PARCS
Primary Atomic Reference Clock in Space
PARCS Team

- **Jet Propulsion Laboratory**
  - Bill Klipstein
  - Eric Burt
  - John Dick
  - Dave Seidel
  - JPL engineers (lots)
  - Lute Maleki
  - Rob Thompson
  - Sien Wu
  - Larry Young

- **Harvard-Smithsonian**
  - Ed Mattison
  - Bob Vessot

- **Politecnico di Torino**
  - Andrea DeMarchi

- **NIST**
  - Steve Jefferts
  - Tom Heavner
  - Liz Donnelly
  - Don Sullivan
  - Leo Hollberg
  - Tom Parker
  - Bill Phillips
  - Hugh Robinson
  - Steve Rolston
  - Fred Walls

- **University of Colorado**
  - Neil Ashby
Clock Comparisons:

**MISSION GOALS**

- Relativistic Frequency Shift $\times 35$
- Gravitational Frequency Shift $\times 12$
- Local Position Invariance Test $\times 120$
- Realization of the Second $1 \times 10^{-16}$
- Studies of the Global Positioning System

- With a Cavity Oscillator:
  - Local Position Invariance
  - Kennedy-Thorndike Experiment
  - Michelson-Morley Experiment
Frequency Shift Measurement

Accumulated Phase Observable:

\[
\frac{\tau_B - \tau_A}{\tau_A} = \frac{\alpha_G}{\tau_A} \int_{t_1}^{t_2} \left[ \Phi_B - \frac{1}{2} \frac{\mathbf{r}_B \cdot \nabla \Phi_B - \Phi_A}{c^2} \right] dt + \frac{\alpha_D}{\tau_A} \int_{t_1}^{t_2} \left[ \frac{\mathbf{v}_A^2}{2c^2} \right] dt - \frac{\alpha_D}{2c^2 \tau_A} \left[ \mathbf{r}_B \cdot \mathbf{v}_B \right]_{t_1}^{t_2} - \frac{\alpha_D}{2c^2 \tau_A} \int_{t_1}^{t_2} \left[ \mathbf{r}_B \cdot \mathbf{a}_B \right]_{\text{Non-Grav}} dt
\]

Limitation: Ground Clock uncertainty of 5 x 10^{-16}.
Expected Results: 1.7 ppm

Requirements: position uncertainty of 1 m
velocity uncertainty of 10 m/s
non-gravitational acceleration of 130 x 10^{-9} g
PARCS as a Truss Attached Payload

PARCS as a JEM-EF Payload
SAO Maser
Cesium-Clock Concept

Atom Preparation Region

Shutter

Microwave Cavity

State Detection Region
Shutters are used inside the vacuum system to shield the atoms in the clock region from laser light.

Design Goals include:
- High reliability (1 year operation at 3 Hz)
- Fast (< 3 ms time from 100% closed to 90% open)
- Non-magnetic (< 1-2 μG stray field at 1cm)
- Ultra-high vacuum compatible (<10^{-12} atm)
- Relatively large aperture (> 1 cm)
- Cannot disturb microgravity environment.
- Light tight

Prototype of high-performance non-magnetic shutter. Device is built using commercial PZT actuators and non-magnetic materials.
Frequency vs. Phase Modulation

Advantages:
Insensitive to Acceleration, Reduced Dead Time, and System Is Always On Resonance $f_0(Cs)$
Independent phase control of cavities

$\phi_1 = \text{const}$

$\phi_2 = \phi_1 \pm \frac{\pi}{2}$

Shorter attack times

*(clearing time is for second cavity only)*
Vibration Sensitivity

Frequency Modulation:
\[
\frac{y_{FM}(f)}{\delta x(f)} \approx 10^{-11} \text{ m}^{-1}
\]

Accelerations at harmonics of the modulation frequency alias into DC

Phase Modulation:
\[
\frac{y_{PM}(f)}{\delta x(f)} \approx 10^{-16} \text{ m}^{-1}
\]

Dramatic reduction in sensitivity to vibrations
Major Systematic Effects for PARCS are:

- **Zeeman Effect**
  - For 1% field stability, $\Delta f/f < 10^{-17}$

- **Cavity Phase Effects**
  - For a titanium cavity and $\Delta T < 0.1$ K, $\Delta f/f < 5 \times 10^{-17}$

- **Spin Exchange Shift**
  - For a Ramsey Time of 2.5 s, $\Delta f/f < 4 \times 10^{-17}$

- **Blackbody Shift**
  - For a $\Delta T$ and temperature uncertainty $< 0.1$ K, $\Delta f/f \sim 3 \times 10^{-17}$
Spin-Exchange Shift with Phase Modulation

![Graph showing shift vs. TR for different source densities: 1 ball/lineside, 4 balls/lineside, 16 balls/lineside, and 50 balls/lineside.](image)

- **Point Source**
- **Extended Source**

**Axes:**
- **Y-axis:** Shift ($\times 10^{16}$)
- **X-axis:** $T_R$ (s)
Time Transfer vs. Clock Stability

- Time-Transfer - 100 ps long term stability
- Clock - $5 \times 10^{-14}/\sqrt{t}$
- Time-Transfer - 50 pseconds

PARCS Accuracy Limit
The Next Generation Atomic Clocks

-------- Optical ?

