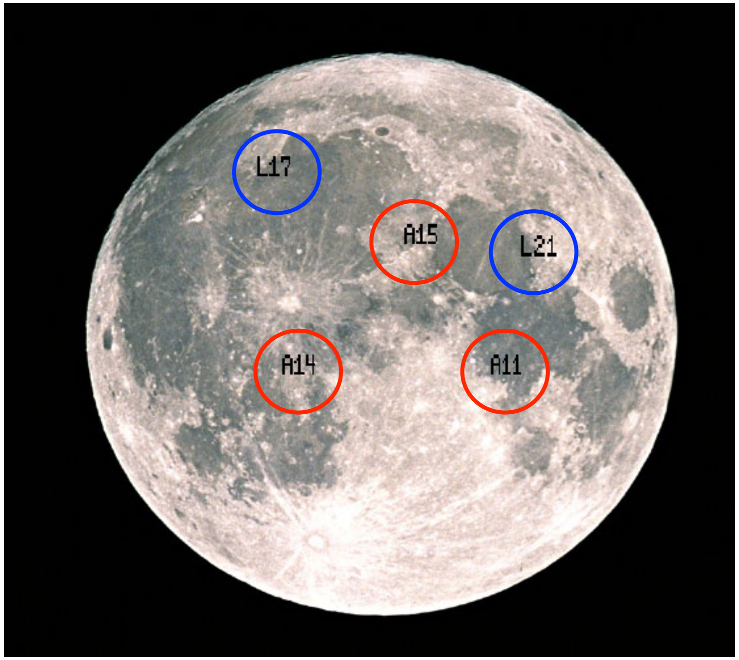
Precision of GR-proofs by space experiments

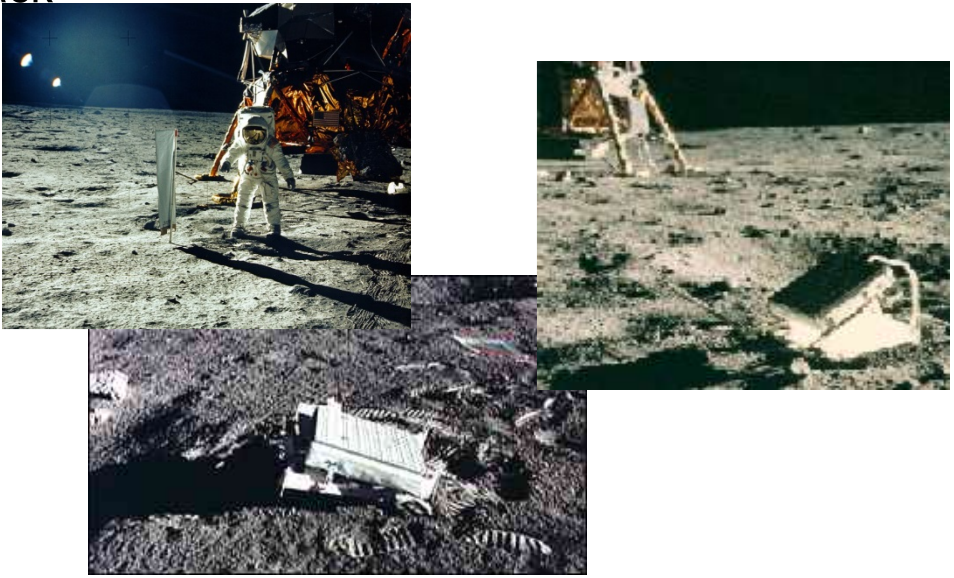


Courtesy: S. Turyshev

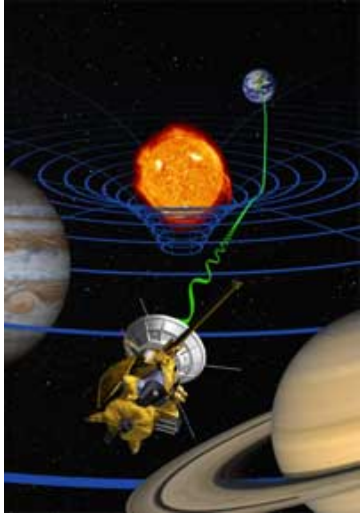
Lunar Laser Ranging

- since 1969 (Apollo 11, 14, 15 and Luna 17, 21)
  Laser-Ranging with retro-refelctors on Moon surface
- Light pulses of about 200 ps with repetition rates of 0.1 s
- Beam „illuminates“ a circle of Ø 20 km on Moon surface
- Out of 10^{20} photons 1one coming back can be identified on Earth
  (ca. 1 per second)
- Accuracy: 3 cm
- Telescopes:: McDonald Obs., Fort Davis TX, Mt. Haleakala, Hawaii and OCA, Grasse





Cassini-Exp. / Shapiro Time Delay



Einstein-Infeld-Hoffmann equation

- Numerical models based on isotropic PPN n-body metric metric
- Planets and asteroids treated as point masses
- Accelerations calculated wrt their barycentric position

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

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

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

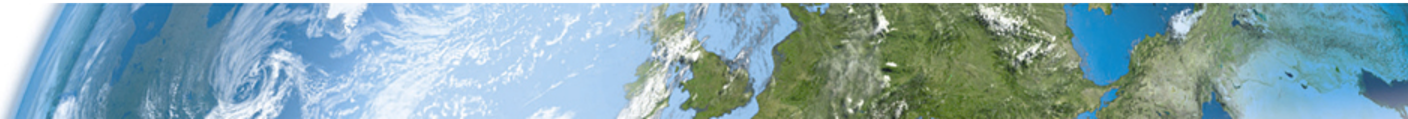
Time delay for curved space-time due to grav. fields of Sun and Earth

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

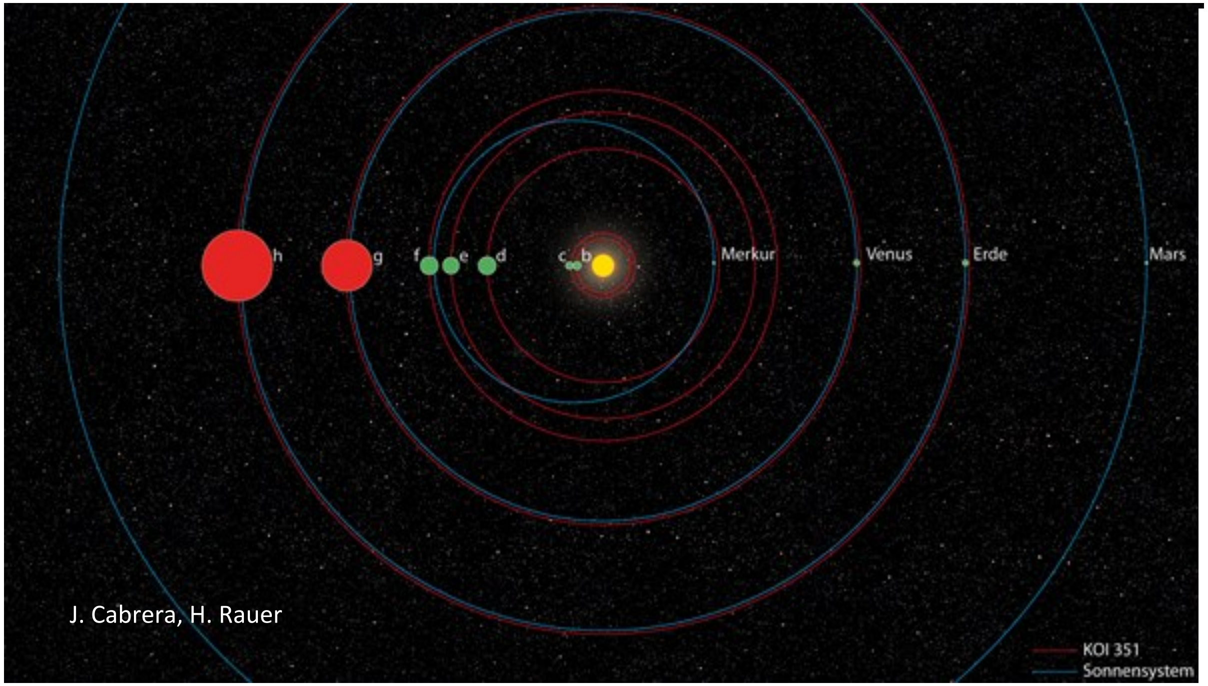
Cassini Conjunction Experiment 2002:

- Satellit - Earth distance > 10^9 km
- Ranging: X~7.14GHz & Ka~34.1GHz (dual band)
- Result: □ = 1 + (2.1 ± 2.3) □ 10□5

DLR



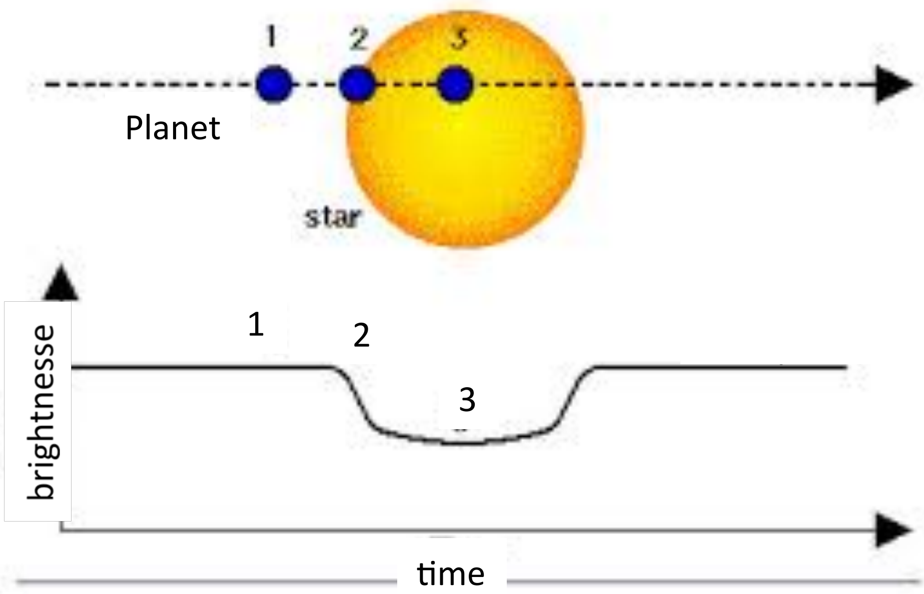
The Planet System KOI-351, detected in 2013



- 2500 light years far distant from sun
- main row star in the Milky Way
- 7 planets on a distance of only 1 AU
- detected with Kepler S/C by transition method between 2008 and 2013

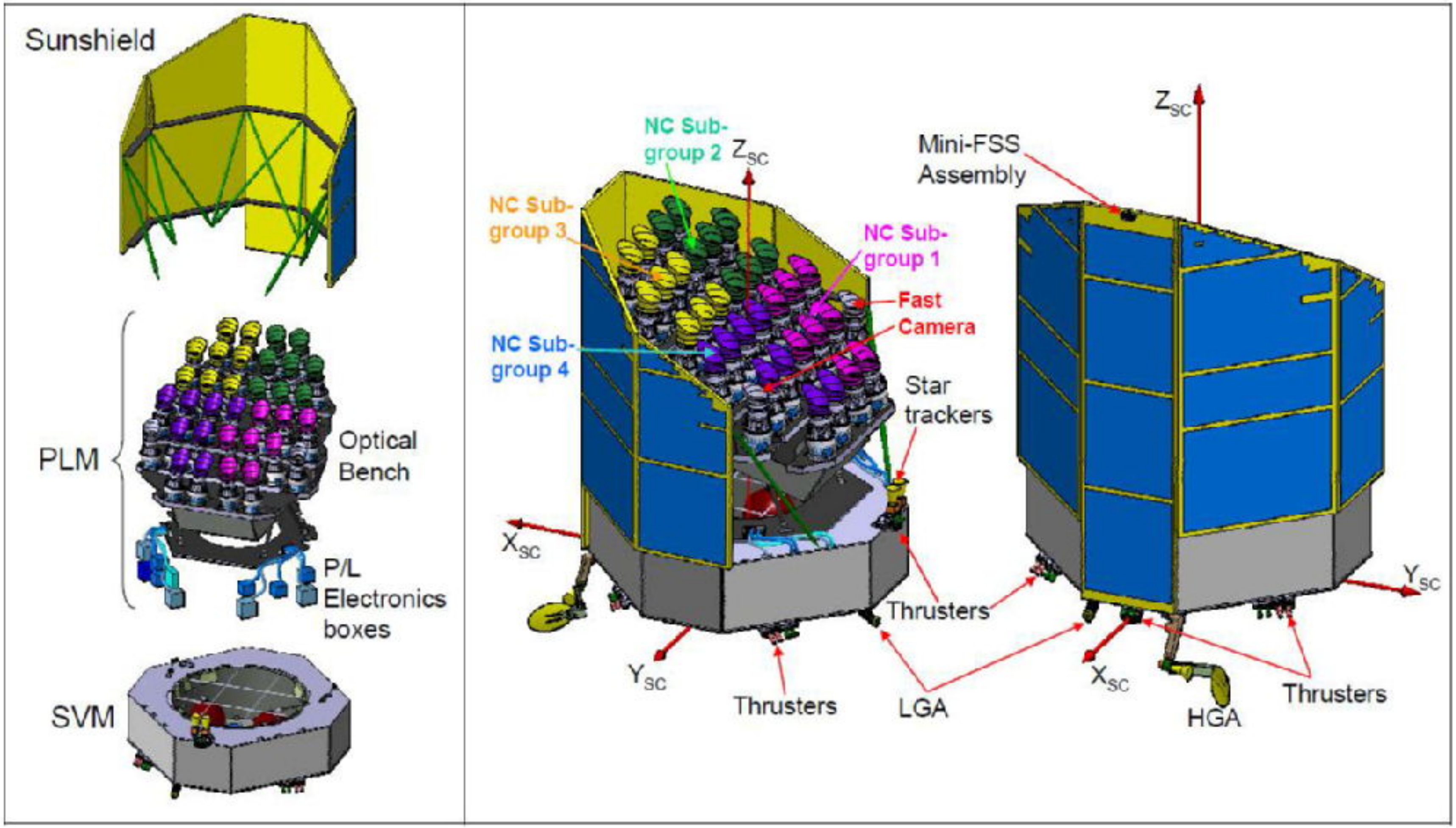
How stable is the system?

