National Physical Laboratory

# Optical Clocks
# for
# Fundamental Physics in Space

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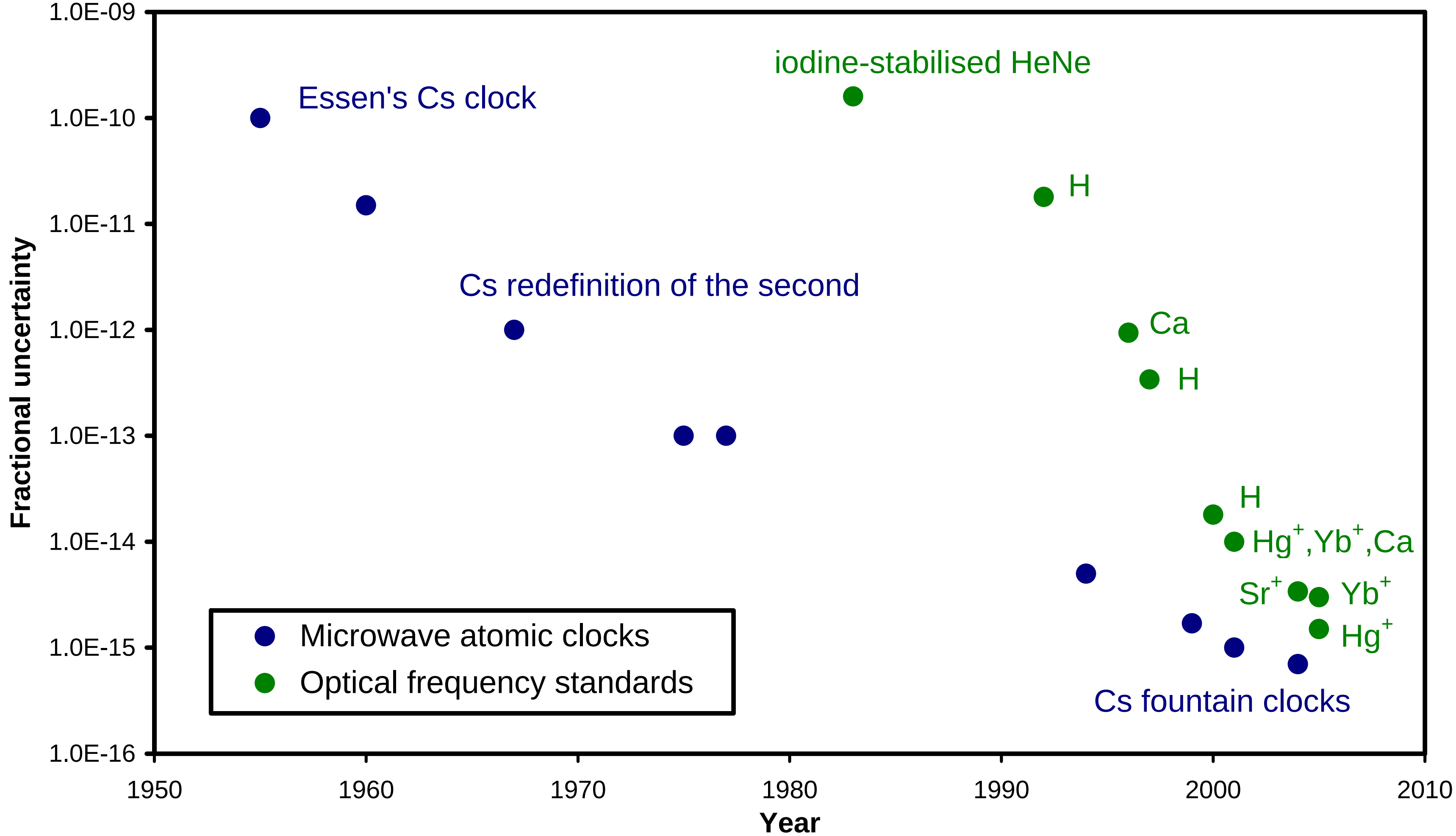
*GAUGE meeting, RAL, 14th November 2006*

