Virtual Research Presentation Conference

Optimization of atomic clock design as pertains to the impact of LO noise and environmental disturbances

Principal Investigator: Daphna Enzer (335E)
Co-Is: Andrey Matsko (335E), David Murphy (335A), Eric Burt (335E)
Program: Spontaneous Concept

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Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

Abstract

We have improved an atomic-clock model to calculate **a new noise metric to characterize clock-environment interactions**.

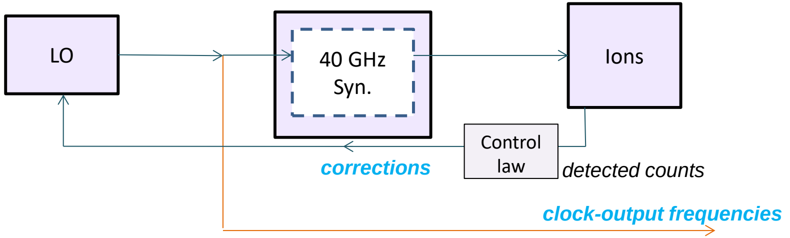
Atomic clocks operate by comparing a local oscillator (LO) to an atomic frequency standard at regular intervals and applying *corrections* at each iteration. We report on these *corrections* and how their noise profile relates to *output* noise.

- Noise/Instability on timescale τ: characterized by Allan deviation (ADEV) $\sigma_y(\tau)$ [for any *y(t)* frequency series]

$$\sigma_y^2(\tau) = \mathrm{E}[(< y(t-\tau) > - < y(t) >)^2]/2$$

($\mathrm{E}[\;]$ *and* $<>$ both denote simples averages but over different samples and sample sizes.)

- Traditional clock performance metric: ADEV of *output frequency*



noise-floor:

$$\sigma_{y_{out}}(\tau) = \frac{1}{\pi \, SNR \, Q} \sqrt{T_c/\tau}$$

- In contrast, will introduce the ADEV of clock *corrections.* Either ADEV can be degraded above noise-floor due to imperfect LOs or environmental disturbances. In this task we specified the relationship between the two ADEVs, **to help identify the source of such disturbances**.

Problem Description

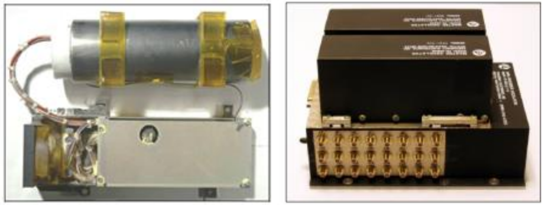
a) Context:

- Atomic clocks more often operating in **space or remote test environments**.
    - More **environmental disturbances** (e.g. temperature, magnetic, radiation)**.**
    - More need to understand **LO sensitivities** and how **LO variation impacts clock output**.
- Typical state-of-the-art LO used is **Ultra-Stable Oscillator (USO).**
    - **Would like to develop a compact Photonic LO (PLO) for the mercury ion clock;** needed to find out the performance capability.

b) Comparison to state-of-the-art and Relevance to NASA and JPL:

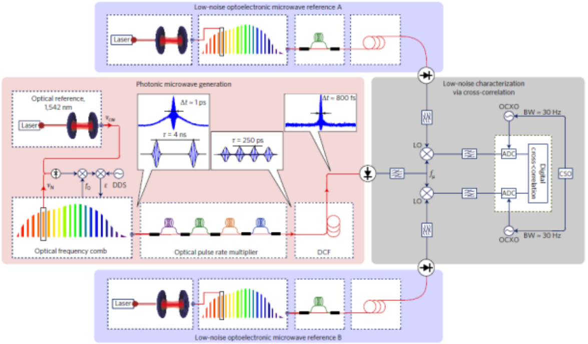
- Part 1: New *Corrections-ADEV* diagnostic
    - Can allow for efficiently **proving/disproving LO as source** of clock output disturbances.
    - Can allow for efficiently **characterizing LO** response to environmental disturbances.
    - These help illuminate space-clock sensitivities and **design better space-clocks** for the future.
    - Already, this is a useful **tool for the DSAC mission** (Deep Space Atomic Clock). 1) Other techniques to diagnose the source of disturbances involve averaging data series and looking for correlations with other channels; not always conclusive. 2) Understanding USO in space environment also crucial for future missions.
- Part 2: Our **Photonic LO modeling** could enable better clocks for the future. In particular, it will allow us to **propose an experimental Task**.

