Atomic Clock Technology

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Goals and definitions of terms
Atomic resonance properties and interrogation techniques
Basic atomic clock architecture
Cesium beam atomic clocks
Hydrogen maser atomic clocks
Rubidium gas cell atomic clocks
Contrast cesium, hydrogen, and rubidium performance
Other clock technologies
Goals

Understand different clock technologies so that intelligent decisions can be made to optimize system performance, cost, lifetime and reliability.
Normalized frequency:

- Also called “fractional frequency offset”

\[ y = \frac{(\nu - \nu_0)}{\nu_0} \]

- Example:
  - -1 Hz offset at 5 MHz (4 999 999 Hz) is -2e-7
The Allan deviation is a statistical measure (analogous to the well known standard deviation) of frequency stability.

\[ \sigma_y(\tau) = \left[ \frac{1}{2(M - 1)} \sum_{i=1}^{i=M-1} (\bar{y}_{i+1} - \bar{y}_i)^2 \right]^{1/2} \]

Allan deviation can be predicted from basic atomic resonance parameters (more on this later)
Why Atomic Clocks?

- Atoms of a given element and isotope are identical.
- Properly designed apparatus can interrogate atomic resonances to form precise and stable frequency references.
- The best atoms are “hydrogen like” in their atomic structure: $^1$H, $^{133}$Cs, $^{87}$Rb.
- While cesium defines the SI second, stored ions and optical transitions in other atoms ($^{199}$Hg$^+$, $^{171}$Yb$^+$, $^{88}$Sr$^+$, Ca) may be candidates for evolutionary laboratory standards.
Basic (Passive) Atomic Clock

Cesium: $v_0 = 9\,192\,631\,770$ Hz (definition)
Hydrogen: $v_0 = 1\,420\,405\,751.770\,(3)$ Hz
Rubidium: $v_0 = 6\,834\,682\,610.904\,29(9)$ Hz
Atomic Energy Levels and Resonance

$E_2 - E_1 = h\nu_0$

--Atoms can reside only in well defined energy states
--Transitions between energy states define a resonance, usually in the microwave region
Accuracy and Stability
Accuracy vs Stability

Stable-not accurate

Stable-linear drift-not accurate

Accurate-not stable (noisy)

Stable and Accurate
Design Considerations

- Accuracy: preserve the intrinsic accuracy of the atomic resonance
- Short Term Stability: extract information with highest signal-to-noise from the atoms. Characterized with Allan deviation.
- Long Term Stability: control the effects of time (aging) and environment (e.g., temperature) on the atomic interrogation?
- Accuracy and stability are usually interrelated.
- How do we achieve reasonable size, cost, and operational reliability?
Accuracy

- Presumption of ensemble of identical unperturbed atoms at rest at 0 K
- Realities of practical devices:
  - Atoms are in motion: Doppler effects
  - Confinement effects
  - Interrogation effects
  - Environmental effects
Calibration vs Accuracy vs Stability

- Calibration does not guarantee accuracy indefinitely

- 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.

  13th Conférence Général des Poids et Mesures (1967)

  Clarification of 1997: …cesium atoms at rest at a temperature of 0 K.

- Stability implies absence of noise or change—says nothing about accuracy
Clocks operate with frequency offsets with respect to the atomic resonance frequency; understanding and controlling these offsets is essential.

“Primary” frequency standards either have no offsets or we can precisely calculate and control offsets.

Offsets we can calculate and stabilize are OK.

Some offsets can’t be exactly calculated and require calibration.
Atomic Resonance Requirements

- Narrow resonance – we seek resonances with high quality factor

\[ Q = \frac{v_0}{W} \]

\( v_0 \) is resonance frequency and \( W \) is atomic linewidth

- High signal-to-noise ratio – good short term stability

\[ \sigma_y(\tau) \approx \frac{1}{S : N * Q} \]
--Atoms can reside only in discrete energy states

--States populations are essentially equal for microwave resonances in thermal equilibrium

--Signal-to-Noise considerations require we alter the population distribution

--Common techniques to alter the population distribution include “optical pumping” and “state selection”

Goal: deplete one state, induce transitions back into this state, detect the results
Cesium Beam Frequency Standards
Cesium (caesium) resonance forms the internationally acknowledged definition of the SI second interval of time

Mature technology, excellent reliability and stability and performance at reasonable cost

- Two levels of performance in commercial products today

Device of choice when superior long term stability (and environmental immunity) or when autonomy is required

- Intrinsic accuracy—calibration not required
- No “aging” of frequency
Cesium Beam Tube Cartoon

Magnetically-Selected CBT
Cesium Beam Tube

5071A Caesium Beam Tube Cut-away
Cesium Spectrum
Cesium Spectrum
(high resolution)

Linewidth $\approx 450$ Hz
Atomic line $Q \approx 20$ million

$v_0 = 9\ 192\ 631\ 770$ Hz
Atomic Beam Pluses and Minuses

+ Cesium beam is a primary standard and does not require calibration
+ Beam has no interaction with its “confinement”
  - Most accurate and most stable atomic clock, in long term
+ No first order Doppler frequency offsets in properly designed and built apparatus
+ Beam density is low enough for minimal self-interaction
- Relatively complex and expensive apparatus
- Linewidth limited by time-of-flight through the apparatus
+/- Lifetime: 6 years for high performance; 12+ years for standard performance
National Company
Atomichron
circa 1958