# Recent improvements in optical frequency standards

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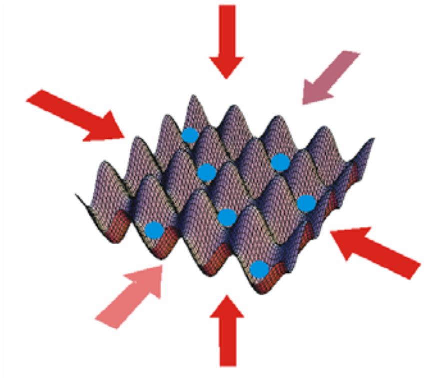
# Optical clocks

instability $\sigma \propto \frac{\Delta f}{f} \frac{1}{(S/N)}$

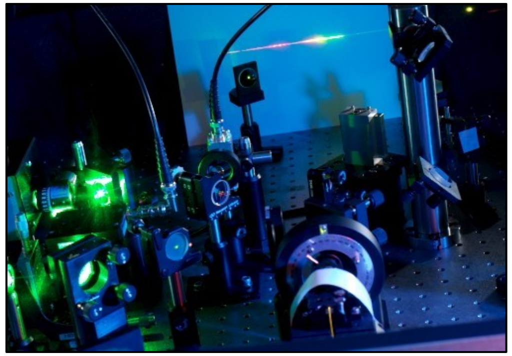
Oscillator
(Ultra-stable laser)

+



Reference
(narrow optical transition
in an atom or ion)

+



Counter
(Femtosecond comb)

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# ESA studies

**Optical frequency synthesizer for space-borne optical frequency metrology**

18 months (February 2006 – July 2007)

**Feasibility and applications of optical clocks as frequency and time references in ESA deep space stations**

12 months (July 2006 – June 2007)

**Absolute long-distance measurement with (sub)-micrometre accuracy for formation flight applications**

15 months (October 2006 – December 2007)

# Proposal for a Gravity Explorer Satellite Mission Using Optical Clocks

S. Schiller, A. Görlitz, J. Koelemeij, B. Roth, A. Nevsky, A. Wicht, *U. Düsseldorf*
G.Tino, N. Poli, R.E. Drullinger, *U. Firenze/LENS*
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R. Holzwarth, T. Hänsch, *MPQ Munich*
E. Rasel, W. Ertmer, *U. Hannover*
H. Dittus, C. Lämmerzahl, *ZARM Bremen*
A. Peters, *H.U. Berlin*
E. Samain, *Obs. Cote d'Azur*
L. Iorio *U. Bari,* I. Ciufolini, *U. Lecce*

*S.Schiller et al.*
*arxiv:gr-qc/0608081*

# Mission scope

## Explore gravity:

- Fundamental physics:
  - high precision tests of fundamental aspects of General Relativity
  - search for new physics
- Geophysics: gravity field and elevation mapping
  - clock comparison measures difference in *U*
  - map out *U* using movable clocks

## Time and frequency distribution on earth and in space ("master clock"):

- Terrestrial use of optical clocks requires a reference clock in a well-defined potential

  $\Delta U/U = 10^{-9}$ (corresponds to $\Delta h = 1$ cm) results in $\Delta\nu/\nu = 10^{-18}$
- Precision navigation in space
- Space VBLI

## Optical link between different clocks

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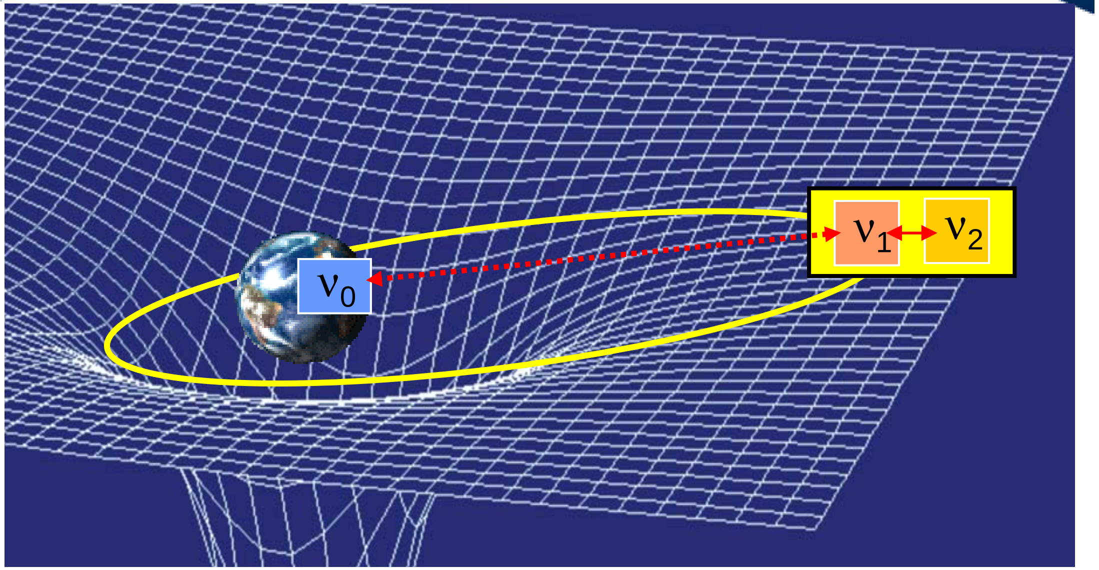
*Slide material courtesy of Stephan Schiller*

