The Yb lattice clock (and others!) at NIST for space-based applications

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Special thanks to:

**NIST Fs-laser team**: Scott Diddams, Tara Fortier, Frank Quinlan et al.

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**JILA folks**: Ana Maria Rey, Jun Ye, and colleagues

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NIST Space Clock Support Capabilities

MWL Ground Station

Cs fountains

NIST Optical Clocks

NIST Timescale

TWSTFT

GPS

Frequency combs

JILA Sr lattice clocks
NIST Timescale and UTC(NIST)

- 4 Cesium Beam standards
  8 more by 2014

- 6 Hydrogen Masers
  8 more by 2014

Measurement System
New digital system under development

UTC(NIST)

Calibrated by NIST-F1
primary frequency standard

International coordination of time and frequency: UTC, TAI, etc.

Two-way satellite time & frequency transfer

GPS

MWL
NIST MWL Ground Station - Status

**Radome pallet**
- dimension: 1.6m(L) x 1.6m(W) x 1.9m(H)
- weight: < 240kg
- Mounted on flat surface (3 bolts)

**Service pallet**
- dimension: 1.7m(L) x 1m(W) x 1.7m(H)
- weight: < 650kg
- Mounted on flat surface (8 bolts)

**Power requirement (for both pallets):**
- 110VAC or 220VAC
- on emergency power
- ≤ 11kW

**Update**
- Location selected
- Delivery of MWL hardware expected in 2014
Building blocks of an atomic clock

Feedback System
- Locks Oscillator to atomic resonance

Oscillator

Atoms/Molecules
- Identical
- Ageless
- High Q
- Can be isolated from environment

Detector

E = hν₀

Counter

456 986 240 494 135
Characterization of clock signals - definitions

Stability – how much the frequency changes over a specified time interval

\[ \sigma_y = \frac{\Delta \nu}{\nu_0} \frac{\sqrt{T_C}}{\sqrt{N} \sqrt{\tau}} \]

Optical clocks have much higher \( \nu_0 \)!

Accuracy – two meanings:
(1) How well the signal produces an exact frequency in terms of the SI second
(2) How well the standard represents the natural frequency of the atomic transition - Uncertainty

Both important – relative importance depends on the application!
1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the $^{133}$Cs atom.

Current “in house” frequency uncertainty $\Delta f/f \sim 3 \times 10^{-16}$. 

*NIST-F1 laser-cooled cesium primary frequency standard*
NIST-F2 Cs Fountain Microwave Clock

Next Generation Microwave Primary Frequency Standard

- Cryogenic drift tube to reduce blackbody shift.
- “Multitoss” atom ball launch to reduce collisional shifts.

Expected uncertainty $\Delta f/f \sim 1 \times 10^{-16}$ or better.
Optical atomic clock performance - uncertainty

State-of-the-art Cs microwave
Building blocks of an atomic clock

**Feedback System**
Locks Oscillator to atomic resonance

**Oscillator**

**Detector**

\[ E = h\nu_0 \]

**Counter**

456 986 240 494 135
Building blocks of an atomic clock

Feedback System
Locks Oscillator to atomic resonance

\[ E = h\nu_0 \]

Detector

\[ \Delta\nu \]

\[ \nu_0 \]
Building blocks of an optical atomic clock

**Feedback System**
Locks Oscillator to atomic resonance

**Laser**
Laser linewidth ~ 1 Hz

**Detector**

\[ E = h\nu_0 \]

\[ \Delta \nu \]

\[ \nu_0 \]

**Fs-laser**
456 986 240 494 135
High stability of optical clocks

![Graph showing clock instability versus averaging time for different types of clocks: H-maser, Cs fountain with CSO, single ion optical clock, and Yb lattice clock.]
Two types of optical atomic clocks

Trapped ions: Al+, Hg+, Yb+, Sr+
- Ion traps suppress motional effects
- Exc. immunity to environmental effects \( \Delta \nu / \nu_0 < 10^{-17} \)
- Limited S/N ratio – typically one clock ion

