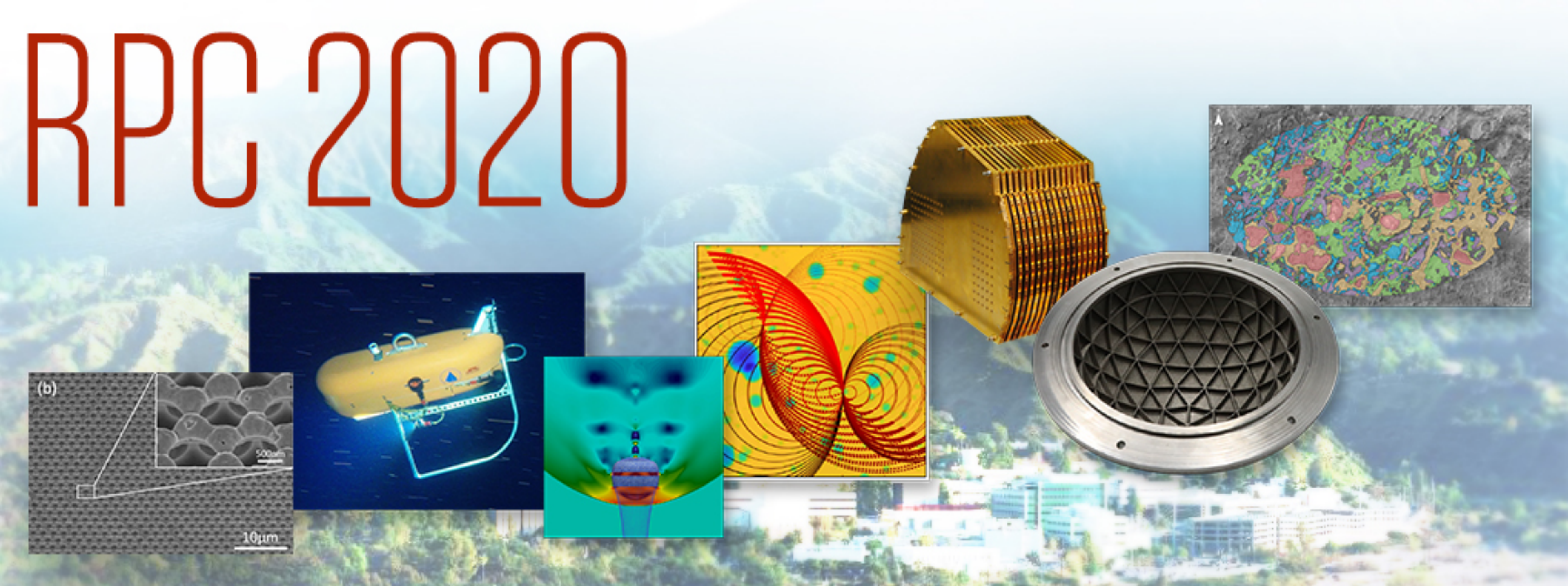

Virtual Research Presentation Conference

A MOLECULAR CLOCK ARCHITECTURE FOR DEEP SPACE INTER-SMALLSAT RADIO OCCULTATION

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Program: (Topic)
Assigned Presentation # RPC-270

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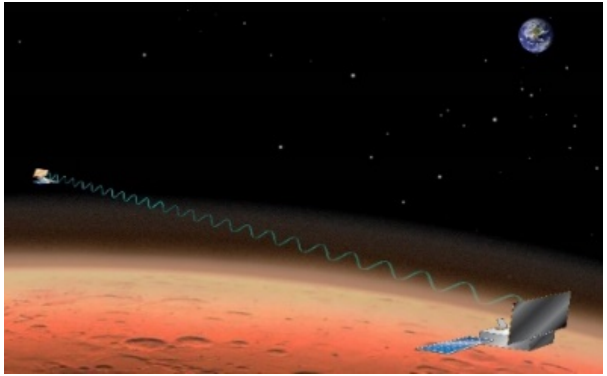
Tutorial Introduction

