Introduction to Microwave Atomic Clocks

Eric Burt
Jet Propulsion Laboratory, California Institute of Technology

IEEE Frequency Control Symposium 2016

May 9, 2016
Acknowledgments

• Robert Lutwack (DARPA)
• Sam Stein (Microsemi)
• Dave Wineland (NIST)
• Jim Bergquist (NIST)
• Jocelyn Guena (Paris Observatory)
• Sebastien Bize (Paris Observatory)
Tutorial Overview

• What is a clock?
  – How good are they?
• What is an Atomic Clock?
• Stable vs. Accurate
• Commercial vs. Laboratory
• Microwave vs. Optical
• Microwave clock examples in detail
  – Cesium Beam, Maser, Rubidium, Fountain, Trapped Ion
• Applications
  – Navigation/GPS, Time Stamping, Space, Fundamental Physics
What are the fundamental components of a clock?
**Clock Schematic**

Everything is an Oscillator *(but some things make better clocks)*

( Oscillator + Counter = Clock )

\[ Q = \frac{\text{Resonant Frequency}}{\text{linewidth (FWHM)}} = \frac{\text{Ring-down Time}}{\text{Period}} \]
**Precision vs. Accuracy**

Stable or Precise, but not accurate

Accurate, but not precise

Accurate and precise
How Do We Characterize Clock Performance?

Time domain: Allan deviation

Frequency domain: phase noise (oscillators)

Systematic Sensitivities
- electromagnetic
- thermal
- barometric
How to Interpret the Allan Deviation

“x” = time or phase
“y” = frequency = dx/dt

Allan Deviation, $\sigma_y(\tau)$ is RMS of $x$ at averaging time, $\tau$: 

$$\sigma_{adev}(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2}$$

$$y_i = \frac{x_{i+1} - x_i}{\tau}$$

Compare to Std Deviation:

$$\sigma_{sdev}(\tau) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \mu)^2}$$
How to Interpret the Allan Deviation

Prototypical ADEV Curve

Allan Deviation, $\sigma_y(\tau)$

Averaging Time, $\tau$ [sec]

“Flicker Floor”
Typically noise floor of measurement or Temperature Sensitivity

White (Gaussian) Noise in $x$, $\propto 1/\tau$
Typically in-band measurement noise

White Random Walk in $dx/dt$, $\propto \tau^{1/2}$
Typically random physics evolution

Linear Drift of $x$, $\propto \tau$
Typically Systematic physics evolution

Typically in-band physics noise
How Do We Compare Clocks

Same Lab: 1 Hz offset method

Example:
- $1 \times 10^{-13}$ change is $\sim 1 \mu$Hz on 10 MHz
- $\Rightarrow 1 \times 10^{-13}$ s change in phase in one cycle
- On 1 Hz beat note, this is integrated for 1 s to give a 1 $\mu$s phase change on the 1 Hz beat
- $1 \times 10^{-13}$ s is very hard to detect, 1 $\mu$s is readily detected.
How Do We Compare Clocks

- Remote Comparisons
  - GPS
  - TWSTT
  - Fiber
  - Free space
World Time Standards

“Bureau International des Poids et Mesures” (BIPM)

- UTC
- UTC(x)
  - USNO, NIST, OP, PTB, NPL, etc...
- TAI: Atomic Time
- TT(BIPM): Primary Standards
- Other...
What is an Atomic Clock?
The Physics Package is a very narrow (high-Q) passband filter. For most high performance microwave atomic clocks, Q > 10^{10}
Basic Microwave Atomic Clock Physics

• What is oscillating? Passive vs. Active clocks
• Frequency perturbations
  – Light shift (AC Stark shift)
  – Magnetic (Zeeman) shift, $1^{st}$ and $2^{nd}$ order
  – Doppler shift, $1^{st}$ and $2^{nd}$ order
Atomic Clock Schematic: Modulation

Modulation Source → Modulator

Signal → RF Frequency

Q = ν₀/γ

“Capture region”

DeModulator → Signal Derivative

Frequency

Depodulated Signal → RF Frequency

© Microsemi

Courtesy of Microsemi
Basic Microwave Atomic Clock Physics: Atomic Interactions

- Hyperfine transitions: 1-40 GHz
- Atomic interactions:
  - **Coulomb** interaction
  - **Fine structure**: electron spin interacts with nuclear electric field (optical)
  - **Hyperfine structure**: nuclear spin interacts with the magnetic field created by the moving electron (microwave)
Basic Microwave Atomic Clock Physics: Simplified Cesium Atomic Level Structure

- **N** = principle quantum number
- **L** = angular momentum quantum number
- **S** = electron spin quantum number
- **I** = nuclear spin quantum number
- **J** = **L**+**S**: total electron angular momentum
- **F** = **I**+**J**: total atomic angular momentum

**Integral F => existence of first-order field-insensitive** $m_F=0 - m_{F'}=0$ transition

- **Field-Sensitive Zeeman Structure**
- **Fine Structure** $6P_{3/2}$
  - $F'=5$
  - $F'=4$
  - $F'=3$
  - $F'=2$

- **Angular Momentum** $6P (L=1)$
  - $6P_{1/2}$
  - $6S_{1/2}$

- **Coulomb:** $n=6$

- **Hyperfine Structure**
  - **Field-Sensitive Zeeman Structure**

- **Transition** $9.192$ GHz

- **852 nm**
Energy Levels: A closer look at Zeeman structure

Energy levels in a magnetic field: The Zeeman Effect

9192 MHz

MAGNETIC FLUX DENSITY
Basic Microwave Atomic Clock Physics:
Atomic Clock Stability

\[ Q = \frac{\nu_0}{\gamma} \]

- \( S/N \) is limited by atomic beam flux
- \( \nu_0 \) is resonance frequency – choice of atom
- \( \gamma \) is linewidth – limited by Fourier transform of measurement time, \( gT = \) constant

In an atomic beam, interaction time (and thereby \( \gamma \)) is limited by time-of-flight of atoms through microwave field.