The Transition Method



Venus transition
at sun on 6.6.2012

PLATO S/C


Sunshield
PLM
Optical Bench
P/L Electronics boxes
SVM
NC Sub-group 2
Z_SC
NC Sub-group 3
NC Sub-group 1
Fast Camera
NC Sub-group 4
Star trackers
X_SC
Y_SC
Thrusters
Thrusters
LGA
Mini-FSS Assembly
Z_SC
Y_SC
Thrusters
X_SC
HGA
Thrusters

Galileo S/C: A chance for Fundamental Physics?

- 2 L3 FOC satellites launched on 22/08/2014 in:

Elliptical orbit with deviation from nominal orbit of -9.500km up to +2.700km

    Eccentricity 0.23

    Speed Apogee ~3km/s and Perigee ~5km/s

Delta Inclination of 6 degrees with respect to nominal plane

Orbit has been changed because Earth sensors are not reliable for these altitudes -> gyros might become mandatory input for AOCS (gyro spec to be checked)

    Yaw steering (clocks never pointing to the sun) coincidence at Perigee could exceed the tolerance

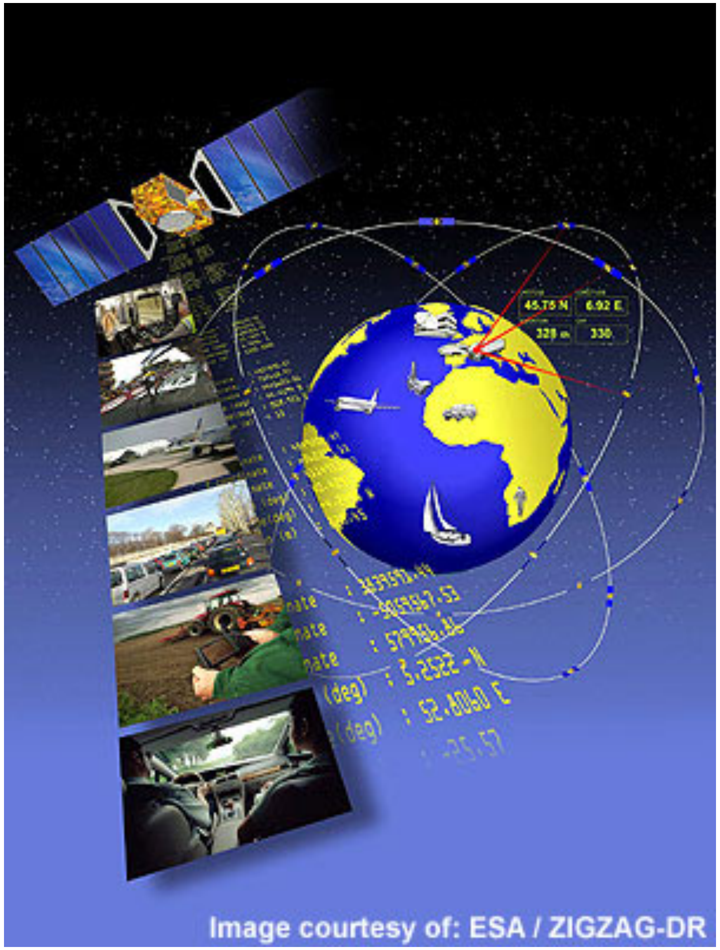
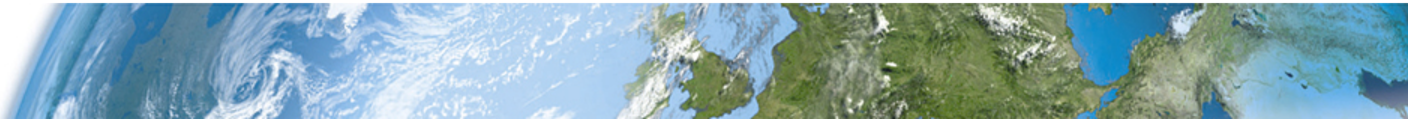
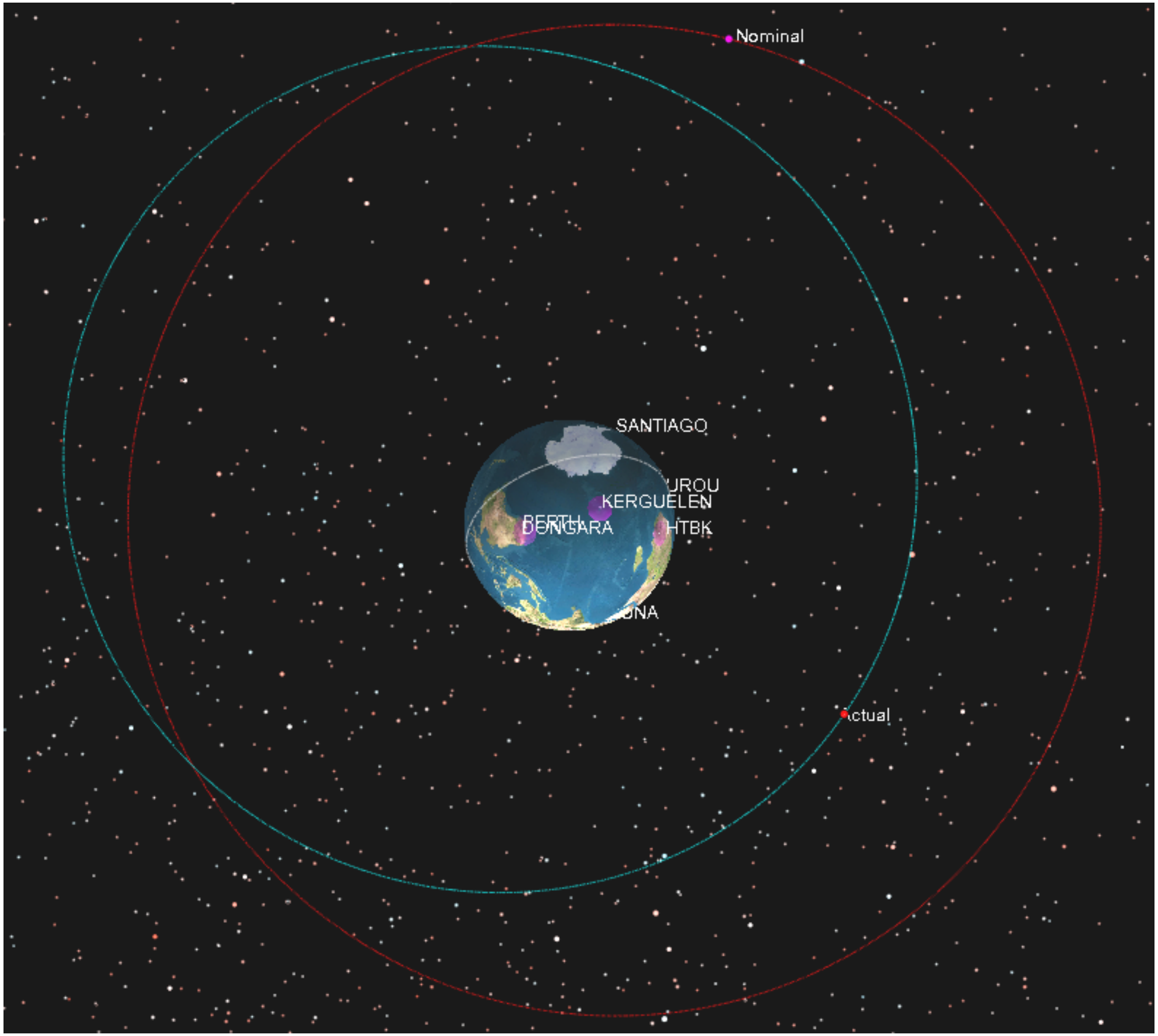
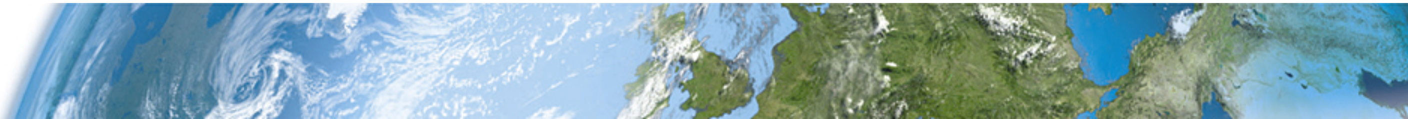
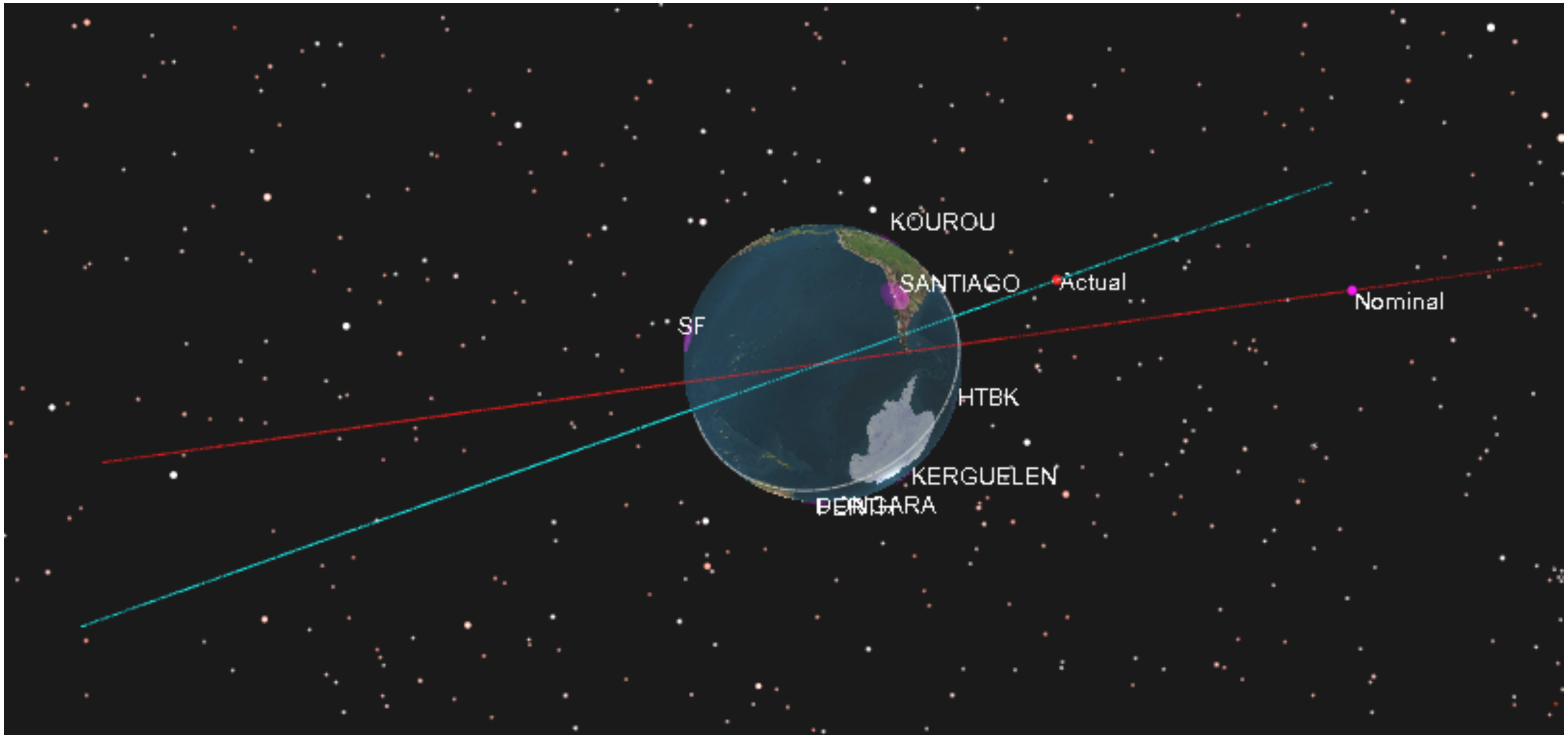


Image courtesy of: ESA / ZIGZAG-DR



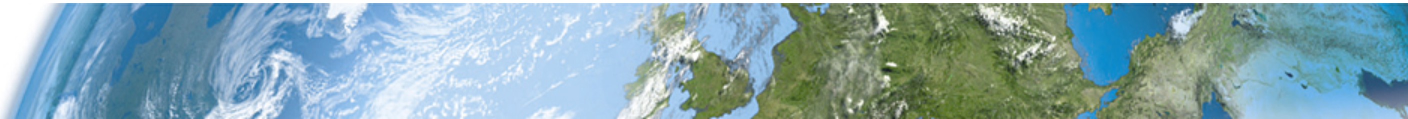

Nominal
SANTIAGO
UROU
KERGUELEN
PERTH
DONGARA
HTBK
NA
ctual




KOUROU
SANTIAGO
Actual
Nominal
SF
HTBK
KERGUELEN
PERTH
DONGARA

What could be done with 2 GNNS satellites which failed their orbit?

