National Aeronautics and Space Administration

A Molecular Clock Architecture for Deep Space Inter-SmallSat Radio Occultation

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Program: FY21 R&TD Topics **Strategic Focus Area: Electronics, Devices and Sensors**

Objectives

The overall goal of this R&TD is to explore the feasibility of the molecular-terahertz clock for inter-small-satellite deep-space radio occultation experiments. The objectives are 1) To theoretically analyze the ultimate achievable stability due to the limitations of heterodyne spectroscopy, detection, and quantum projection noise floors. 2) To establish a quartz-cell-based spectroscopy experimental platform and preliminarily evaluate the system parameters. 3) To design, fabricate, and test a third-generation CMOS clock integrated chip with goals to improve the signal-to-noise ratio and reduce environmental sensitivity.

Background

The proposed clock is a "full-electronic" clock, taking advantage of recent progress in sub-terahertz electronic integrated chips and devices. The molecules are sealed in a cell that is either made directly out of a sub-terahertz waveguide or a dielectric quartz cell. We expect this type of molecular clock can be seamlessly integrated with electronics to improve onboard timing precision, especially the long-term drifting caused by crystal quartz oscillators.

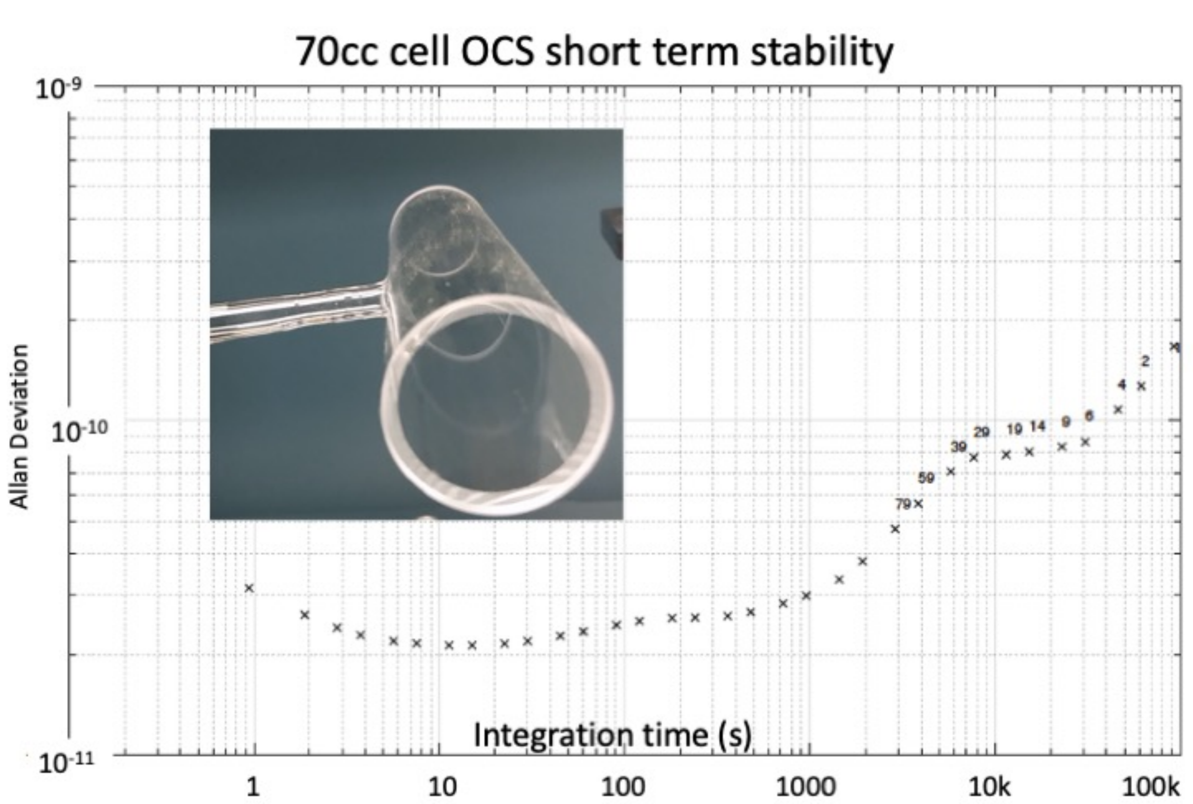

Figure 1. Stability (Allan Deviation) of sub-terahertz carbonyl clock with 70cc quartz cell