Quartz Space USO Example:



Bloch, M., Mancini, O., McClelland, T., "What We Don't Know About Quartz Clocks in Space," *Proceedings of the 41st Annual Precise Time and Time Interval Systems and Applications Meeting*, Santa Ana Pueblo, New Mexico, November 2009, pp. 457-472.

PLO Example:



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Photonic microwave signals with zeptosecond-level absolute timing noise

Xiaopeng Xie[1†], Romain Bouchand[1†], Daniele Nicolodi[1†], Michele Giunta[2,3], Wolfgang Hänsel[2], Matthias Lezius[2], Abhay Joshi[4], Shubhashish Datta[4], Christophe Alexandre[5], Michel Lours[1], Pierre-Alain Tremblin[6], Giorgio Santarelli[6], Ronald Holzwarth[2,3] and Yann Le Coq[1*]

Methodology

Part 1: New Corrections-ADEV Diagnostic

a) Derived **noise-floor** of new corrections-ADEV. Confirmed with clock model.

b) Derived impact of **LO sinusoidal and/or drift disturbance.** Confirmed with clock model.

c) Compared to disturbing the **atomic/ion reference frequency** rather than the LO.

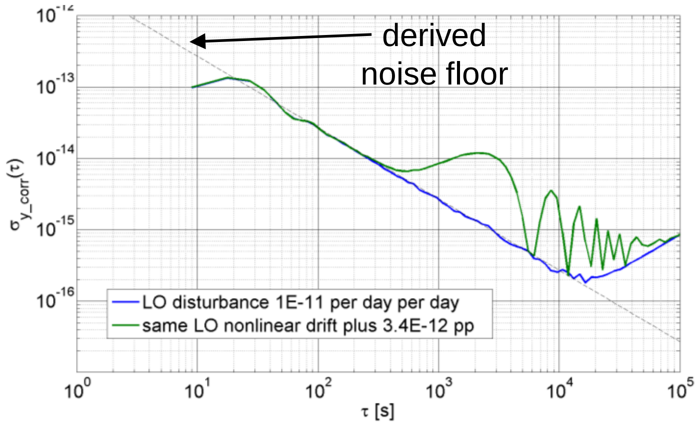
d) Used new diagnostic to **analyze laboratory clock data.** Uncovered unusual noise floor behavior in some configurations that could lead to better understanding of our mercury lamp and detection system if investigated further.

Part 2: PLO Modeling

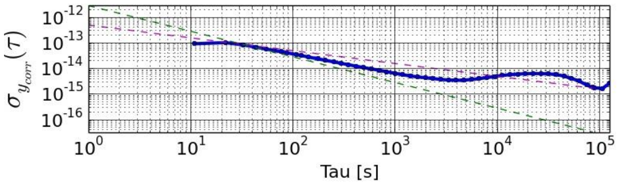
a) Researched parameters to model (for both the PLO and for the mercury ion clock).

b) Modeled performances.

Example model results for corrections-ADEV: noise floor and impact of LO disturbances



Example experimental results for corrections-ADEV



Results

LO vs Ion Frequency Disturbances
(to both ADEVs)

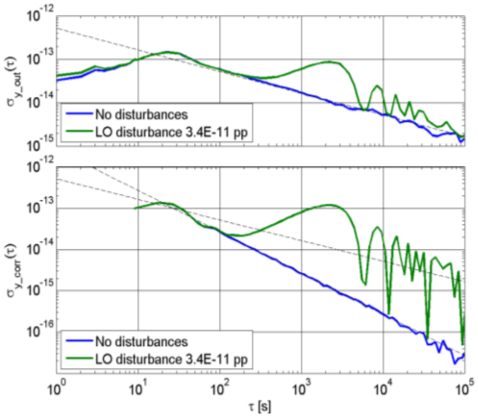
Part 1: Corrections-ADEV Diagnostic

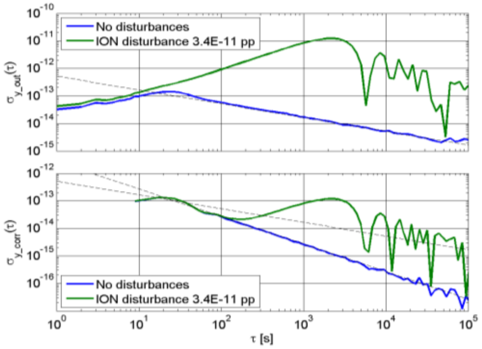
- Led to paper, to submit to *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control (TUFFC)*

a) Accomplishments versus goals: **Corrections versus Output ADEV Comparison led to useful diagnostic for a space clock.**
   a) A peak/drift due to LO appears roughly the same on the two ADEVs, whereas if due ion-resonance-frequency changes, it appears much bigger on the output-ADEV.
   b) Satisfies goal of developing a better data processing algorithm, to figure out clock-stability limitations and to improve the clock performance.

b) Significance: **Will help interpret space clock performance and limitations. Will also help characterize LO response to environmental disturbances. Both will aid in improving future space clock design and performance.**

c) Next steps:
   a) Publish this work. Start using diagnostic for clock analysis.
   b) Further study of unusual mercury lamp behavior.