It’s very difficult to construct a stable uniform microwave field longer than a wavelength.

Remember Equation 1:

\[
\sigma(\tau = 1 \text{sec}) = \frac{1}{(S'/N)_{1\text{Hz}} \times Q}
\]
Basic Microwave Atomic Clock Physics
Ramsey Separated Oscillatory Fields

Common RF Source

RF Phase

Atom Phase

"Quantum Beat"

Phase Sync

Measure Phase

©Microsemi

Courtesy of Microsemi
A Brief History of Atomic Clocks

- Stern-Gerlach (1922)
- Nuclear Magnetic Resonance (1938): Rabi, Ramsey
- Separated oscillatory fields (1949) – invention
- Separated oscillatory fields – in laboratory clocks
- First operational clocks (1955) – Essen and Perry
- Masers – Ramsey
- Lasers (1960)
- Celestial time -> atomic time (1967)
- Commercial cesium beam clocks (1964 ->)
- Laser Cooling (1978)
- Ion trapping (1950’s)
- Optical clocks part 1 (1980’s – 1990’s)
- Atomic fountain clocks (1995)
- Ultra stable clocks part 1 (1980’s ->)
- Combs (1999)
- Optical clocks part 2 (1999)
- Ultra stable microwave clocks part 2 (2005)
- Clocks in space
Commercial vs. Laboratory

Goals

- “Robustness”
- Continuous operability
- Fieldability
- Stability
- accuracy
Microwave vs. Optical

• GHz vs. $10^{14}$-$10^{15}$ Hz: Q
• Robustness
• Systematic sensitivity
• Lasers
• Combs (See Chris Oats tutorial)
Microwave Atomic Clock Examples:
The Cesium Beam Tube Clock
Cesium Beam: The Stern Gerlach Effect

Vacuum Pump

Window

©Microsemi

Courtesy of Microsemi
Cesium Beam Tube: Magnetic Resonance

\[ v = 9192 \text{ MHz} \]

Courtesy of Microsemi
Ramsey: Separated Oscillatory Fields

\[ \nu = 9192 \text{ MHz} \]

“A Magnet”  “C Field Region”  “B Magnet”

Vacuum Pump

Signal

Courtesy of Microsemi
Cesium Beam Tube

Ramsey’s Lab - 1949
Cesium Beam Tube

1955 NPL Cesium Clock

Essen & Perry 1953
Cesium Beam Tube

NBS-6 circa 1975

1975 National Bureau of Standards
U.S. Gov't not subject to copyright

PTB CS1 (1965 - present)
Cesium Beam Tube Construction

Source: U.S. Patent # 3,967,115

Courtesy of Symmetricom
Cesium Beam Tube Spectrum

Linewidth (and Q) limited by time-of-flight of atoms through microwave region

Signal/Noise limited by atomic beam flux: \( \text{Noise} \propto \sqrt{\text{Signal}} \)

\[ Q = 2 \times 10^7 \]

\[ \frac{(S/N)_{1Hz}}{} = 3000 \]

\[ \sigma(1 \text{sec}) = \frac{1}{(S/N)_{1Hz} \times Q} \approx 2 \times 10^{-11} \]
Cesium Beam Tube Instruments

Laboratory/Timekeeping

Telecom

Space/GPS

Courtesy of Microsemi
Cesium Beam Frequency Standard Summary

+ "Primary" frequency standard
  - Absolute accuracy (within known limits)
  - No long-term drift of frequency
  - No environmental sensitivity
  - No retrace (power cycle) error

+ Mature Technology
  - > 10,000 CFS built over 40-year history
  - High reliability

- Relatively large, complex and expensive
  - 3U Rack-mount, ≈50 Watts, $50-75K

• Commercial instrument of choice for absolute accuracy and reliability
  • Laboratory frequency reference for science and calibration
  • Major contributor to international time-keeping (UTC)
  • Top-level telecom synchronization

Courtesy of Microsemi
Commercial Cesium Beam Tube Stability

5071A Cesium Beam Frequency Standard

Overlapping Allan Deviation

Averaging Time

©Microsemi

Specication - Long life Tube
Speciation - High Performance
Typical

Courtesy of Microsemi
Microwave Atomic Clock Examples: The Rubidium Gas Cell Clock
Rubidium

Rb Gas Cell Physics Package

Magnetic Shield

- Lamp Oven
  - Lamp
  - Rb-87
  - Lamp
  - Coil

- Filter Oven
  - Filter
  - Rb-85
  - Cell

- Cavity Oven
  - Absorption
  - Rb-87
  - Cell

- (3) Oven Temperature Sensors and Heaters

- Lamp Exciter

- RF Excitation

- Signal Out

- C-Field Current

- Photo-Detector

©Microsemi

Courtesy of WJ Riley 2002 PTTI Tutorial
State detection by optical scattering

Light Source → Scatter → Detect Fluorescence → Detect Absorption

Courtesy of Microsemi
“Fortuitous” overlap between the optical absorption lines of the two naturally-occurring isotopes, $^{85}\text{Rb}$ and $^{87}\text{Rb}$.

