Atomic Clock for the "GPS-Denied" Environment -- Undersea

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GNSS satellites provide accurate: Time (w/ epoch uncertainty ≈ 10 ns), frequency (w/ fractional unc. $\approx 10^{-13}$) and position (unc. ≈10 cm) worldwide at low cost. Those incredible systems meet or exceed most. In contrast, much of the Earth is covered by salt water and hence has no GNSS signals, but Position Navigation and Timing (PNT) information is required for many undersea applications (e.g. active and passive seismic monitoring, temperature profiles, ocean-geo science, navigation). We are exploring approaches for atomic clocks for undersea applications with objectives of < 1 ms timing uncertainty at 1 year in harsh ocean conditions, and with low power consumption (< 100 mW).

Quartz crystals and Chip Scale Atomic Clocks (CSAC) play critical roles in undersea timing. Commercial CSACs perform exceptionally well on only 120 mW, operate over a wide temperature range (-20 C to +70C). They represent a significant market ($>10^5$ sold as of 2019*) with diverse applications (GNSS receivers, instruments...) and achieving microsecond timing for days). [1-2] However, these fantastic low-power clocks were not optimized for undersea and very long duration timing.

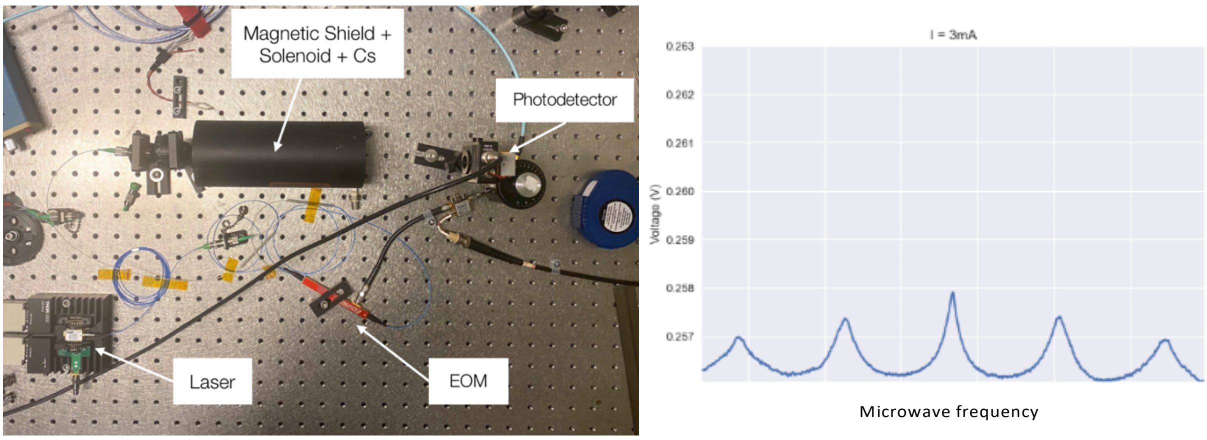

Fig.1. Image of our simple experimental test-bed for undersea atomic clocks. On the right are CPT signals verses microwave frequency (at 4.6 GHz). The multiple peaks illustrate the Zeeman structure for a small DC magnetic field. The resonance width of the magnetically "insensitive" central (m=0 to m=0) component is about 10 kHz FWHM. The other components could serve as an atomic magnetometer.

We are testing concepts and evaluating performance of Cs atomic vapor-cell clocks designed specifically for undersea applications (constrained by power consumption, low temperatures (-10 to +10 C), harsh environment) that require reliable timing over durations of greater than one year. The approach is based on the same principles used in CSACs (laser-pumped Coherent Population Trapping (CPT) but operating in a very different range of the parameter space (Fig 1.). The initial results look promising, and we believe that it will be possible to improve the long-term timing performance relative to other low-power alternatives for the undersea environment.

The range of undersea applications of clocks is surprising, including, seismic monitoring of many types and even ocean water temperature profiles measured precisely by accurate timing of acoustic signals. This is particularly challenging in polar regions under ice, but the data is critical for climate modeling.[3]

[1] https://ww1.microchip.com/downloads/en/DeviceDoc/00003876.pdf

[2] S. Knappe, V. Shah, P.D. Schwindt, L. Hollberg, J. Kitching, L. Liew, and J. Moreland A microfabricated atomic clock Appl. Phys. Lett., 85, 1460-1462 (2004).

[3] Peter F. Worcester, Matthew A. Dzieciuch, and Hanne Sagen, Ocean Acoustics in the Rapidly Changing Arctic *volume 16, issue 1* | Spring 2020 | Acoustics Today, https://doi.org/10.1121/AT.2020.16.1.55