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

• Near Future – (maybe) space clock

• More Distant Future – optical clocks & redefinition
Acknowledgements

Tom Heavner, Liz Donley and Tom Parker - the rest of the NIST-F1 team
Filippo Levi – IEN Turin Italy – who has worked with us on fountains for years
Jon Shirley – for answering all the theory questions
Len Cutler, Mike Garvey and Bill Riley – the real experts in the field who always have patient, well thought out answers to (sometimes stupid) questions and also provide last minute view graphs for talks!
Atomic Clocks - General
An Energy View of an Atom

Hydrogen-like (or alkali) atoms

Hyperfine structure of \(^{87}\text{Rb}\), with nuclear spin \(I=3/2\), 
\[ \nu_0 = \Delta W/h = 6,834,682,605 \text{ Hz} \] 
and 
\[ X = \left[-\frac{\mu J/J}{(\mu I/I)}\right]H_0/\Delta W \] 
calibrated in units of \(2.44 \times 10^3\) Oe.
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, $E=hf$ where $h$ is Planck’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.

$$\nu = \frac{E_{\text{final}} - E_{\text{initial}}}{h}$$
• 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)
Block Diagram – simplified a little

Applied Frequency - $\nu_0$

Signal Amplitude

-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5

0.0 0.2 0.4 0.6 0.8 1.0

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
Clock Performance

Clock 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
Ramsey's method of separated oscillating fields

The final projection depends on the relative phase between the superposition and the microwave field!
Laboratory Primary Frequency Standards
Definition of the Second

- The second is defined as 9,192,631,770 cycles of the hyperfine transition of a cesium-133 atom which is isolated from its environment (e.g., T=0, B=0, etc.) and at rest on the geoid of the earth (about “sea-level”).
- Note that what is really being defined is the frequency of the transition as being 9.192631770 GHz.
Accuracy and the Environment

• The definition of the second is essentially impossible to realize, we cannot get to absolute zero, the magnetic field is never zero etc.
• Laboratory (Primary) Standards deal with this by measuring the effect of these environmental frequency shifts and correcting the output frequency of the clock to achieve a, more or less, close approximation of the definition.
Magnetically Selected Thermal Beam

Illustration by Boris Starosta
Thermal Cesium Beam Clocks at NIST
NIST Standards vs Time

Clock Uncertainty (ns/day)

Frequency Uncertainty

YEAR


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

Laser-Cooled Clocks
Clock Performance

Clock 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
Ramsey Resonance in NIST-7 and NIST-F1

NIST-7

NIST-F1
Description of Cesium Fountain
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.
Laser Cooling of Atoms

Laser Frequency is tuned slightly below the atomic resonance:

\[ \omega_{\text{laser}} = \omega_{\text{atom}} - \delta \]

The atom is Doppler shifted into resonance with the laser beam on the right and thus absorbs photons from only this beam. Each photon transfers momentum \( \hbar \mathbf{k} \) to the atom. Since the subsequent photon emission is in a random direction, there is a net reduction in the atomic velocity.
Laser Cooling - molasses
Detection Region
NIST-F1 measured total deviation $\sigma_T(\tau)$
## Error Budget

<table>
<thead>
<tr>
<th>Physical Effects</th>
<th>Bias Magnitude ($\times 10^{-15}$)</th>
<th>Type B Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Order (quadratic) Zeeman</td>
<td>+44.76</td>
<td>0.02</td>
</tr>
<tr>
<td>Second Order Doppler</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cavity Pulling</td>
<td>0.0</td>
<td>0.02</td>
</tr>
<tr>
<td>Rabi Pulling</td>
<td>0.0</td>
<td>0.0001</td>
</tr>
<tr>
<td>Cavity Phase (distributed)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluorescent Light Shift</td>
<td>0.00001</td>
<td>0.00001</td>
</tr>
<tr>
<td>Spin Exchange</td>
<td>0.0 * (0.4-4)</td>
<td>0.1</td>
</tr>
<tr>
<td>Blackbody</td>
<td>20.6</td>
<td>0.26</td>
</tr>
<tr>
<td>Gravitation</td>
<td>+180.54</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### Electronic Shifts

<table>
<thead>
<tr>
<th>Electronic Shifts</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R.F. Spectral Purity</td>
<td>0</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Integrator Offset</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Microwave leakage</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Total Type B Uncertainty** 0.36
Zeeman

- (3,0)-(4,0) frequency is the “clock” transition
- (3,1)-(4,1) transition shifts by 701 kHz/ gauss, we use this to measure the magnetic field
- The (3,0)-(4,0) clock transition shifts by 427.45 Hz/ gauss
- In NIST-F1 the field is 0.85 mGauss and the shift is $\sim 2 \times 10^{13}$
Blackbody

• Radiation associated with non-zero temperature peak at about 10µm
• Frequency shift is relatively large ~$2 \cdot 10^{-14}$
• Shift is about $3 \cdot 10^{-16}/°C$
• Temperature Uncertainty is mainly due to leakage of room temperature radiation
• Final Uncertainty is Assigned 1°C ~ $\delta f/f = 3 \cdot 10^{-16}$
NIST-F1 operates with spin-exchange shift of \( \approx 0.4 \pm 0.1 \times 10^{-15} \).
Gravity

- Relativistic Effect...the higher above the reference geoid you go, the faster the clock runs.....the shift is about $10^{-16}/m$. This shift is $2\cdot10^{-13}$ in Boulder!!!!
- With care, the correction is good to less than $10^{-16}$.
- The reference geoid is approximately mean sea level.
## Error Budget