*Carver & Alley 1958*

Isotopic Filtering of Rubidium 87 D Lines

©Microsemi

Courtesy of WJ Riley 2002 PTTI Tutorial
RbO atomic resonance linewidth, $\gamma$, is limited by decoherence of population inversion due to collisions with walls and other Rb atoms.

Nitrogen “buffer gas” atoms “immobilize” Rb with minimal decoherence:
- Reduces Rb-Rb and Rb-wall collisions
- Eliminates first-order Doppler shift

Dicke 1953
Rubidium RF Spectrum

Linewidth (and Q) limited by decoherence due to collisions between Rb and Rb, buffer gas, and cell walls.

Signal/Noise limited by shot noise of background light: 

\[ \text{Noise} \propto \sqrt{\text{Intensity}} \]

\[ Q = 2 \times 10^7 \]

\[ (S/N)_{1\text{Hz}} = 3000 \]

\[ \sigma(1\text{sec}) = \frac{1}{(S/N)_{1\text{Hz}} \times Q} \]

\[ \approx 2 \times 10^{-11} \]
Factors that impact rubidium clock performance

- Short-term stability
  - Optimize linewidth & S/N
  - Lamp output – gas mix, RF drive, temperature, etc.
  - Filter cell – gas mix, temperature
  - Resonance cell – Microwave phase stability, gas mix, cell temperature

- Medium-term stability
  - Thermal control circuits, thermal isolation
  - Gas mixtures to reduce temperature sensitivity
  - Ambient pressure effects (“oil-canning”)
  - Magnetic shielding

- Long-term stability (drift)
  - Stability of buffer gas mixture
  - Rubidium migration

EG&G RFS-10 Physics
HP 5065A circa 1970

- 33 Watts, 37 lbs
- $\sigma_y(\tau) < 5 \times 10^{-12} \tau^{-1/2}$
- Drift < 2x10^{-11}/month

©Tom van Baak
www.leapsecond.com

Courtesy of Microsemi
Microwave Atomic Clock Examples:  
Chip Scale Atomic Clocks
Microwave atomic clock examples: Chip-Scale Atomic Clock (CSAC)

Requires Resonant Cavity

High-Bandwidth VCSEL is Enabling Technology

Laser Power

Detuning [GHz]
CSAC: A 10 mW Physics Package

- Tensioned polyimide suspension
- Microfabricated Silicon vapor cell
- Low-power Vertical-Cavity Surface Emitting Laser (VCSEL)
- Vacuum-packaged to eliminate convection/conduction
- Overall Thermal Resistance 7000°C/W


Courtesy of Microsemi
Commercial CSAC: SA.45s

©Microsemi

Lid
Top Shield
C-Field Coil
Physics Package
PCB
Lower Shield
Baseplate

©Microsemi
SA.45s Short-term Stability

FREQUENCY STABILITY

Overlapping Allan Deviation, $\sigma_y(\tau)$

Averaging Time, $\tau$, Seconds
Microwave Atomic Clock Examples:
The Hydrogen Maser
Active Hydrogen Maser

- Active Device analogous to laser
- Excellent short term stability (10^{-13} at 1 s, 10^{-15} at 1000 s)
- Drifts with cavity/wall properties: 10^{-16} – 10^{-15} /day typical
• $Q$ is very high: $\approx (1.4 \text{ GHz}/1 \text{ Hz}) = 10^9$
• Signal is very small: $\approx -110 \text{ dBm}$
• S/N is dominated by front-end electronic noise
Commercial Hydrogen Maser

Microsemi Model MHM2010

Courtesy of Microsemi
Hydrogen Maser Long-term Stability

FREQUENCY STABILITY
USNO NAV-12 vs. Master Clock

Overlapping Allan Deviation, $\sigma_y(\tau)$

<table>
<thead>
<tr>
<th>Tau</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.60e+03</td>
<td>2.63e-15</td>
</tr>
<tr>
<td>7.20e+03</td>
<td>2.54e-15</td>
</tr>
<tr>
<td>1.44e+04</td>
<td>2.24e-15</td>
</tr>
<tr>
<td>2.88e+04</td>
<td>1.77e-15</td>
</tr>
<tr>
<td>5.76e+04</td>
<td>1.46e-15</td>
</tr>
<tr>
<td>1.15e+05</td>
<td>1.41e-15</td>
</tr>
<tr>
<td>2.30e+05</td>
<td>1.34e-15</td>
</tr>
<tr>
<td>4.61e+05</td>
<td>1.02e-15</td>
</tr>
<tr>
<td>9.22e+05</td>
<td>8.61e-16</td>
</tr>
<tr>
<td>1.84e+06</td>
<td>9.41e-16</td>
</tr>
<tr>
<td>3.69e+06</td>
<td>1.56e-15</td>
</tr>
<tr>
<td>7.37e+06</td>
<td>2.41e-15</td>
</tr>
</tbody>
</table>

Averaging Time, $\tau$, Seconds

U.S. Gov't not subject to copyright

Courtesy of Microsemi
Active Hydrogen Maser Summary

+ Active oscillator
  • Gain provided by continuous injection of population-inverted atoms
  • Very high Q
+ Good short-term stability
  • Limited by noise in electronic receiver for small signal