- Clock stabiliy: 10^{-15} per orbit
- Grav. Redshift test improvement: 10^2
- Perihelion shift: 10^1
- Alternative theory tests
  Yukawa potential at length scale 104 m: 10^5

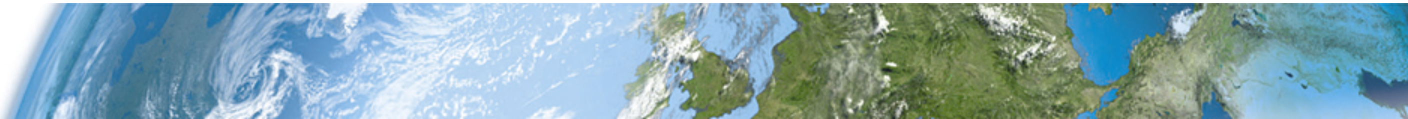


New Target Orbit for GSat 201

Orbit insertion: 5.11.2014

Perigee (km)	13,728.7	to	17,340.8
Apogee (km)	25,922.1	to	25,858.8
Height diff. (km)	12,193.4	to	8,518.0
Excentricity	0.2326	to	0.1522

DLR

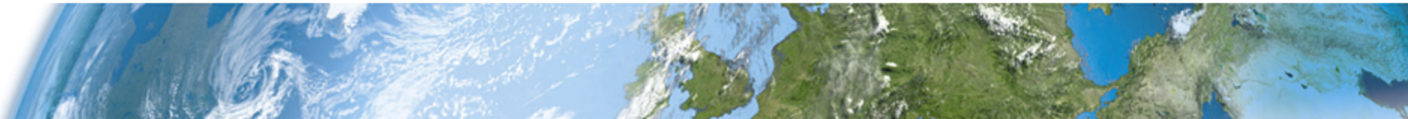


Observation Tools

- Satellites and orbital platforms
  - Observations from Satellites (e.g. astronomical and astrophysical telescopes)
  - Experiments with Satellites (e.g. spacecraft tracking by Doppler shift)
  - Experiments on Satellites (e.g. GP-B)

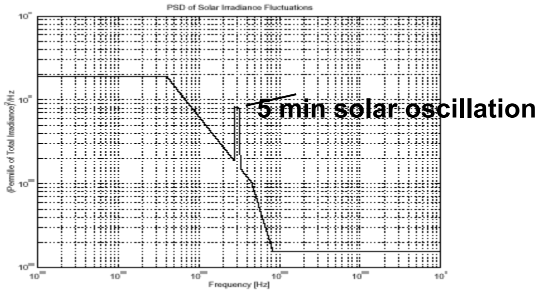
- Needs a toolbox of hihgly precise sensors to measure
  - Distance (e.g. Laser Ranging, Doppler shift, optical transponders)
  - Time (e.g.cavity clocks / frequency standards, atomic / optical clocks, freq. combs)
  - Acceleration (SQUID-based sensing, gyroscopes, inertial sensors)
  - Angles (pointing, star sensors, VLBI)

- Needs reliable and precisely operating actuators
  - Thrusters
  - Reaction wheels
  - Piezo-techniques for mirror pointing



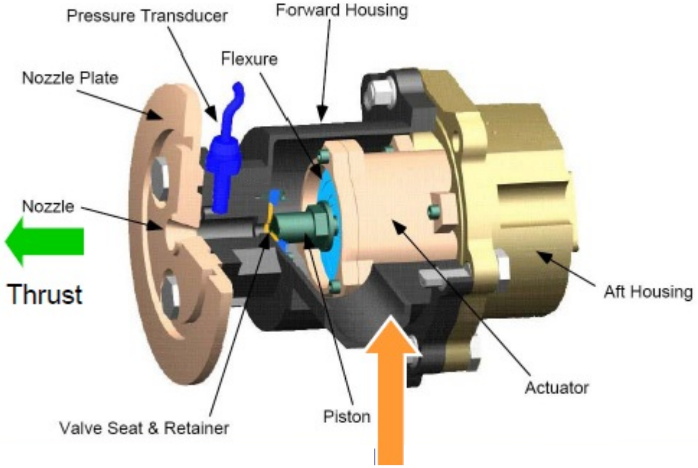
Drag-free Thrust Control

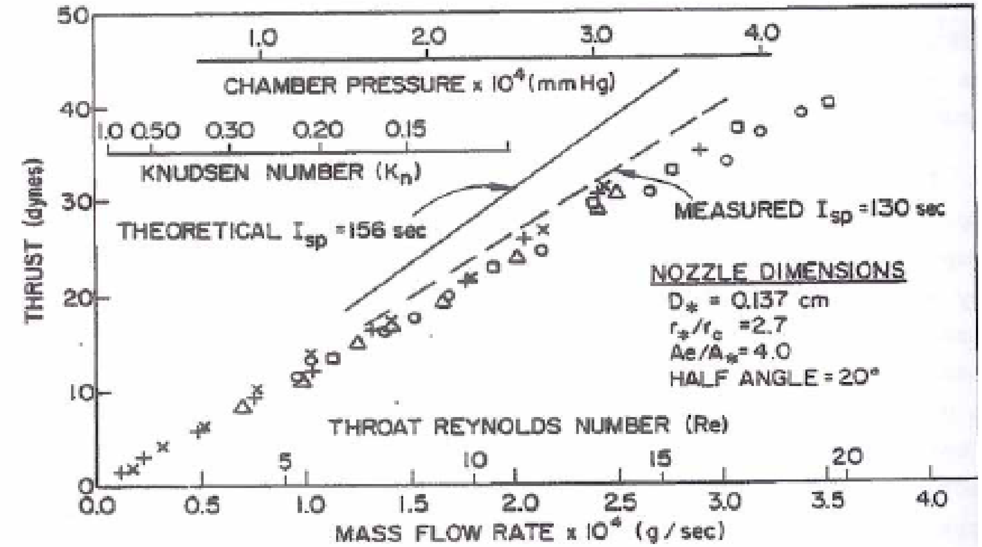
- mN/µN-Thrusters:
  - for compensation of forces deviating the satellite on its ideal free fall orbit (geodesic)
  - for compensating of tidal forces and satellite dynamics in formation flight
- Disturbance forces
  - atmospheric drag:
    forces: ca. 1mN; moments: 10 µN · m
  - radiation pressure by Earth albedo:
    forces: ca. 10 µN; moments: 1 µN · m
  - magnetic moments by s/c interaction with the Earth magnetic field (typically):
    moments: 100 µN · m, after moment compensation: 10 µN · m
  - solarer radiation pressure:
    forces: ca. 10 µN, moments: 0.1 µN · m



- Thrust requirements
  - **thrust co0ntrol: $\Delta S < \pm 0.1$ µN**
  - **residual acceleration: $< 10^{-15}$ m/($s^2 \cdot Hz^{0.5}$)**
  - **permanent operation**

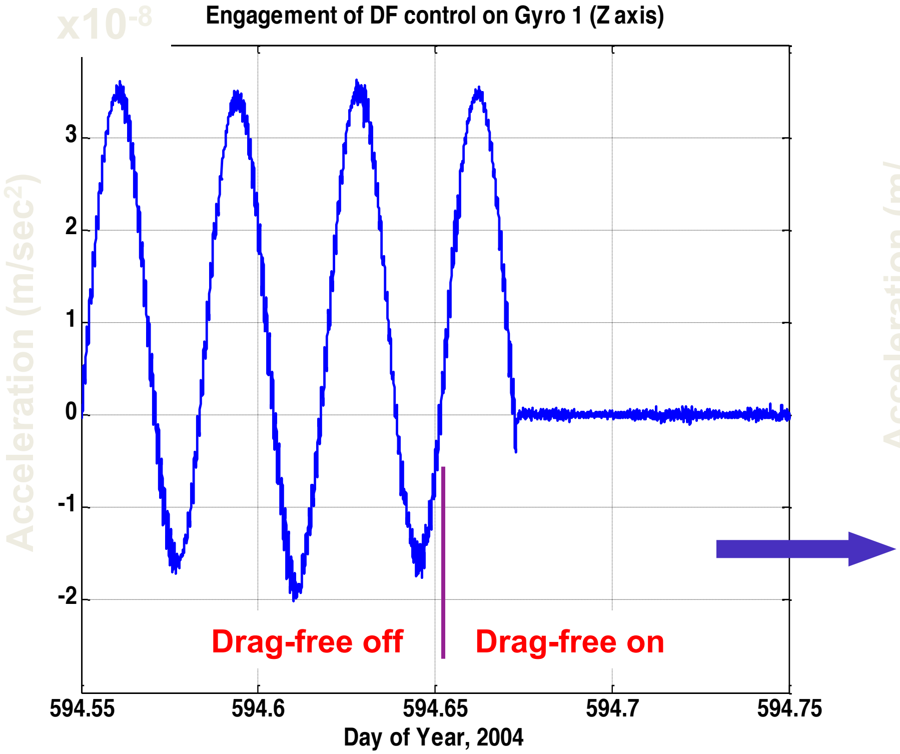
- **Gas-proportional thruster on Gravity Probe B**
  - Set of 4x4 =16 proportional thrusters,
    fuel: He (boil-off gas from 2.3 m^3 Dewar)
    at 670 to 2,330 Pa
    $S < 10$ mN for 6 DOF
    $I_{sp} = 130$ s
    mass flux: 6.5 mg / s
    noise: 25 $\mu N \cdot Hz^{-0,5}$

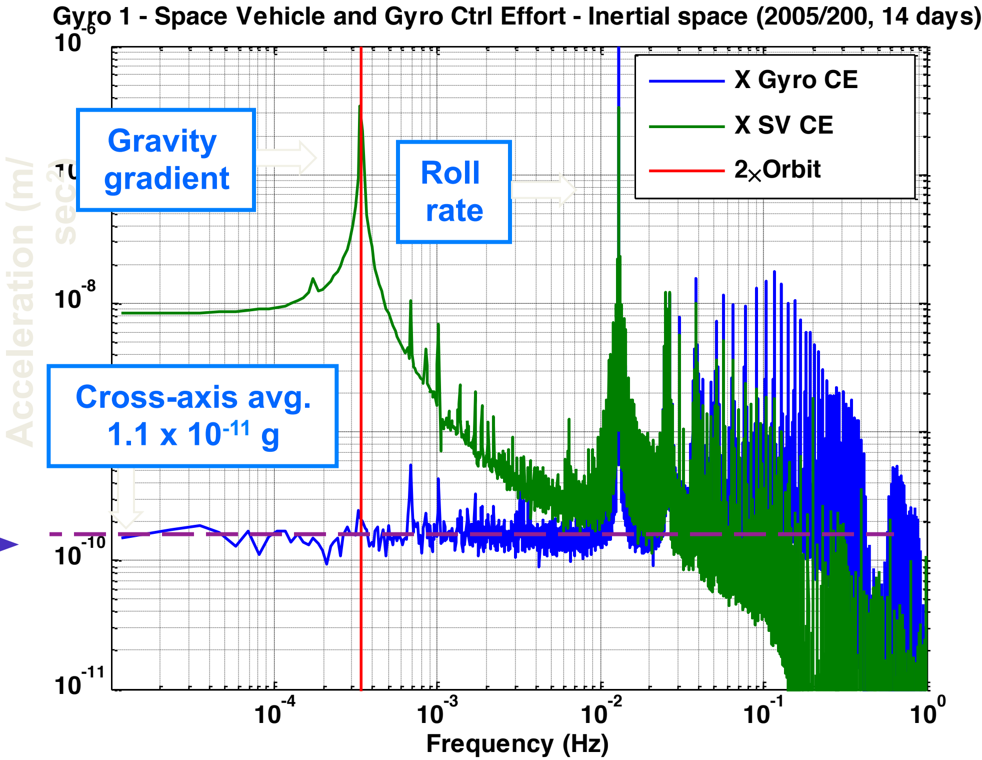




Sourc:e: Stanford University

- Drag-free performance of GP-B





F. Everitt et al.

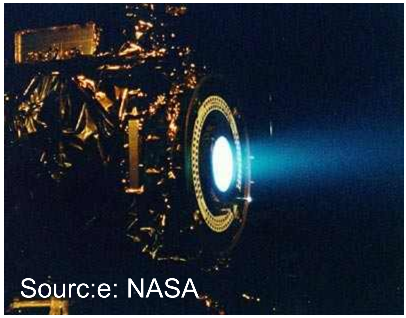
Satellite Thrusters

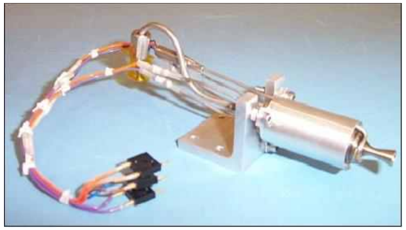
- Huge dynamic range
  - ~ µN < S < 40 kN; 200 s < I_{sp} < 3,000 s

