Boulder Flatirons
Charles H Townes: Jan’s all-time hero and role model

“Good bye, and thanks for all you have done”  
Picture from “CREOL at 25”, Orlando FL 2012
This award was presented by Charlie Townes to Venia and me at CLEO May 1984

The following speaker was Richard P Feynman, talking about some half-crazy 1984 Quantum computing idea...
Some of my Best Friends, in High School, were Radio Tubes
There is a difference in the University town of Fort Collins Colorado!
Advances in Laser Locking -- Accuracy and S/N

\[ \text{Locking Accuracy at the level of } 1 \times 10^{-6} \text{ Linewidths!} \]

- Finally, 32 years after PDH, 10 orders of linewidth reduction, the Optical Comb, and all that Jazz: we can approximate the line-splitting skill of our Cesium clock colleagues!

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CH$_4$ Saturated Absorption at 3.39 $\mu$m

Sharp! (Doppler/1000) Contrast $\sim$12%
PDH - The *ideal* laser frequency stabilizer!

**Offset Issues:**
1. Weak reflected beams – optical isolation insufficient
2. Pure Phase modulation – contamination by AM (the RAM problem)

**Noise Issues:**
1. Cavity length changes – temperature and vibration
2. Thermal noise of coatings and substrates
3. Unwelcome shot-noise from image-frequency sidebands
• Atomic confinement $\ll \lambda$ ($e^{i k x} \sim 1$, $k = 2\pi/\lambda_{\text{probe}}$)
• Trap potential identical for $|g\rangle$ and $|e\rangle$
• Precision improvement by $N^{1/2}$

$$\frac{\delta \omega(\tau)}{\omega_0} = \frac{1}{Q} \times \frac{1}{\sqrt{N}} \times \sqrt{\frac{T_c}{\tau}}$$

• Long coherence time; Zero Doppler shift, Zero recoil shift

• No light shift from the trap; but, interaction effects? Accuracy?
Systematic evaluation of an atomic clock at $2 \times 10^{-18}$ total uncertainty

T.L. Nicholson$^{1,2}$, S.L. Campbell$^{1,2}$, R.B. Hutson$^{1,2}$, G.E. Marti$^{1,2}$, B.J. Bloom$^{1,2}$, R.L. McNally$^{1,2}$, W. Zhang$^{1,2}$, M.D. Barrett$^{1,3}$, M.S. Safranova$^{4,5}$, G.F. Strouse$^{6}$, W.L. Tew$^{6}$ & J. Ye$^{1,2}$

The pursuit of better atomic clocks has advanced many research areas, providing better quantum state control, new insights in quantum science, tighter limits on fundamental constant variation and improved tests of relativity. The record for the best stability and accuracy is currently held by optical lattice clocks. Here we take an important step towards realizing the full potential of a many-particle clock with a state-of-the-art stable laser. Our $^{87}$Sr optical lattice clock now achieves fractional stability of $2.2 \times 10^{-16}$ at 1s. With this improved stability, we perform a new accuracy evaluation of our clock, reducing many systematic uncertainties that limited our previous measurements, such as those in the lattice ac Stark shift, the atoms’ thermal environment and the atomic response to room-temperature blackbody radiation. Our combined measurements have reduced the total uncertainty of the JILA Sr clock to $2.1 \times 10^{-18}$ in fractional frequency units.
In the future, a new standard of Frequency/Time will be needed

When?
Optical Progress will have slowed down
Candidate Systems have had full & multiple Evaluations
Remote comparisons are possible/convenient

Adapted from P Gill 2013
FIG. 19 (color online). Measurements between atomic clocks of different species can constrain possible variation of fundamental constants. A number of comparisons between distinct atomic-clock species are used here to constrain time variation of $\alpha$ and $\mu$. From Huntemann et al., 2014.
GPS allows transferring frequency to $3 \times 10^{-14}$ and time to $\approx 10$ ns in one day.
Planned European Metrology Fiber Network (2010) (planned in Paris)

First results in preprint circulation May 2016
Surely there could be 1 all-optical link across?
Probably these guys don’t have any dark fibers we could use ....

