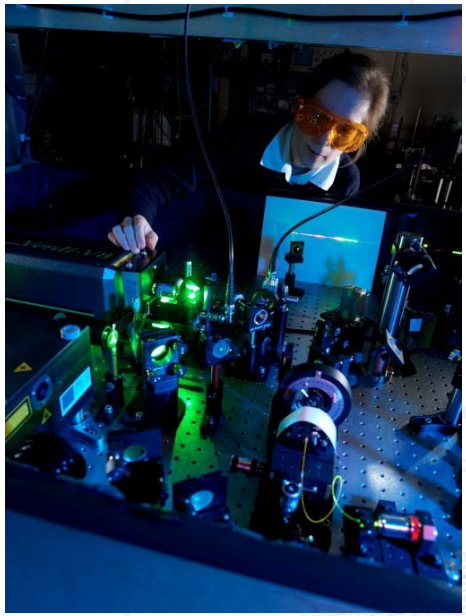
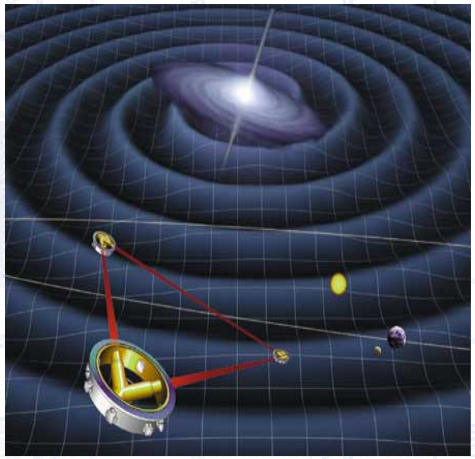
NPL
National Physical Laboratory

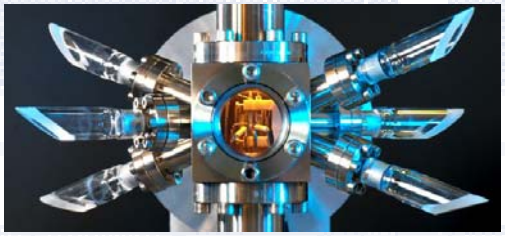
Optical Clocks and Frequency Metrology for Space



Femtosecond laser comb



LISA courtesy of ESA



Strontium ion trap

Hugh Klein

National Physical Laboratory, NPL, UK

hugh.klein@npl.co.uk

International Workshop Washington DC, 22-24th May 2006

From Quantum to Cosmos: Fundamental Physics Research in Space

Optical Frequencies for Space Science

- Optical clocks and frequency metrology
- Example: Sr^+ 674 nm trapped ion standard at NPL
- Space applications
- European Space Agency (ESA) studies
- Optical Frequency Comb for Space (OFCS) Workshop 2nd - 3rd October 2006 at NPL

Hugh A Klein and David JE Knight,

"A study of ultra-stable optical clocks, frequency sources and standards for space applications"

ESTEC contract 13290/98/NL/MV October 1999

Optical clocks offer better stability and potential accuracy than microwave clocks

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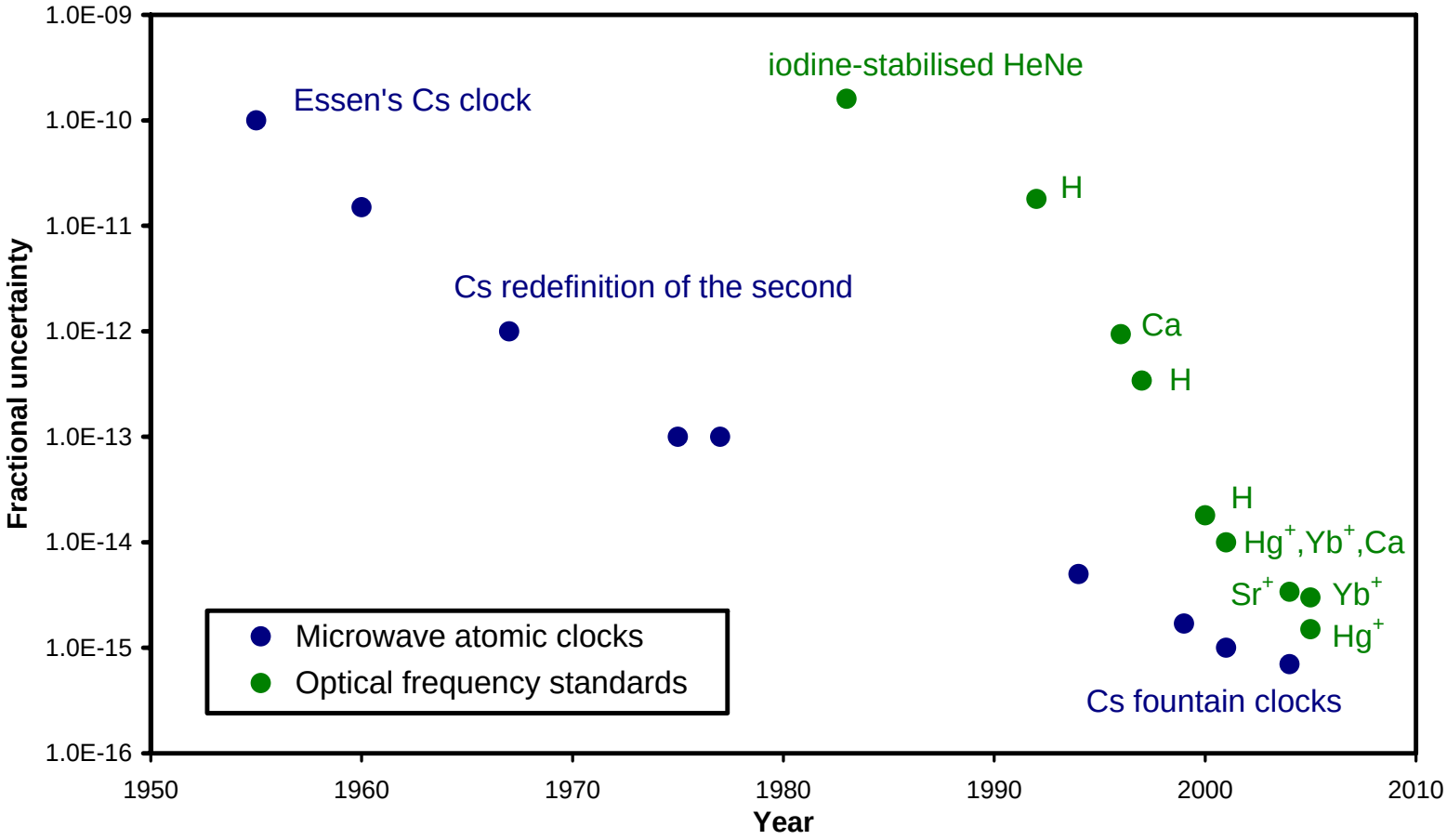
Optical frequency standards