- Extremely low thrust systems
  - Arcjet Engines:
    Hybrid systems for continous or pulsed thrust
    light arc ignition of gases
    100 mN < S < 1N; 500 s < I_{sp} < 2,000 s
  - Ion-thrusters (Hall thruster):
    non -chemical systems for continous thrust over long time
    ionisingerung of a Xenon atom beam
    2 kW< P < 50 kW
    40 mN < S < 7200 mN; 3,000 s < I_{sp} < 9,000 s
  - Magneto-plasma dynamical thrusters:
    beam acceleration by EM-fields
    S up to 100 N; $I_{sp} \approx$ 5,000 s
  - Cold gas thruster:
    inert gas (typically N_2) exhaust
    1mN < S < 10 N; 50 s < I_{sp} < 80

- Micropropulsion systems:
  - Typically Fundamental Science Mission (e.g. LISA) need µN – thrust w
    sub µN – precision control


Sourc:e: Purdue School of Aeronautics and Astronautics

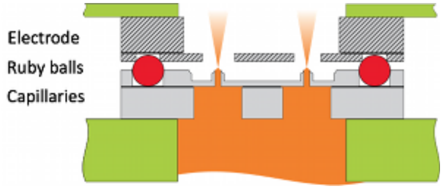

Sourc:e: NASA

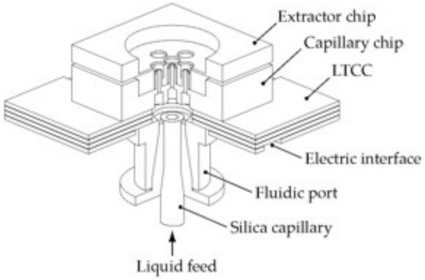


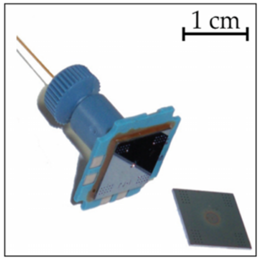

Sourc:e: NASA

Micropropulsion Systems

- **MEMS-based propulsion**
  - Main incitement and motivation: development of thrust systems for nano-satellites
  - Microfabricated: Liquid Micro-Thruster, Micro-Ion Engine,…
    Requirements:
    Thrust level 1–1000 N
    Impulse bit 1–100 N s
    Specific impulse 160 s
    Mass <0.1 kg
    Power consumption <1 W
    Volume <1 cm^3
    Operating temperature <1700 K

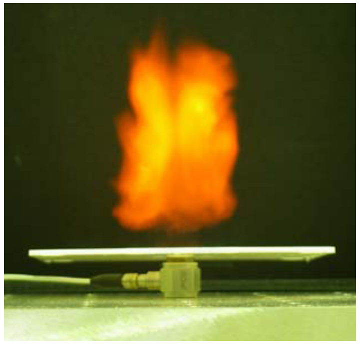




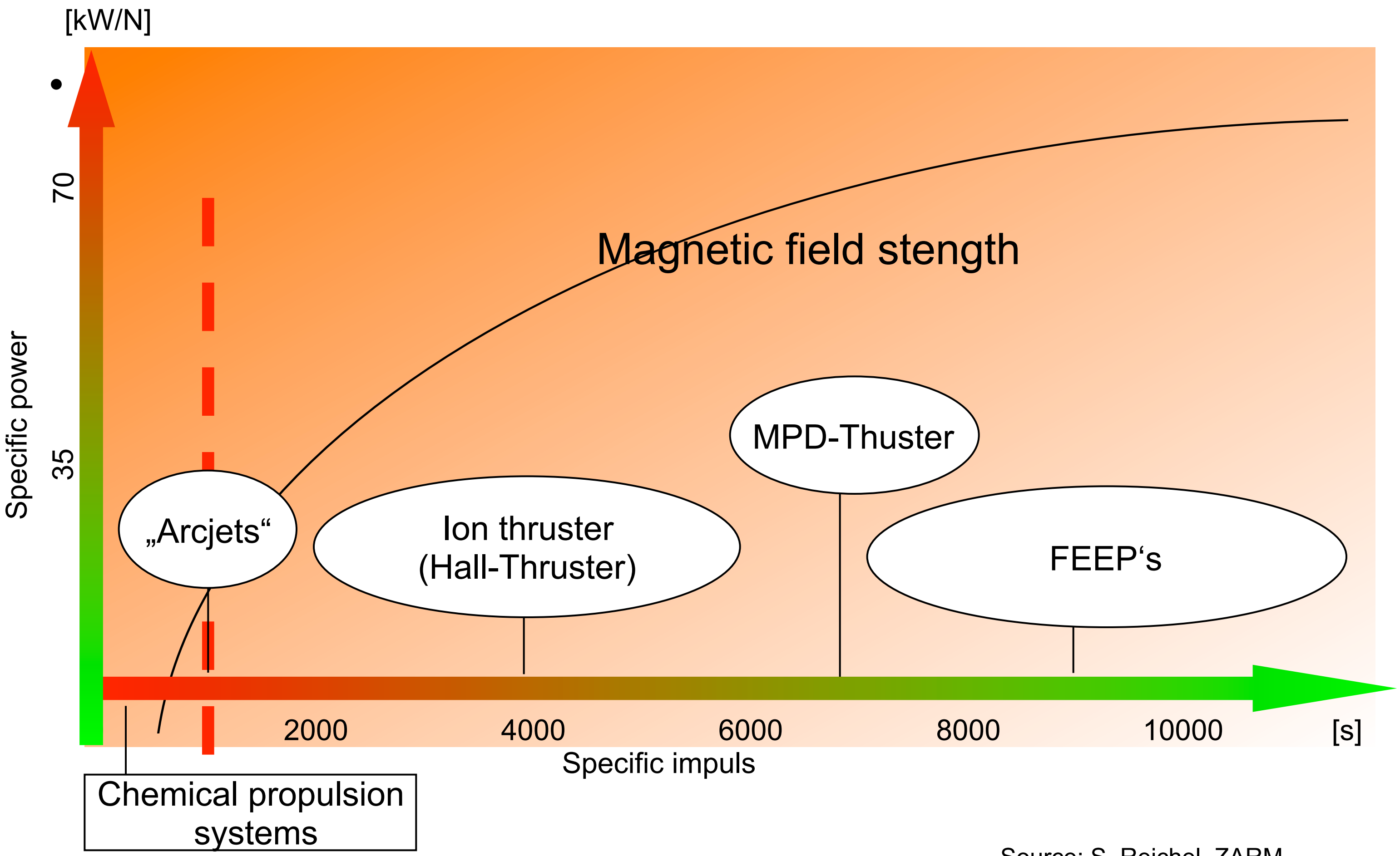


Sourc:e: École Polytech. d. Lausanne

- **Laser induced ablative thrusters**
  - *S. Karg,* DLR-TP
  - New concept for low thrust propulsion



Micropropulsion Systems

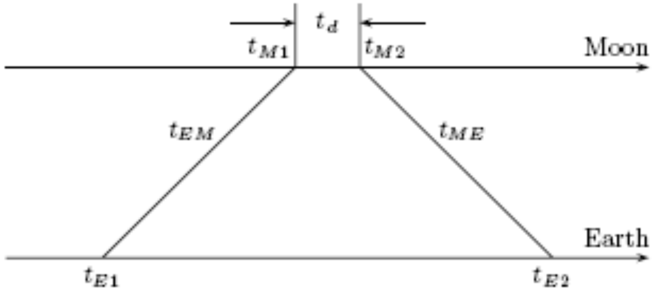


Source: S. Reichel, ZARM

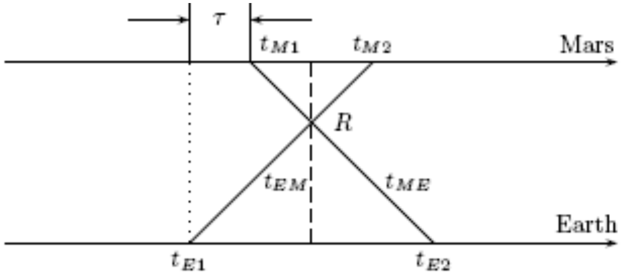
Optical links and Laser ranging

- Optical transponders (on-board lasers, telescopes, timing receiver)
- Demonstrated over 0.17 AU (24 million km) with Messenge
  S/C and
  Mars Global Surveyor S/C (1-way, 80 million km)
- Nd:YAG laser, pulse rate 8 Hz
- Needs atmospheric correction: calibration can be done by ranging to near earth objects (e.g. LAGEOS) from different stations

	Messenger S/C	MOLA on Mars Global Surveyor S/C (1-way only)
range	$2.4\cdot10^7$ 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 power	3.84 W (up), 0.16 W (down)	8.4 W
beam divergence	60 μrad (up), 100 μrad (down)	50 μrad
receive area	0.042 m^2(up), 1.003 m^2 (down)	0.196 m^2



Echo transponder for
e.g. lunar laser ranging
Time delay must be known



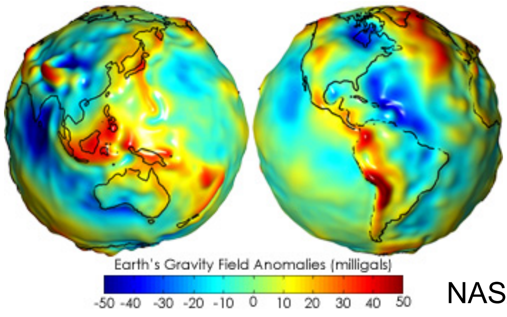
Asynchronous transponder for
satellite laser ranging
Repetition rate must be known

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

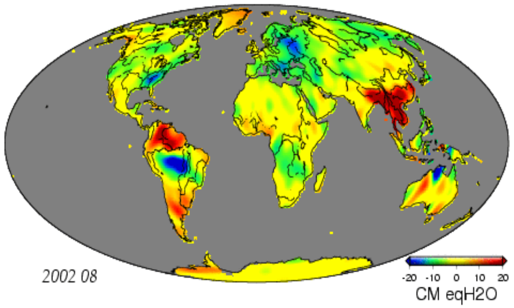
GRACE

(Gravity Recovery And Climate Experiment)

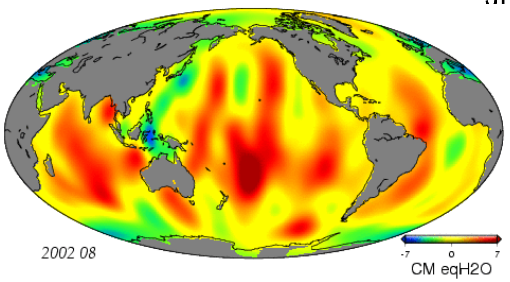
- Joint NASA/German Aerospace Center mission
- Aims to continuously measure Earth's gravity field
- Pair of S/C around Earth, 220km distance along orbit
- The distance between the S/C varies depending on the Earth mass distribution
- Distance measurement by a two-way microwave-ranging link (accuracy in the μm range)
- Polar Orbit 500km above Earth
- Input to
  - Oceanography
  - Hydrology
  - Glaciology
  - Geology
  - Climate change analysis
- End of lifetime: expected 2015 – 2016
- Follow on mission GRACE-FO will start in 2017 in order to guarantee a continuous flow of data