# Mission scenario

## Orbital phase I

Highly elliptic orbit, ~ 1 year duration

Test of Local Position Invariance and gravitational redshift

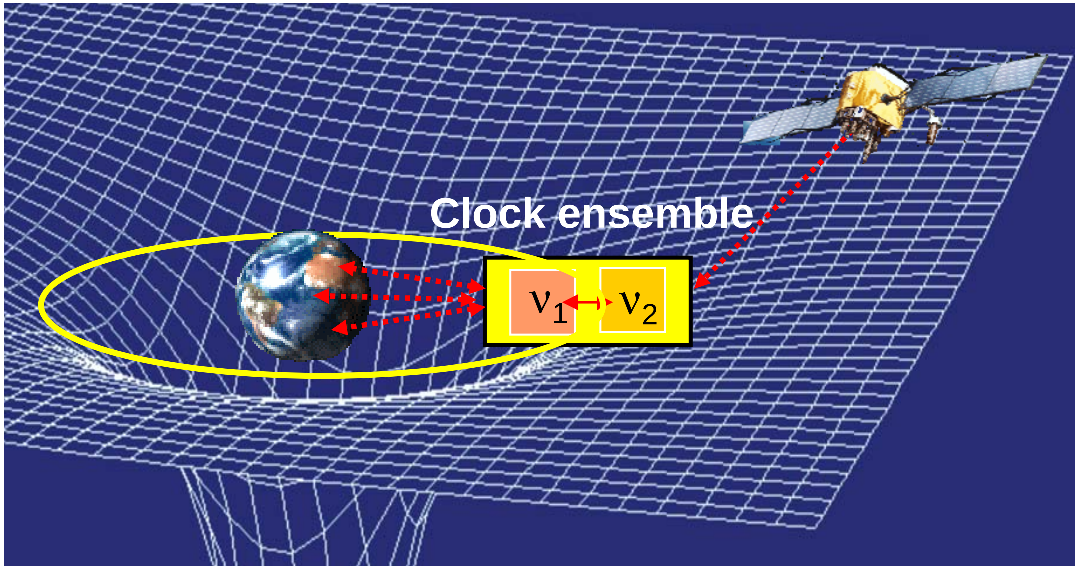



## Orbital phase II

Geostationary, several years duration

Master clock for earth and space users

Geophysics

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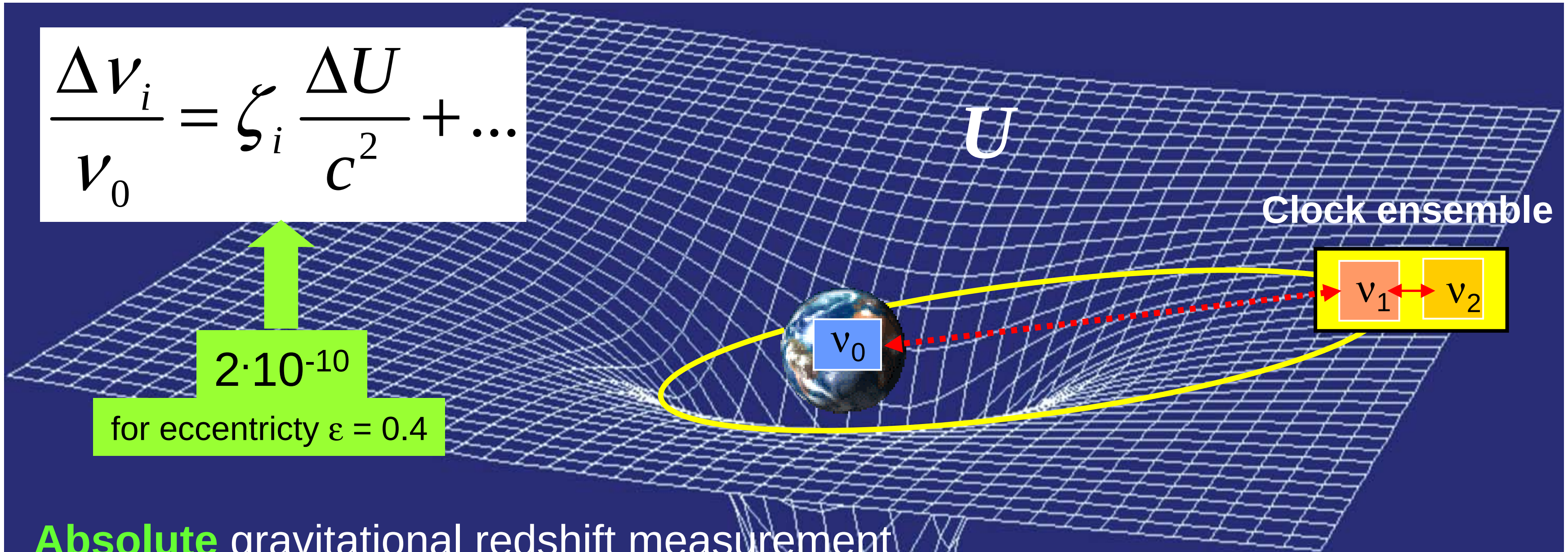
# Measurement of the gravitational redshift