PS: did you read “The Flash Boys”?
View of the Earth four hours before apogee from a Molniya orbit, if longitude of the apogee is 90° W.
The spacecraft altitude is 24,043 km over the point 87.35° W 47.04° N.

\[ \frac{R_{\text{perigee}}}{R_e} = \frac{6591}{6371} = 1.035 \rightarrow 96.6\% \]

\[ \frac{R_{\text{apogee}}}{R_e} = \frac{30414}{6371} = 4.774 \rightarrow 20.95\% \]

GR Shift = (0.966 – 0.2095) * 5.228 \times 10^{-10} = 3.958 \times 10^{-10} \Rightarrow 79 \text{ kHz for 1.5 \mu m laser}
Earth’s Rotation as a Distance Modulator

Aphelion +1.65 x10^{-10}  

noon \[\text{midnite}\]  

Perihelion - 1.65 x10^{-10}  

General Relativity Redshift:  \[\frac{\delta\omega}{\omega} = \frac{GM}{Rc^2} \approx 9.8 \times 10^{-9}\]

Fractional Distance Shift:  \[\text{midnite} \leftrightarrow \text{noon} \sim \pm 4.2 \times 10^{-5}\]

For Sr clock (429 THz) this is about \(\pm 180\) Hz!

Present measurement precision < 5 milli-Hz

European fiber network colleagues should compare absolute frequencies in mid-summer!
After S Dali
“The Persistence of Memory”
Home Sweet Home

Standard Time

The kitchen closed at 7:30
JILA 1987 ULE Reference Cavity

Vacuum Shell, heated

Outer thermal shell, cooled
Tapered Shape
Reduces Acceleration Sensitivity

Symmetrical Mounting
* Cancels *
vertical acceleration sensitivity
(A. Ludlow)
Choice of Stiff Cavity Material vs Low/Zero Thermal Expansion

ULE has zero CTE near room temperature
Silicon has zero CTE near 124 K, and near 4 K
Optical coherence & spectral resolution

Cavity length $L \sim 1 \text{ m} \rightarrow \Delta L \sim 10^{-16} \text{ m}$ (size of a nucleus: $10^{-14} \text{ m}$)

Mirror Thermal Noise: a fundamental process (Numata, Bergquist, ...)

Mike Martin: Sr 40 cm ULE cavity

Bishof et al., PRL 111, 093604 (2013).

Swallows et al., IEEE TUFFC 59, 416 (2012)

Fractional stability

Thermal noise limit: $\sim 1 \times 10^{-16}$

linewidth: 26 mHz

Coherence time $\sim 20 \text{ s}$

$Q \sim 2 \times 10^{16}$
Crystal-based Mirror coatings have 10x lower thermal noise

Mark Notcutt (Stable Laser Systems) will discuss cavity stability re vibrations

What about Locking the Laser to Molecular Saturated Absorption?
Sub-Hz Optical Frequency Reference System

Predicted Results, 10 cm cavity length, 1 s τ

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Let’s Calculate what we could do with Saturated Molecular Absorption

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<td>72</td>
<td>pi</td>
<td>3.14159</td>
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</tbody>
</table>
Let’s Calculate what we could do with Saturated Molecular Absorption -2-
Let’s Calculate what we could do with Saturated Molecular Absorption -3-

CO\textsubscript{2} Cavity-Enhanced Sat Abs
1571 nm overtone
Expt parameters: 5m vs flat, 10 cm
Calc: Cavity width \(\sim 20\) kHz
Molecular resonance \(\sim 1.02\) MHz
Contrast 9\% on 840 \(\mu\)W
\(\sim 10\) mK \(\rightarrow\) pressure shift \(\rightarrow 1\) Hz