NASA



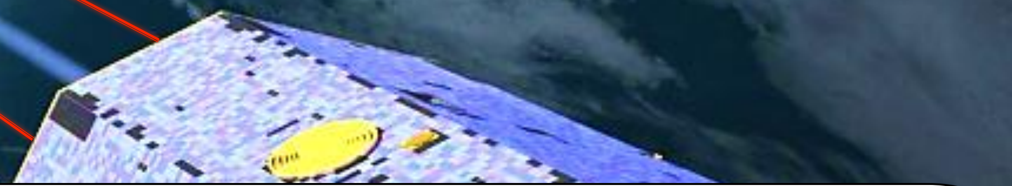
JPL

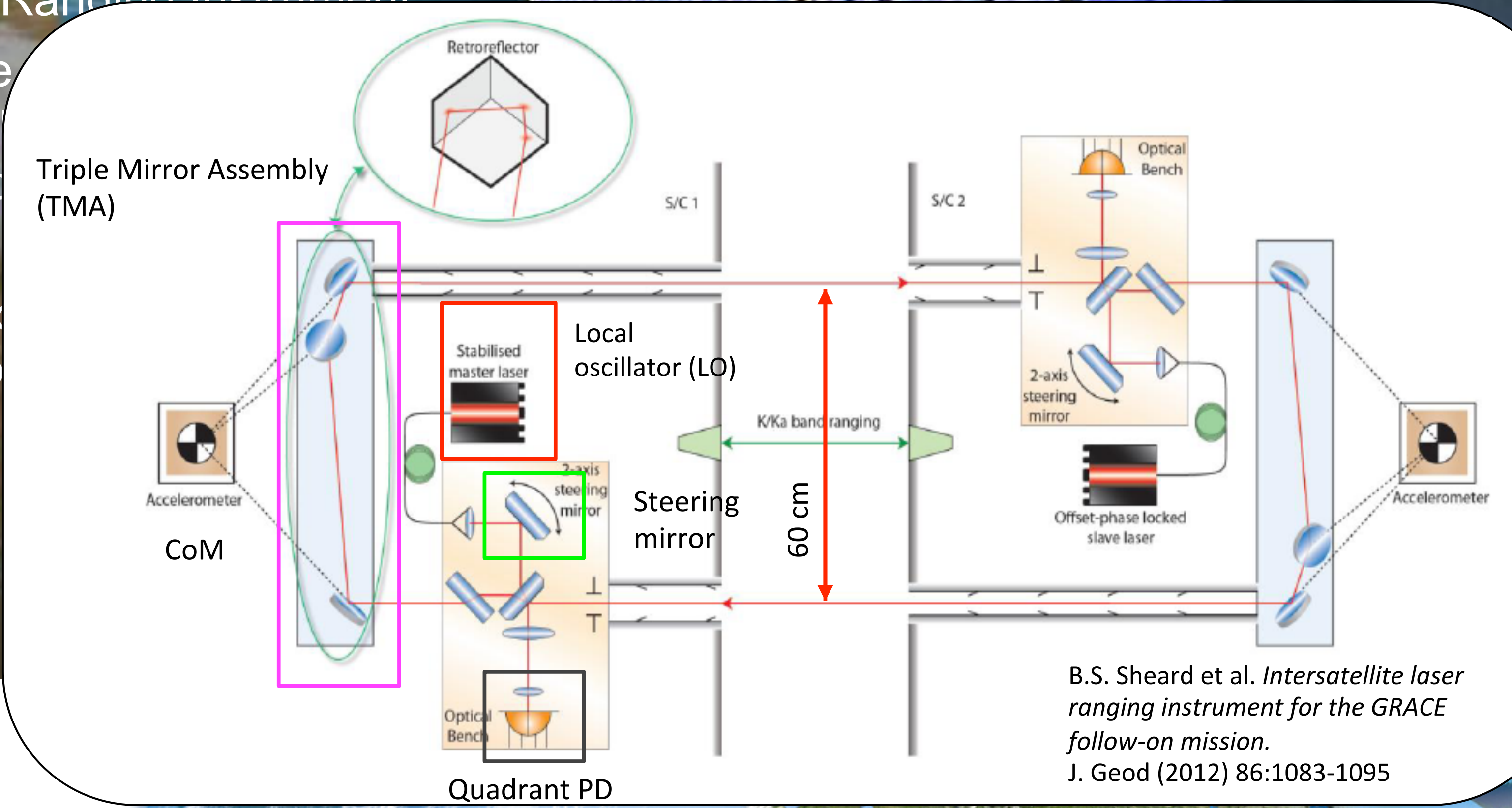


JPL

GRACE – Follow On

- Start: August 2017
- The basic principles of the GRACE mission do not change
- Additional second distance measurement system LRI
- LRI – Laser Ranging Instrument
- The distance
accuracy will
at least a fac
- DLR-RY will
LRI by CiK to
ground supp

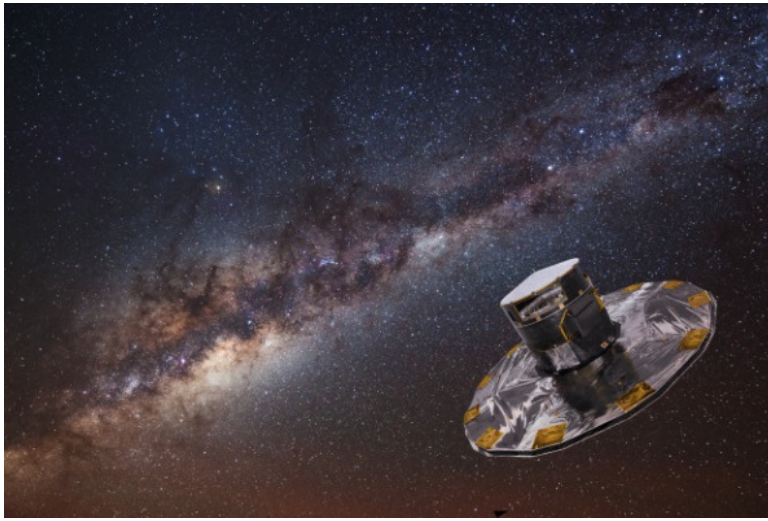




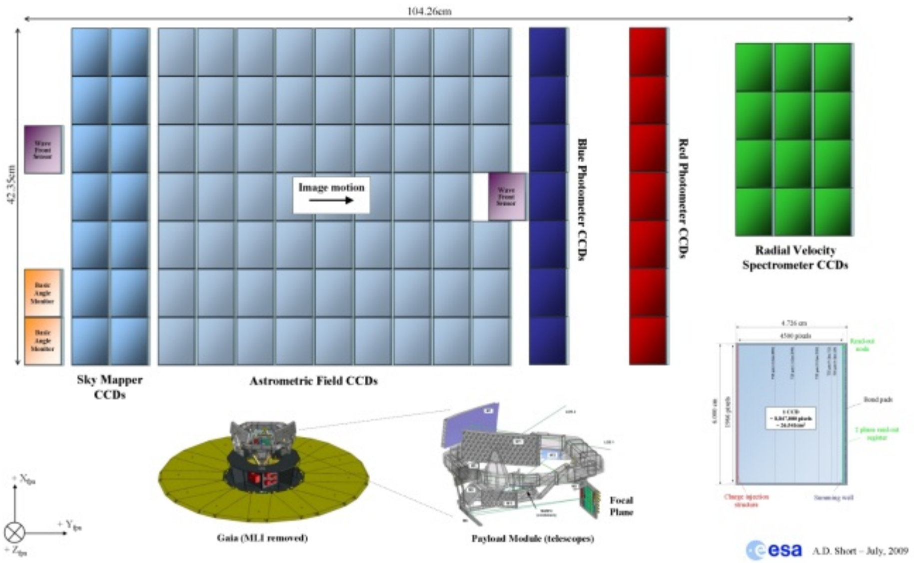
B.S. Sheard et al. *Intersatellite laser ranging instrument for the GRACE follow-on mission.*
J. Geod (2012) 86:1083-1095

GAIA

Global Astrometric Interferometer for Astrophysics



- Launch: Dec 19, 2013
- Orbit: Lissajous-type orbit around L2
- Most precise 3D map of the Milky Way and its dynamic
  based on paralaxe determination, distance, and velocity measurements
- Determination of brightness, temperature and composition
- 2 identical telescopes and imaging systems, BP/RP (Blue and Red Photometers) and RVS (Radial-Velocity Spectrometer)
- Angle measurement: 24 marcs (50 times better than Hipparcos)
- Distance measurements: up to 30,000 ly; with accuracies between 10^{-5} and 0,2



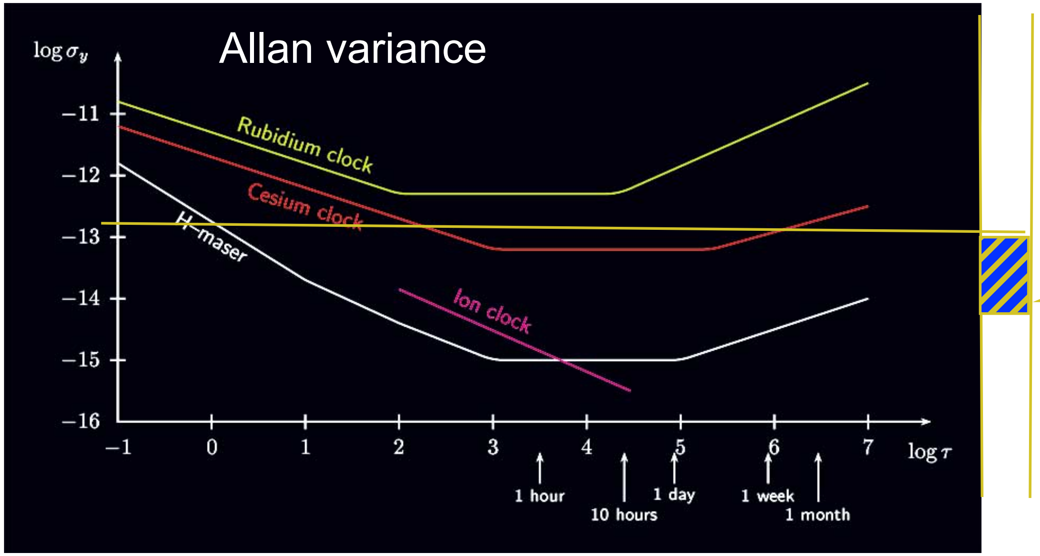
Clocks to explore space-time

- Redundant measurements
  - Measuring acceleration of S/C on geodesic via ranging and Doppler tracking
  - Measuring redshift of clocks on-board S/C

for example Pioneer Anomaly

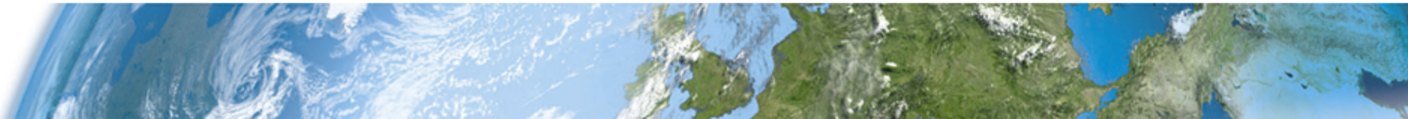
$$\frac{\Delta\nu}{\nu} = \frac{1}{c^{2}}\int_{20AU}^{90AU} a_{PA}\,\mathrm{d}x \approx 10^{-13}$$

- Clock exploration does not depend on geodesic motion, independent from acceleration
- Cock exploration is cumulative
- Clocks automatically isolate the pure gravity sector
- Clocks represent an absolute DC-accelerometer

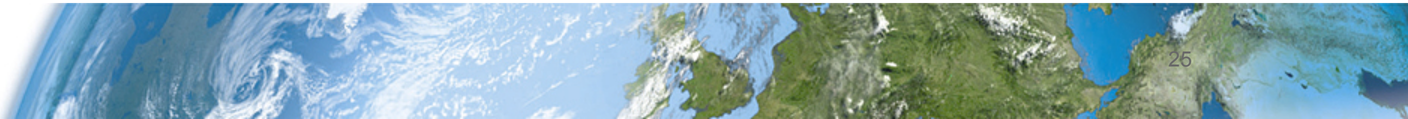


requirement for deep space missions

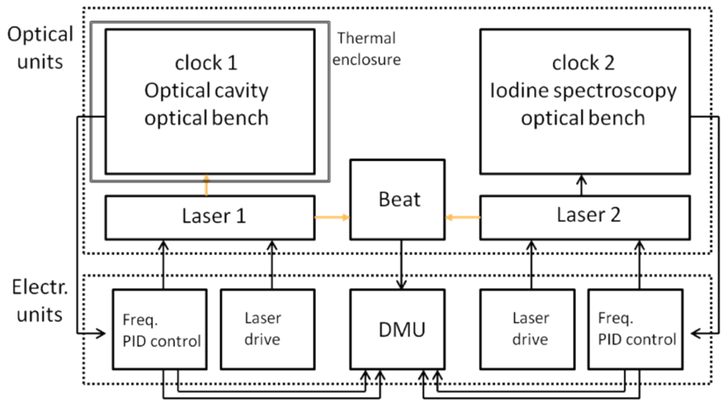
Challenge:
long term stability



The Future



STAR / BOOST ?


