Towards Optical Atomic Clocks

Outline

Introduction to optical clocks

Accuracy and stability of an optical frequency standard with Ca atoms

Optical frequency measurement

Future prospects: optical lattice clock
Measurement of the “magic wavelength”
Applications that require better atomic clocks

Generation of more stable time scales

Tests of fundamental theories:
  General Relativity
  Quantum Electrodynamics
  Cosmology
  Constance of fundamental constants

Navigation
  Deep-space navigation
  Pioneer anomaly
Deep Space Network


4 „Swingbys“ near Venus, Jupiter, Earth at 300 km distance

Required accuracy: +/- 25 km

Telemetry using 3 antennas on earth only works with the best clocks available.
Temporal Variation of Fundamental Constants

\[ \frac{\partial \ln f}{\partial t} = \frac{\partial \ln R_y}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t} \]

\( \frac{\partial \alpha}{\partial t} \) and \( \frac{\partial R_y}{\partial t} \) estimate (weighted mean of present Yb\(^+\), Hg\(^+\), H data)

1σ confidence range

Peik et al. PRL 2004
Principle of Clocks

- Oscillator
- Neutral atoms
- Servo-electronics
- Detector
- Error signal
- Absorption signal
Stability of Atomic Clocks

Stability:
necessary averaging time, to detect a certain effect?

depends on relative line width $\Delta \nu/\nu_0$
atom number $N$ and cycle time $T_c$

$$\sigma_y(\tau) \approx \frac{\Delta \nu}{\nu_0} \sqrt{\frac{T_c}{N \tau}}$$

goal: small instability

reduction of $\Delta \nu$ with cold trapped atoms;
increase $\nu_0$ (optical frequencies instead of microwaves)
171Yb+ Single-Ion Frequency Standard

transition: \( ^2S_{1/2} - ^2D_{3/2} \)

\[ \lambda = 436 \text{ nm}, \Delta \nu = 3.1 \text{ Hz} \]
\[ \sigma_y(\text{min}) \approx 5 \cdot 10^{-15} \text{ s}^{-1/2} \]

- two traps agree within a few Hz
- shift due to stray fields

frequency comparison of two traps  
(same conditions)

- \( \langle \Delta \rangle = 0.2 \text{ Hz} \)
- \( \langle \Delta \rangle / \nu = 3 \cdot 10^{-16} \)

Quantum jump probability

\text{Detuning at 435.5 nm (Hz)}
Sub-Doppler Cooling of Calcium

first stage:

- $T \approx 3 \text{ mK}$

second stage: quench-cooling:

- $T \approx 10 \text{ } \mu\text{K}$

T. Binnewies et al., PRL 87, 123002-1 (2001)
Cold and Ultracold Atom Interferences

Doppler width
3 MHz

Fourier width
1 MHz

Doppler width
0.2 MHz

- optimum contrast of the atom interferences
- higher S/N (all atoms contribute to the signal)
- better known line shape
- novel detection scheme applicable

ultracold atoms
Time-Domain Atom Interferometers

Interference signal:
\[ S(\Delta \Delta \Phi) \propto 1 - C \cos(\Delta \Phi) \]

Phase evolution between the pulses:
\[ \phi = t \cdot E / \hbar \]

Beam splitters

Asymmetric atom interferometer
\[ \Delta \Phi_a = [2\pi(v - v_0) + \delta] \cdot 2T + \Phi_2 - \Phi_1 + \Phi_3 - \Phi_4 \]

Symmetric atom interferometer
\[ \Delta \Phi_s = 2\Phi_2 - \Phi_1 - \Phi_3 \]

Signal (10^6 s^{-1})

Signal (10^6 s^{-1})
Spurious Phase Shifts in an Optical Clock

\[ I(\nu - \nu_0) \sim \cos \left( [2\pi(\nu - \nu_0) + \delta] \cdot 2T + \Phi_2 - \Phi_1 + \Phi_3 - \Phi_4 \right) \]

\[ \Phi(\vec{r}(t_i)) = \vec{k} \cdot (\vec{r}_0 + \vec{v}_0 \cdot t_i + \frac{1}{2} \vec{g} \cdot t_i^2) + k \frac{r_\perp(t_i)^2}{2R} \]

**velocity**  **gravity**  **wavefront curvature**

Correction of Spatial Phase Errors

\[ \Delta \Phi = \text{const} \cdot T^2 \]

The \text{const} depends on horizontal alignment and wavefront curvature.

