Optical Clocks and Frequency Metrology for Space

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From Quantum to Cosmos: Fundamental Physics Research in Space
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
Optical clocks and frequency metrology for space

Optical frequency standards

Optical clocks offer better stability and potential accuracy than microwave clocks
Optical clocks

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

\[
\text{instability} \quad \sigma \propto \frac{\Delta f}{f} \frac{1}{(S/N)}
\]

Reference - Atoms or Trapped Ion(s) + Oscillator - Ultra-stable Laser + Counter - Femtosecond comb
Optical frequency standards with high Q \( \sim 10^{15} \)

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
Stability

Allan deviation

- Active H-maser
- NPL CsF1, short term
- Ion trap projected
- Hg ion trap NIST compared to Ca
- NPL Sr ion trap (limited by synthesiser)

Averaging Time (seconds)

Allan Deviation

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\textbf{88Sr\textsuperscript{+} term scheme with 674nm “optical clock” transition}

\begin{itemize}
  \item \textit{5s^2S_{1/2}}
  \item \textit{5p^2P_{1/2}}
  \item \textit{4d^2D_{3/2}}
  \item \textit{4d^2D_{5/2}}
  \item 1092 nm
  \item 674 nm
  \item 422 nm
\end{itemize}

- \textbf{Zeeman structure of the 88Sr\textsuperscript{+} clock transition}

- \textbf{Natural linewidth 0.4 Hz}

- \textbf{Number of jumps in 40 interrogations vs. Laser Frequency (kHz)}

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Strontium endcap trap

V_1, V_2 \sim \text{few V}

V_{ac} \sim 260 \text{ V}

\Omega = 17.8 \text{ MHz}

V_{ac} \cos \Omega t

0.56 \text{ mm}

\Omega = 17.8 \text{ MHz}

V_{ac} \sim 260 \text{ V}

V_1, V_2 \sim \text{few V}
Diode laser system
674 nm probe

- Current supply
- FM sideband lock
- 674 nm extended cavity diode laser
- Optical isolator
- Phase modulator
- To laser PZT
- To femtosecond comb
- To ion trap
- Fiber link
- AOM
- ULE super-cavity
- APD
- λ/4 PBS
- ULE high-finesse etalon
- Vibration-isolation platform

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Self-referenced optical frequency comb

\[ f_{\text{probe}} = m f_{\text{rep}} \pm f_0 \pm \delta \]

Trapped ion probe laser

Hydrogen-maser or Cs fountain referenced repetition rate

\[ I(f) \]

Offset frequency

\[ f_0 \]

\[ 0 \]

\[ n_1 f_{\text{rep}} + f_0 \]

\[ x 2 \]

\[ 2 n_1 f_{\text{rep}} + 2 f_0 \]

\[ n_2 f_{\text{rep}} + f_0 \]
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

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


- Measured absolute frequency of
  \[ f_{\text{Sr}} = 444\,779\,044\,095\,484.6\, (1.5) \text{ Hz} \]
- Relative standard uncertainty \( \sim 3.4 \times 10^{-15} \)
  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: $^{88}\text{Sr}^+$ optical frequency standard with stability and reproducibility exceeding that of the caesium fountain primary frequency standard
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
• **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

**Pictures courtesy of ESA**
Proposed mission using optical clocks:


- 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)*

<table>
<thead>
<tr>
<th>Test</th>
<th>Current</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropy of $c$</td>
<td>$4 \cdot 10^{-10}$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Isotropy of Coulomb interaction</td>
<td>$1 \cdot 10^{-15}$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Relativistic Doppler effect <em>(time dilation)</em></td>
<td>$2 \cdot 10^{-7}$</td>
<td>$\times 10^2$</td>
</tr>
<tr>
<td>Universality of Gravitational redshift $(m_e/m_p)$</td>
<td>$1 \cdot 10^{-3}$</td>
<td>$\times 10^7$</td>
</tr>
<tr>
<td>Universality of Gravitational redshift $(\alpha)$</td>
<td>$2.5 \cdot 10^{-5}$</td>
<td>$\times 10^6$</td>
</tr>
<tr>
<td>Lense - Thirring effect</td>
<td>$3 \cdot 10^{-1}$</td>
<td>$\times 10^2$</td>
</tr>
<tr>
<td>Absolute gravitational redshift</td>
<td>$1.4 \cdot 10^{-5}$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Perigee advance</td>
<td>$3 \cdot 10^{-3}$</td>
<td>$\times 10$</td>
</tr>
<tr>
<td>Newtonian potential</td>
<td>$10^{-11}$</td>
<td>$\times 10$</td>
</tr>
</tbody>
</table>

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

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

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[8] Iono et al., PLA 293, 315 (2002)
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 $3 \times 10^{17}$ 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

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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 Hambesfahr, Johann Furthner & Alexandre Moudrak

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International Workshop at NPL

Optical Frequency Combs for Space (OFCS)
National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

2nd - 3rd October 2006

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:

Hugh Klein: Optical Clocks and Frequency Metrology for Space
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

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