Optical Frequency Standards

What are they and what are they good for?

E.A. ALDEN
Leanhardt Lab
Department of Physics, University of Michigan

This talk

- Define Optical Frequency Standards
- Compare Frequency Standards
- Describe structure of an atomic clock
Units

Time

Current standard:

- Symmetric Xenon 54 core
- Hyperfine splitting of the 6s electron level
- $f = 9,192,631,770 \text{ Hz}$

Future standard?

Mass

Current standard:

Future standard?

Avogadro Project


Frequency Comparison of Two High-Accuracy $^{27}$Al Optical Clocks

C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, and T. Rosenband

AMO Journal Club

02/01/2013

www-personal.umich.edu/~ealden
\( \sigma(\tau) = \langle \frac{\Delta \nu}{\nu} \rangle_{\tau} \)

**THE ELECTROMAGNETIC SPECTRUM**

- **Penetrates Earth Atmosphere?**
  - Y: Yes, N: No

- **Wavelength (meters)**
  - Radio: \( 10^3 \)
  - Microwave: \( 10^{-2} \)
  - Infrared: \( 10^{-5} \)
  - Visible: \( 5 \times 10^{-6} \)
  - Ultraviolet: \( 10^{-8} \)
  - X-ray: \( 10^{-10} \)
  - Gamma Ray: \( 10^{-12} \)

- **Frequency (Hz)**
  - \( 10^4 \) to \( 10^{29} \)

- **Temperature of bodies emitting the wavelength (K)**
  - 1 K, 100 K, 10,000 K, 10 Million K

- **About the size of...**
  - Buildings, Humans, Honey Bee, Pinpoint, Protozoans, Molecules, Atoms, Atomic Nuclei
What is a clock?
What is a good clock?

- Doesn’t lose many seconds?
Why is an atom a good clock?

- Assumption:
  - atoms are equivalent
  - $\alpha$ is constant
  - light has constrained properties

www.laserfocusworld.com
Accessed 2013
• Fractional frequency uncertainty

Theory Limit -

$$\sigma_\nu = \frac{\Delta \nu}{\nu} \sqrt{\frac{T}{\tau N}}$$

$\Delta \nu$ is the linewidth of the system
$\nu$ is the frequency of the sampling probe
$T$ is the duty cycle of the experiment
$\tau$ is the total experiment time
$N$ is the sample size per duty cycle
Choose Transition Wisely

“forbiddenness”

natural linewidth $\Delta \nu$
Optical Clock Level Structure

\[ ^3P_0 \quad \quad \quad \quad ^1S_0 \]
\[ ^{199}\text{Hg} \quad I=\frac{1}{2} \]

Diagram:

- \( ^3P_1 \) to \( ^3P_0 \) with \( \tau=115(6)\text{ns} \) and \( \gamma=1.3 \text{ MHz} \)
- \( ^1S_0 \)

\[ \tau=1.51s^2 \]
\[ \gamma=0.1 \text{ Hz} \]

References:

Even Narrower Transition?

\[ ^3P_1 \rightarrow ^3P_0 \rightarrow ^1S_0 \]

M1

E1
Make $\Delta v$ small

$$\sigma(\tau) = \left\langle \frac{\Delta v}{v} \right\rangle$$

- Narrow linewidth transition
- Narrow linewidth laser
- Large number of addressed resonators
- Long coherence times
- Long measurement times
- Laser excitation geometry (transit broadening)
- So on….

\[\begin{array}{|c|c|c|}
\hline
\text{Physical Effect} & \text{Bias} & \text{Type B Uncertainty} \\
\hline
\text{Gravitational Red shift} & +179.95 & 0.03 \\
\text{Second-Order Zeeman} & +180.91 & 0.025 \\
\text{Blackbody} & -22.84 & 0.28 \\
\text{Microwave Amplitude Shift} & -0.05 & 0.15 \\
\text{Spin Exchange (low density)} & (-0.32)^a & (0.17)^b \\
\text{AC Zeeman (beaters)} & 0.05 & 0.05 \\
\text{Cavity Polling} & 0.02 & 0.02 \\
\text{Rabi Polling} & 10^{-4} & 10^{-4} \\
\text{Ramsey Polling} & 10^{-4} & 10^{-4} \\
\text{Magnetron Transitions} & 0.02 & 0.02 \\
\text{Fluorescence Light Shift} & 10^{-4} & 10^{-7} \\
\text{Cavity Phase (distributed)} & 0.02 & 0.02 \\
\text{Second-Order Doppler} & 0.02 & 0.02 \\
\text{DC Stark Effect} & 0.02 & 0.02 \\
\text{Background Gas Collisions} & 10^{-3} & 10^{-3} \\
\text{Bloch-Siegert} & 10^{-4} & 10^{-4} \\
\text{RF Spectral purity} & 3\times10^{-4} & 3\times10^{-5} \\
\text{Integrator offset} & 0 & 0.01 \\
\hline
\end{array}\]

*For information purposes only. Not used in total, see section 1-B for details.