Optical clocks offer better stability and potential accuracy than microwave clocks

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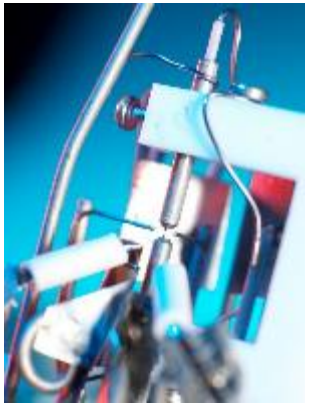
Optical clocks

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

- **Based on forbidden optical transitions in atoms or ions**
- **Optical frequencies are 10^5 times higher than microwave**
- **Q-factor ~10^{15} (or even higher)** Diddams et al Science 293 825 (2001)



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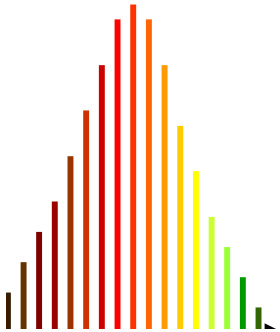

Reference - Atoms or Trapped Ion(s)

Oscillator - Ultra-stable Laser

Counter - Femtosecond comb

Optical frequency standards with high Q ~10^{15}

Trapped ion based standards (Sr^+, Hg^+, In^+, Ca^+, Al^+)

(NPL, NRC, NIST, PTB, MPQ Innsbruck, CRL)

- No 1st-order Doppler shift; Minimum 2nd-order Doppler shift
- Field perturbations minimised at trap centre and background collision rate low
- Long interaction times; electron shelving technique (quantum jumps) - high detection efficiency

Atom based standards (H,Mg,Ca, Sr,Yb,Ag)

(MPQ, Hannover, PTB, NIST, JILA, SYRTE, Tokyo, KRISS)

- High signal to noise with many atoms
- Optical Lattices need “magic wavelength” trapping field to null ac stark shifts