Neutral atoms: Sr, Yb, Hg
- Need to use laser traps for tight confinement
- Good immunity to environmental effects
- Potential for very high stability
Comparison of Hg$^+$ and Al$^+$ Clocks at NIST

$$\frac{\nu_{Al^+}}{\nu_{Hg^+}} = 1.052 \, 871 \, 833 \, 148 \, 990 \, 438 \pm 5.5 \times 10^{-17}$$
Frequency Comparison of Two High-Accuracy Al\(^+\) Optical Clocks

C. W. Chou,\(^*\) D. B. Hume, J. C. J. Koelemeij,\(^\dagger\) D. J. Wineland, and T. Rosenband

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 23 November 2009; published 17 February 2010)

\[ \Delta v/v_0 = 8.6 \times 10^{-18} \]
Relativistic geodesy

1 part in $10^{18}$ corresponds to 1 cm displacement

Use 1 fixed clock and 1 clock in the field to map out $g$

What about gravitational fluctuations (Kleppner)? 10-20 cm/day
Advantages of an optical lattice

Confine neutral atoms in ion-like environment

- Tight confinement
- Long interaction time
- Large numbers (~$10^4$)

Doppler & recoil-free
high Q
high S/N

~ 20 lattice clocks around the world (Sr, Yb, and Hg)!

NIST Optical Frequency Standards

Optical Lattice Clocks

- Ytterbium (NIST)
- Strontium (JILA)
- $\sim 10^{-16}$, rapidly improving
Many abundant isotopes, different spins (I = 0, 1/2, 5/2)

Today we focus on NIST-based experiments on $^{171}\text{Yb}$ (I = 1/2)
Lasers for the Yb lattice clock

- 798 nm MOPA+PPKTP
  - hollow cathode
  - 399 nm, P ~ 40 mW

- 1112 nm fiber laser + PPLN waveguide
  - ULE cavity
  - 556 nm, P ~ 10 mW

- 1030 nm fiber laser, 1319 nm Nd:YAG + PPLN waveguide
  - vertical ULE cavity
  - AOM
  - 578 nm, P ~ 10 mW

- 759 nm
  - ECDL+ Ti:Sa
  - Ca, etc.

- Frequency comb
**Lattice clock measurement sequence**

- **399 nm MOT**: 60 ms
  - $N \sim 10^6$
  - $T \sim 5$ mK
- **556 nm MOT**: 80 ms
  - $N \sim 10^6$
  - $T \sim 50$ $\mu$K
- **Probe atoms in lattice**: ~ 80 ms
  - $N \sim 10^4$
  - $T \sim 15$ $\mu$K
- **Norm. shelving detection**: 40 ms
  - Optical pumping
  - 60 ms

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**NISt**
Trapped Yb atoms
Laser stabilization: sub-Hz linewidth lasers

Sub-Hz optical spectroscopy

900 ms probe time

\[ \Delta \nu = 1 \text{ Hz} \]
\[ Q = 5 \times 10^{14} \]
Two Yb lattice clocks - comparisons

A second Yb lattice clock system

Clock spectroscopy

5 Hz
High stability of optical clocks

![Graph showing stability of different clock types over averaging time.](image-url)

- H-maser
- Cs fountain w/ CSO
- Single ion opt. clock
- Yb lattice clock
1.8 \times 10^{-18} \text{ instability for the Yb lattice clock}

\begin{equation}
3 \times 10^{-16} \tau^{-1/2}
\end{equation}

Necessary to control collision effects and have clean lattice spectra!
## Frequency uncertainty for NIST Yb clock

<table>
<thead>
<tr>
<th>Effect</th>
<th>Shift ($10^{-16}$)</th>
<th>Uncertainty ($10^{-16}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackbody</td>
<td>-25.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Lattice polarizability</td>
<td>3.7</td>
<td>2.1</td>
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<tr>
<td>Cold Collisions</td>
<td>-16.1</td>
<td>0.8</td>
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<tr>
<td>First-order Zeeman</td>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>Second-order Zeeman</td>
<td>-1.7</td>
<td>0.1</td>
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<tr>
<td>Probe light</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>AOM phase chirp</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Others</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-38.7</strong></td>
<td><strong>3.4</strong></td>
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</table>

**Systematic Total: $3.4 \times 10^{-16}$**

Lemke et al, PRL 103, 063001 (2009)
### Transition frequency uncertainty

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Good prospects for a Yb lattice clock at ~ \(10^{-17}\)
Reducing the uncertainty further

What’s next……..