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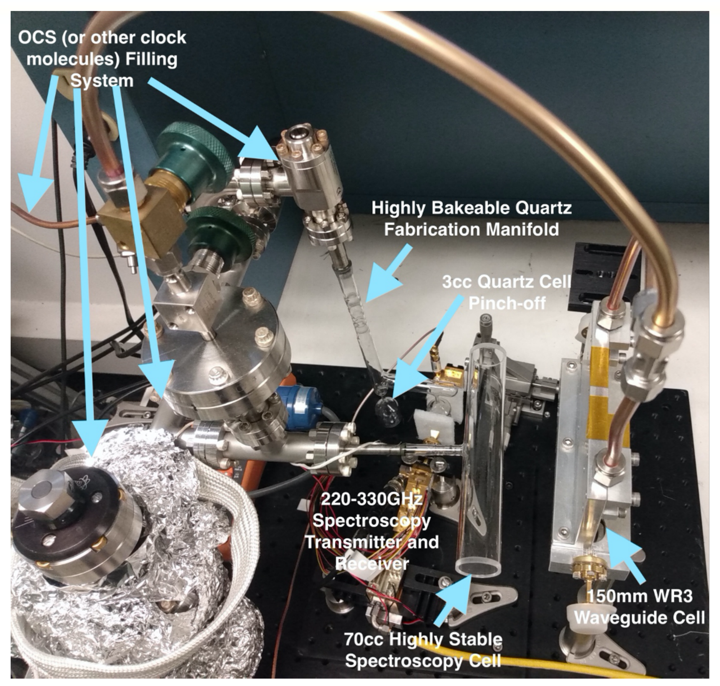

Figure 2. Multi-function molecular spectroscopy/clock system.

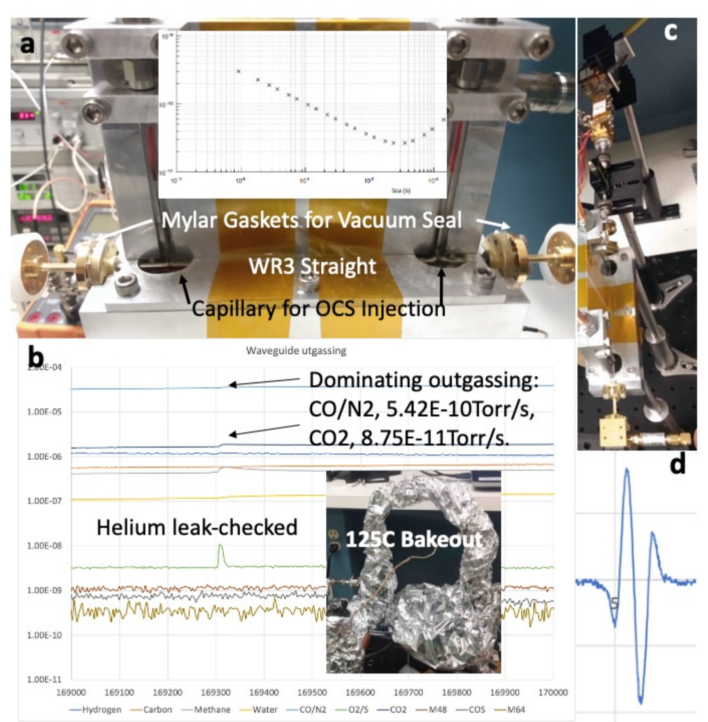

Figure 3. Waveguide-based molecular cell experiments. a) Leak-free 150mm WR3 waveguide with Swagelok capillary tubes as OCS injection. The inlet shows a typical 3x10^(-10)/sqrt(tau) stability limited by molecules number. The stability keeps improving until 200 seconds averaging time, indicating there is no wave reflection caused instability we observed in open clock configuration. b) Waveguide ultra-high vacuum preparation, outgassing experiment, 125C bakeout, leak-checking. c) waveguide-based spectroscopy setup with 220-330GHz transmitter and receiver. d) molecular spectroscopy signal.