Ultimate stabilities and accuracies beyond a part in 10^{17} are projected

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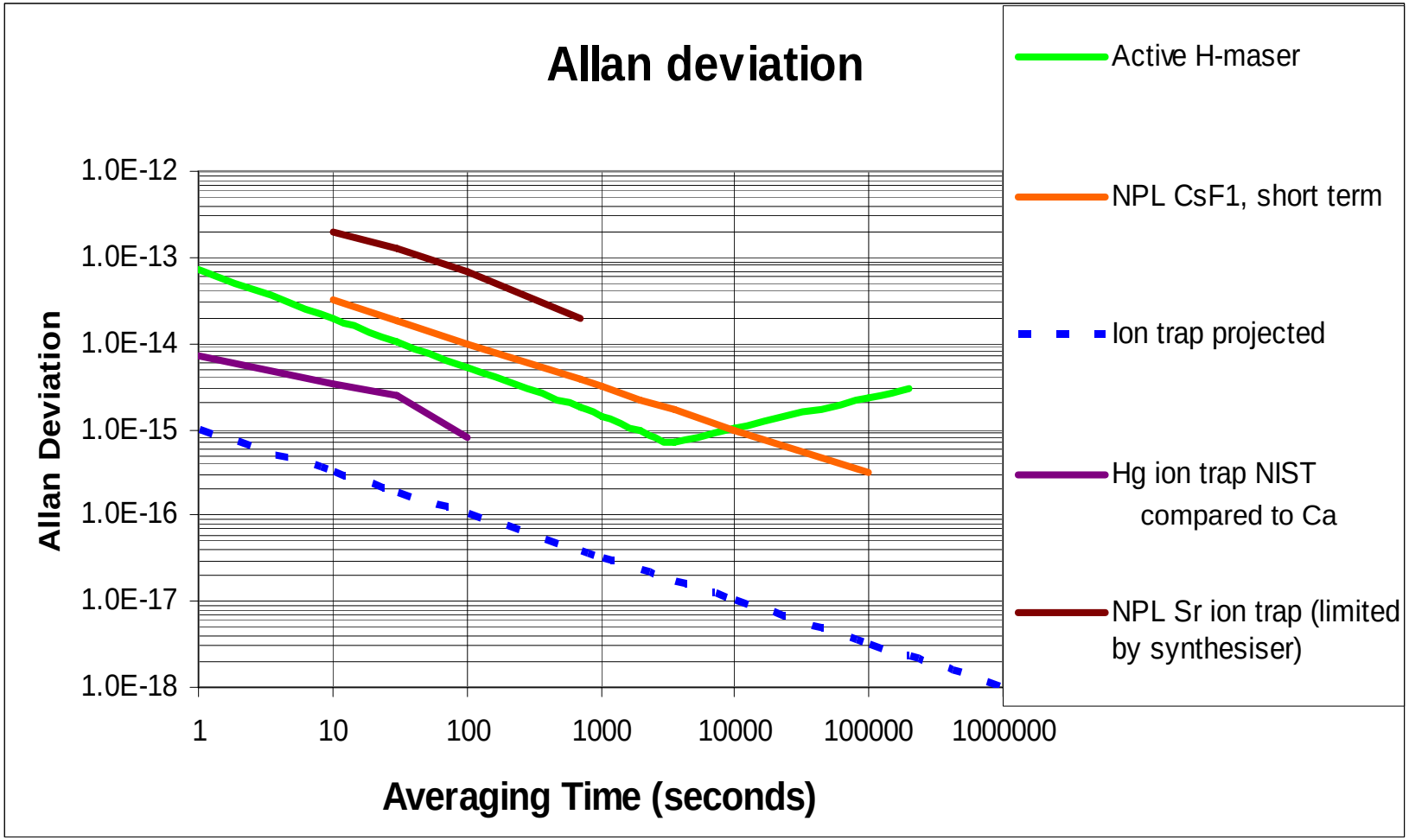
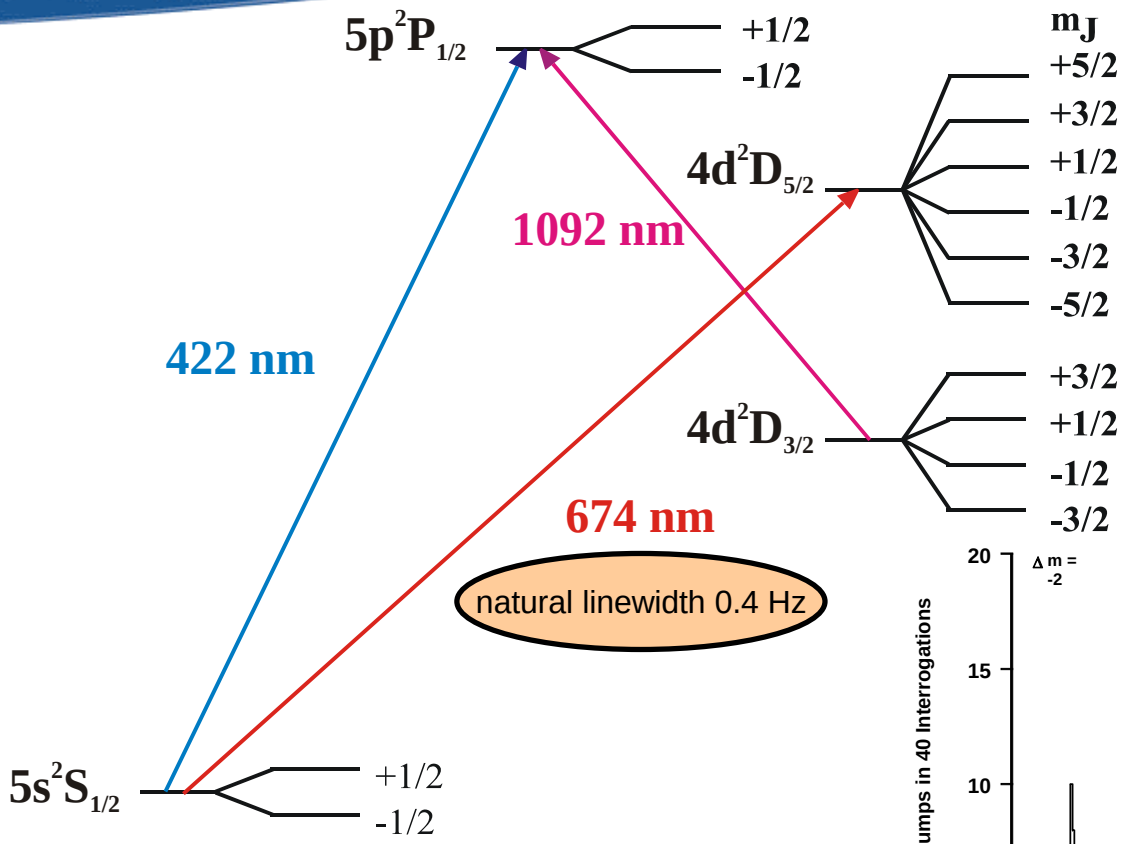
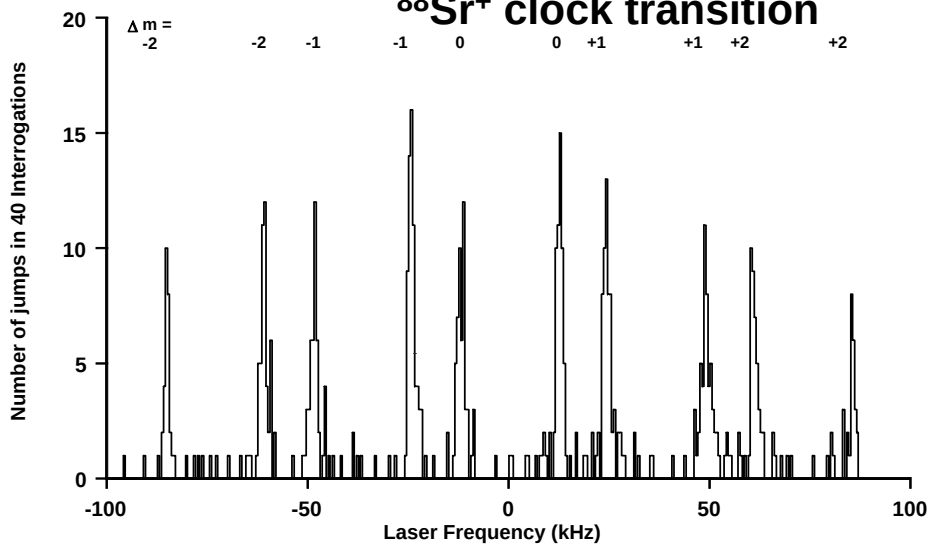
Stability