A build-up cavity to enhance (temporarily!) lattice-based shifts and reduce density

A temperature-controlled chamber to minimize BBR uncertainties
Conclusions and future prospects

NIST is preparing for the ACES mission (STE QUEST)?

Stability of optical clocks far surpasses all others, and optical lattice clocks are designed for high stability – $1.8 \times 10^{-18}$ in 20,000 s

In the near future – there will be many different clocks at $10^{-17}$ level, many of which will be striving for the $10^{-18}$'s

Key issues: BBR shift, lattice light shifts

Key questions:

How do we handle gravity at the $10^{-18}$ level? (QUEST?)

How do compare remote clocks < $10^{-16}$ level? (ACES, QUEST?)

How best to space qualify optical clocks (SOC)?
Acknowledgments

Yb Clock
- **Present:** Andrew Ludlow, Nathan Lemke, Jeff Sherman, Rich Fox, Nathan Hinkley, Kyle Beloy, Nate Phillips
- **Past:** Zeb Barber, Yanyi Jiang, Marco Pizzocaro, Nicola Poli, Jason Stalnaker, Chad Hoyt, Leo Hollberg

Frequency Comb
- Tara Fortier, Matt Kirchner, Scott Diddams, *et al*

Al\(^+\), Hg\(^+\) Clocks
- Jim Bergquist, Till Rosenband, James Chou, *et al*

Sr Lattice Clock
- Jun Ye, Matt Swallows, Mike Martin, Mike Bishof, *et al*

Cs Fountain & Timescale
- Steve Jefferts, Tom Heavner, Tom Parker, Stefania Romisch

Funding: NASA (Fundamental Physics), DARPA QuASAR, NIST

Thanks to Tom O’Brian and Andrew Ludlow for help with the slides!
Finding the magic wavelength

(Clock Shift vs. Lattice Intensity)

\[ \lambda_{\text{lattice}} = 759.3597 \text{ nm} \]

\[ \lambda_{\text{lattice}} = 759.3480 \text{ nm} \]
Reducing the Cold Collision Shift

Δν = 2.5(2.4) mHz

In a 1-D lattice ➔ collision shift < 5x10^{-18}

Can operate with larger lattice volume ➔ low density

High stability of optical clocks

- Microwave standards at \( \sim 10^{10} \) Hz.
  - Direct cycle counting.
  - Convenient broadcast frequencies.
- Optical standards at \( \sim 10^{15} \) Hz.
  - Femtosecond laser frequency combs permit first direct measurements of optical frequencies.
  - Disseminate optical time and frequency information at convenient carrier wavelengths.

Intercomparisons of different technology combs at 10\(^{-19}\) level.

Repetitive pulse train ◇ Frequency Comb ◇ “ruler for frequency/time”

Optical Synthesizer
Is this a blackbody?

Blackbody situation – what’s left?

\[ \Delta \nu_{BBR} = -\frac{1}{2} \alpha_{\text{clock}} \langle E^2 \rangle_T \left[ 1 + \eta_{\text{clock}} \right] \]

300 K

\[ \langle E^2 \rangle_T \approx (8.319 \, \text{V/cm})^2 \left( \frac{T}{300 \, \text{K}} \right)^4 \]

\~1 \, \text{K effective temperature uncertainty}

\1.3\% \text{ shift uncertainty}

\3 \times 10^{-17} \text{ clock uncertainty}
Reducing the Cold Collision Shift

-1.4(3) mHz, 14500 s,
extrapolate white freq noise 1s:
5 x 10^{-16} at 1s
What is a good clock? Uncertainty/stability

Cs fountain instability \( \sim 10^{-13} \tau^{-1/2} \)

Cs fountain uncertainty \( \Delta v/v_0 < 4 \times 10^{-16} \)  
(1 second in 60 million years)
Maybe some UTC transfer stuff?

NIST-F1 vs AT1E

6 hydrogen masers + 4 cesium beam standards.
Time scale performance among best in the world.