Atomic Clocks: Primary Frequency Standards at NIST

S.R. Jefferts
NIST – Time and Frequency Division
Outline

• Atomic Clocks - general

• Primary Frequency Standard
  • Beam Standards
  • Laser-Cooled Primary Standards

• Systematic Frequency Shifts in Primary Frequency Standards

• Possible Future – PARCS space clock

• Certain Future – optical clocks
Acknowledgements

Tom Heavner, Jon Shirley and Tom Parker - the rest of the NIST-F1 team
Filippo Levi and Coworkers at IEN (Torino)
Atomic Clocks - General
The Elements
Hyperfine structure of $^{87}\text{Rb}$, with nuclear spin $I=3/2$, $\nu_0=\Delta W/h=6,834,682,605$ Hz and $X=[(-\mu J/J) + (\mu I/I)]H_0/\Delta W$ calibrated in units of $2.44 \times 10^3$ Oe.
Block Diagram – simplified a little

Signal Amplitude

Applied Frequency - $v_0$

Atomic Resonator and Atomic State Detector

Syncronous Demodulator

Loop Filter and Gain

Microwave Synthesizer – High Frequency 9.2 or 6.8 GHz

Modulation Oscillator (low Frequency ~100Hz)

VCO (Voltage Controlled Oscillator)

Output – eg 5 MHz

Modulation Width
A Little Quantum Mechanics

• The allowed states (configurations) of an atom have discrete (quantized) energies, in the long run, atoms are only allowed to exist in these quantized states (these are the only stable states)

• Atoms of the same element (and isotope) are indistinguishable, for example, all cesium 133 atoms are the same

• Energy and Frequency are equivalent, $E=nh\nu$ where $h$ is Plank’s constant

• Atoms move between their allowed energy levels by absorbing or emitting a photon of the correct frequency for the difference between the beginning and ending energies.
The “rules” just given explain the high long term stability of atomic frequency standards. The atoms behave (define the frequency) the same way tomorrow that they do today and did yesterday. In an ideal atomic standard this would be rigorously true, in the real world the atoms interact with their environment and experience slight frequency shifts.

These shifts are typically caused by things like

- Less than perfect magnetic shielding
- Collisions between atoms
- Gravitational effects
- Thermal radiation
- Electronics drifts
- etc
Microwave Field

• The change in state (up to down) is driven by an microwave field
• The interaction is between the electron and the field...essentially the electron is “flipped”
• The “clock” transition is, to first order, not shifted by a magnetic field, but requires that the magnetic field of the microwaves be parallel to the C-field (quantization axis)
Definition of the SI second

The **second** is 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 cesium 133 atom.[1]

This definition refers to a cesium atom

*at rest at a temperature of 0 K (absolute zero)*

The ground state is defined at **zero electric and magnetic fields**.

Must also correct for **gravitational effects** – clocks are corrected to the reference geoid (sea-level)
Magnetically Selected Thermal Beam

Illustration by Boris Starosta

12 September 2013
Laser Safety Seminar
Thermal Cesium Beam Clocks at NIST
NIST Standards vs Time

Clock Uncertainty (ns/day)

YEAR


Frequency Uncertainty

10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18}

Laser-Cooled Clocks

NBS-1  NBS-2  NBS-3  NBS-4  NBS-5  NBS-6  NIST-7  NIST-F1  PARCS

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Laser Safety Seminar
NIST-F1,F2
Cesium Fountain Primary Frequency Standards
Clock Performance

Clock Stability is given by:

\[ \sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)} \]

Atomic Line Q  \hspace{1cm} Signal to Noise

Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease \( \Delta\omega = 1/T_{\text{Ramsey}} \))
- Increase The Frequency of the Clock Transition
- Improve the S/N
Ramsey Resonance in NIST-7 and NIST-F1

NIST-7
65Hz Linewidth

NIST-F1
1 Hz Linewidth
Cesium Fountain Schematic

- Load and launch $\approx 10^7$ Cs atoms in 300 ms. Atoms are all in $|F=4, m_F\rangle$.

- State Selection $\pi$-pulse moves atoms in $|F=4, m_F=0\rangle \rightarrow |F=3, m_F=0\rangle$.

- Optical pulse removes remaining $|F=4, m_F\neq0\rangle$ atoms, leaving a pure $|F=3, m_F=0\rangle$ sample.

- Ramsey spectroscopy atoms. (SOF on way UP and way DOWN.)