Abstract

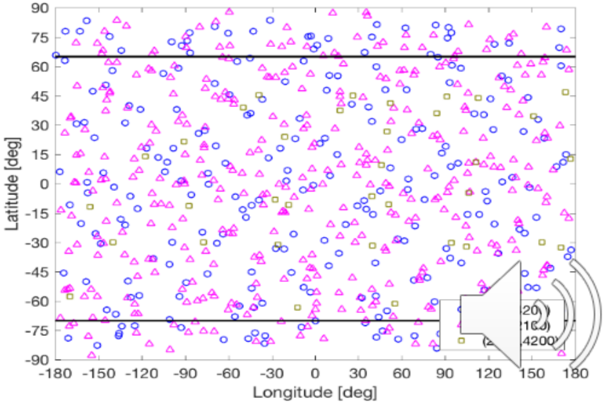
- JPL has been advancing the radio occultation mission concepts using SmallSat constellation on Venus, Mars, and outer planets, to address some of the high priority science goals identified in the latest VEXAG and MEPAG documents, including high vertical resolution measurement of temperature, pressure and electron density with high spatial and temporal coverage.
- The mission concepts require 10^{-13} stability averaged at 100 seconds for the on-board clock that can be put into a CubeSat.
- This R&TD task proposed the concept of a "full electronic" terahertz molecular clock to meet the above stability requirement with 2-3W power, 0.3L size and a 0.8kg mass.
- First year effort included A) a system-level quantitative analysis showing the feasibility, B) a table-top THz-molecular platform construction and preliminary test, and C) design, fabrication and test of the 3rd generation CMOS integrated clock chip aiming to reduce both fast noise and long-term drift.

Problem context:

- **Science:** Deep Space One-way Radio Occultation with Global SmallSats Constellation*
    - Intersatellite radio occultations from a smallsat constellation around Mars or Venus provide high vertical resolution measurements of **temperature and pressure** (in neutral atmosphere) and **electron density** (in ionosphere) with high spatial and temporal coverages that address high-priority MEPAG and VEXAG objectives.
    - Two-way does not need very good clock, but adds system complexity.
    - One-way need on-board clocks with good short-term stability.
- **Scientific observation targets: Mars lower altitude atmosphere or Venus or Titan with thick ones.**
    - MEPAG goal II, Mars climate history
        - A1.1: Measure the state and variability of the lower atmosphere from turbulent scales to global scales (High Priority).
    - MEPAG goal IV, Prepare for Human Exploration
        - B1.2: monitor surface pressure and near surface meteorology (High Priority)
        - B1.3: Measure temperature and aerosol under dusty conditions.
- **Requirements on on-board clocks**
    - Stability of 10^{-13} at 100s
        - → Need assist from atom/molecular
    - Size, Weight and Power constraints: <1L, <1.33kg, <10W (1U Cubesat).
        - → Need Integrated technology in electronics, mechanics and photonics.
    - Technology with inherent merits of long lifetime, high reliability, radiation-hardened, low environmental sensitivities.
        - → Need simple architecture and leverage from proven technology/components, better COTS



RO coverage over 7 days from a constellation of 3



* http://www.lcpm12.org/wp-content/uploads/2017/08/0910-0930-Williamson.pdf, Williamson/Mannucci/Ao

State of the art, our approach, innovation and methodology:

- Goal: 10^{-13} stability averaging at 100 seconds
- Miniaturized Oven-Controlled-crystal-Oscillators (M-OCXO), 0.5W-1.3W power with 0.03L size and 0.1kg mass, but they only provide 10^{-10} to 10^{-12} stability at 100 seconds.
- Ultra-stable OCXOs (known as USOs) provide 10^{-13} stability with significantly increased power (~4.5W), size (~2.3L) and mass (~1.5kg).
- Our approach: **a "full electronic" molecule-disciplined M-OCXO terahertz clock -->**