- Intrinsic accuracy limited by wall properties, cavity detuning, H density
  • Requires periodic frequency calibration
  • Long-term drift

- Relatively large and expensive device relative to other commercial clocks
  • Floor-standing, 150W, about $200K
  • Typically housed in environmental chamber to minimize perturbations

• Instrument of choice for Ultimate short-term stability
  • Radio astronomy
  • International timekeeping
  • Fundamental science
Active Hydrogen Maser Stability

Overlapping Allan Deviation vs. Averaging Time

- Hydrogen Maser Specification
- Commercial Rubidium Oscillator
- High Performance Cesium

Courtesy of Microsemi
Sidebar: New Techniques
**Side bar 1: Laser Cooling**

**How it works**

Atom with Velocity $v$ to "right"

**Doppler shift:**

$\Delta f = \frac{f_0(v/c)}{c}$

Atom with Velocity $v$ to "left"

**No absorption**

Absorb "red-detuned" photon directionally with change in momentum:

$\Delta p = -\frac{hc}{f_0 - \Delta f}$

Incident Photon With energy $h(v_0 - \Delta v)$

Emitting Photon With energy $h(v_0)$

Net effect: atom slows down in 1D
Now add “red-detuned” lasers in all three directions

**ALL DIRECTIONS SLOWED BY LIGHT:**

“OPTICAL MOLASSES”

Sub-Doppler cooling -> ~ 1 uK
Average velocity ~ 1 cm/s
**Side bar 1: Laser Cooling**

*Why it is useful for clocks*

Atom confinement for $O(s)$ instead of $O(ms)$

- Enables trapping and in-situ interrogation
  - Eliminate “end-to-end” effects
  - trapping
  - Extends confinement indefinitely:
    - very long interrogation times possible

- Enables moving atom ensembles over macroscopic distances
  - Atomic fountains
Side bar 2: Neutral Atom Trapping

- Combine detuning and Zeeman shift to create a position-dependent restoring force
- Circular polarization drives $\Delta m = 1$ Zeeman transitions
- Strong field away from geometric center shifts transition into resonance with laser
  - $\Rightarrow$ light pressure
- Weak field in center: laser off resonance – little or no interaction with atoms
- Atoms localized (and cooled) in 1D
- Extend to 3D: Magneto Optical Trap (MOT)
Side bar 3: Ion Trapping
The quadrupole Paul Trap
(Hans Dehmelt and Wolfgang Paul, Nobel Prize, 1989*)

Well Depth: \[ D = \frac{q_e V_0^2}{4m\Omega r_0^2} \]

Typical: several eV

\[ V_0 = \text{rf amplitude (e.g., 300V)} \]
\[ m = \text{ion mass (e.g., mercury 3.3x10^{-25} kg)} \]
\[ \Omega = \text{rf frequency (e.g., 2\pi x 10 MHz)} \]
\[ r_0 = \text{ring inner radius (e.g., 1 mm)} \]

*Normal Ramsey shared this Nobel prize for his invention of the method of separated oscillatory fields
Number of ions scales up linearly

\[ N_{lin} = \frac{3}{5} \left( \frac{L}{R_{sph}} \right) N_{sph} \]

Side bar 3: Ion Trapping
The multipole linear ion trap*

Microwave Atomic Clock Examples Part 2: The Cesium Fountain Clock
Atomic fountain clocks: concept

Cryogenic Sapphire Oscillator

μW from laser stabilized comb

J. Guéna et al., IEEE TUFFC 59, 391 (2012)

Ramsey fringes

Atomic quality factor:

\[ Q_{at} = \nu_{ef} / \Delta \nu \approx 9.8 \times 10^9 \]

Best frequency stability (Quantum Projection Noise limited): 1.6x10^{-14} @1s

\[ \sigma_{\delta P} \approx 2 \times 10^{-4} \text{ in a single measurement} \]

(\sim 1.6 \text{ s})

Best accuracy: (2-3)x10^{-16}

Slide courtesy J. Guéna, SYRTE
Atomic Fountain Clocks: Installations

PRIMARY STANDARDS: Most national metrology labs, including:

• NIST (USA)
• NPL (UK)
• SYRTE (France)
• PTB (Germany)

CONTINUOUSLY RUNNING ENSEMBLES:

• USNO (USA)
• Others soon...
Atomic Fountain Clocks: Early research at USNO circa 1997