- Detection region measures populations in $|F=4, m_F=0\rangle$ and $|F=3, m_F=0\rangle$. 

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Laser is detuned to the red of the ground-to-excited state transition.

As an atom moves toward the laser, it is Doppler-shifted into resonance -- it absorbs a photon and is “kicked” backwards. It re-emits the photon in a random direction. Net result is cooling.

Cooling limit ~ 120 µK for Cs.

Velocity ~ 9 cm/s
Laser Cooling II
Sisyphus Cooling

1. Suppose atom \( m = | + \frac{1}{2} \rangle \) has \( v \) to the right
2. De-tuning and light shift => absorb at top
3. Radiates to \( | - \frac{1}{2} \rangle \), down to the bottom
4. Up the hill again

Cooling limit \( \sim 0.5 \, \mu K \), Velocity \( \sim 0.5 \, \text{cm/s} \)

Pumped up
Radiates down

0.5 \( \mu K \)

852 nm

Polarization of the Ground State by light shift from optical standing wave

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U.S. Primary Frequency Standard

NIST-F1

Magnetic Shields: Microwave Cavities and Flight Tube are Inside

Detection Region

Cs Optical Molasses Region

Optical Bench: Lasers, etc.
## NIST-F1 Error Budget Today

<table>
<thead>
<tr>
<th>Physical Effect</th>
<th>Bias</th>
<th>Type B Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Red shift</td>
<td>+179.95</td>
<td>0.03</td>
</tr>
<tr>
<td>Second-Order Zeeman</td>
<td>+180.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Blackbody</td>
<td>-22.98</td>
<td>0.28</td>
</tr>
<tr>
<td>Microwave Effects</td>
<td>-0.026</td>
<td>0.12</td>
</tr>
<tr>
<td>Spin Exchange (density =8)</td>
<td>0.0 (-0.56)</td>
<td>0.06 (0.16)</td>
</tr>
<tr>
<td>AC Zeeman (heaters)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Cavity Pulling</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Rabi Pulling</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Ramsey Pulling</td>
<td>$10^{-4}$</td>
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</tr>
<tr>
<td>Majorana Transitions</td>
<td>0.02</td>
<td>0.02</td>
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<td>0.02</td>
</tr>
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<td>DC Stark Effect</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Background Gas Collisions</td>
<td>$10^{-3}$</td>
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<td>Bloch-Siegert</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
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<tr>
<td>RF Spectral purity</td>
<td>$3 \times 10^{-3}$</td>
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</tr>
<tr>
<td>Integrator offset</td>
<td>0</td>
<td>0.01</td>
</tr>
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</table>

**Total Type B Standard Uncertainty**

Total Type B Standard Uncertainty (including Spin Exchange) **0.30** (0.34)
ADEV NIST-F1 vs AT1E

Theo $\tau - \frac{1}{2}$

NIST-F1 vs Maser

NIST-F1 vs AT1E

Allan (Total) Deviation

NIST-F1

$Laser Safety Seminar$
Blackbody Shift

\[ \frac{\delta \nu}{\nu_0} = \beta \left( \frac{T}{T_0} \right)^4 \left( 1 + \varepsilon \left( \frac{T}{T_0} \right)^2 \right) \beta = -(1.710 \pm 0.006) \times 10^{-14} \]

- This uncertainty (±1K) dominates NIST-F1 budget
- At 300K the uncertainty in the calculated value of \( \beta \) amounts to almost \( 10^{-16} \)
- Calculation and measurement of DC Stark shift
- Direct measurement of AC stark has been problematic with results varying at the \( 10^{-15} \) level….difficult measurement….NO measurements at \( 10^{-16} \) level

*Unlikely to get well below \( 10^{-16} \) with room temperature fountains*
Microwave Shifts

- Neglecting Blackbody these are the dominant uncertainty in NIST-F1
- Frequency accuracy at $\frac{\delta v}{v} \approx 10^{-16}$ requires ~1 µradian phase control on the interrogating signal.
- Enters into the standard in a number of ways, leakage, cavity phase, spurs etc.
- These will probably be the ultimate limiting systematic effects on microwave standards
Mature Standard

- 45+ evaluations
- Limited by Blackbody
- Highly Reliable
- Probably won’t improve
The cryogenic fountain: NIST-F2

Blackbody shift dominant in NIST-F1

\[ \downarrow \]

NIST-F2 has cryogenic (~80K) Ramsey cavity and drift region

\[ \downarrow \]

Blackbody reduced to about \( 1 \times 10^{-16} \).

