# Phase Stability in Next-generation Atomic Frequency Standards

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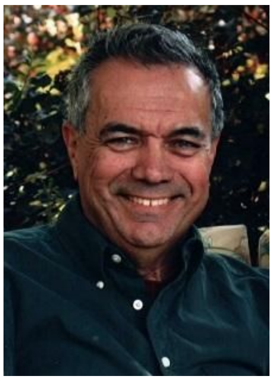
## Abstract



Atomic clocks (or oscillators) formthe basis of standard, everyday timekeeping. Separated, hi-accuracy clocks can maintain nanosecond-level autonomous synchronization for many days. The world's best Cs time standards are atomic fountains that use a RF quantum transition at 9,192,631,770 Hz and reach total frequency uncertainties of $2.7 – 4 \times 10^{-16}$ with many days of averaging time.[1] But the days of averaging prohibit real-time use of this accuracy, and even the accuracy of today's commercial Cs of a few $\times 10^{-13}$. A new class of optical atomic standards with quantum transitions having $\pm 1 \times 10^{-15}$ uncertainty at ~200 THz, which is inconvenient for applications, drives an optical frequency-comb divider (OFD), thus providing exceptional phase stability, or ultra-low phase noise (ULPN), at convenient RF frequencies. Most importantly, this scheme produces exquisite *real-time accuracy* at RF, as in the previous example of a few $\times 10^{-13}$ accuracy, as quickly as fractions of a second. This single property elevate their usage to a vast array of applications that extend far beyond everyday timekeeping. "Accuracy" is the agreement with a standard realization of a reference, carrier, or local oscillator (LO) frequency. "Phase stability" quantifies the precision with which we can determine frequency as a function of averaging time in the time domain or phase noise in the frequency domain, a single-sideband (SSB) measurement of noise denoted as $L(f)$. The $L(f)$ measurement is used in virtually all technology sectors because it fully decomposes and describes phase instability, or phase noise, into all of its components at an offset-frequency from the carrier on a frequency-by-frequency basis. I show how accurate oscillators with low-phase noise dramatically improves: (1) position, navigation, and timing; (2) high-speed communications, (3) private messaging and cryptology, and (4) spectrum sharing. This talk outlines game-changing possibilities in these four areas, given next-generation, nearly phase-noise free, quantum-based (or atomic) frequency generators with $\pm 1$ x $10^{-15}$ accuracy whose properties are sustained across an application's environmental range. I show how the combination of high atomic accuracy and low-phase noise coupled with reduced size, weight, and power usage pushes certain limits of physics to unlock a new paradigm – creating networks of separated oscillators that maintain extended phase coherence, or a virtual lock, with no means of synchronization whatsoever except at the start. "Phase coherence" means that separate oscillators maintain at least 0.1 rad phase difference at a common, or normalized, carrier frequency for long periods after synchronization. Quantum-based fractional-frequency accuracy within $\pm 1 \times 10^{-15}$ when combined with equally low-phase noise synchronization at $1 \times 10^{-15}$ (1 fs in 1 s), means the relative phase difference increases only as $\sqrt{\tau} \cdot 10^{-15} \cdot$ carrier frequency ($\omega_o$). In terms of time, this means that a 1 ns time difference wouldn't occur in a network for 15 days! I will show a summary of several ongoing U.S. programs in which the commercial availability of such low-phase noise, atomic oscillators is now a real possibility.

[1] Circular-T combined uncertainty due to type-A, type-B, frequency transfer, and dead time as reported at BIPM.