Courtesy US Naval Observatory
Atomic Fountain Clock Ensemble at SYRTE

FO1 fountain
$^{133}\text{Cs hfs}$

CSO Macroscopic oscillator

FO2 dual fountain
$^{87}\text{Rb},^{133}\text{Cs hfs}$

FOM transportable fountain
$^{133}\text{Cs hfs}$

H-maser

GPS
TWSTFT

NMIs & BIPM

Slide courtesy J. Guéna, SYRTE
## SYRTE fountain uncertainty budgets

<table>
<thead>
<tr>
<th>Unit 10^{-16}</th>
<th>FO1</th>
<th>FO2-Cs</th>
<th>FOM</th>
<th>FO2-Rb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic Zeeman Shift</td>
<td>-1274.5 ± 0.4</td>
<td>-1915.9 ± 0.3</td>
<td>-305.6 ± 1.2</td>
<td>-3465.5 ± 0.7</td>
</tr>
<tr>
<td>BlackBody Radiation</td>
<td>172.6 ± 0.6</td>
<td>168.0 ± 0.6</td>
<td>165.6 ± 0.6</td>
<td>122.8 ± 1.3</td>
</tr>
<tr>
<td>Collisions and Cavity Pulling</td>
<td>70.5 ± 1.4</td>
<td>112.0 ± 1.2</td>
<td>28.6 ± 5.0</td>
<td>2.0 ± 2.5</td>
</tr>
<tr>
<td>Distributed Cavity Phase Shift</td>
<td>-1.0 ± 2.7</td>
<td>-0.9 ± 0.9</td>
<td>-0.7 ± 1.6</td>
<td>0.4 ± 1.0</td>
</tr>
<tr>
<td>Spectral Purity and Leakage</td>
<td>&lt;1.0</td>
<td>&lt;0.5</td>
<td>&lt;4.0</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Ramsey &amp; Rabi pulling</td>
<td>&lt;1.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Microwave Lensing</td>
<td>-0.7 ± 0.7</td>
<td>-0.7 ± 0.7</td>
<td>-0.9 ± 0.9</td>
<td>-0.7 ± 0.7</td>
</tr>
<tr>
<td>Second-Order Doppler Shift</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Background Collisions</td>
<td>&lt;0.3</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td><strong>Total without Red Shift</strong></td>
<td><strong>1033.1 ± 3.5</strong></td>
<td><strong>-1637.5 ± 2.1</strong></td>
<td><strong>-113.0 ± 6.9</strong></td>
<td><strong>-3341. ± 3.3</strong></td>
</tr>
<tr>
<td>Red Shift</td>
<td>-69.3 ± 1.0</td>
<td>-65.4 ± 1.0</td>
<td>-68.7 ± 1.0</td>
<td>-65.4 ± 1.0</td>
</tr>
<tr>
<td><strong>Total with Red Shift</strong></td>
<td><strong>-1102.4 ± 3.7</strong></td>
<td><strong>-1702.9 ± 2.3</strong></td>
<td><strong>-181.7 ± 6.9</strong></td>
<td><strong>-3406.4 ± 3.5</strong></td>
</tr>
</tbody>
</table>

**References**

Contribution of SYRTE fountains to TAI

Data extracted from the BIPM Circular T

- Each month typically 4 to 6 Cs fountains over the world contribute to the accuracy of TAI with a calibration of a H-maser.

- About 40 to 50 % of the calibration were provided by the LNE-SYRTE fountains over the past 8 years

- Since 2012 FO2-Rb contribute as a secondary representation of the second and participate to the steering of TAI starting June 2013.

Slide courtesy J. Guéna, SYRTE
Microwave Atomic Clock Examples Part 2: Trapped Ion Clocks
Trapped Ion Clocks

Two flavors:

1) Laser Cooled
2) Room Temperature
Trapped Ion Clocks: Laser Cooled

NIST laser-cooled trapped mercury ion clock

199Hg Microwave Clock
(inaccuracy = 3.4 parts in 10^13)

Support Rod
(for applying electric field)

Imaging Lens

End Cap

Trap Rod

40.5 GHz Microwave Horn

T = 4 K

photos courtesy Jim Bergquist and Dave Wineland, NIST
Trapped Ion Clocks: Laser Cooled

NIST laser-cooled trapped mercury ion clock

• 10s Ramsey, 8 ions
• Achieved $3 \times 10^{-15}$ accuracy and $3.3 \times 10^{-13}/\tau^{1/2}$ short-term stability*
• Comparable to laser-cooled fountains at the time
• Atomic line Q as good as $10^{13}$ using a 100 s Ramsey time (not shown)

Courtesy Jim Bergquist and Dave Wineland, NIST

Trapped Ion Clocks: Room Temperature (JPL)
Room Temperature Mercury Trapped Ion Clocks Overview

• Long life, continuous, high stability operation
  – Ultra-stable timekeeping & autonomy
  – Amenable to small, low power operation.

• Mercury Ion Clock Paths and Applications:

  1. Ultra-Stable Performance\(^1\): UTC timescales
     “Compensated” Multi-pole ion clock technologies:
     • \(10^{-16}\) at 1 to 10 days, drift \(\leq 10^{-17}/\text{day}\).
     • \(10^{-15}\) short term stability (~1 sec) via super LO’s.

  2. Space: DSAC Technology Demonstration Mission\(^2\) (TRL 5-7)
     • Deep Space: 20W and 5 kg goal
     • GNSS: \(1 \times 10^{-13}\) short term, \(10^{-15}\) at 1 to 10 days
     • Science and other apps….

  3. Ultra-small, low power
     • Few cm\(^3\) ion trap\(^3\)
     • Miniature UV light sources\(^4\) and LO’s

---

\(^2\) R.L. Tjoelker, et al., to be published in IEEE TUFFC
\(^3\) J.D. Prestage, et al., PTTI (2013)
\(^4\) L. Yi, et al., PTTI (2013)
**Room Temperature Mercury Trapped Ion Clocks Overview**

**Key Performance Features:**

- $10^6$-$10^7$ $^{199}$Hg$^+$ trapped ions
  - No wall collisions, high Q microwave line
  - Buffer gas cooled to $\sim$300K
  - Multi-pole ion trap — low T sensitivity

- **State selection:**
  - Optical Pumping from $^{202}$Hg$^+$ lamp
  - 1-2 UV photons per second scattered