Allan deviation
Allan Deviation
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
1
10
100
1000
10000
100000
1000000
Averaging Time (seconds)
Active H-maser
NPL CsF1, short term
Ion trap projected
Hg ion trap NIST compared to Ca
NPL Sr ion trap (limited by synthesiser)

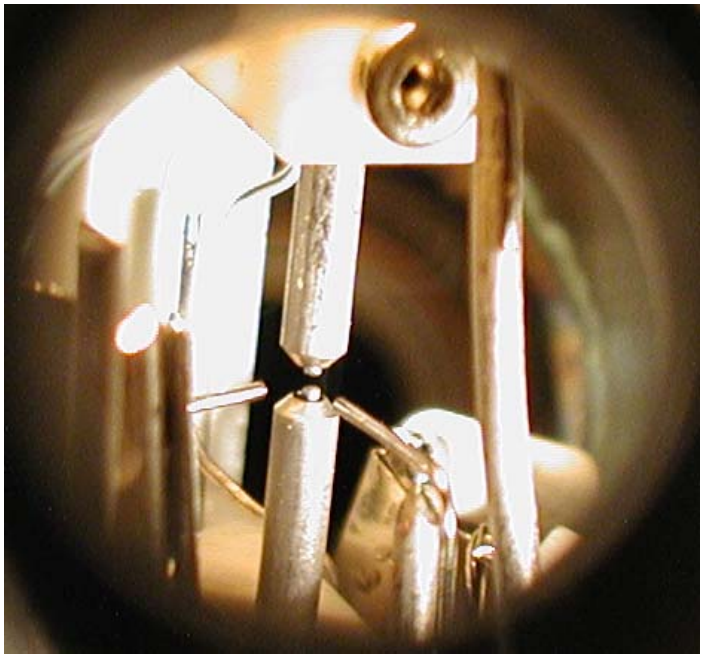
$^{88}Sr^{+}$ term scheme with 674nm "optical clock" transition