$$\frac{\Delta\nu_i}{\nu_0} = \zeta_i \frac{\Delta U}{c^2} + \ldots$$




**Absolute** gravitational redshift measurement

- Test of higher-order relativistic corrections

*(Linet & Teyssandier 2002, Blanchet et al 2001, Ashby 1998)*

- Comparison with a ground clock *(via microwave/optical link)*
- Requires precise orbit determination (laser ranging)

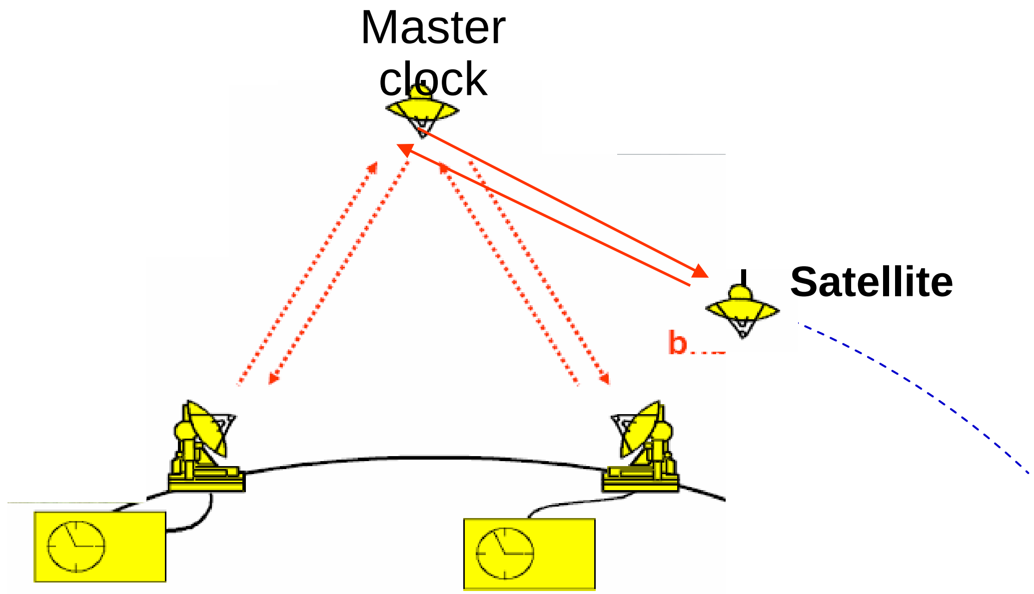
Gravitational redshift **universality** test: $\zeta_1 = \zeta_2$ ? (Local Position Invariance)

- Intercomparison of **dissimilar** on-board clocks

*Slide material courtesy of Stephan Schiller*

# Time distribution and clock comparisons

- Time distribution world-wide
- Comparison of distant clocks (common view)