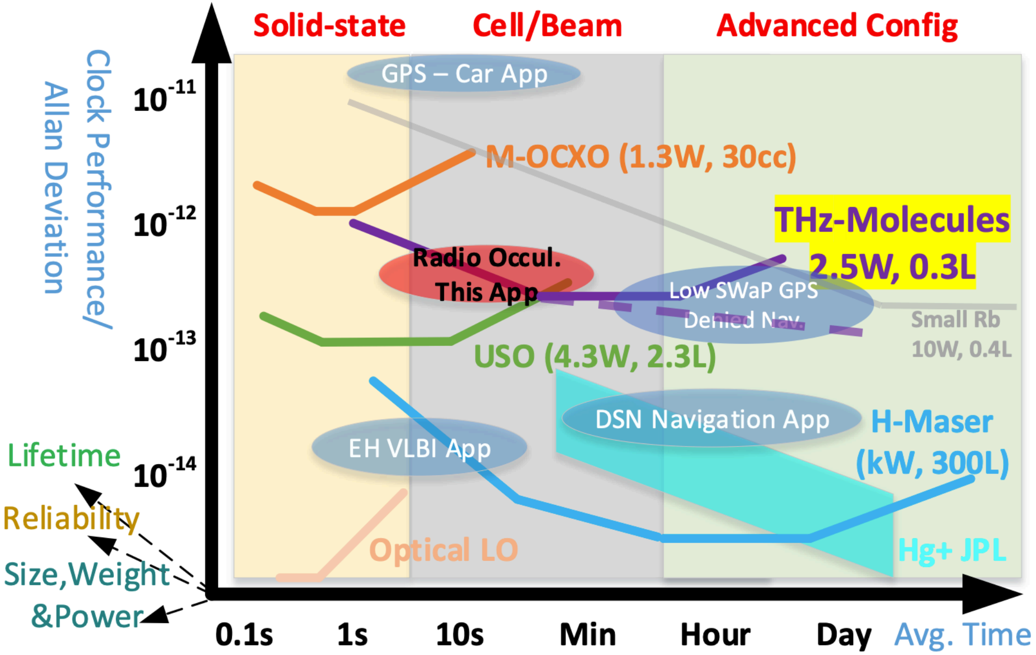
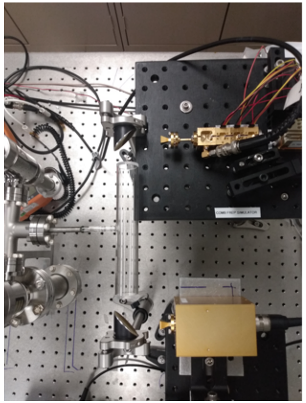


Figure caption: Missions requirements and different type of clocks: The solid purple line is the THz-Molecular clock with waveguide as the gas container, which exhibits higher drift due to the cavity pulling effect. The dashed purple line is with free-space THz beam to interrogate with molecules in sealed quartz vapor cell, which has much lower drift. Both the deep space inter-satellite radio occultation and low size, weight and power (SWaP) GPS denied navigation may benefit from the THz-Molecular clock technology development. As indicated in the other coordinates, the lifetime and reliability are very important factors in applying clock technology to space. The "full-electronic" THz-Molecular clock architecture has an unique strength for system simplicity, which may lead to better reliability and longer lifetime.

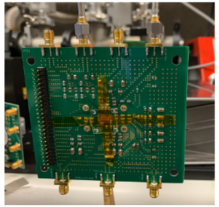
First year effort results

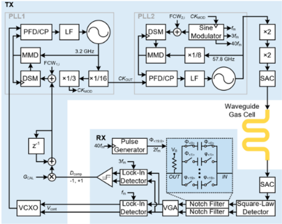
We have identified the dominating stability limitation for the current experimental result [1] is the phase noise at even harmonics of modulation frequency introduced via the intermodulation process [2]. We developed a comprehensive analytical tool for a variety of instability factors [3].

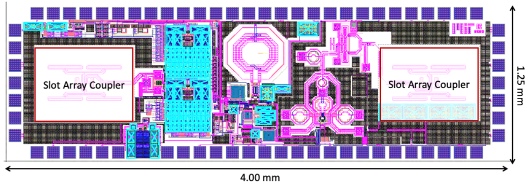
- What will not work: CMOS on-chip LC VCO noise is too high
- What will work: an off-chip dielectric resonate oscillator is needed
- Dual-notch filter at even harmonic of modulation frequency is essential
- 0.1mW THz power is sufficient (98% reduction than original proposed)
- 0.5W OCXO is sufficient (60% reduction than original proposed)
- 3rd generation CMOS clock chip designed, fabricated and partially tested