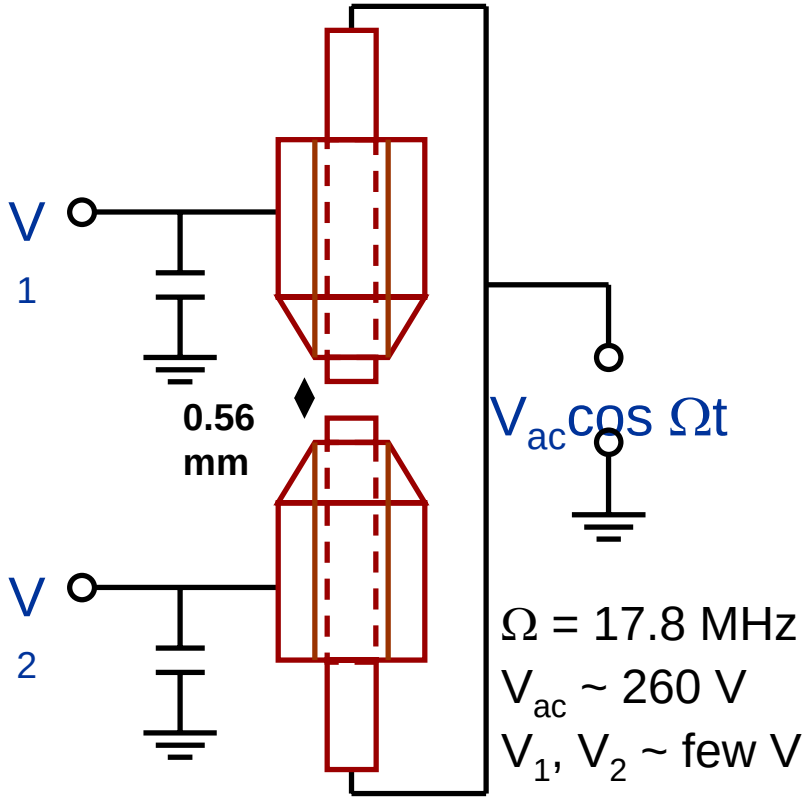


Zeeman structure of the $^{88}Sr^{+}$ clock transition

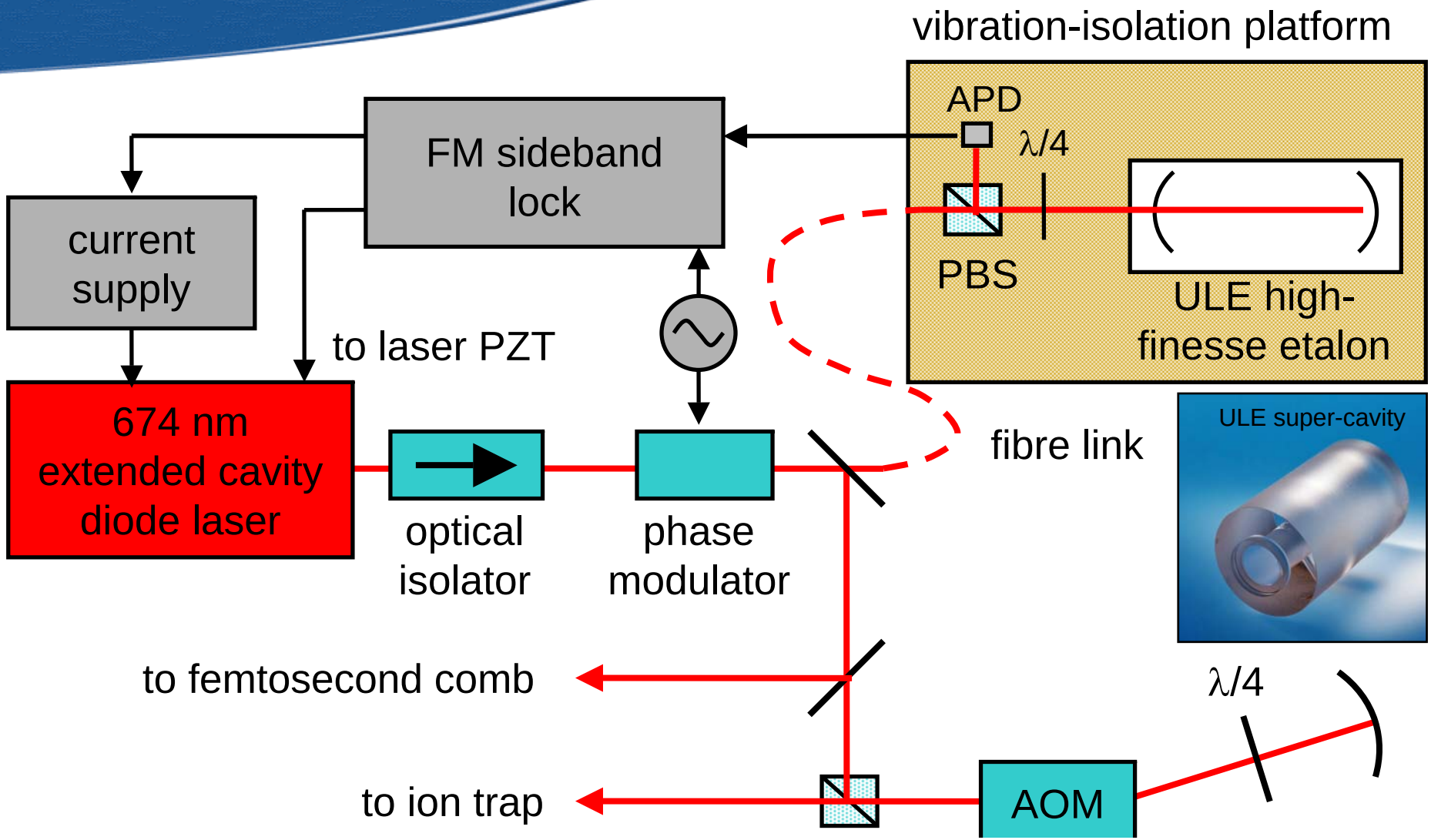


Strontium endcap trap





Diode laser system
674 nm probe