Collaboration with:
Sarah Bickman
Mike Anderson
Mark Notcutt
July 2011
Sub-Hz Optical Frequency Reference System

Predicted Results, 10 cm cavity length, 1 s τ

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>Wavelength (nm)</th>
<th>Power (mW)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCCH</td>
<td>P(16)</td>
<td>1534.742</td>
<td>1.2</td>
<td>0.34</td>
</tr>
<tr>
<td>CO</td>
<td>R(7)</td>
<td>1568.04</td>
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<td>R(24)</td>
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<td>12.</td>
<td>0.25</td>
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</table>
Jan’s Proposed Tools
For the STAR Mission

Multiple Redundant Cavities

Duplicate Atomic Clocks

Gas-Cell Frequency Standard
CO or CO$_2$
1500 nm telecom optics

Ke-Xun Sun’s Multipass Idea for the Gas Cell
Accurate Removal of RAM from FM Beams?

- Finally, 32 years after PDH, 10 orders of linewidth reduction, the Optical Comb, and all that Jazz: we can approximate the line-splitting skill of our Cesium clock colleagues!

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Boulder CO 80309-0440
jhall@jila.colorado.edu
http://jila.colorado.edu/hall
jan@HallStableLasers.com

The RAM-Buster!
US PTO- Prov.2015/04/14/62147276

Int’n’l Frequency Control Symposium April 2015
Denver CO
Testing: Locking at the **CENTER** of the resonance?

#1 “Tune off the resonance and check the baseline”
dc Offset is ~ 0.67 mV at Doubly-Balanced Mixer

HOWEVER the Offset is the same with Light ON or Light OFF ???

It is not RAM, instead it is weak non-optical pickup of the rf wave

Anti-RAM Gain seems to be ~ 1 E6!

How is this RAM-Buster Gain even Possible?
**the Big Idea: Compare two Approaches for Active Anti-RAM**

1) Modulation at 1 MHz, Gain = 1E6 \( \rightarrow \) Needed BW is > 3 GHz

2) “Gas Pedal” Cancellation Servo: Gain at 1 MHz > 1E6 but BW needed is ~ 1 kHz!

---

F du Burck, A Goncharev, O Lopez  Metrologia 46, 599 (2009)
the RAM-Buster Accessory
Testing the RAM-Buster - the 2nd Way

Also see Wei, Ye & Hall  Opt Lett April 1, 2014  (fiber modulator)
Starting Optical Alignment: ~10% RAM
EOM “prism” scans beam over fiber core - Pure Q Error
I- Gain ~0.2 Hz      Q - Gain ~10 Hz  (for unity gain)
High “I” gain -- medium “Q” gain
Q- and I- Gains ~ 40 Hz, for unity gain
Testing the **RAM-Buster**

way #3  ➔ FFT of the rf PDH-lock error signal  ➙
Characteristics of the Residual Amplitude Modulation

What can a PID servo do?
25 Hz span
31.25 mHz RBW

RAM peak 3.4 ppm
Using interim Detector
300 k Transimpedance

Calc Shotnoise (1Hz)

330 mV dc light 1.1 uA

wave194
no light

wave195
V3 H1

wave192d
V7 H4

wave191
V1 H1

10x Detector Output Noise Density, V/Sqrt(Hz)
Rise of RAM noise toward the carrier
Data file 159 May29B, 2014
Res LW is 0.125 Hz
Line slope is -1/2

\[ \text{RBW} = 2 \times 0.125 \text{ Hz} \]

'half.wav192' gain = 70 dB
'half.wav189' gain = 30 dB
'half.wav188' gain = 40 dB

Inside Loop remaining RAM; Controller is PI

-->RAM diverges faster than \( f^{-1.5} \)
Residual Error Signals (10x DBM outputs) with RAM-Buster Locked