This is the total shift: a 1K error yields an uncertainty of \( 5 \times 10^{-18} \).
NIST-F2 Physics Package

Cryogenic (80K) Region with Ramsey microwave cavity C-field, magnetic shields and drift region

Room-temperature molasses collection and launch region with detection region above molasses region
Microwave Structure

Very Similar to NIST-F1

- Cavities tuned to resonance at 80K
  - 4 feed cavity, feeds balanced to -60dB
  - Feeds balanced to within 100 µradians
  - Q is ~ 30K
  - Resonance width in Kelvin similar to room temp

- Drift Region (above Ramsey)
  - Below Cutoff for all modes except TE_{11}
  - Anti-resonant for TE_{11} at 9.192 GHz and 80K

- All microwaves FM far (~5 MHz) off resonance when atoms are below the Ramsey cavity
Magnetic Field vs time

About 1 Ramsey Fringe on $|3,1\rangle$ to $|4,1\rangle$ line

INRIM-F2 Magnetic Field Stability – Similar at NIST

35 nT

From USGS 24 Hours: Stop is 21:30 UTC April 28, 2011

Data is from the USGA Boulder monitoring site

Conclusion - NIST-F2 is a really expensive sundial!!

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NIST-F2 Stability – high density June 2010

![Graph showing total Allan deviation vs. averaging time]

Averaging Time, \( \tau \), Seconds

Total Allan Deviation, \( \sigma_{\text{total}}(\tau) \)

1e-16
1e-15
1e-14
1e-13
1e-12

Averaging Time, \( \tau \), Seconds

1e+0 1e+1 1e+2 1e+3 1e+4 1e+5

Total Allan Deviation, \( \sigma_{\text{total}}(\tau) \)

1e-16
1e-15
1e-14
1e-13
1e-12

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# NIST-F2 Error Budget Today

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<td>-0.096</td>
<td>0.005</td>
</tr>
<tr>
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<td>-0.0025</td>
<td>0.10</td>
</tr>
<tr>
<td>Spin Exchange (density =10)</td>
<td>0.0 (0.07)</td>
<td>0.01 (0.18)</td>
</tr>
<tr>
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<td>0.02</td>
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<td>0</td>
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Total Type B Standard Uncertainty 0.11  
(Including Spin Exchange) 0.20

**Dominant Uncertainty**

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Comparing F1 & F2

- Comparison of F1 and F2 is a measurement of the Blackbody shift of F1.....among other things!
- Uncertainty table looks quite different for comparison vs evaluation. Common mode rejection of several systematic frequency shifts (eg – Gravity)

Scheme is to operate F1 and F2 concurrently – since we are running F1 anyway, get an eval. for F1 and report to BIPM.

Measure the same maser using F1 and F2, subtract the data to remove the maser.

Correct for everything except the blackbody, the difference is the frequency shift associated with F1 blackbody.
F2- F1 both corrected for all known systematic frequency shifts. The weighted average (in red) constitutes our best measurement of the blackbody shift. The result $(\text{Blackbody}_{\text{measured}} - \text{Blackbody}_{\text{theory}}) = (0.02 \pm 0.40 \pm 0.29) \times 10^{-15}$ level, the best to date.

(Note – result is given as result ± Type A uncertainty ± Type B uncertainty – uncertainties are 1σ)
Conclusions

- Next Generation cesium fountains at NIST and INRIM should contribute to TAI at the high $10^{-17}$ level (eventually), and the low $10^{-16}$ level very soon.
- NIST-F2 cryogenic fountain should be beginning operation (contributing to TAI very shortly)
Cavity Phase and Leakage

Leakage below the Ramsey cavity in NIST-F1...
..maximum at optimum power and multiples thereof.

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NIST-F2 Zeeman Correction

Predicted-Measured Fringe Position = -0.067±0.04 fringes
Leakage - cont

Drift tube on NIST-F1 allows only TE_11 to propagate. Tube is shielded from leakage by cutoff chokes at each end and the tube is cut to be antiresonant at 9.1926 GHz. No leakage allowed. Microwaves are far detuned after resonance.