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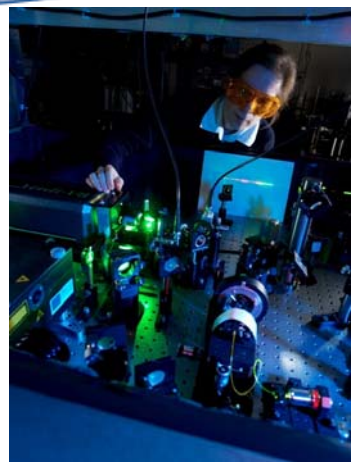
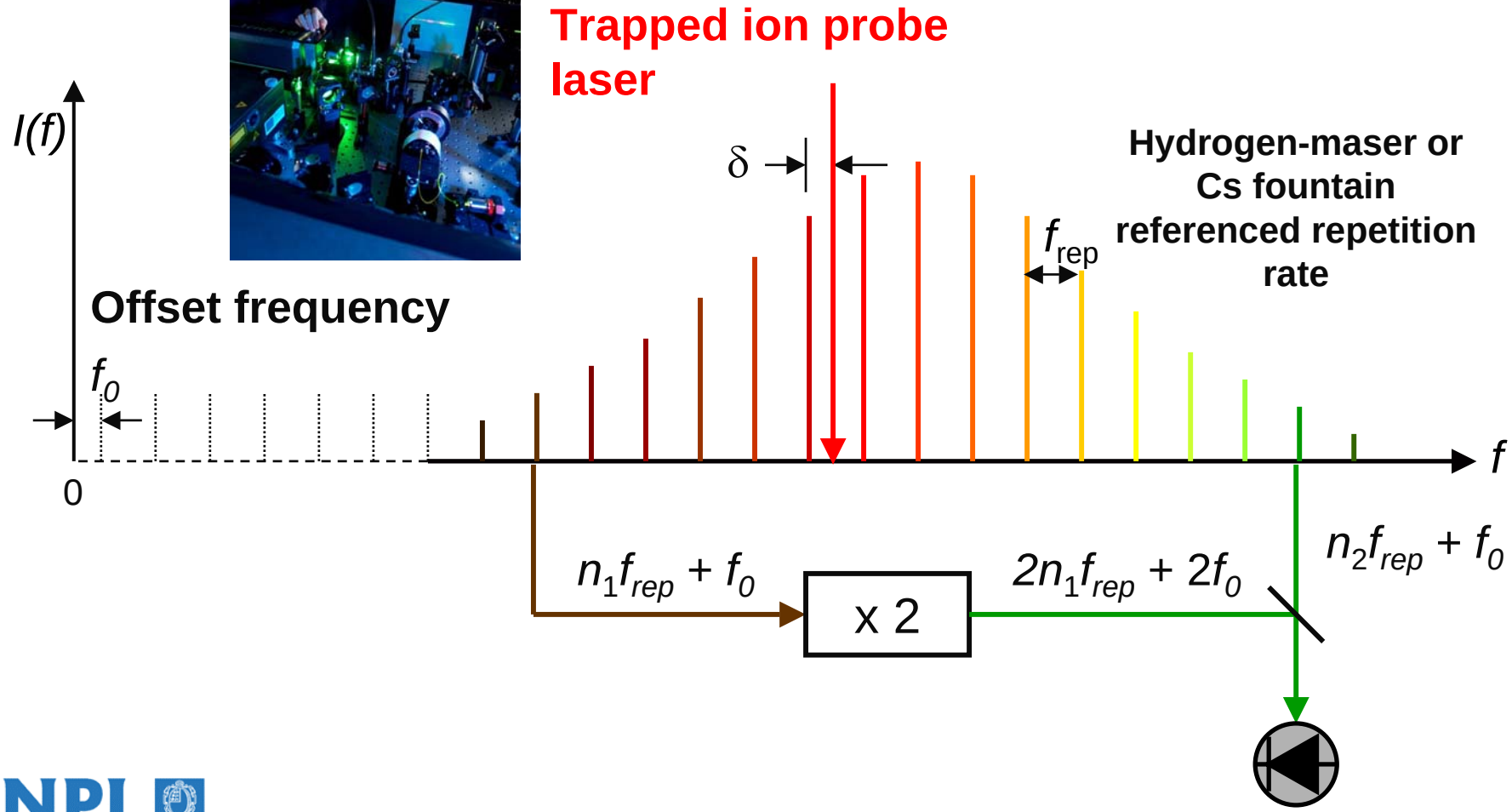
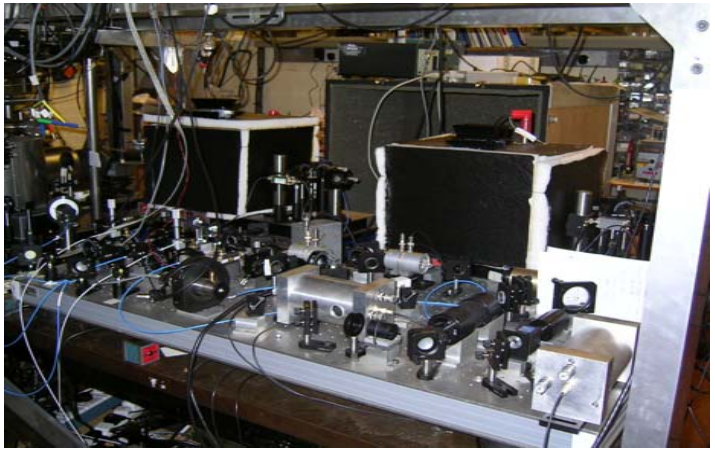
Self-referenced optical frequency comb

