Ultrastable Light Sources for Optical Atomic Clocks in Space

Dominic Meiser
dmeiser@txcorp.com
Brief background on Tech-X

Founded in 1994

World-class experts in photon and electron behavior
- Electromagnetics
- Plasma physics
- Fluid dynamics
- Accelerator physics

45 scientists and software professionals
- PhDs comprise 2/3 of staff
- Located in Boulder, Colorado

Leadership simulation products and consulting services:
- Coupled, large-scale physics simulations
- Performance improvement consulting: CUDA, OpenCL, algorithms, solvers
- Big data distribution, management, and visualization
We collaborate with many partners in industry, academia, and DOD
We have collaborated with many of the key researchers in the field. Many of them are located in Boulder, CO:

- Murray Holland (JILA, CU, NIST, Boulder)
- James K Thompson (JILA, CU, NIST, Boulder)
- Jun Ye (JILA, CU, NIST, Boulder)
- John Bollinger and Dave Wineland (NIST, Boulder)
- Andrew Ludlow (NIST, Boulder)
Optical Atomic Clocks are the most stable clocks today

Stability of clocks has improved exponentially for nearly 7 decades
Optical Clocks accelerate this trend
Overall clock stability approaching 1 part in $10^{18}$

An optical lattice clock with accuracy and stability at the $10^{-18}$ level


An Atomic Clock with $10^{-18}$ Instability

B. J. Bloom et. al., nature 506, 71, (2014)
N. Hinkley et. al., science 341, 1215 (2013)
There are many applications of space-borne atomic clocks

Navigation (GPS)
Synchronization of computer networks
Chronometric geodesy
  – $1^{-18}$ corresponds to 1cm height differences
  – Complimentary to gravimetry
Communication: Coherent all optically switched networks
  “Master clock” in space for timing distribution (e.g. NSA global distributed time and frequency architecture)
Quantum networks of clocks and cryptography
The Best Optical Atomic Clocks Can Detect Small Height Changes

Comparison of two clocks elevated by 1ft relative to one another
~3hrs averaging per data point

Clock 1

Clock 2
Clocks can be used to detect underground structures

Clocks with $10^{-18}$ accuracy can determine geoid to within 1 cm

Gravitational potential: $\sim \frac{M}{r}$
Gravitational force: $\sim \frac{M}{r^2}$

By measuring both it is possible to tomographically reconstruct gravitational perturbations:

- Ground water
- Oil and gas reservoirs, minerals, etc.
- Caves, Bunkers?

Difficult to defeat because gravity cannot be shielded
Quantum networks of clocks allow secure distribution of time

Use a quantum cryptographical protocol to link nodes in atomic clock network
Optimal resource utilization
Robust against failures of clocks in networks
  - Internal failure
  - Sabotage
Resilient against eaves dropping
Not possible with microwave clocks

ESA is working towards optical atomic clocks in space

4 workshops on optical atomic clocks in space over last few years
ste-quest mission (Space-Time Explorer and QUantum Equivalence Principle Space Test)
SOC project: Put optical atomic clock on ISS by 2020

Transportable Strontium Source (LENS/U.Firenze)

- main requirements:
  1. compact design
  2. reliability
  3. low power consumption

- main planning choices:
  1. compact breadboard for frequency production
  2. all lights fiber delivered
  3. custom flange holding MOT coils and oven with 2D cooling

optical breadboard 120 cm x 90 cm

[The „Space Optical Clock“ Project S. Schiller et. al. (SOC presentation)]
ESA is planning to have an optical atomic clock in space by 2020.

### Optical Atomic Clocks for Space

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### Technical Supporting Document

Patrick Gill  
Helen Margolis  
Anne Curtis  
Hugh Klein  
Stephen Lea  
Stephen Webster  
Peter Whibberley

Laboratory prototypes of ion and lattice clocks wrapped up in 2013.  
Space qualification of several other key components underway.
How do optical atomic clocks work?