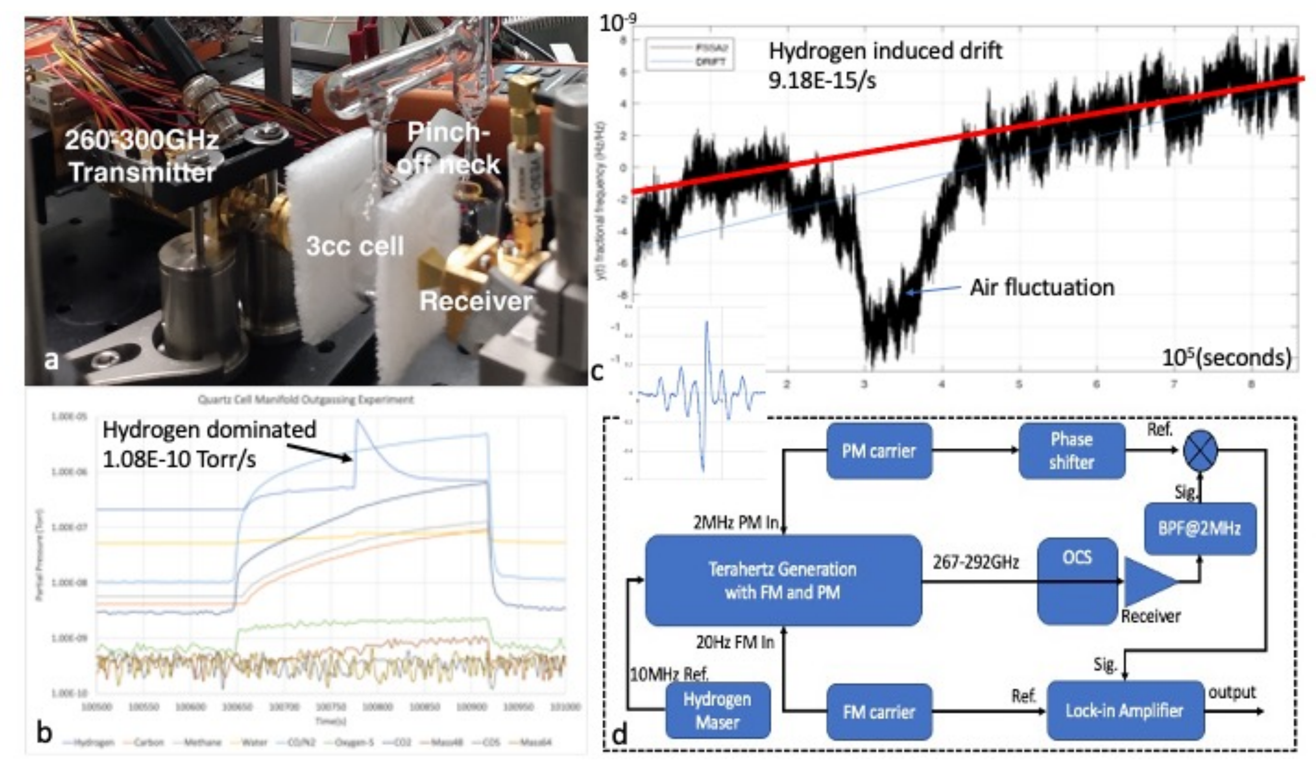

Figure 4 Quartz cell (3cc) spectroscopy, outgassing, and drift analysis. a) clock configuration with 3cc cell connected to the pinch-off neck of the manifold. b) outgassing experiment after 350C bakeout. c) 10 days clock data with the assumption that hydrogen outgassing dominated the linear drift. d) Phase modulation schematic to acquire high signal-to-noise ratio signal in the inset.