Symmetricom
TimeCesium
circa 2007

Symmetricom
5071A
Circa 2007
Active Hydrogen Maser
Frequency Standards
Active Hydrogen Masers

- Active masers provide the best short term frequency stability for averaging times less than 1 day
- Mature technology with good operating lifetime and reliability
- Relatively large, complex and expensive
- Design of choice when the ultimate frequency stability is required
Hydrogen Maser

Hydrogen Maser Physics Package

Maser Signal (-105 dBm)

Cavity

Tuning Varactor

Magnetic Shields

Switching Varactor

Quartz Bulb

State Selector

Hydrogen Dissociator

Source Discharge Oscillator
Maser Block Diagram

- MPG
- IF Amp
- L.O. Multiplier
- Receiver Amplifier
- Varactor Control
- Phase Detector & 10 MHz VCXO
- 14 digit Synthesizer
- Signal Buffers
- Cavity Register
- Synchronous Detectors
- Power Module
- Source Pressure Control
- Hydrogen Source
- Palladium Purifier
- Maser Physics Package
- Switching Varactor
- 28.75 Hz
- 5.751 KHz
- 10 MHz
- 405 KHz
- 24 V Battery
- 110 VAC
- 24-29 VDC
- H₂ supply
- -105 dBm
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Maser Accuracy and Stability

- Thermal motion of the atoms induces a second-order Doppler effect of approximately \(-5 \times 10^{-11}\).

- Confinement ("wall shift") of hydrogen atoms induces a frequency offset of approximately \(-3 \times 10^{-11}\).

- Cavity pulling—dependent on cavity tuning error

- Spin-exchange frequency shift

- Magnetic field in the atomic environment

- To maintain aging of \(2 \times 10^{-16}/\text{day}\) requires that these effects be constant to better than \(10 \text{ ppm/day}\).
Active Hydrogen Maser

-- Frequency Stability is +40X superior to high performance cesium
-- Requires frequency calibration for most applications
Passive Hydrogen Maser
Passive Hydrogen Masers

- Smaller size achieved by dielectric loading of maser cavity
  - Lower cavity Q precludes maser oscillation—operates in a passive mode using traditional frequency lock loop servo

- Short term frequency stability better than cesium

- Exhibits frequency drift/aging inferior to cesium

- Small installed base; little long term experience
  - Two manufacturers in Russia
Passive Hydrogen Maser

Passive Hydrogen Maser Physics Package

- Cavity Tuning
- Magnetic Shields
- Dielectric
- Signal Output
- Storage Bulb
- State Selector
- Hydrogen Dissociator
- Source Discharge Oscillator
Rubidium Gas Cell Frequency Standards
▶ Most Widely Used Type of Atomic Clock
  ▪ Smallest, Lightest, Lowest Power, Least Complex, Least Expensive, Longest Life, Good Performance, Stability & Reliability

▶ Device of Choice When Better Stability Than a Crystal Oscillator is Needed
  ▪ Lower Aging, Lower Temperature Sensitivity, Faster Warm-up, Excellent Retrace
Gas Cell Confinement

---Nitrogen atoms immobilize the rubidium atoms, slowing their velocity and minimizing wall collisions.
---Interaction between rubidium and buffer gas introduces large frequency offset (which must be calibrated).
Optical Pumping

--Incident pumping photons stimulate transitions into an excited optical state

--Atoms in the excited state decay to the ground states with equal probability

--Continued pumping out of one ground state effectively moves the atoms into the other state

\[ E_2 - E_1 = h\nu_0 \]
Rubidium Gas Cell

Magnetic Shield

Lamp Oven

Filter Oven

Cavity Oven

Lamp

Filter

Absorption

Coil

Cell

Cell

C-Field Coil

(3) Oven Temperature Sensors and Heaters

RF Excitation

Signal Out

Photo-Detector

C-Field Current

Lamp Exciter

Rb-87

Rb-87

Rb-85
The cells in the latest commercial RFS designs have (along with their cavities) gotten much smaller. While this comes at the expense of a broader line, lower Q and poorer short-term stability, good performance e.g. \( \sigma_y(\tau) = 1e^{-11} \) at 1 second can still be realized.