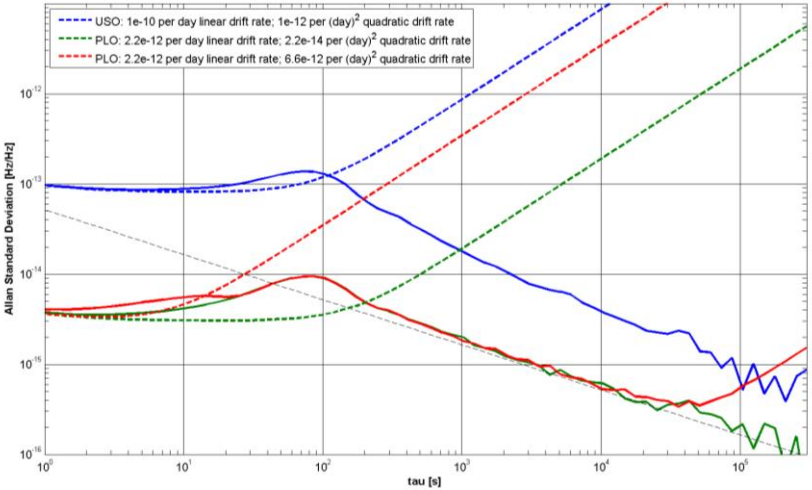
Results

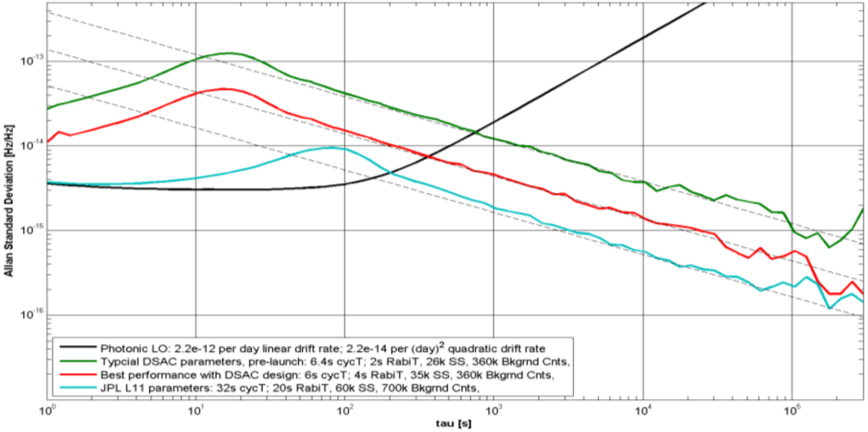
Part 2: PLO Modeling

a) Accomplishments versus goals: **Modeled best performing JPL mercury clock with PLO vs USO to predict factor of 5-10 improvement, which was the goal**. **(green vs. blue curve, top plot)**
   - a) Showed this PLO improvement relies on high SNR clock, at least for long term performance. (Lower plot shows degraded performance for lower SNR clocks. Caveat: loop parameters could be adjusted to give PLO level performance at short time scales.)

b) Significance:
   - a) Indicates potential usefulness of photonic local oscillators in mercury ion clocks.

c) Next Steps:
   - a) Attract funding for experimental testing of this idea as well as for the development of space-qualified clocks containing a photonic local oscillator.





Publications and References

- Daphna Enzer, David Murphy, Eric Burt, “Allan Deviation of Atomic Clock Frequency-Corrections: A New Diagnostic Tool for Characterizing Clock Disturbances,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control (TUFFC),* 2020. **In preparation**
- Daphna Enzer, David Murphy, Eric Burt, “Allan Deviation of Atomic Clock Frequency-Corrections: A New Tool for Characterizing Clock Disturbances,” *Precise Time and Time Interval Systems and Applications (PTTI),* San Diego, CA, 2021. **In preparation**
- Andrey Matsko, Daphna Enzer, Eric Burt, Robert Tjoelker “On Impact of Local-Oscillator Phase-Noise on Atomic Clock Performance,” *Precise Time and Time Interval Systems and Applications (PTTI),* San Diego, CA, 2021. **In preparation**