Upper graph: I-ch-DBM output (10x)
- RAM-Buster locked
- G(I) = 8
- G(Q) = 9

Lower graph: Q-ch-DBM output
- Both ch Locked: Q-ch
- Output of DBM 10x Buffer

Graphs show dbV/Sqrt(Hz) vs. frequency (Hz) with various outputs and locked states.
Fig. 2 Two Approaches to Measuring RAM – at the ppm Level.

a) Out-of-Loop RAM via PDH signal; b) Selected 21¾ h data between noise bursts;
c) Corresponding Allan Deviation; d) FFT of down-shifted cavity reflection signal. Original 1.18 MHz rf carrier is now shifted to 1 kHz, where the small residual 1.5 μV rms peak is less than shotnoise in the 0.25 Hz RBW spectrum, and is just visible in 25 coherently-added sweeps. So the effective noise BW is ~10 milliHz. - HOWEVER, this signal is 1.2 μV with the light blocked!
Frequency-Jump Saturated Absorption Spectroscopy

Crossed saturation and probe polarizations. Frequency to AOM jumps ±350 kHz. RAM and differential Doppler absorption cancelled by feedback to AOM power. Laser Amplitude noise is reduced to ~3 dB above signal shotnoise by Hobbs’s idea.
Signals in Frequency-Jump Spectroscopy

Sat Beam Transm After Hobbs 2

Time Gating for Abs Signal

Probe Absorption After Hobbs 1

Transm Sat Pwr
RAM Servo Locked - Freq on side of line

RAM Servo input
Sat Abs Sig
Signal Gate
Transm Sat Pwr
Freq Servo Locked – RAM Servo OFF

Form RAM sig via Hobbs 2 from Sat beam, meas. after cell

Sat Power after cell jumps between 2 freqs
Both RAM and Freq Servos are ON

Freq noise equiv (1s) ~ 50 Hz (~1 E-13 at 1 s)

RAM input

Signal Gate

Sat Abs Signal
12 V pp => 0.6 MHz
$\delta \nu \approx 15$ kHz

Freq-jumping Sat Beam, after cell
Inner Shell Temp
Drift -200 uK/60 ks

Freq Drift
+6.6 mHz/s

Iodine Resonance
w Jumper Lock
~750 kHz :
Lock instability ~1E-5 * Δν
Narrow-line Lasers

< 1 Hz   Young, Cruz, Itano, Bergquist prl 82, pp. 3799-3802 (1999)
~100 mHz Jiang, Ludlow, Lemke, Fox, Sherman, Ma, and Oates Nature Photon. 5 158 (2011)
< 80 mHz Kessler, Hagemann, Grebing, Legero, Sterr, Riehle, Martin, Chen, Ye Nat. Phot (2012)
< 30 mHz Bishof, Zhang, Martin, Ye Phys Rev Lett 111 093604 (2013)

Thermal noise limit  ~ 2 E-16   ULE spacer, SiO2 mirror blank, amorphous multilayer mirrors
Reduced thermal noise limit  : expect ~10x with crystalline layer mirrors   (Ye & Zhang, JILA)

Next:
Siicon crystal cavity with crystalline mirrors, at 4 degrees K !

collaboration of Ye group, PTB, and Garrett Cole
Provisional Conclusions

With present sub-optimum laser power, we lost \( \sim 10x \) in S/N

But

We now have \( S_\nu \cong 20 \text{ Hz}/\text{Sqrt}(\text{Hz}) \),

near to best from

last century’s JILA work with Modulation Transfer Spectroscopy w J Ye & L-S Ma
Talking Science in Munich - 2005

Jan, Thomas Udem

Ted, Ron Drever
Thanks for Listening

• http://jila.colorado.edu/hall/
• http://HallStableLasers.com

• Jun - http://jila.colorado.edu/YeLabs/

• Lindy – http://Sci-TeksDiscoveryProgramforKids.org

• NIST - http://tf.nist.gov/timefreq/

• 50th Year of Lasers - http://LaserFest.org
Nd:YAG + 2H gen

F = 15 kHz
Fsr = 541 MHz

45° Faraday

RAM Reference

PDH Signal

PDH Locking, with "RAM Buster" Accessory
Anti-RAM Servo - digs below the (open-loop) noise level!
Sub-Hz Optical Frequency Reference System©

Predicted Results, 10 cm cavity length, 1 s tau

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Sub-Hz Optical Frequency Reference System©
The offset frequency arises from:
Group velocity $\neq$ Phase velocity

The Comb Concept

J-B Fourier 1822; T W Hänsch, V P Chebotayev ~1979
Phase coherent distribution – at any frequency!