Optical units

clock 1
Optical cavity
optical bench

Thermal enclosure

clock 2
Iodine spectroscopy
optical bench

Beat

Laser 1

Laser 2

Electr. units

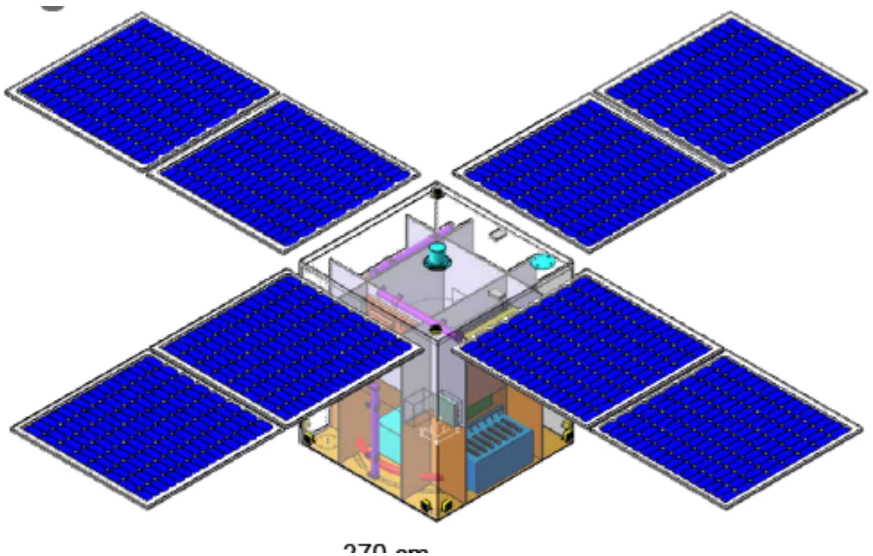
Freq.
PID control

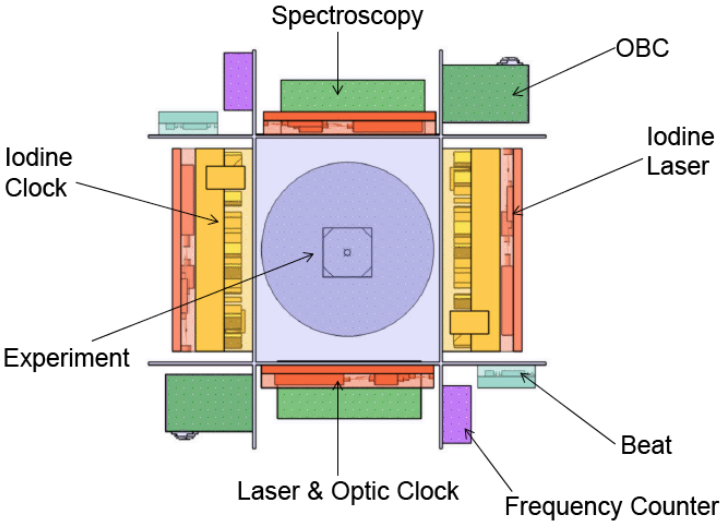
Laser drive

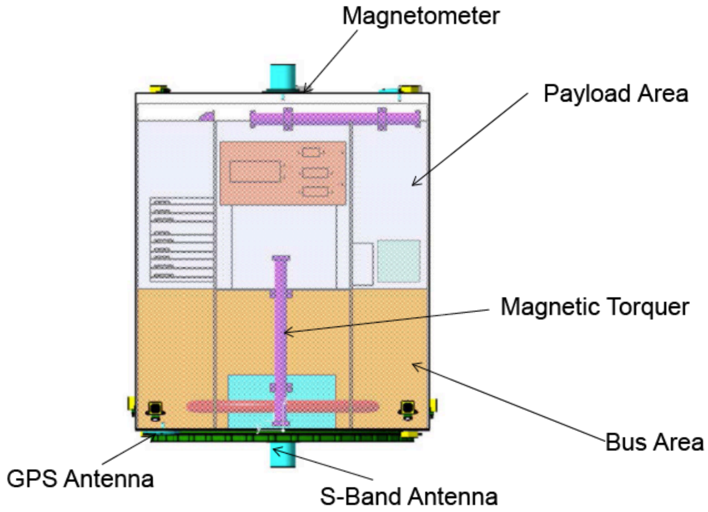
DMU

Laser drive

Freq.
PID control





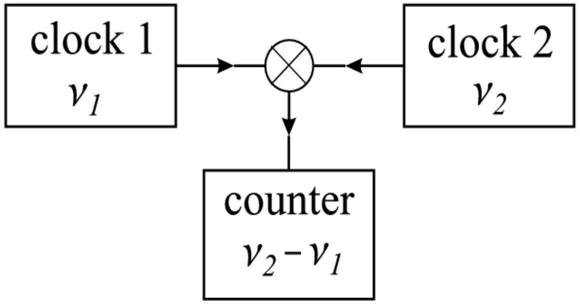


Source: STAR / BOOST collaboration

Kennedy-Thorndike experiment - Frequency comparison: BOOST (BOOst Symmetry Test)

CLOCK 1
with a dependence
on v

CLOCK 2
with a different
dependence on v



BEAT measures difference in frequencies

SATELLITE

→

v

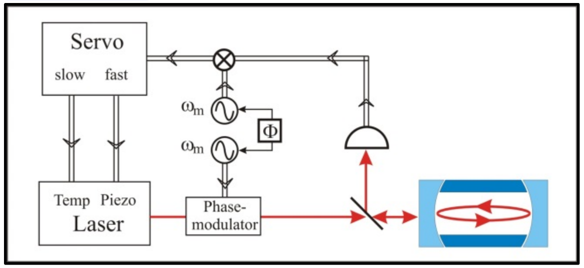
⇒Large v variation desired to enhance the effect

Source: C. Braxmaier

Kennedy-Thorndike experiment - Frequency comparison: BOOST (BOOst Symmetry Test)

CLOCK 1: w/depend. on v

Cavity

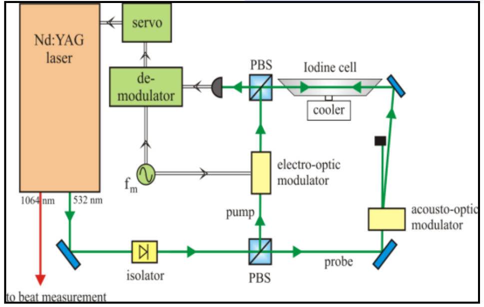


clock frequency depends on c:

$\sim c\,(v)/L$

CLOCK 2: w/different depend. on v

Atom clock



clock frequency does NOT depend on c: $\sim E/h$

BEAT

SATELLITE

→

V

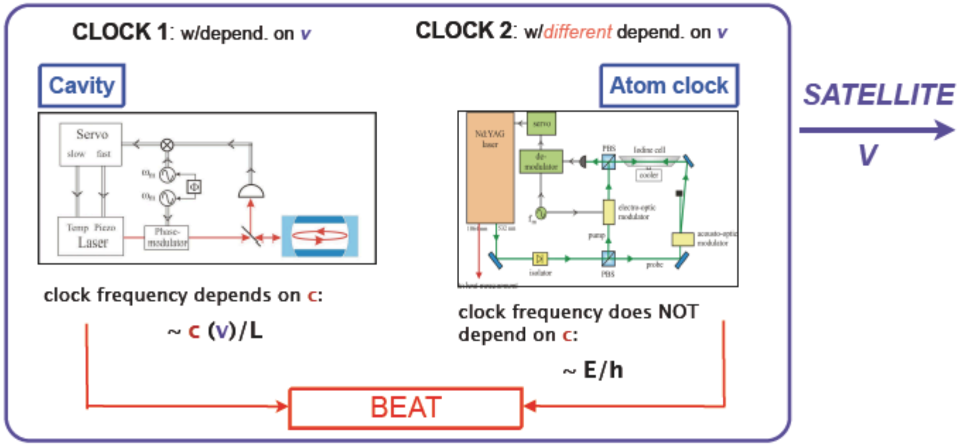
Source: C. Braxmaier

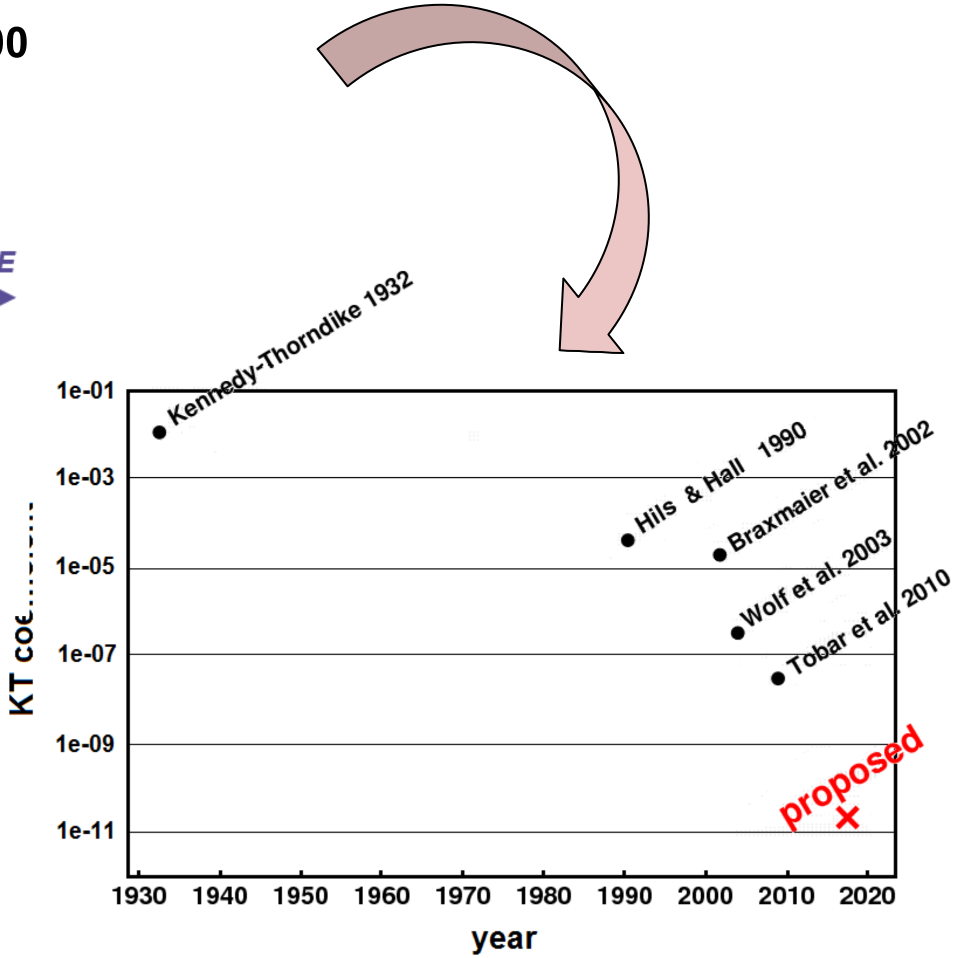
BOOST (BOOst Symmetry Test): Kennedy-Thorndike

- Testing the foundations of Special Relativity (Lorentz Boost Invariance)
  - *“Is the speed of light independent of the velocity of the Laboratory frame”*
- High velocity changes (direction) on short time scales necessary

→ **Satellite experiment:** Comparison of optical cavity and iodine clock

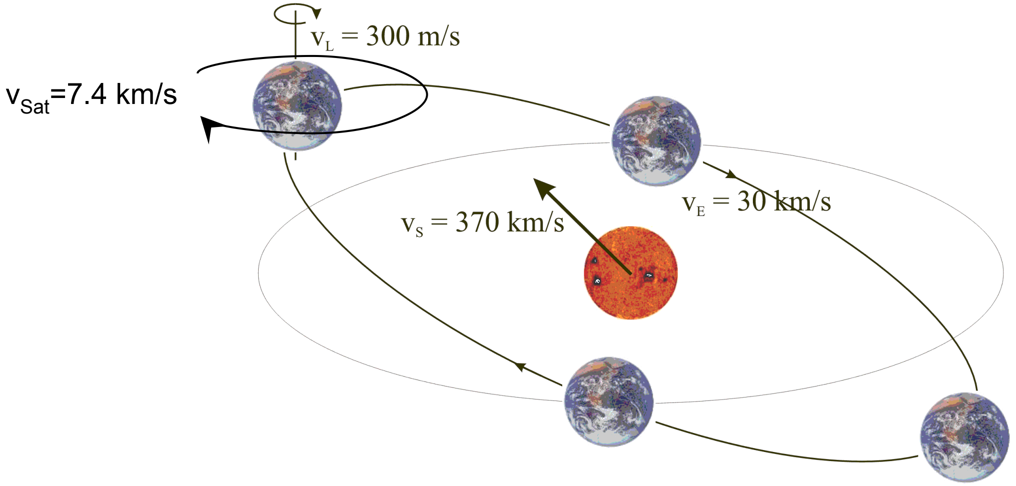
- Possible **improvement**: Factor **1600**
- SSO, 500km, 90min





Modulation of v - Laboratory @ satellite

Ref. frame: Cosmic Microwave Background (CMB)



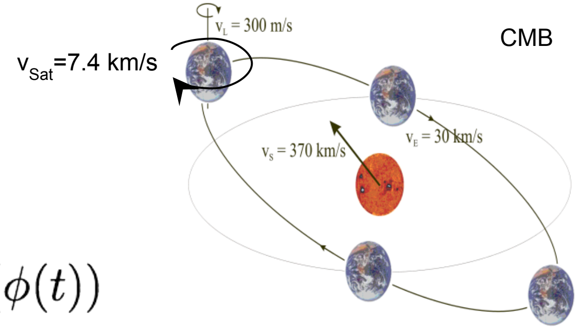
Velocity of an experiment on satellite

$$\vec{v} = \vec{v}_{\mathrm{Sol}} + \vec{v}_{\mathrm{E}} + \vec{v}_{\mathrm{Sat}}$$

Gain on velocity ratio

$$\frac{v_{\mathrm{Sat}}}{v_L} = \frac{7.4\,\mathrm{km/s}}{0.3\,\mathrm{km/s}} = 25$$