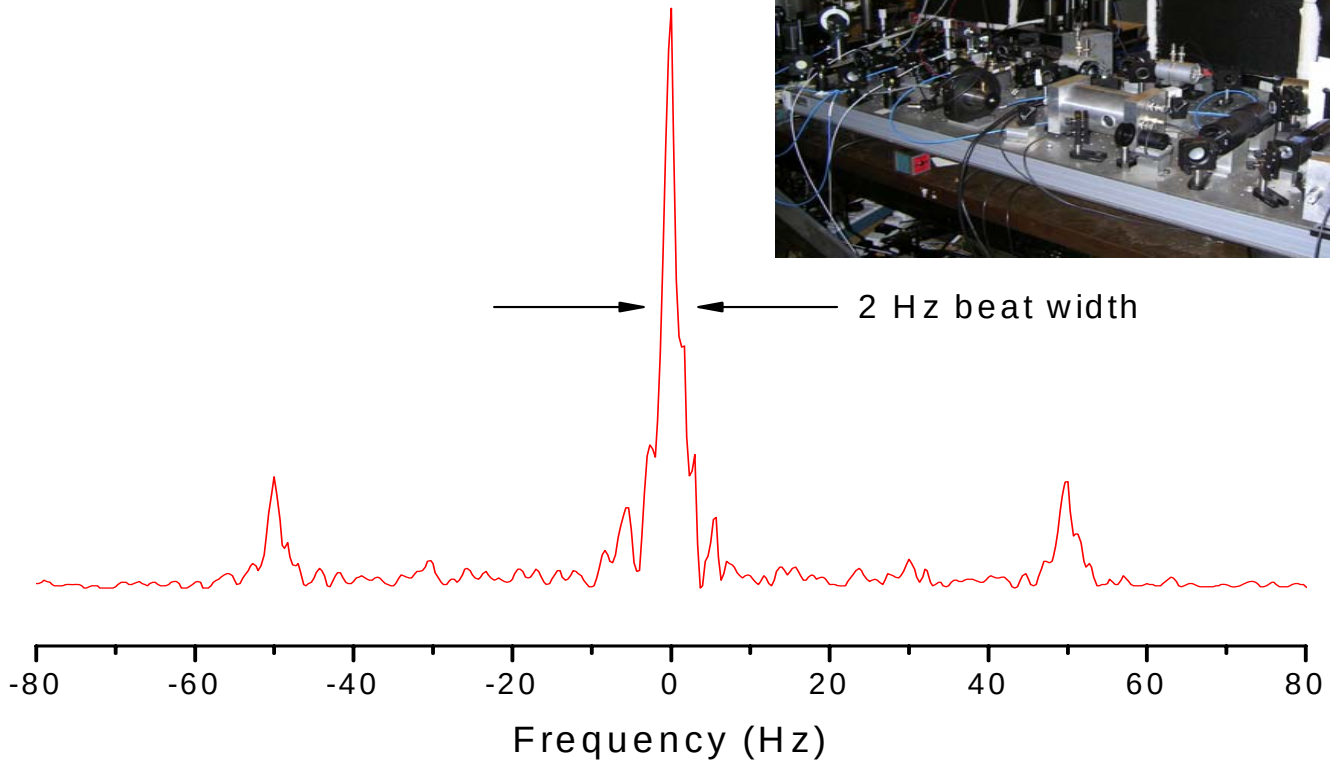
$$f_{\text{probe}} = m\, f_{rep} \pm f_0 \pm \delta$$





Diode Laser linewidth of 1.5 Hz demonstrated at NPL





Beat frequency between two laser diodes at 674 nm, with a 3 s averaging time

Trapped $^{88}Sr^{+}$ ion optical clocks recent results at NPL

Margolis et al Science 306 pp 1355-1358 (2004)

- **Measured absolute frequency of**
  f_{Sr} = 444 779 044 095 484.6 (1.5) Hz
- **Relative standard uncertainty ~ 3.4 × 10^{-15}**
  Within a factor of four of the NPL caesium fountain standard
- **Has been put forward as a secondary representation of the second**
- **1.5 Hz wide probe laser demonstrated.**

Our aim: $^{88}Sr^{+}$ optical frequency standard with stability and reproducibility exceeding that of the caesium fountain primary frequency standard

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Space applications of optical clocks

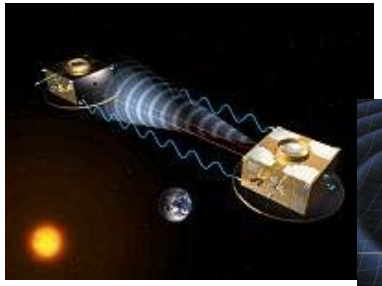
- **Tests of stability of fundamental constants**
- **Tests of Special and General relativity**
- **Gravity wave detection**
- **Star and planetary survey using very deep baseline interferometry**

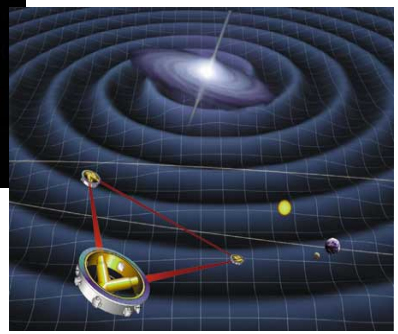
Proceeding of the 1st ESA International Workshop on Optical Clocks 8-10 June 2005 Noordwijk

"Cosmic Vision" – Space science for Europe 2015-2025

http://www.esa.int/esapub/br/br247/br247.pdf

Space missions and accurate position measurement

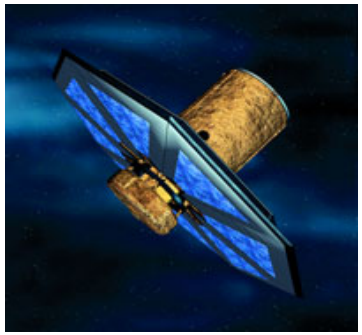




Pictures courtesy of ESA

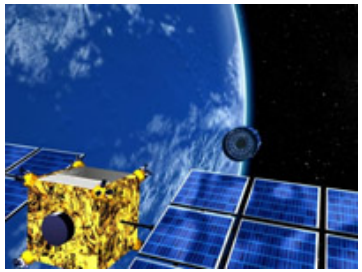
•LISA Pathfinder and LISA

Conversion of differential distance measurement information to optical frequency shift



•DARWIN

Satellite formation precision monitoring down to micron level over 100 - 200 m



•XEUS

X-ray mirror/detector satellite pair in formation at 50 m separation

Proposed mission using optical clocks:

Stephan Schiller et al. “Precision tests of general relativity and of the equivalence principal using ultra-stable optical clocks: a mission proposal” Proc 39th ESLAB Symposium Noordwijk 19-21 April 2005.