- **High Clock Transition:**
  - 40,507,347,996.8 Hz — low B sensitivity

- Adapts to variety of Local Oscillators — flexible

**Key Reliability Features:** — practical

- No Lasers
- No Cryogenics
- No Microwave cavity
- No Light Shift
- Low Consumables
The Multi-pole Ion Trap – A Comparison

Multi-pole (12) RF Trap

Spherical Quadrupole RF Trap

Linear Quadrupole RF Trap

Field-free region at one point in center of trap

Field-free region on a line

Field-"free" Region in a volume


Mercury Ion Energy Level Diagrams

**199Hg+ energy level scheme**

- **S<sub>1/2</sub>**
  - F=1
  - F=0

- **P<sub>1/2</sub>**
  - F=1
  - F=0

194 nm optical pumping

Clock transition:

199Hg+: 40.5 GHz

**201Hg+ energy level scheme**

- **S<sub>1/2</sub>**
  - F=1
  - F=2

- **P<sub>1/2</sub>**
  - F=1
  - F=2

194 nm optical pumping

Clock transition:

201Hg+: 29.9 GHz

Better 198/201 overlap =>
- possibly more signal
- possibly faster OP

- **199Hg**
- **201Hg**
**Mercury Ion Normal Clock Operation**

- **Ion Loading, State selection**
- **Microwave interrogation**
- **State readout**

- Detect decaying signal:
  - Lamp off during microwave interrogation avoids light shift
  - Detection gate = OP time: optimal SNR
Mercury Ion Level Structure Revisited: State Preparation Challenges

$^{201}\text{Hg}^+$

$P_{1/2} F=2$

$m_f=+2$

$S_{1/2} F=1$

$m_f=-2$

$m_f=+2$

$m_f=-1$

$29 \text{ GHz}$

$201\text{Hg}^+$

$S_{1/2} F=1$

$m_f=+1$

$m_f=0$

$m_f=-1$

$194 \text{ nm}$

$S_{1/2} F=2$

$m_f=+2$

$m_f=+1$

$m_f=0$

$m_f=-1$

$m_f=-2$

Compare to $^{199}\text{Hg}^+$:

$S_{1/2} F=0$

$m_f=0$

$m_f=+1$

$m_f=-1$
Mercury Ion Level Structure Revisited: State Preparation Challenges

199Hg⁺ Optical Pumping

P₁/₂F=1

S₁/₂F=1

S₁/₂F=0

194 nm

201Hg⁺ Optical Pumping

P₁/₂F=2

S₁/₂F=1

S₁/₂F=2

194 nm
Mercury Ion Level Structure Revisited: State Preparation Challenges

$^{201}\text{Hg}^+$ Optical/Microwave Pumping scheme

Microwave pump:
- $\Delta m=0 \Rightarrow$ polarization same as clock
- inverted level structure $\Rightarrow \Delta m=0$ levels well resolved
Room Temperature Mercury Ion Clock Performance

Allan Deviation

Time (sec)

DSAC Technology Demonstration Mission (TDM) will operate with a quartz based USO.
Room Temperature Mercury Ion Clock Frequency
40.5 GHz Sensitivities impacting long term stability
(Secondary sensitivities enter through these)

1. Magnetic Shifts
   - Shield external fluctuations
   - Stable bias field
   \[ \nu = \nu_o + C_B B^2 \quad C_B \propto \frac{1}{\nu_o} \quad \frac{1}{\nu_o} \frac{\partial \nu}{\partial B} \propto \frac{B}{\nu_o^2} \]

2. Second-order Doppler Shifts
   - Ion number/space charge & temperature variations
   - Low sensitivity due to multi-pole ion trap design.
   \[ \frac{\Delta f}{f} = -\frac{3k_B T}{2mc^2} (1 + \frac{2}{3} N_d^k) \quad N_d^k = \frac{1}{k-1} \]

3. Pressure/collision Shifts
   - Use low shifter for buffer gas (Neon).
   - Reduce all other gases via ultra high vacuum practices.
   - Minimize time variability of trace gasses.

Achievable long term stability depends on the specific implementation.
Achieving Ultra-Stability in Room Temperature Ion Clocks: Magnetic Compensation

Second order Doppler shift

\[
\left( \frac{df}{f} \right)_{TSOD} = - \frac{3k_BT}{2mc^2} \left( 1 + \frac{2/3}{k-1} \right)
\]
Ultra-Stability using Magnetic Compensation

Second order Zeeman shift (Briet-Rabi)

\[
\left(\frac{df}{f}\right)_{soz} = -\frac{A}{2} \sqrt{1 + \left(\frac{2\mu_B B}{hA}\right)^2}
\]

Compensated number shift

Second order Doppler shift

\[
\left(\frac{df}{f}\right)_{TSOD} = -\frac{3k_B T}{2mc^2} \left(1 + \frac{2/3}{k - 1}\right)
\]
Long-Term Performance of LITS-9: Magnetic Compensation

![Graph showing frequency offset vs. ion number, with various lines and markers indicating different pole configurations.]

Sensitivity to ion number $< 5 \times 10^{-17}$

1% change: $< 1 \times 10^{-18}$
Long-Term Performance of LITS-9: Magnetic Compensation

\[ \Delta f = -950(26) \mu \text{Hz} = 2.3 \times 10^{-14} \]

\[ \Delta f = -64(19) \mu \text{Hz} = 1.6 \times 10^{-15} \]

Compensation gives 15x reduction in sensitivity

Ion number reduced by 20%
LITS-9: Record Q

New lamp operational method:
- record line Q for LITS: $4.7 \times 10^{12}$
- second highest Q ever recorded for a microwave standard

$T_r = 65$ s!