With ultracold atoms the residual shifts due to spatial phases contribute less than 1 Hz \((2 \times 10^{-15})\).

\text{horizontal alignment:} \quad < 100 \ \mu \text{rad} \ (0.3 \ ')

\text{radius of curvature:} \quad R > 6 \ \text{m} \\
\text{(small sensitivity at} \ T=10 \ \mu \text{K})
Correction of Spatial Phase Errors

frequency shift as a function of the pulse separation time $T$

resolution dependence
Temporal Phase Errors: AOM Chirp

- Instantaneous optical phase during a laser pulse for different AOM center frequencies
- Measured and calculated shift using optical Bloch equations with measured temporal laser phase
Density-dependent shift at $T \approx 20 \, \mu$K:

$$\Delta \nu = A \cdot \langle \rho \rangle$$

$$A = (-2 \pm 6) \cdot 10^{-11} \, \text{Hz cm}^3$$

frequency uncertainty

$$u(\nu) = 0.06 \, \text{Hz}$$

Collisional Frequency Shift at $T = 20 \, \mu$K

<table>
<thead>
<tr>
<th>Atom</th>
<th>$A/\nu$ (10^{-24} , \text{cm}^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs ($F = 3)$</td>
<td>-600 $\pm$ 60</td>
</tr>
<tr>
<td>Rb ($F = 1)$</td>
<td>-6.4 $\pm$ 16.4</td>
</tr>
<tr>
<td>Ca</td>
<td>-0.04 $\pm$ 0.12</td>
</tr>
</tbody>
</table>

mean-field energy:

$$E_{MF} = \frac{4\pi \hbar^2 a}{m} n < 0.1 \, \text{Hz} \cdot h$$

s-wave scattering length (50 $a_0$ – 300 $a_0$)
## Uncertainty budget

<table>
<thead>
<tr>
<th>Effect</th>
<th>T = 12 µK (2003)</th>
<th>T = 12 µK near future</th>
</tr>
</thead>
<tbody>
<tr>
<td>spatial phases - Doppler effect</td>
<td>1.0 Hz</td>
<td>150 mHz</td>
</tr>
<tr>
<td>temporal phase contributions</td>
<td>1.6 Hz</td>
<td>200 mHz</td>
</tr>
<tr>
<td>asymmetry of line shape</td>
<td>0.05 Hz</td>
<td>50 mHz</td>
</tr>
<tr>
<td>magnetic field (64 Hz/mT²)</td>
<td>0.2 Hz</td>
<td>200 mHz</td>
</tr>
<tr>
<td>quadratic Stark effect (</td>
<td>E</td>
<td>&lt; 2 V/cm)</td>
</tr>
<tr>
<td>black body radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>oven</td>
<td>3.9 Hz</td>
<td></td>
</tr>
<tr>
<td>walls</td>
<td>0.07 Hz</td>
<td>70 mHz</td>
</tr>
<tr>
<td>laser frequency drift</td>
<td>0.1 Hz</td>
<td>100 mHz</td>
</tr>
<tr>
<td>influence of cold atom collisions</td>
<td>0.06 Hz</td>
<td>60 mHz</td>
</tr>
<tr>
<td>statistical uncertainty of the frequency meas.</td>
<td>3.0 Hz</td>
<td>5 mHz</td>
</tr>
<tr>
<td>Cs clock (1⋅10⁻¹⁵)</td>
<td>0.5 Hz</td>
<td></td>
</tr>
<tr>
<td><strong>total uncertainty δν</strong></td>
<td><strong>5.5 Hz</strong></td>
<td><strong>370 mHz</strong></td>
</tr>
<tr>
<td><strong>total relative uncertainty δν/ν</strong></td>
<td><strong>1.2⋅10⁻¹⁴</strong></td>
<td><strong>8⋅10⁻¹⁶</strong></td>
</tr>
</tbody>
</table>
New Setup

direct loading from thermal atomic beam is replaced by:
• Zeeman slower
• 2-D molasses to deflect slow atoms to MOT region
• better loading rate: $10^9$ trapped atoms within 1 s
Optical frequency measurement of calcium