<table>
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<tr>
<th>Error Signal - normalized at optimum power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance from axis (cm)</strong></td>
</tr>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

NIST cavity R=3cm

“square” cavity

Hz (midplane)

0.80 | 0.85 | 0.90 | 0.95 | 1.00 | 1.05

Distance from axis (cm)

Rabi pulse area in units of optimum excitation (2b_0τ=π/2)

With quadratic term too
Much larger than predicted by previous theory
- pulsed standards are different!

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Generic Problems in the Realization of the second

• Collision Shift (a different approach in the next talk)
• Blackbody Shift
• Microwave Effects
Actual Multi-toss Data

**Seven balls non overlapped**

![Signal (V) vs Arrival time (s) for non-overlapped balls](chart1)

**Seven balls overlapped**

![Signal (V) vs Arrival time (s) for overlapped balls](chart2)

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Collision Shift

- Frequency Shift proportional to Cesium Density (everything else held constant) so, vary density and extrapolate to zero density

Intercept Uncertainty

$\sim 4 \times 10^{-16}$
Blackbody

- Radiation associated with non-zero temperature peak at about 10µm (room temp)
- Frequency shift is relatively large \( \sim 2 \cdot 10^{-14} \) at room temperature
- Shift goes like \( T^4 \)
- Shift is about \( 3 \cdot 10^{-16}/°C! \)
- Temperature Uncertainty is mainly due to leakage of room temperature radiation
- Final Uncertainty is Assigned 1C \( \sim \frac{\delta f}{f} = 2.8 \cdot 10^{-16} \)
Clock Performance

Clock (in)Stability is given by:

\[ \sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)} \]

Atomic Line Q

Signal to Noise

Clock Stability can be improved by:

- Increase Ramsey (Observation) Times (Decrease \( \Delta\omega = 1/T_{\text{Ramsey}} \))
- Increase The Frequency of the Clock Transition
- Improve the S/N
NIST Standards vs Time

The graph illustrates the progression of NIST standards over time, showing a decrease in clock uncertainty from 1940 to 2010. Each point represents a notable NIST standard, such as NBS-1, NBS-2, NBS-3, NBS-4, NBS-5, NBS-6, NIST-7, NIST-F1, and PARCS. The y-axis represents clock uncertainty in ns/day, and the x-axis represents the year. The graph also highlights the transition from vapor-cell clocks to laser-cooled clocks.

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Ramsey Resonance in NIST-7 and NIST-F1

NIST-7
65Hz Linewidth

NIST-F1
1 Hz Linewidth

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F1 Evals used compared to TAI
Clock Performance

Clock (in)Stability is given by:

\[ \sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)} \]

Atomic Line Q \quad \text{Signal to Noise}

Clock Stability can be improved by:

• Increase Ramsey (Observation) Times (Decrease \( \Delta\omega = 1/T_{\text{Ramsey}} \))
• Increase The Frequency of the Clock Transition
• Improve the S/N
Commercial Atomic Clocks

• Commercial Atomic Clocks come in three basic flavors – Cesium beam clocks, Rubidium cell clocks and Hydrogen masers

• All atomic clocks depend on the same basic quantum mechanical principals just discussed
Rubidium Clocks

Adapted from figure by John Vig
Rubidium - Stability

(Frequency drift removed – $3 \times 10^{-13}$/day typical)

Allan Deviation

$\tau^{-1/2}$

Courtesy of Bill Riley
Hydrogen Maser
Hydrogen Maser - Stability

(Frequency drift removed – $1 \times 10^{-16}$/day typical)

Allan Deviation

$\tau$ (sec.)

$1 \times 10^{-16}$ to $1 \times 10^{-11}$

Low 2nd order drift
Stability of Various Commercial Clocks

![Graph showing stability of various commercial clocks.](image)

- Quartz
- Rubidium
- Cesium

Log (σy(t)) vs. Log (τ), seconds

- 1 day
- 1 month

Laboratory Cesium Standard

Courtesy of J. Vig

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Commercial Atomic Clocks

- Sizes from $\sim 10 \text{ cm}^3$ to $10^6 \text{ cm}^3$
- Power from $\sim 100\text{mW}$ to $100 \text{ W}$
- Stability (1s) from $\delta f/f \sim 10^{-9}$ to $\delta f/f \sim 10^{-13}$
- Price from $\sim $1k to $250k$ (not space qualified if you want space qualified x 10)
- Stability at 1 year $\delta f/f \sim 10^{-9}$ to $\delta f/f \sim 3 \times 10^{-15}$
Ramsey's method of separated oscillating fields

The final projection depends on the relative phase between the superposition and the microwave field!