$(\Delta f = 8.6$ mHz$)$
## Stability Evaluation: what determines small residual instability?

<table>
<thead>
<tr>
<th>Effect</th>
<th>Sensitivity</th>
<th>Units</th>
<th>Change</th>
<th>$\Delta f/f$ (x10^{-17}/day)</th>
<th>Uncertainty (x10^{-17}/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature-dependent second-order Doppler shift</td>
<td>+1.1(2.2)x10^{-8}</td>
<td>torr^{-1}</td>
<td>-3.6(0.9)x10^{-7} torr</td>
<td>-1.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Collision shift due to neon buffer gas</td>
<td>+8.5(1.7)x10^{-9}</td>
<td>torr^{-1}</td>
<td>-3.6(0.9)x10^{-7} torr</td>
<td>-1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Collision shift due to other background gas (CH₄ dominates)</td>
<td>-3.6x10^{-5}</td>
<td>torr^{-1}</td>
<td>$\leq$ +7.1x10^{-11} torr</td>
<td>--</td>
<td>0.94</td>
</tr>
<tr>
<td>Number-dependent second-order Doppler shift</td>
<td>+7.1(0.8)x10^{-15}</td>
<td>$(\Delta N/N)^{-1}$</td>
<td>-0.32(0.05)</td>
<td>-0.84</td>
<td>0.23</td>
</tr>
</tbody>
</table>

---

**Improve Vacuum**

---

L10 Design

DC electronics (behind)
Optics
Magnetic shields
C-field solenoid (red)
Quadrupole trap
Multi-pole trap
Microwave delivery

~1 meter
Quadrupole to Multi-pole Transfer Efficiency

Trapped Hg+  Quadrupole Trap  Multi-pole Trap

electron beam

Graph showing amplitude over time.
Short Term Clock Performance

Clock Transition Spectroscopy:

Here:
• Peak SNR ~70
• SNR*Q < 4x10^{-14}/sqrt(tau)

Initial short term stability

• 4.5x10^{-14}/sqrt(tau)
• T=40s
Initial FSTL1 Long-Term Performance: comparison to UTC(USNO)

- GPS CP Time transfer
- Sealed vacuum
- No observed drift at $2.4 \times 10^{-16}$/day level
Microwave Atomic Clock Applications
Microwave Atomic Clock Applications

- GPS
- Deep Space Navigation
- Chip-scale clocks
- Fundamental Physics
Microwave Atomic Clock Applications: GPS
Microwave atomic clock applications: Deep space navigation

Enables Multiple Space Craft Per Aperture Tracking at Mars

Today’s 2-Way Radio Navigation

Tomorrow’s 1-Way Radio Navigation

= DSAC on-board
Microwave atomic clock applications: 
Deep space navigation

NASA’s DSAC Technology Demonstration Mission

Develop advanced prototype (‘Demo Unit’) mercury-ion atomic clock for navigation/science in deep space and Earth

- Perform year-long demonstration in space beginning mid-2016 – advancing the technology to TRL 7
- Focus on maturing the new technology – ion trap and optical systems – other system components (i.e. payload controllers, USO, GPS) size, weight, power (SWaP) dependent on resources/schedule
- Identify pathways to ‘spin’ the design of a future operational unit (TRL 7 → 9) to be smaller, more power efficient – facilitated by a detailed report written for the next DSAC manager/engineers
DSAC Demonstration Summary & Future

10X further ion clock stability already demonstrated on ground if needed in space applications
Fundamental Physics with Rb/Cs fountains (SYRTE)

- 16 years of $^{87}$Rb ground state hyperfine frequency measurements against Cs: FO2-Rb against FO1 or FOM, and since 2009 against FO2-Cs operated simultaneously.

- Feb. to Aug. 2012 measurement

$$6 \, 834 \, 682 \, 610.904 \, 312 \, (3) \, \text{Hz} \, (\pm 4.4 \times 10^{-16})$$

$\Rightarrow$ recommended value of Rb hf frequency

---

**Graph:**

- **Title:** FO2Cs – FO2Rb long term comparison (Dec. 2009 – Feb. 2016)
- **Data:**
  - Average difference: $1.1 \times 10^{-16}$
  - Statistical unc. down to $4.8 \times 10^{-17}$

---

*Slide courtesy J. Guéna, SYRTE*
Rb/Cs: search for time variation in fundamental constants

**Weighted least-squares fit to a line**

\[
\frac{d}{dt} \ln\left( \frac{v_{Rb}}{v_{Cs}} \right) = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}
\]

⇒ limit on a potential variation of fundamental constants:


\[
\frac{d}{dt} \ln\left( \frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49} \right) = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}
\]

**With QCD calculations:** T.H. Dinh, et al., PRA79 (2009)

\[
\frac{d}{dt} \ln[\alpha^{-0.49} (m_q / \Lambda_{QCD})^{-0.021}] = (-10.7 \pm 4.9) \times 10^{-17} \text{ yr}^{-1}
\]