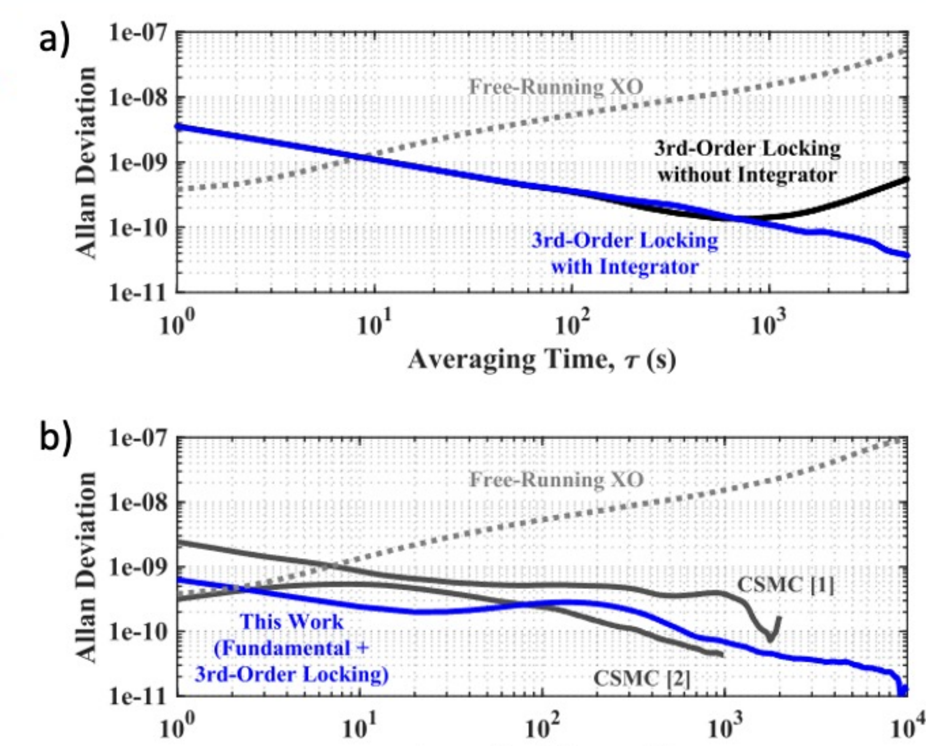

Figure 5. Measured Allan Deviation. (a) Allan Deviation of CSMC based on 3rd-order Locking with and without an integrator in the loop. (b) Allan Deviation of dual-loop CSMC based on fundamental and 3rd-order locking.

Approach and Results

The two-year efforts and results showed that the THz-molecular clock is capable of reaching at least 3x10^(-11) stability at 1 second (Fig.1). The limiting factor to the short-term stability is most likely the phase noise of the radio/microwave frequency local oscillators, which matched the numeric analysis. The electronic noise from the receiver could be another limit factor. The portable breadboard clock system (Fig.2), which has the flexibility for different types of clock molecules (e.g. carbonyl sulfide in this task), provides multiple functions: A) a 70cc quartz vapor-cell clock/spectroscopy configuration to achieve high stability, B) a highly-bakeable, ultra-low outgassing quartz vapor-cell clock/spectroscopy configuration with the capability to fabricate standalone 3cc quartz molecular clock vapor cell, C) a 150mm WR3 waveguide-based leak-free vapor-cell clock/spectroscopy configuration. We have developed the leak-free waveguide/sample cell fabrication technology, which is under the patenting process.

We have characterized the environmental impact on the long-term stability and lifetime of the clock. The outgassing of the vapor cell is a dominating factor in the clock system, especially in the 70cc quartz cell only bakeable to 200C (limited by the window-tube joints, see Fig.1 photo) and the 150mm waveguide cell bakeable to 150C (limited by the vacuum sealing gasket material, Fig.3). We have reached ultra-low outgassing in the 3cc specially designed quartz cell (Fig.4). As the breadboard clock is not enclosed, we observed short-term frequency fluctuation caused by the sub-terahertz wave reflection (Fig.4c) surrounding the clock, which has been eliminated in the full-waveguide experiment (Fig.3a).

On the MIT side, we have designed, fabricated, and demonstrated the 3rd generation CMOS clock chip with TSMC technology. Fig. 1(a) shows measured Allan Deviation of a chip-scale molecular clock (CSMC) based on 3rd-order locking with and without a digital integrator. When 3rd harmonic detection is without an integrator, Allan Deviation starts to increase for averaging time (τ) is larger than 10^3 s. This is because the variation of the free-running frequency cannot be suppressed by more than the loop gain of the clock. On the other hand, when the output frequency is regulated by changing the frequency control word of the phase-locked loop according to the integrated 3rd harmonic detection output, Allan Deviation decreases as the averaging time increases. As shown in Fig. 2(b), with the dual loop architecture based on fundamental and 3rd order locking, the CSMC achieved Allan Deviation of 5.37×10^{-10} and 2×10^{-11} at $\tau = 1$ s and 10^4 s, respectively.

Significance/Benefits to JPL and NASA

We have achieved a complete end-to-end clock demonstration in the laboratory environment. The results showed that the THz-molecular clock has sufficient stability i.e. 10^(-11) that can fulfill dual one-way radio occultation measurement in the mission concept of CubeSats constellation orbiting Mars. The TRL is elevated to >3. If using a photonic-microwave local oscillator with ultra-low phase noise in combination with a lower noise sub-terahertz detector, the clock has the potential to reach the stability requirement of one-way radio occultation, i.e. 10^(-13). The volume of the clock (excluding commercial bench-top electronics) is estimated to be below 0.3L, comparing to 2.5L of an ultrastable crystal oscillator with similar power consumption.

A preliminary study shows outgassed background gas collision broadening could be a life-limiting factor.

The laboratory technology demonstration, clock breadboard, and fabrication hardware platform can serve as the basis for further technology maturation proposals. The phase noise analysis from this task has been incorporated into the 2021 ROSES-Decadal Survey Incubation proposal led by 389R for radar applications. We plan to additionally propose the 2021 or 2022 ROSES-PICASSO program.

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Publications

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- Lin Yi et al., "Sub-Terahertz Heterodyne Spectroscopy of Carbonyl Sulfide", *2021* Joint Virtual Conference of European Frequency and Time Forum & the IEEE International Frequency Control Symposium. July 7, *2021*—July 17, *2021*, Virtual.
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