### Physical Effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Bias Magnitude ($\times 10^{-15}$)</th>
<th>Type B Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Order (quadratic) Zeeman</td>
<td>44.76</td>
<td>0.02</td>
</tr>
<tr>
<td>Second Order Doppler</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cavity Pulling</td>
<td>0.0</td>
<td>0.02</td>
</tr>
<tr>
<td>Rabi Pulling</td>
<td>0.0</td>
<td>0.0001</td>
</tr>
<tr>
<td>Cavity Phase (distributed)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluorescent Light Shift</td>
<td>0.00001</td>
<td>0.00001</td>
</tr>
<tr>
<td>Spin Exchange</td>
<td>0.0 * (0.4-4)</td>
<td>0.1</td>
</tr>
<tr>
<td>Blackbody</td>
<td>20.6</td>
<td>0.26</td>
</tr>
<tr>
<td>Gravitation</td>
<td>180.54</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### Electronic Shifts

<table>
<thead>
<tr>
<th>Shift</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.F. Spectral Purity</td>
<td>0</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Integrator Offset</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Microwave leakage</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Total Type B Uncertainty**: 0.36
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
NIST-F2 vs. NIST-F1 – a measurement of the Blackbody Shift

The data shown in blue are the individual runs since pressure control on the dewar. The final point (in red) is the average of all runs. F1 is corrected for blackbody, Zeeman and spin-exchange, F2 is corrected for spin-exchange and Zeeman.
How Do We Do Better?

- Work Harder on Earth – possible, but difficult, no matter how hard we work Ramsey times will be limited to \( \sim 1 \) s
- Go into Space – no gravity allows long Ramsey times – better accuracy
Physics Package – Parabolic flight

This is the entire physics package with pumping
All specialized vacuum parts (e.g. windows, seals etc are COTS)
Source region can be made much smaller with custom pieces
Ramsey Interaction zone has 2 layers of magnetic shielding – all of the clock has at least one layer.
Vescent Laser System for AFRL/NIST cold Cs. Clock
This is the entire physics package with pumping.

All specialized vacuum parts (e.g. windows, seals etc are COTS).

Source region can be made much smaller with custom pieces.

Ramsey Interaction zone has 2 layers of magnetic shielding – all of the clock has at least one layer.
Microwave Synth & Quartz

Stability above is based on one quartz
5 selected quartz oscillators together give sufficient headroom to
avoid Dick-effect at \( \sigma(y(\tau)) = 2 \times 10^{-13} / \sqrt{\tau} \).
Will require an additional 1.2 W or so.
MK III Physics Package
GPS MK 3 Vacuum Chamber

- Cavity, cavity nipple and detection region will be made of aluminum. Ti shown in green, Cu in Cu color.
GPS MK 3 w

- Titanium Molasses Chamber
- Titanium Window Flanges
GPS MK3 unmounted, no detection optics

- Miniature Vacuum pump on left side
- Shielded Molasses chamber
- Folded Collimators
Source Region

Current Design
(Flight EM (MK3))

Proposed Design

SIDE VIEW

TOP VIEW
Cs, Rb laser-cooled vs. KERNCO GPS
Predicted Performance

- Assumes Atom Shot Noise limit and removal of 14 cm of length on current design (we believe that 20 cm reduction is achievable, 14 cm is obvious).

- Assumes 4 additional quartz oscillators at 300 mW and 8 cm³ each.

- Clock cycle time is 0.5s and Ramsey is 0.18s

\[
\sigma_{\downarrow y}(\tau) = \frac{1}{T_{\downarrow R}} \frac{1}{\sqrt{2N}} \frac{\sqrt{T_{\downarrow C}}}{\tau}
\]

This gives \(\sigma_{\downarrow y}(\tau) = 2.1 \times 10^{-13} / \tau^{1/2}\)

for a very conservative atom number of \(5 \times 10^4\) (we see 10x this in the lab routinely).
Scientific Goals

- Relativistic Frequency Shift
- Gravitational Frequency Shift
- Local Position Invariance Test
- Realization of the Second
- Studies of the Global Positioning System
How Do We Do EVEN Better?

- Microwave Standards probably limit in the $\delta f/f \sim 5 \cdot 10^{-17}$ level ..... Then What?
- Remember $\sigma \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta \omega)(S/N)}$

SO.. Make $\omega$ bigger!
Neutral Optical Clocks

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

10^{15} \text{ Hz}

Image of Trapped Ca Atoms:
Optical Clock at 657 nm is based on a narrow transition in neutral calcium.

New techniques are now available for optical-to-microwave comparisons.

*Oats, Hollberg, Optical Frequency Measurements Group, Time and Frequency Division, NIST*
Ion Trap Clocks

Image of Trapped $^{199}$Hg$^+$ Ions

Linear RF Ion Trap

Ion Traps:
- Long Ramsey Times (100 s)
- Small Trapping Volume (Lamb-Dicke Regime)
- 40.5 GHz Transition
- Optical Transition at 282 nm ($10^{15}$ Hz)

* Bergquist, Itano, Bollinger, Wineland, Ion Storage Group, Time and Frequency Division NIST
Conclusions

• Laser-Cooling for Frequency Standards allows higher accuracy in both microwave and optical clocks

• Cesium Primary Frequency Standards fulfill present and foreseeable future needs up to $\delta f/f = 10^{-16}$ or so

• Future (>10 years) Primary frequency standards will probably be based on optical transitions.