Comparison between classic 1” long (LPRO) and latest ultra-miniature (X72) integrated Rb gas cells.
Gas Cell Atomic Clock
Pluses and Minuses

►+ Buffer gas confinement allows small size and economical construction
►+ Rubidium has a fortuitous isotope overlap to allow optical pumping
►- Buffer gas introduces a large frequency shift which results in poor accuracy, is difficult to perfectly stabilize over time (aging) and environment (temperature, barometric, etc)
  ▪ Buffer gas mixtures can reduce thermal effects, one gas with a positive temperature coefficient (N₂) and one with a negative temperature coefficient (Ar)
  ▪ Barometric effects (1e-10/atmosphere) are small and non-cumulative
Modular Rubidium Standard

Height less than 0.72”

3.5”

3.0”

0.7”
Rubidium Standard Instruments

Defense Customization

Rack Mount Instrumentation
Rubidium Operational Accuracy

- Rubidium gas cell devices are secondary standards which have great utility once calibrated
  - Buffer gas offset is ~1e-6; to achieve aging of <5e-11/month requires that buffer gas properties remain constant to <50 ppm/month (which is achieved)

- Initial calibration is a factory process following an extended period (weeks) of aging and stabilization

- Subsequent calibration may be manual or automatic (eg by servo to GPS timing signals)
Performance Comparisons
Performance Comparisons

► Aging – Change in frequency over time
  ▪ Cumulative over life or until recalibrated
► Temperature
► Short Term Stability (noise)
  ▪ Comes from resonance Q and signal-to-noise
► Intermediate Term Stability
  ▪ Driven by environmental sensitivities in rubidium
► Long Term Stability
  ▪ Driven by aging in rubidium and environmental sensitivities in cesium
Aging

- Cesium beam exhibits no frequency aging behavior
- Hydrogen maser exhibits aging of $2 \times 10^{-15}$ to $2 \times 10^{-16}$/day, improving with age
- Rubidium gas cell exhibits typical frequency aging of 1 to $5 \times 10^{-11}$/month
  - Aging effects in rubidium are not fully understood
    - Physical/chemical loss of N₂ buffer gas into the Rb film and/or glass envelope of the absorption/resonance cell?
    - Light shift (AC Stark) effects?
  - Early life rubidium aging can be much higher
Temperature Performance

▶ Cesium: 1e-15/°C typical
  ▪ Difficult to characterize; origin uncertain

▶ Maser: <2e-15/°C
  ▪ Difficult to characterize; origin uncertain

▶ Rubidium: 1 to 2e-12/°C typical
  ▪ Light shift effects
  ▪ Buffer gas effects
  ▪ RF Power effects
  ▪ Can be ameliorated by temperature compensation
# Atomic Clock Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Intrinsic Accuracy</th>
<th>Stability (1s)</th>
<th>Stability (floor)</th>
<th>Aging (/day) initial to ultimate</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Hydrogen Maser</td>
<td>~10^{-11}</td>
<td>~10^{-13}</td>
<td>~10^{-15}</td>
<td>10^{-15} to 10^{-16}</td>
<td>~150X</td>
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<tr>
<td>Cesium Beam</td>
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<td>~10^{-11}</td>
<td>~10^{-14}</td>
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<td>~20X</td>
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<td>Passive H Maser</td>
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<td>~10^{-12}</td>
<td>5x10^{-15}</td>
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<td>~10^{-11}</td>
<td>~10^{-13}</td>
<td>10^{-11} to 10^{-13}</td>
<td>~X</td>
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<tr>
<td>Hi-quality Qz</td>
<td>10^{-6} to 10^{-8}</td>
<td>~10^{-12}</td>
<td>~10^{-12}</td>
<td>10^{-9} to 10^{-11}</td>
<td>~0.5X</td>
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</tbody>
</table>
Temperature Compensation

- Temperature Compensation Requires No Additional Hardware in Some Modern Designs.
- It Does Require More Test Effort to Measure Uncompensated TC, Calculate & Load Compensation Data, and Confirm Compensated TC.
- Dynamics Limit Amount of Improvement – Temperature Sensor Location and Response Time Are Factors.
- Compensation May Degrade Short-Term Stability Depending on Tuning Resolution and Compensation Algorithm.
Emerging and Advanced Clock Technologies
Emerging Clock Technologies

- Coherent Population Trapping Clocks
  - Uses lasers to perform the optical pumping

- Chip Scale Atomic Clocks
  - Ultra miniature size and low power requirement

- Optically pumped cesium beam
  - Use optical techniques for state selection and detection

- Fountain Clocks
  - Atoms are cooled and “tossed” upward in Earth’s gravity
  - Used for primary standards where ultimate accuracy is desired

- Optical clocks relying upon optical atomic transitions
**Physics Comparison**

### Conventional Rb Physics
- Requires resonant microwave cavity
- RF Discharge lamp *(1 Watt)*
- 3 (or 2) cells, ovens, controllers

### Coherent Population Trapping (CPT) Physics
- High-bandwidth Vertical-Cavity Surface Emitting Laser *(VCSEL)*
- Microwaves applied directly to VCSEL *(No cavity)*
- Potential for very small oven assembly
Symmetricom SA.31m

Smaller Size (1/3 X72)
51x51x18 mm

Lower Power (1/2 X72)
5 W, 25 °C

Quartz oscillator footprint
Chip Scale Atomic Clock

- Ultra small, ultra low power, modest performance
- Power: <30 mW
- Stability: <1e-11 Allan deviation at 1 hour averaging time
- Size: < 1 cm³

CSAC Physics Package

CSAC Prototype
Optically Pumped Cesium Beam

9192 MHz

Optical Pumping Laser Source

F=3

F=4

F=3

Fluorescence Detection Laser Source

Photo Detector

Optically Pumped CBT
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