Ca-Frequency-standard
456 THz

Comparison
frequency chain / frequency comb

Primary Standard
Cs-Fountain
9.2 GHz

October 2003

ν_{Ca} = 455 986 240 494 143 Hz
± 5.5 Hz

\[ \frac{u(ν_{Ca})}{ν_{Ca}} = 1.2 \cdot 10^{-14} \]
Principle of Clocks

oscillator

neutral atoms

detector

servo - electronics

absorption signal

error signal
Interrogation Laser

Resonance frequencies: 0.7 Hz vertical, 0.6 Hz horizontal

finesse: 79 000
linewidth (FWHM): 19 kHz
Beat between Two Independent Lasers

optical phase difference between two lasers

power spectrum of the beat

laser linewidth ~ 1 Hz
drift 0.06 Hz/s
Measured Stability

Allan standard deviation $\sigma_y(\tau)$ limited by technical and laser noise of Ca-standard

Quantum-Projection noise limit

$\sigma_y(1s) = 5 \cdot 10^{-17}$

$(N_0 = 3 \cdot 10^7 \text{ atoms})$

$T_{cycl} = 30 \text{ ms}$

$$\sigma_y(\tau) = \frac{1}{\pi} \cdot \frac{1}{4T_0} \sqrt{\frac{1 - \bar{p}}{N_0 K^2 \bar{p}}} \cdot \sqrt{\frac{T_{cycl}}{\tau}}$$
Optical Frequency Comb

time domain:
fs-laser with repetition frequency $f_{\text{rep}}$

frequency domain:
comb of frequencies

self-referencing
to measure $v_{\text{ceo}}$

$$v(m) = v_{\text{ceo}} + mf_{\text{rep}}$$
$$v(2m) = v_{\text{ceo}} + 2mf_{\text{rep}}$$
$$v_{\text{ceo}} = 2v(m) - v(2m)$$
Fiber Laser fs Frequency Comb

Er\textsuperscript{3+}-doped fs-fiber laser, $\lambda \sim 1550$ nm

- long term operation: 88 h without interruption
  $3 \cdot 10^{21}$ counts

Stenger et al., PRL 88 073601 (2002)

frequency measurement of a cavity-stabilized diode laser

performance of a Ti:Sapphire comb
Concept of an optical lattice clock

“Magic Wavelength”
- no net light shift
10^7 neutral atoms

Advantages

• Very long interaction time
  small line width

• Confinement to the Lamb-Dicke regime \( \Delta x < \lambda \)
  no first-order Doppler effect

• Large number of atoms
High signal-to-noise-ratio
\( S/N \sim N^{1/2} \)

• Prospects to surpass this quantum limit with entangled states

Earth alkali elements Mg, Ca, Sr and Yb, Hg have metastable $^3P_0$ state

- accessible by 1 photon transition in fermionic isotopes, $\Delta \nu \sim \text{mHz}$
- or by 2 and 3 photon Raman transitions also in bosonic isotopes
- “magic wavelengths”
- efficient cooling possible
Measurement of Ca - “Magic Wavelength”

Theory:
using available atomic data and adjusting line strength of the 2 most important transitions

magic wavelengths:

$^3P_1 : (800.8 \pm 2.2) \text{ nm}$

$^3P_0 : (735.5 \pm 20) \text{ nm}$

Degenhardt et al. PRA 70, 023414 (2004)
Optical dipole trap

- Conservative light forces in focused laser beam to trap atoms
- Trap depth: 8 W @ 514 nm, $w_0 = 50 \, \mu m \Rightarrow U_{dip} = 40 \, \mu K$
- Loading of dipole trap: overlap with MOT ~ 2% transfer
- Quench-cooling is compatible with trap operation as long as the light-shifts are right! (poster Felix Vogt)

0 ms 10 ms 20 ms 30 ms expansion after turning off the MOT

- how close will laser cooling lead towards quantum degeneracy?
Conclusion

- Calcium clock at present
  - frequency uncertainty $1.2 \cdot 10^{-14}$
  - negligible collisional frequency shift
- Reliable fiber based femtosecond comb
- Measurement of “magic wavelength”
- Optical dipole trap for calcium

**Future:**
- Uncertainty $\approx 10^{-15}$ with ballistic atoms
- Clock with instability $< 10^{-16}$ in one second
- Optical lattice clock with low uncertainty
- Quantum degeneracy
Ca and Sr standards:
  Tatiana Nazarova
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  Paul-Eric Pottie
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  Fritz Riehle
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