- **Suggests very stringent multiple tests of both relativistic theory (special and general) and the stability of fundamental constants**
- **Will require lasers that are both ultra-narrow (linewidth below one Hz), and very stable**
- **Highly eccentric orbit and drag free operation**

Potential for up to four orders of magnitude improvement over present tests

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 (α)	$2.5 \cdot 10^{-5}$ [4]	x 10^5
	Lense - Thirring effect	$3 \cdot 10^{-1}$ [5]	x 10^2
General Relativity	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 τ = 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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Developments in optical clock components

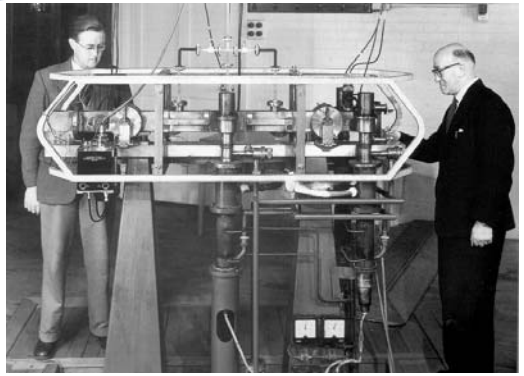
GROUND STATIONS

- Need transportable systems
- Reduced size

SPACE

- Size and weight reduced
- Power requirements reduced
- All components space qualified:
  - Radiation tolerant or shielded
  - Must survive launch!

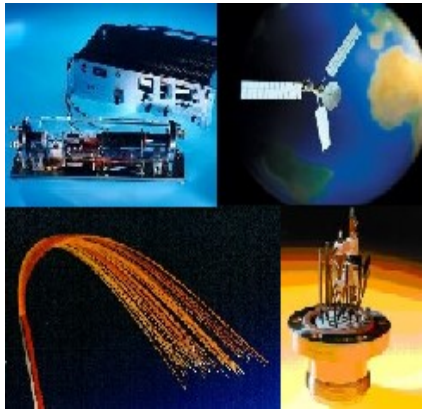
Realisation of SI unit of Time optical clocks in space



- **Optical redefinition of the second**
- **The ultimate clocks for realising the second may have to be in space:**
  - **to reduce fluctuating geoid related gravitational red shifts.**
  - **issues at 3 x10^{17} level**

Daniel Kleppner, March 2006 Physics Today "Time Too Good to Be True".

- **Hydrogen or a Hydrogenic system offers attractions as a calculable standard**



A optical redefinition of the second is likely.

Time keeping beyond a part in 10^{16} may require clocks in space

Examples of NPL led ESA studies

- **ESA study started February 2006:**

Optical Frequency Synthesizer for Space-Borne Optical Frequency Metrology

Marc Fischer Patrick Gill, Theodor Hänsch, Ronald Holzwarth, Hugh Klein, Volker Klein, Steve Lecomte, Helen Margolis,Gaetano Mileti and Stefan Schiller

- **ESA study starting July 2006:**

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

Patrick Gill, Hugh Klein, Helen Margolis, Stephen Webster, Fritz Riehle, Ekkehard Peik, Harald Schnatz, Uwe Sterr, Wolfgang Schaeffer, Gerhard Hejc, Alexander Pawlitski,
Jens Hammesfahr, Johann Furthner & Alexandre Moudrak

International Workshop at NPL

2nd - 3rd October 2006

Optical Frequency Combs for Space (OFCS)

National Physical Laboratory

Teddington, Middlesex TW11 0LW, UK

- **International workshop to be hosted by NPL and consortium partners**
- **Seeking input from the wider scientific and technological communities**
- **Examine potential space applications of new frequency metrology capability**
- **Both ground- and space-based, applications covered.**

Invited Speakers already confirmed:

Christophe Salomon (ENS, Paris), Massimo Inguscio (LENS, Firenze), Lute Maleki (JPL, Pasadena), Scott Diddams (NIST Boulder), Jun Ye (JILA Boulder), Franz Kaertner (MIT, Cambridge) Harry Ward (Glasgow), Wolfgang Ertmer (Hannover) and Fritz Riehle (PTB, Braunschweig)

With the support of:

People

Hertz-Level Measurement of the Optical Frequency in a single $^{88}Sr^{+}$ Ion

Stephen Lea, Guilong Huang, Krzysztof Szymaniec Patrick Gill, Geoff Barwood, Helen Margolis and Hugh Klein

Time Frequency and the Metre Group,

National Physical Laboratory (NPL) UK

This work was partially funded by ESA and the UK NMSD Quantum Metrology and Length Programmes.

NPL