*Slide courtesy J. Guéna, SYRTE*
**Rb/Cs: search for annual variations**

- **Differential redshift test**
  \[ \frac{d\nu}{\nu} = (1 + \beta) \frac{dU}{c^2} \]
  \[ \beta^{(87)Rb} - \beta^{(133)Cs} = (-4.7 \pm 5.3) \times 10^{-7} \]

- **Variation of constants with gravity**
  \[ c^2 \frac{d}{dU} \ln \left( \frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49} \right) = (-4.7 \pm 5.3) \times 10^{-7} \]
  \[ \frac{d}{dt} \ln \left( \alpha^{-0.49} \left( \frac{m_q}{\Lambda_{QCD}} \right)^{-0.021} \right) = (-4.7 \pm 5.3) \times 10^{-17} \text{ yr}^{-1} \]
Fundamental Physics with Ion Clocks: 
\(^{201}\text{Hg}^+/^{199}\text{Hg}^+\) Dual Isotope Clock

- HF clocks: depend on \(\alpha, \mu\) via 
  \[ A \propto (m_e e^4/\hbar^2) [\alpha^2 F_{\text{rel}}(Z\alpha)] (\mu m_e/m_p) \]
- some ambiguity
- Direct optical clock comparisons depend only on \(\alpha\)
- \(\mu \propto m_q/\Lambda_{\text{QCD}}^*\)
- \(B_{201} \approx -B_{199}^{**}\)

\[ \frac{\partial}{\partial \alpha} \ln \frac{f_{201}}{f_{199}} = \left[ B_{201} - B_{199} \right] \frac{\partial}{\partial \ln \left( \frac{m_q}{\Lambda_{\text{QCD}}} \right)} \]

- \(B_{201} - B_{199} \approx 0.2\) - BIG!
- Would provide a stand-alone independent limit on \(m_q/\Lambda_{\text{QCD}}\) variation

Dual isotope clock will reduce systematic sensitivity in difference measurement

Fundamental Physics with Ion Clocks: Hyperfine Anomaly (Bohr-Weisskopf Effect*)

$^{201}\text{Hg}^+$ HF clock: 29.9543658213(17) GHz
(E.A. Burt, et al., PRA 79, 062506 (2009))

$^{199}\text{Hg}^+$ HF clock: 40.50734799684159(41) GHz
(D.J. Berkeland, et al., PRL 80, 2089 (1998))

Point nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = \left(\frac{\mu_{I_1}/I_1}{\mu_{I_2}/I_2}\right) \frac{F_1}{F_2}$$

Finite nucleus:

$$\frac{\Delta f_1}{\Delta f_2} = (1 + \Delta) \left(\frac{\mu_{I_1}/I_1}{\mu_{I_2}/I_2}\right) \frac{F_1}{F_2}$$

HF anomaly

*A. Bohr and V.F. Weisskopf, PR 77, 94 (1950)
Hyperfine Anomaly

$^{201}\text{Hg}^+$ HF clock:
29.9543658213(17) GHz

$^{199}\text{Hg}^+$ HF clock:
40.50734799684159(41) GHz
(D.J. Berkeland, et al., PRL 80, 2089 (1998))

$\frac{\Delta f_1}{\Delta f_2} = (1 + \Delta) \left( \frac{\mu_{I_1}/I_1}{\mu_{I_2}/I_2} \right) \frac{F_1}{F_2}$
$f_{201} = -0.739479805577(3)$

$\Delta \left( S_{1/2}, ^{199}\text{Hg}^+, ^{201}\text{Hg}^+ \right) = -0.0016257(5)$
E.A. Burt, et al., PRA 79, 062506 (2009)

Previous values
Hg: -0.001627(19), (Reimann and McDermott, PRC 7, 2065 (1973))
Hg$^+$: -.0034 to +0.0056 (Grandinetti, et al., (1986))

- Value now limited by knowledge of $\mu_I$
- Agrees with neutral value: valence screening has minimal effect
Microwave Clock Applications: Fundamental Physics and ACES

ISS

ACES ground terminal

FSTL1 reference:

- Timing Accuracy in Space
- Improved Gravitation Red Shift Measurement
Microwave Clock Applications: Magnetometry Doppler-Free Field-Sensitive Spectroscopy

F=1, m_F=-1 to F=2, m_F=-1
\[ \Delta m_F = 0 \]

Lamb-Dicke Confinement:
\[ \lambda = 1 \text{ cm} \]
\[ r_0 < 1 \text{ mm} \]

uWave Horn

29.954... GHz

C-field
Doppler-Free Field-Sensitive Spectroscopy

$F=1, m_F=-1$ to $F=2, m_F=-1$

$\Delta m_F = 0$

$f_{-1,-1} = 29\ 954\ 561\ 137(30)$ Hz

$B_0 = 139.341(42)$ mG

$\Delta f = +195$ kHz

Residual broadening due to C-field current source instability

- space applications
- $^{201}$Hg$^+$ magnetometer for $^{199}$Hg$^+$

E.A. Burt, et al., PRA 79, 062506 (2009)

29.954... GHz

uWave Horn

C-field
Do fundamental constants (and clocks) vary with time?

- Prestage PRL [1]
- Cosmology vs. clocks: different things to say [2]
- Early microwave measurements [3]
- Optical clocks take over alpha-dot [4]
- Microwave clocks play a role in variation of nuclear constants [5]
Textbook References
(see specific slides for journal references)

- Woodgate
- Foote
- Metcalf
- Vanier and Audoin
- Vanier and Tomescu
- Yariv
- Nagourney