Estimation of KT-coefficient



Estimate

$$\frac{\delta_v c(v)}{c_0} = (\beta - \alpha - 1)\,.\,\boxed{\frac{\delta(\vec{v}^{\,2})}{c_0^2}}$$

$$\frac{\delta(\vec{v}^{\,2})}{c_0^2} = \frac{2\delta(\vec{v}) \times \vec{v}}{c_0^2} \simeq \frac{2|\vec{v}_{\mathrm{Sat}}||\vec{v}_{\mathrm{Sol}} + \vec{v}_{\mathrm{Earth}}|}{c_0^2} \cos(\phi(t))$$

$$\simeq \frac{2\ (7.4\,\mathrm{km/s})\ (370\,\mathrm{km/s} + 30\,\mathrm{km/s})}{(3 \times 10^5\,\mathrm{km/s})^2} \quad \boxed{=5.8 \times 10^{-8}}$$

Estimate

$$\boxed{\frac{\delta_v c(v)}{c_0}} = (\beta - \alpha - 1)\,.\,\frac{\delta(\vec{v}^{\,2})}{c_0^2}$$

with 1x10^{-16} clock stability @ orbit time

Measure

e.g. 90 min (instead of 1 day=1440 min on Earth ⇒ factor 4 gained)

integration in 5000 orbits

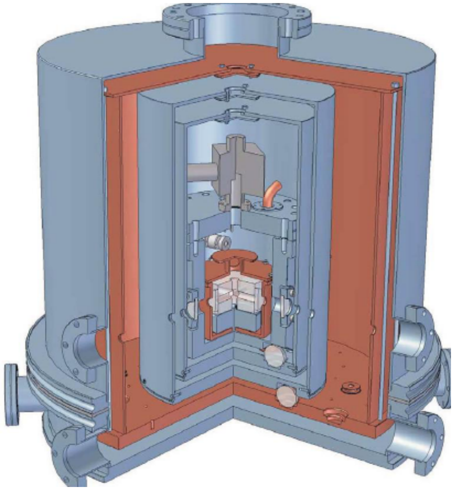
for 2 yrs → 50% duty cycle ⇒ $\boxed{1.4 \times 10^{-18}}$

Source: C. Braxmaier

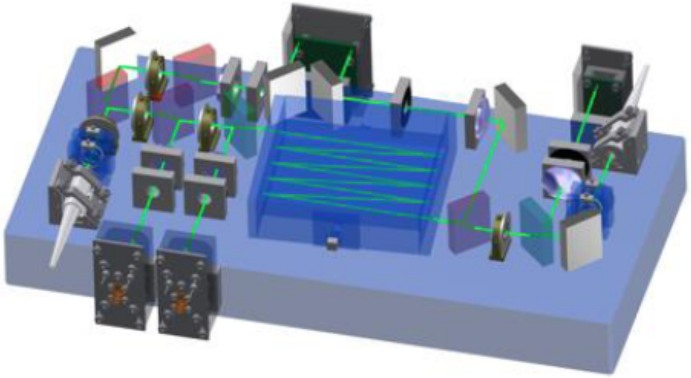
BOOST (BOOst Symmetry Test): Technology Reqmts

→ Payload design in DLR compact satellite bus feasible!

Cavity Reference
10^{-16} @ 2700s
@ 1016nm



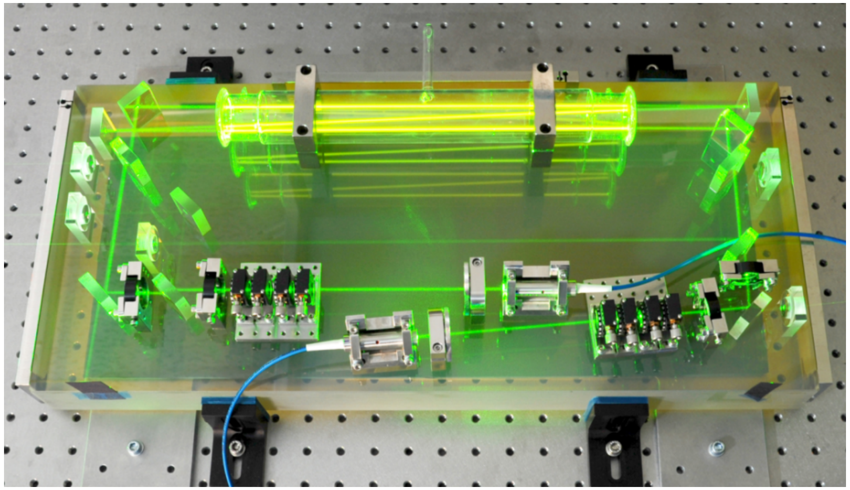
Molecular Clock Reference
10^{-16} @ 2700s @ 508nm



Iodine Setup: EM (35cm x 18 cm)

Status: Iodine standard

- Compact setup: 25cm x 55cm x 10cm
- 30cm long iodine cell in triple pass configuration
- Use of specific AI technology
- MTS @ 532nm
- Modulation either using fiber-EOM or AOM
- $< 3 \times 10^{-15}$ @ 1000s

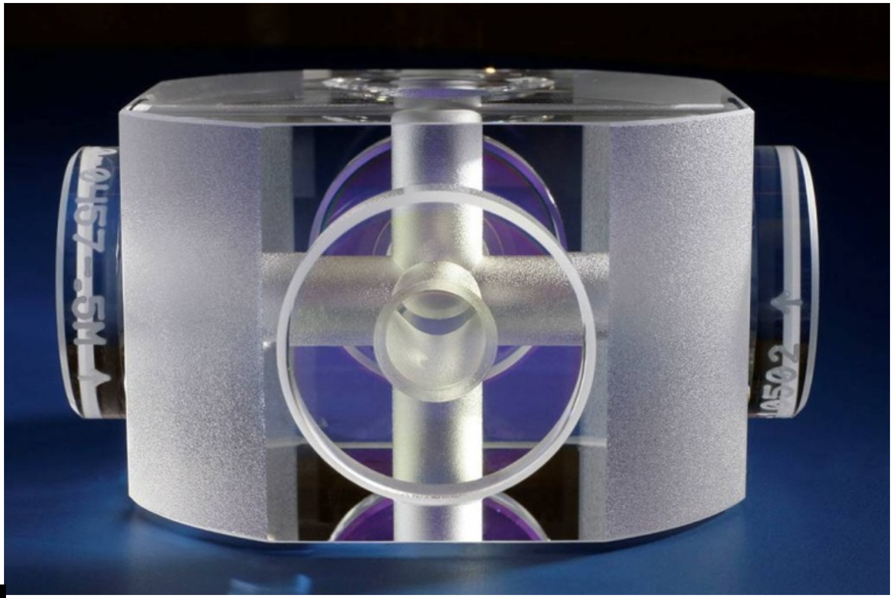


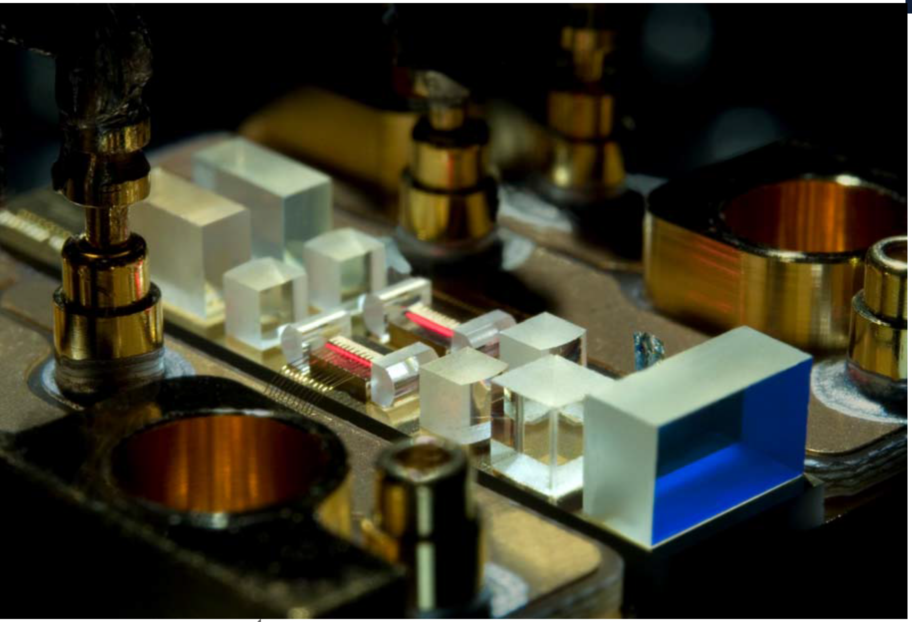
- MTS @ 508 nm → 1/10 of line width compared to 532 nm
- Expected performance for clock instability: $< 1 \times 10^{-16}$ @ 2700 s

Source: C. Braxmaier

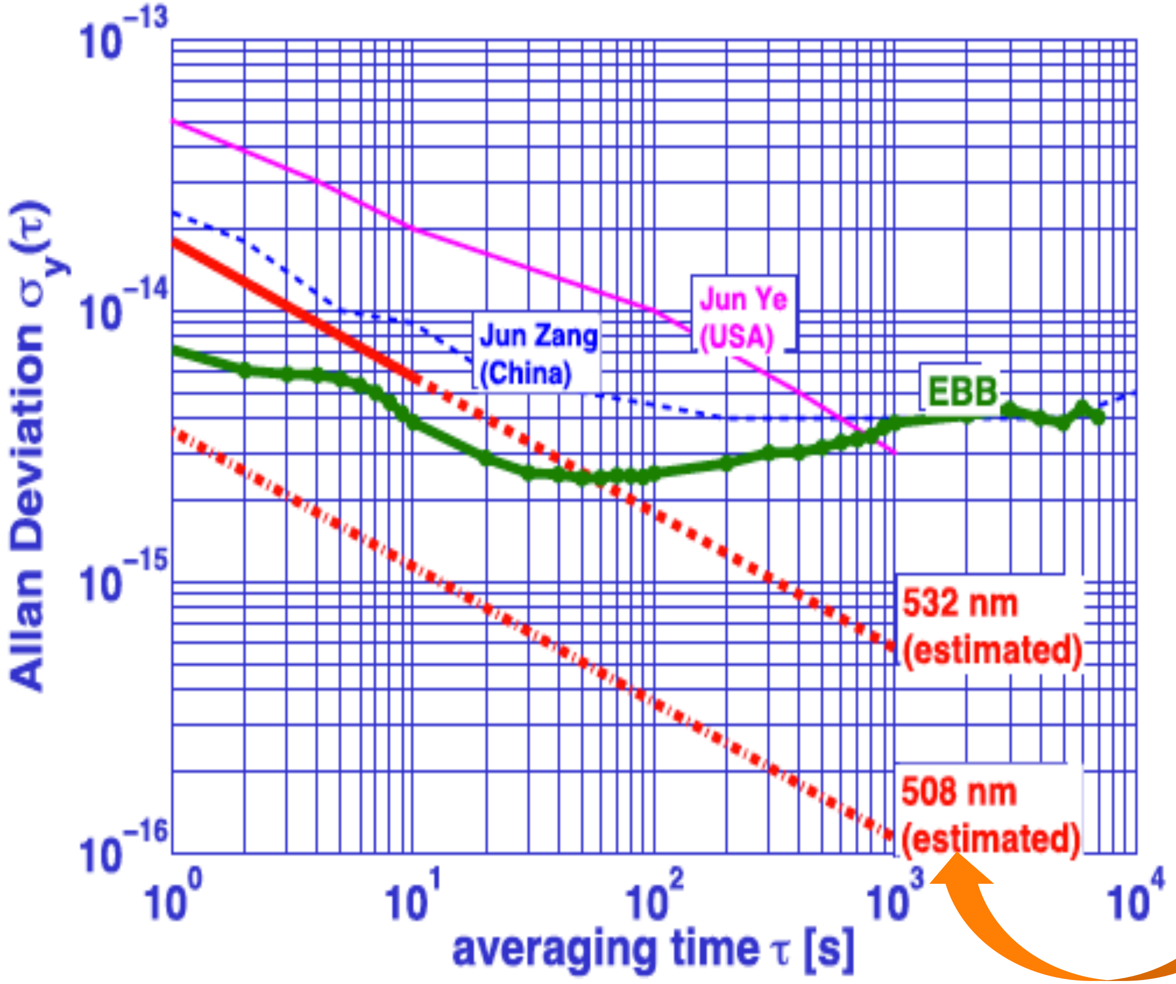
Cavities

- Made from ULE or FS or Zerodur
- 1064nm JPL GRACE FO cavity
  - $5*10^{-14}$ @ 1000s
  - TRL 5
- 1064nm SODERN Cavity
  - 10^{-15} @ 100s
  - TRL4-5



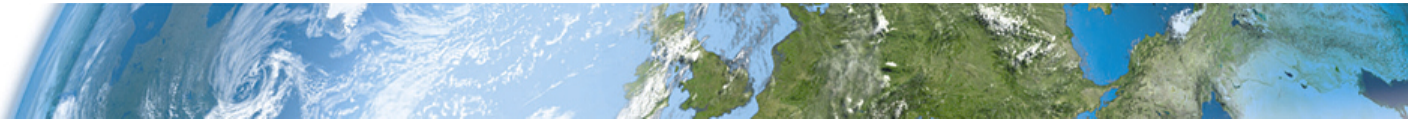


Source: C. Braxmaier



Proposed Performance

But that´s not all:



Quantum sensors

Based on:

(1) Ultra-precise optical metrology
$\delta\nu/\nu < 10^{-17}$ in the optical frequency domain