Atomic transition frequency defines time
Spectroscopy with ultra-stable laser to read out atomic transition frequency
Convert optical signal \(10^{14}\) Hz to electronic signal (GHz) by means of optical frequency comb

Time/frequency is defined in terms of optical transition frequency

Meta-stable transitions in e.g. Group II elements (Strontium, Yterbium)
Optical excited states with transition frequencies in the $10^{14}$Hz range and lifetimes > 100s
Laser cooled to micro Kelvin temperatures
Trapped in optical potentials
Neutral atoms have the advantage of better signal to noise ratio (=> Higher bandwidth)
Ultra-stable lasers are needed to read out the timing signal

Linewidth < 1Hz (corresponds to Q=10^{15}) to get benefit from narrow atomic lines
Made by electronically locking a diode laser to a reference cavity
Construction of the reference cavity is the biggest challenge
Thermal noise in mirror substrates are limiting factor for laser linewidth
Cavity length fluctuations: ~10^{-18}m
For comparison:
- Bohr Radius: 10^{-10}m
- Diameter of Nucleus: 10^{-15}m
Frequency combs allow translation of optical to electronic signals

Optical transition frequency too fast for electronics
Frequency combs translate optical frequencies to electronic frequencies

\[ n_1 f_{\text{rep}} + f_0 \]
\[ 2n_1 f_{\text{rep}} + f_0 \]
\[ 2n_1 f_{\text{rep}} + 2f_0 \]

beat frequency = \( f_0 \)
Reference cavities are one of the greatest challenges for clocks

Until recently limiting factor in lab settings
Precision manufacturing
Vibration isolation
Temperature stabilization
Many of these challenges will be amplified for clocks in space
We have found a way to produce ultrastable lasers without reference cavities

Large impact in fundamental science and technology:

- 10's of papers based on this idea
- ~100 citations for this paper, 1000's overall
Simple idea: Use atoms with clock transition as a laser medium

Produces very stable light from the start

Key questions:

– Can a laser like this even work (<1 photon in cavity)?
– Is it bright enough for clocks?
This is a very exotic light source

Qualitatively different from existing lasers
Many fundamental questions had to be answered
Optical version of maser

J. G. Bohnet et. al., nature 484, 78 (2012).
Better frequency stability predicted than with reference cavities

Conservative: 1 part in $10^{18}$ (vs $10^{16}$ for ref. Cavity)

Fundamental limit: $\Delta \nu = C \gamma$

($C$: cooperativity parameter of CQED, $\gamma$: atomic linewidth)

Much lower than Schawlow-Townes
The intensities are high enough for clock applications. Max. Intensity: \( P_{\text{max}} = \hbar \omega_a N^2 C \gamma / 8 \). 10 femto Watt sufficient, demonstrated by long distance fiber links for time distribution.
Light source is stable against fluctuations in the reference cavity

Atoms don't “see” cavity because so few photons in laser

Therefore little effect of cavity on atoms

Suppression by 4 orders of magnitude demonstrated in experiment

Theoretically much larger suppression possible
The principles of this light source have been confirmed in experiment.

Line width
Collective emission process
Suppression of cavity noise feeding into laser radiation

Simulation will play an important role in preparing this technology for space

So far reduced models and proof of concept calculations

These are insufficient for optimizing design of light sources for real world clock applications

Many different parameters to optimize:
  – atomic species
  – optical pumping scheme
  – cavity geometry
  – atom loading, beam geometry, etc.

Switching between these in experiment is very difficult and time consuming

=> Need simulation to support design
Simulations can help with optimizing laser pumping scheme

Most theoretical studies to date have focused on simplified reduced models
For design and optimization purposes it is necessary to use more detailed atomic models
Atomic motion and spatial inhomogeneities must be modeled

Pumping
- Needed as energy supply

Trapping inhomogeneities and other stray fields

Reloading schemes needed to overcome atom loss
- Beam laser
- Atomic “conveyor belt”
Optical atomic clocks in space offer unique opportunities

We have proposed a light source capable of boosting clock performance by 2 orders of magnitude.

The basic principles of this light source are now well understood.

Simulation will play a key role in moving this technology from the laboratory into the real world and into space.