Femtosecond Laser Comb
$10^6 : 1$ Reduction Gear
(not to scale!)

Radio Frequency
$Q \sim 10^8 - 10^{11}$

Optical frequency
$Q \sim 10^{14} - 10^{15}$

$\frac{\omega_3}{\omega_1} \sim 10^6$
Precise distribution of ultra-stable signals


SYRTE/PTB, NIST, ...

> 30 km fiber:
1 x 10^{-17} @ 1 s;
1 mHz optical linewidth;
0.1 fs jitter (20 MHz BW)
Squeeze-insensitive Optical Reference Cavity

Fig. 1. (a) CAD rendering of a SC mounted at the squeeze insensitive angle with Viton o-ring contacts. Note that this is the experimental design. (b) Cross section of a SC mounted at the squeeze insensitive angle with cylindrical ULE contacts. This is the design used for the finite element analysis model. Important coordinate systems and dimensions are labeled. The sphere is 50.8 mm in diameter and has a 6 mm diameter bore drilled through it along the optical axis. The mirrors are optically contacted to the sphere on flats separated by $L = 48.5$ mm and are 12.7 mm in diameter and 4.2 mm thick. The two support contacts are attached to the sphere along the support axis which is oriented at $\theta_{\text{support}} = 37.31^\circ$ with respect to the $y$ axis and have dimensions $d_{\text{support}} = l_{\text{support}} = 1$ mm.

Leibrandt, Thorpe, Notcutt, Drullinger, Rosenband, Bergquist  Opt Exp. 19, 3471 (2011)
A cavity-stabilized laser with acceleration sensitivity below $10^{-12}/g$

David R. Leibrandt,* James C. Bergquist, and Till Rosenband
National Institute of Standards and Technology, 325 Broadway St., Boulder, CO 80305, USA
(Dated: January 3, 2013)

We characterize the frequency-sensitivity of a cavity-stabilized laser to inertial forces and temperature fluctuations, and perform real-time feed-forward to correct for these sources of noise. We measure the sensitivity of the cavity to linear accelerations, rotational accelerations, and rotational velocities by rotating it about three axes with accelerometers and gyroscopes positioned around the cavity. The worst-direction linear acceleration sensitivity of the cavity is $2(1) \times 10^{-11}/g$ measured over 0–50 Hz, which is reduced by a factor of 50 to below $10^{-12}/g$ for low-frequency accelerations by real-time feed-forward corrections of all of the aforementioned inertial forces. A similar idea is demonstrated in which laser frequency drift due to temperature fluctuations is reduced by a factor of 70 via real-time feed-forward from a temperature sensor located on the outer wall of the cavity vacuum chamber.

PACS numbers: 42.62.Eh, 42.60.Da, 46.40.-f, 07.07.Tw

FIG. 1: (a) Computer-aided design (CAD) drawing of the mounted Fabry-Perot cavity. The spherical cavity spacer is 50 mm in diameter. (b) Cross-sectional view showing the details of the contact between the cavity and the mount. A Torlon ball is compressed between the flexure spring and the vacuum pump-out hole in the cavity. FS: fused silica.

Accelerometers, Gyros Rotation Sensors, Thermal Sensors

Use Feed-Forward Correction:
50x improvement re accelerations
70 x improvement re temperature

Enabling Technology: phase-locked lasers in a moving automobile!