Aluminum Chip Plate + Chip + PCB1







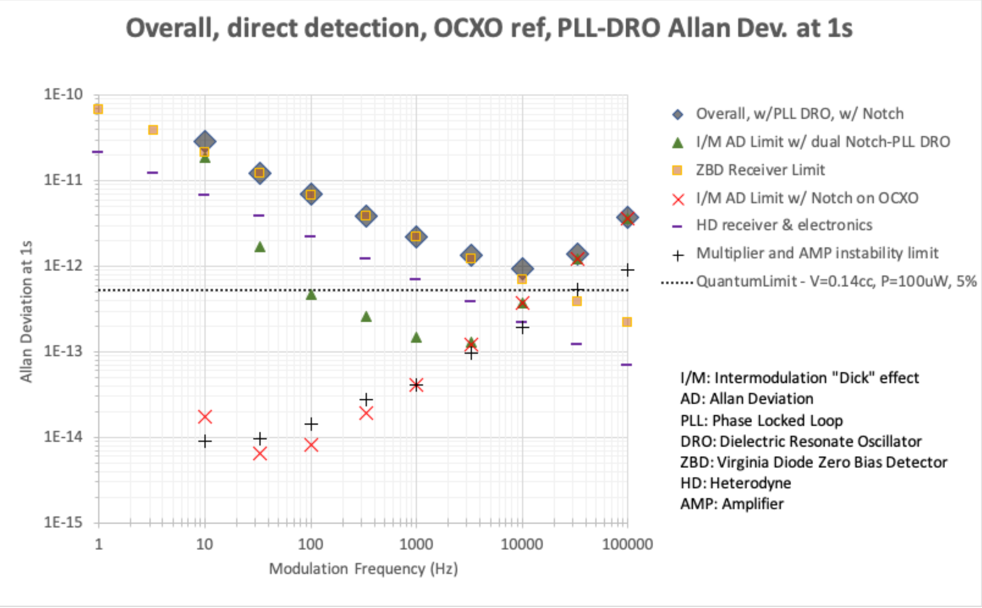


Figure 1. Instability limit for a molecular-THz clock with direction detection scheme. a) grey diamond: the overall stability limit of Allan deviation at 1 second integration time. It includes the contribution from b), c), f) and g). The optimal modulation frequency for derivative spectroscopy is at 10kHz with a stability limit of 1x10^-12 at 1 second. b) green triangle: the stability limit caused by the PLL-DRO phase noise at the Fourier frequency of the second harmonic of modulation frequency. It includes the contributions from the free-running DRO, PLL achievable bandwidth (<modulation frequency), the reference OCXO, and the dual-notch filter [4]. c) stability limit caused by the practical ZBD 1/f noise [5] at input power -4dBm. d) individual stability limit from the 10MHz OCXO reference (Microsemi 9700B) [6]. e) stability limit from ideal receiver without 1/f noise and followed electronics with 1/f noise at -4dBm [5]. f) stability limit from commonly used multiplier [7] and power amplifiers [8]. g) quantum shot noise limit from molecules OCS with 10Pascal, 300K, 0.14cubic centimeter volume with 5% participation. The DRO considered exhibits the performance of commercial off the shelf part near 12GHz [9]

Second Year Planning

- Demonstrate a table-top THz-molecular clock with COTS components and benchtop instruments and verify our system analysis and design
  - Low phase noise THz generation with PLL-DRO + multiplier
  - Quartz-vapor cell “free-space” versus Waveguide “all attached”
- Explore power, size and saving for clock components
  - Molecular cell container
  - THz generator power and performance trade-off
  - Clock controlling integrated chip

Publications and NTRs

[A]. Lin Yi et al., “A Molecular Clock Architecture for Deep Space Inter-SmallSat Radio Occultation”, invited talk, The Precise Time and Time Interval Systems and Applications (PTTI) meeting, San Diego, California, January, 2020.

[B]. Lin Yi et al., “ Phase Noise and Stability Convolution Software for Precision Frequency and Timing Applications,” JPL-New Technology/Software Report, No.51742

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[1] Cheng Wang et al, “A Terahertz Molecular Clock on CMOS Using High-Harmonic-Order Interrogation of Rotational Transition for Medium-/Long-Term Stability Enhancement,” accepted to *IEEE JOURNAL OF SOLID-STATE CIRCUITS*, 2020. https://www.semanticscholar.org/paper/A-Terahertz-Molecular-Clock-on-CMOS-Using-of-for-Wang-Yi/e432f94c31381ff6c6f094c8a3aa92d3c13d44ab

[2] Roland Barillet et al., “Limitation of the clock frequency stability by the interrogation frequency noise: experiment results,” *IEEE Transaction on Instrumentation and Measurement*, Vol. 42, NO.2, April 1993.

[3] Lin Yi et al., “ Phase Noise and Stability Convolution Software for Precision Frequency and Timing Applications,” JPL-New Technology/Software Report, No.51742

[4] Csaba Szekely et al., “Reducing local oscillator phase noise: Limitations on the frequency stability of passive frequency standards: Tests of a new concept,” *IEEE Transaction on Instrumentation and Measurement*, Vol. 41, NO.4, April 1994.

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