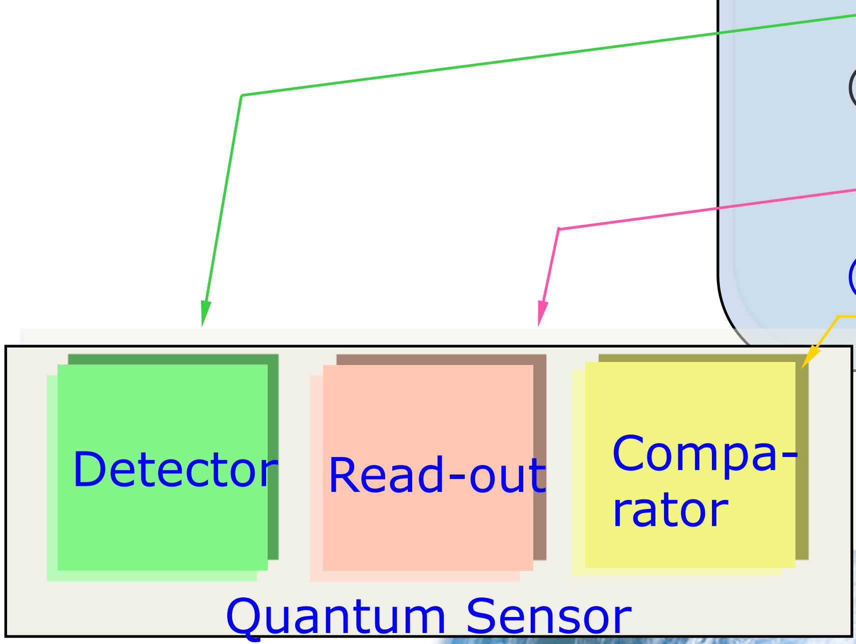
(2) Phase-sensitive atom interferometry
$\delta E/E < 10^{-19}$
due to the sub-microscopic quantum mechanical structure

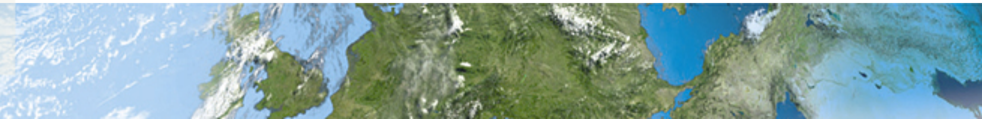
Needs experimental competence in:

(1) Processing ultra-cold atomic ensembles:
- „classical‟ laser cooled ensembles: ~ 1 µK
- Bose-Einstein Condensates (BEC): < 50 nK
- ultra-cold molecules

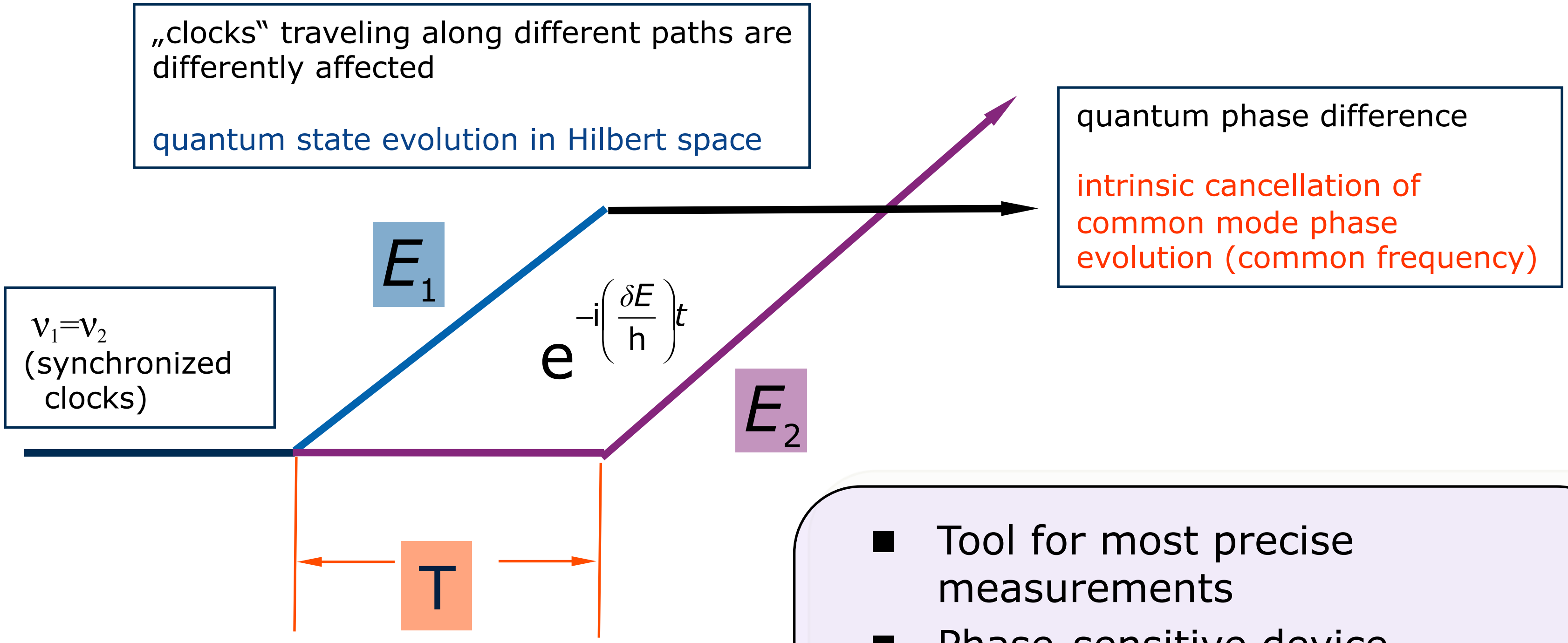
(2) Measuring the phase highly precise:
- highly stable, phase-locked EM-osciallters (RF-, THz-, optical)

(3) Calibrating oscillators:
- frequency comb





Atom Interferometer



„clocks“ traveling along different paths are differently affected

quantum state evolution in Hilbert space

quantum phase difference

intrinsic cancellation of common mode phase evolution (common frequency)

$\nu_1 = \nu_2$
(synchronized clocks)

- Tool for most precise measurements
- Phase-sensitive device
- Sensitivity scales with higher orders of T
- Intrinsic measurement of differential frequencies

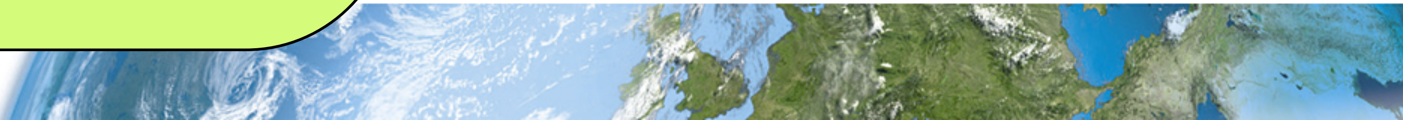
- Optimized for:
  - Long interrogation time T
  - Narrow atom velocity distribution
  - Maximized grav. potential differences
  - Minimized external disturbances (em-fields, accustic noise, seismic noise, thermal gradients)

Atom Interferometers in Space

- Highest sensitivity of atom interferometers can be obtained under conditions of weightlessness

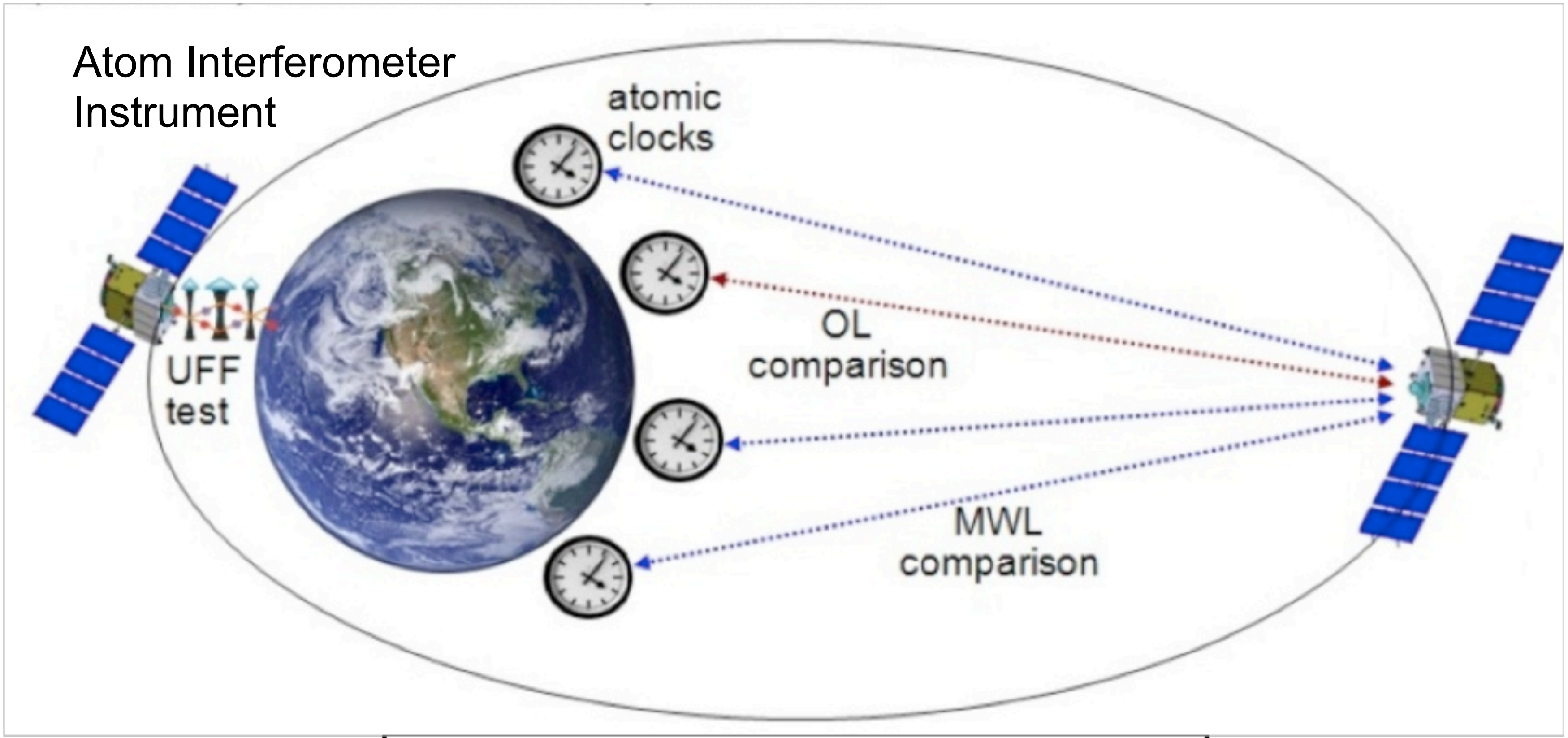
- Interrogation time T can be maximized (> 10 s)
- Sensitivity ($\delta\varphi$) is proportional to T^2 or T^3 (For comparison: $\delta\nu$ of atomic fountain clocks scales with T only.)
- Compensation of gravity allows to reduce atom temperature
- Reduces atom velocity (< 10 cm/s)
- Ultra-cold temperatures enable large atomic ensemble sizes (> 1 cm)
- Further improvement by using degenerated quantum gases (BECs) as sources

- Reduction of disturbances of different noise sources
- Dominant sources like seismicity and accustic noise can be nearly completely depressed under weightlessness

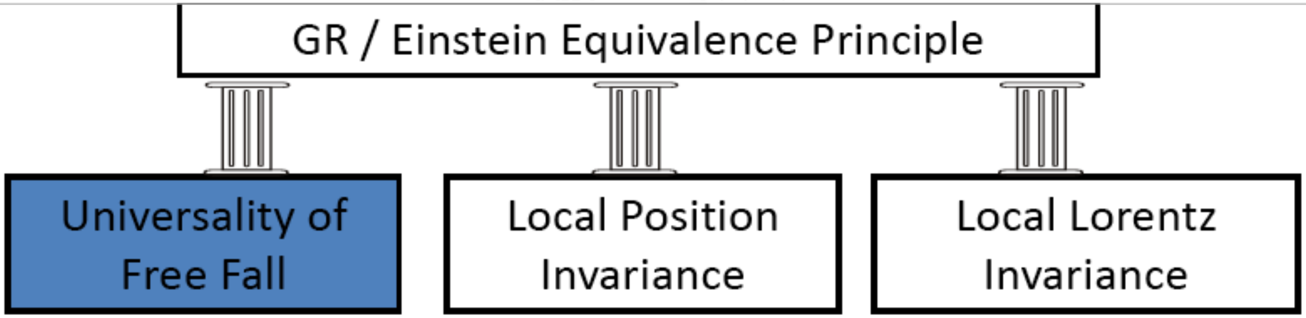


STE-QUEST (SpaceTime Explorer – Quantum Equivalence Space Test)

- Testing the foundations of General Relativity and measuring



Atom Interferometer Instrument



GR / Einstein Equivalence Principle

Universality of Free Fall

Local Position Invariance

Local Lorentz Invariance