Table 1 – The list of known frequency biases for NIST-F1. This includes both the magnitude of the biases as well as the uncertainty of each individual contribution to the final uncertainty.
<table>
<thead>
<tr>
<th></th>
<th>Ion Clock</th>
<th>Lattice Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al(^+) [7, 1]</td>
<td>Sr [9]</td>
</tr>
<tr>
<td>(\nu) [Hz]</td>
<td>1.1 (\times) 10(^{15})</td>
<td>4.3 (\times) 10(^{14})</td>
</tr>
<tr>
<td>(\delta\nu) [Hz]</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>(N) [#]</td>
<td>1</td>
<td>4000</td>
</tr>
<tr>
<td>(T) [s]</td>
<td>0.150</td>
<td>0.08</td>
</tr>
<tr>
<td>(\sigma_{\nu}) [1/\sqrt{\tau}]</td>
<td>3.7 (\times) 10(^{-16})</td>
<td>2 (\times) 10(^{-15})</td>
</tr>
<tr>
<td>System</td>
<td>Instability $\sigma_\nu [\frac{1}{\sqrt{\tau}}]$</td>
<td>Uncertainty $\sigma_\nu$</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Al$^+$ [7, 1]</td>
<td>$3.7 \times 10^{-16}$</td>
<td>$8.6 \times 10^{-18}$</td>
</tr>
<tr>
<td>Yb$^+$ [8]</td>
<td>$2 \times 10^{-15}$</td>
<td>$7.1 \times 10^{-17}$</td>
</tr>
<tr>
<td>Sr [9]</td>
<td>$2 \times 10^{-15}$</td>
<td>$1 \times 10^{-16}$</td>
</tr>
<tr>
<td>Rb [10]</td>
<td>$7 \times 10^{-16}$</td>
<td>$3.7 \times 10^{-16}$</td>
</tr>
<tr>
<td>Hg$^+$ [11]</td>
<td>$9 \times 10^{-15}$</td>
<td>$7 \times 10^{-15}$</td>
</tr>
<tr>
<td>Hg$_{1\gamma}$ [5]</td>
<td>$5.7 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td>Yb [12]</td>
<td>$5.1 \times 10^{-13}$</td>
<td>$1.4 \times 10^{-15}$</td>
</tr>
<tr>
<td>Cs [13]</td>
<td>$5.8 \times 10^{-13}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Ag$_{2\gamma}$ [14]</td>
<td>$10^{-13\ast}$</td>
<td></td>
</tr>
<tr>
<td>Quartz [15]</td>
<td>$10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>Chronometer</td>
<td>$10^{0.5}$</td>
<td></td>
</tr>
</tbody>
</table>
Measurement of FFU

- Frequency comb
- Another clock
And the point of all this…

when ↔ where

Recalculating
Geoid

phys.org Accessed 2013
OFS: What is it good for? Absolutely Something

Proximity to mass and motion

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The paper

Optical Clocks and Relativity  Science  2010
C. W. Chou*, D. B. Hume, T. Rosenband, D. J. Wineland
Frequency Comparison of Two High-Accuracy Al$^+$ Optical Clocks

C. W. Chou, * D. B. Hume, J. C. J. Koelemeij, † D. J. Wineland, and T. Rosenband

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA

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We have constructed an optical clock with a fractional frequency inaccuracy of $8.6 \times 10^{-18}$, based on

$$\frac{\Delta \nu}{\nu} = 8.6 \times 10^{-18}$$
The End

Mike Mosedale

We’re going to need a bigger rug!
Even Narrower Transition?

\[ \begin{align*}
\text{\(3P_1 \quad 3P_0\)}
\end{align*} \]

2 x 564 THz

\[ \begin{align*}
\text{\(S_1\)}
\end{align*} \]