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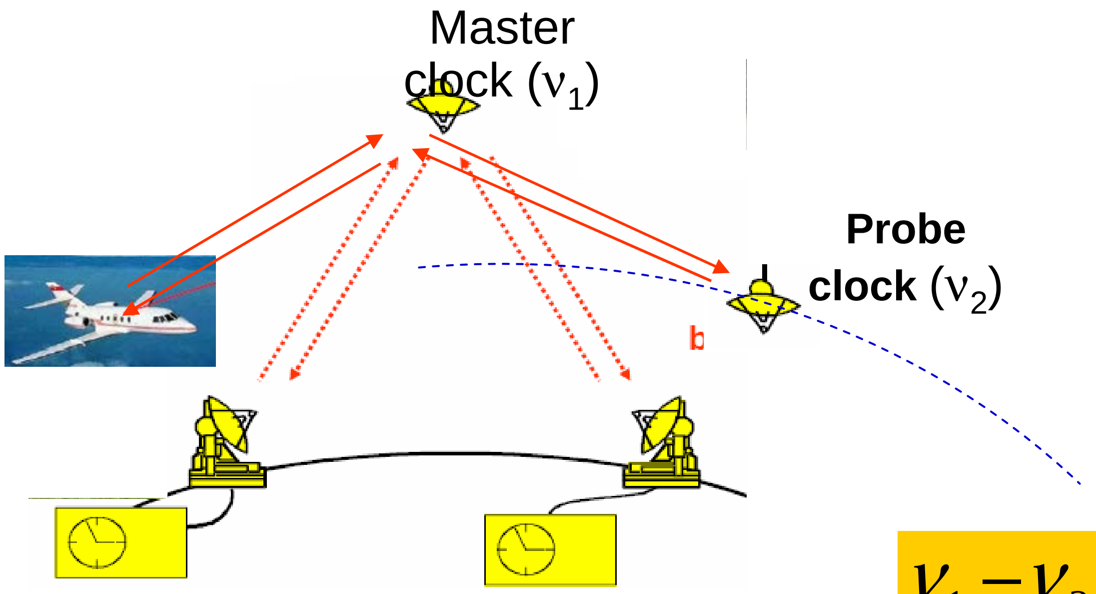
# Gravity (geopotential) measurements

Comparison between master and probe clock (via microwave optical link)

Yields information about gravitational potential




$$\frac{\nu_1 - \nu_2}{\nu} = \frac{U(r_1) - U(r_2)}{c^2}$$

*Slide material courtesy of Stephan Schiller*

# Is there scope to combine cold atom sensors and optical clocks in a mission to test fundamental physics?

What would be the orbit implications?

Are there things that either technology can do better than the other?

What peripheral objectives could add value in either case?

# Optical clock mission: Science goals

*Schiller et al., Proc. ESLAB (2005)*

| | Test | Current | | Improvement |
|---|---|---|---|---|
| Lorentz Invariance | Isotropy of $c$ | $4 \cdot 10^{-10}$ | [1] | x $10^4$ |
| | Isotropy of Coulomb interaction | $1 \cdot 10^{-15}$ | [1] | x $10^4$ |
| | Relativistic Doppler effect *(time dilation)* | $2 \cdot 10^{-7}$ | [2] | x $10^2$ |
| Position Invariance | Universality of Gravitational redshift ($m_e/m_p$) | $1 \cdot 10^{-3}$ | [3] | x $10^7$ |
| | Universality of Gravitational redshift ($\alpha$) | $2.5 \cdot 10^{-5}$ | [4] | x $10^5$ |
| General Relativity | Lense - Thirring effect | $3 \cdot 10^{-1}$ | [5] | x $10^2$ |
| | Absolute gravitational redshift | $1.4 \cdot 10^{-5}$ | [6] | x $10^4$ |
| | Perigee advance | $3 \cdot 10^{-3}$ | [7] | x 10 |
| | Newtonian potential | $10^{-11}$ | [8] | x 10 |

**Clocks:** **$1 \cdot 10^{-18}$ instability at $\tau$ = half orbit period (~ 7 h)**

**Time link:** **$1 \cdot 10^{-18}$ inaccuracy**


[1] *Antonini et al, Stanwix et al, Herrmann et al. (2005)*
[2] *Saathoff et al, PRL (2003)*
[3] *Rovera & Acef, (2001)*
[4] *Bauch & Weyers, PRD 65 081101 (2002)*
[5] *Ciufolini, CQG 17, 2369 (2000)*
[6] *Vessot et al PRL, (1980)*
[7] *Iorio et al., CQG 19, 4301 (2002)*
[8] *Iorio et al., PLA 298, 315 (2002)*


Slide from Stephan Schiller

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