**Calcium Standard**
Chris Oates
Anne Curtis

**Frequency Chain**
Scott Diddams
Tanya Ramond
Albrecht Bartels (Aachen)
Thomas Udem (MPQ)
Eugene Ivanov (UWA)
Isabell Thomann

**Mercury Standard**
Jim Bergquist
Sebastian Bize
Bob Drullinger
Wayne Itano
Rob Rafac
Brent Young
Dave Wineland

**Special Thanks to:**
- Fred Walls, Tom Parker (NIST)
- John Hall, Jun Ye, Steve Cundiff (JILA)
- Robert Windeler (Lucent Technologies)
Cold atom Optical Clocks

The fractional frequency instability: (Allan deviation)

\[
\sigma_y \approx \frac{\text{Noise}}{\pi Q \ast (\text{Signal})} \approx \frac{\Delta v}{v_0} \frac{1}{\sqrt{N_{\text{atoms}}}} \left( \frac{T_{\text{cycle}}}{2\tau} \right) \frac{1}{C}
\]

\(T_{\text{cycle}}\) = time to measure both sides of atomic resonance
\(Q\) = line quality factor \(C\) = fringe contrast
\(\tau\) = averaging time
\(N_{\text{atom}}\) = # of atoms detected in \(T_{\text{cycle}}\)

Eg. What should be possible w/ Calcium transitions?

\(\lambda = 657 \text{ nm, } 456 \text{ THz} \) clock transition
\(\Delta v = 400 \text{ Hz} \) \(C = 30\%\)
\(v_0 = 456 \times 10^{15} \text{ Hz} \) \(N_A = 10^7\)
\(\sigma_y = 3 \times 10^{-16}\) in 1 ms! \(T_{\text{cycle}} = 2 T_{\text{Ramsey}}\)

\(\sigma_y(\tau) = 3 \times 10^{-17} \tau^{-1/2}\)

Other optical transitions w/ 1Hz wide line

\(\sigma_y(\tau) = 1 \times 10^{-19} \tau^{-1/2}\)?
Oscillator Stability

Quantum Limited Instability

\[
\sigma(\tau) \sim \frac{\Delta f}{f_0 \sqrt{\tau}} \frac{1}{\sqrt{N}}
\]

Allan Deviation -- Instability \( \sigma(\tau) \)

Averaging Time (s)
657 nm probe laser system

657 nm ECDL Master

Servo

Detector

Cavity $\Delta v = 9$ kHz

AOM

EOM

Fś-laser system

Slave #1

Slave #2

AOM

AOM

AOM
Quenched narrow line laser cooling

- First demonstrated with trapped ions (Diedrich et al.)
- Use 657 nm pulses to pump atoms towards zero velocity
- Use 552 nm quenching light to pump atoms to ground state

\[\text{\textgreek{h}}k\]
1-D Quenched narrow-line cooling - Results

$T = 4 \, \mu K$

$v_{rms} = 3 \, \text{cm/s}$
3rd Stage, Single Frequency Cooling

- 25 ms blue cooling/trapping
- 5 ms red/green cooling/trapping
- 3rd stage single frequency cooling
  - 2 x 5 cycles 15 us pulses
  - 2 x 8 cycles 25 us pulses (no final green repump)

HWHM = 15.7 kHz
(Lorentzian fit of narrow feature)

$v_{\text{rms}} = 1.0 \text{ cm/s}$
($\sim 2/3$ of a recoil)

$T = 520 \text{ nK}$

60 % of the atoms in narrow peak
Borde-Ramsey Fringes after 4ms Red/Green Trap

11.55 kHz Resolution
single 100 s sweep
Optical Bordé-Ramsey fringes - natural linewidth

60 seconds data acquisition

Demodulated Fringe Amplitude (V)

Relative Probe Frequency (Hz)
Single Hg$^+$ Ion Optical Standard

$^{199}$Hg$^+$

Observe fluorescence ($\lambda = 194\text{ nm}$)

"Clock" transition @ $f_0 \approx 1.06 \times 10^{15}\text{ Hz}$

"Clock" Transition ($\lambda = 282\text{ nm}$)

T$_{\text{probe}} = 20\text{ ms}$

$\sim 6.5\text{ Hz}$

T$_{\text{probe}} = 120\text{ ms}$
Hg+ Optical Frequency Standard

J. Bergquist

S. Bize

U. Tanaka

B. Young

R. Rafac

W. Itano

R. Drullinger

D. Wineland

Stability about $5 \times 10^{-15}/\tau^{1/2}$

Projected uncertainty $10^{-18}$
Comparison of High Stability Optical Frequency Standards: Using fs optical frequency comb
Albrecht Bartels,
Tanya Ramond,
Scott Diddams

Self referenced (2f-3f) fs comb
without microstructure fiber
Locked to diode laser locked to
Ca reference cavity

14 Hrs continuously locked!
Ca absolute frequency measurements - comparisons

![Graph showing Ca absolute frequency measurements comparisons over time with various measurements from PTB harmonic chain, PTB fs-laser, CCDM, and NIST fs-laser.](image-url)
Hg+ Optical Frequency Measurement

Preliminary

Weighted Average of all Data:
... 899 143.6(1.0)

Linear Fit: -0.5 ± 1.2 Hz/year

Original Measurement [PRL 86, 4996 (2001)]
...899 142.6(2.5) Hz

Bergquist, Bize, Diddams …
All - Optical Clock

Self-Referencing of Comb Offset

Femtosecond Laser + Microstructure Fiber

Optical Frequency Standard (f_A)

Clock Output

f_r = f_A/m

Counter
Difference in 1 GHz output between 2 Optical Clocks
(1 s Gate Time)

Instability of 1 GHz Output of Optical Clock

2 x 10^{-14} / \tau \text{ in seconds}
Comparison of Hg$^+$ and Ca

Allan Deviation

Averaging Time (s)

Cs clock

Fiber Noise

$10^{-14}$

$10^{-15}$