UTILIZING CHIP-SCALE ATOMIC CLOCKS FOR COHERENT PROCESSING BETWEEN INDEPENDENT NON-WIRED UNDERWATER ACOUSTIC SENSORS

Roald Otnes, Helge Buen, Joachim Eastwood, Vidar Forsmo

Norwegian Defence Research Establishment (FFI)
PO box 115, NO-3191 Horten, Norway

Contact author: Roald Otnes, email: roald.otnes@ffi.no

Abstract: *Chip-scale atomic clocks (CSACs) have emerged as an enabling technology for high-precision and high-accuracy timekeeping and synchronization in autonomous equipment, with reasonable power consumption. In this paper, we present an experiment which demonstrates the feasibility of coherent co-processing of data from independent non-wired underwater sensors.*

Two CSAC-equipped acoustic recording units were deployed 1 m apart on the sea floor. The small distance between the units is not realistic in the sense of CSAC applications, but results in the time delay between signals received on the units being small, hence challenging the time synchronization. The units were battery-powered with no cables between, and part of the experiment was repeated two days after the deployment. A boat circled the sensor units, and analysis of the recorded sensor data shows that coherent co-processing between the two units is working well, with no observable deterioration during the experiment period.

Keywords: *Chip-scale atomic clock, acoustic sensors, coherent processing*

1. INTRODUCTION

Phase-coherent combination of data from multiple hydrophones augments detection and localization capability through techniques such as beamforming, correlation processing, time delay of arrival, or matched field processing. Phase-coherent combination has traditionally been possible only within hydrophone arrays where the hydrophones are wired to a common unit, as clocks used to sample the hydrophones have not been accurate enough to retain coherence in the sampling instants between independent non-wired units.

This situation has changed in the recent years, with the advent of chip-scale atomic clocks (CSACs) [1]. CSACs have a relatively low power consumption which allows their utilization in battery-powered underwater equipment, and a stated accuracy on the order of 0.05 ppb ($5 \cdot 10^{-11}$) that should be good enough for coherent processing.

In this paper, we present experimental results that confirm that utilizing underwater acoustic sensors equipped with CSACs indeed result in data which can be coherently combined between independent non-wired units.

Coherent processing between non-wired units gives new possibilities. For example, cross-correlation and time-difference of arrival can be performed with long base-lines which brings several benefits; Fischell et al [2] has tested the use of CSACs for bistatic sonar processing on autonomous underwater vehicles, and Tollefsen and Dosso [3] has investigated the potential benefits to matched-field processing when phase-coherently combining data from disparate sensors. We do not in this paper investigate the related question of how to achieve these benefits when considering limited available communication rate between sensors, but note that CSACs can also be used to improve time synchronization in communication protocols.

2. EXPERIMENTAL SETUP

2.1. Equipment

For the experiment, we used two battery-powered acoustic recording units each equipped with a CSAC for accurate sampling, and with a GPS unit to provide the CSACs with an exact common time reference before going into the water. The software utilized to initialize the CSACs from the GPS units is described in [4], and also incorporates a real time clock implementation with accurate time stamping capability.

Each recording unit was equipped with multiple hydrophones, but in this paper we only consider the data recorded by one hydrophone channel on each of the units. Acoustic data was collected with a sampling rate of 32 kHz.

The acoustic signal source was the engine and propeller of a work boat, see Figure 1, providing a broadband signature.

Figure 1: The work boat used as acoustic source for the experiment

2.2. Experiment geometry

The two recording units were lowered onto the sea floor, with about 1 m distance between the units. Due to the height of the recording units, the hydrophones were about 1 m above the sea floor. The water depth was about 20 m.

The small distance between the units is not realistic for applications such as those discussed in [2],[3], but results in the time delay between signals received on the units being small, hence challenging the time synchronization.

The work boat circumnavigated the acoustic recording units at a distance varying between 100 and 600 m. Sea state was low, and noise was of no significance during the experiment period, but there was bottom topography that could lead to multipath arrivals from azimuth angles different from the target.

The equipment was left in the water for the next two days, when the experiment was repeated without any reconfiguration or reinitialization of the equipment.

3. RESULTS

To confirm that data from the two sensor units can be combined coherently, we computed their correlation and searched for the correlation peak. The time difference Δt corresponding to the correlation peak is, for a given sensor geometry, only a function of bearing θ to the source according to

$$\Delta t = \frac{d}{c}\cos(\theta - \beta) \tag{1}$$

where d is the distance between the two hydrophones, c is the sound speed, and β is the orientation of the baseline between the hydrophones relative to North.

The correlation was computed directly on the input signals without any filtering, hence utilizing frequencies up to the Nyquist limit of 16 kHz.

3.1. First day

We used the data from the first day to estimate the sensor geometry to be defined by β = 18.9° and d = 0.917 m (using the measured sound speed c = 1483 m/s).

The resulting time difference and bearing (including left-right ambiguity) is shown in Figure 2, along with GPS-based ground truth. We see good agreement between bearing estimated from acoustic data and GPS position throughout the entire run, indicating that the independent recorders stayed synchronized during this time period.

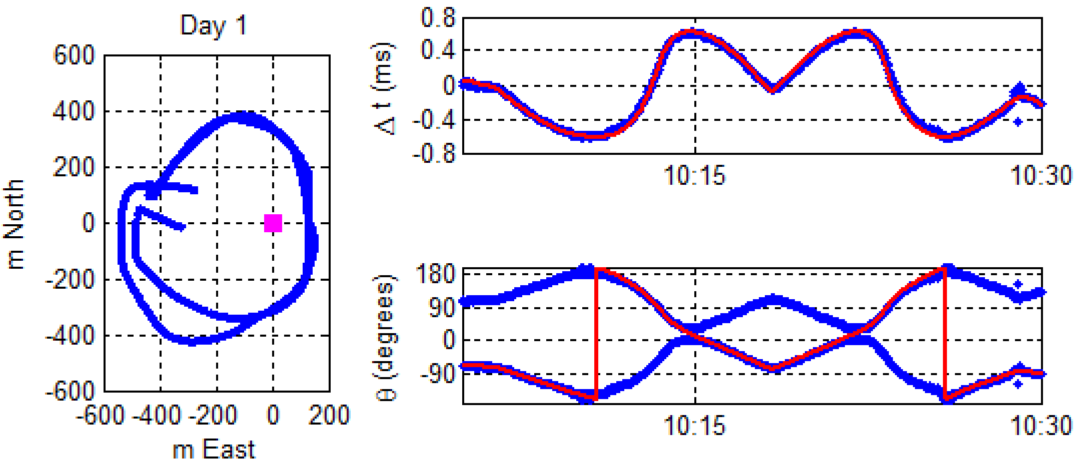

Figure 2: Results from first day. Left: Boat track (blue) relative to sensor position (magenta, in the origin). Right: Time difference Δt and corresponding bearing, estimated from acoustic data (blue) and according to GPS recorder on board boat (red).

3.2. Second and third day

After the first experiment day the sensors were left untouched on the sea floor, and the experiment was repeated on the two next days by again having the boat circumnavigating the sensors.

We reuse the values of d and β estimated from the first experiment day (see above), and do not add any time offsets between the two units. The results are shown in Figure 3, which on this scale (fractions of a ms) do not indicate any deterioration in time synchronization compared to the first day, and coherent processing between the two sensors still performs equally well. The outliers that can be seen are due to multipath propagation as mentioned in Sec. 2.2, and not a symptom of erroneous time synchronization.

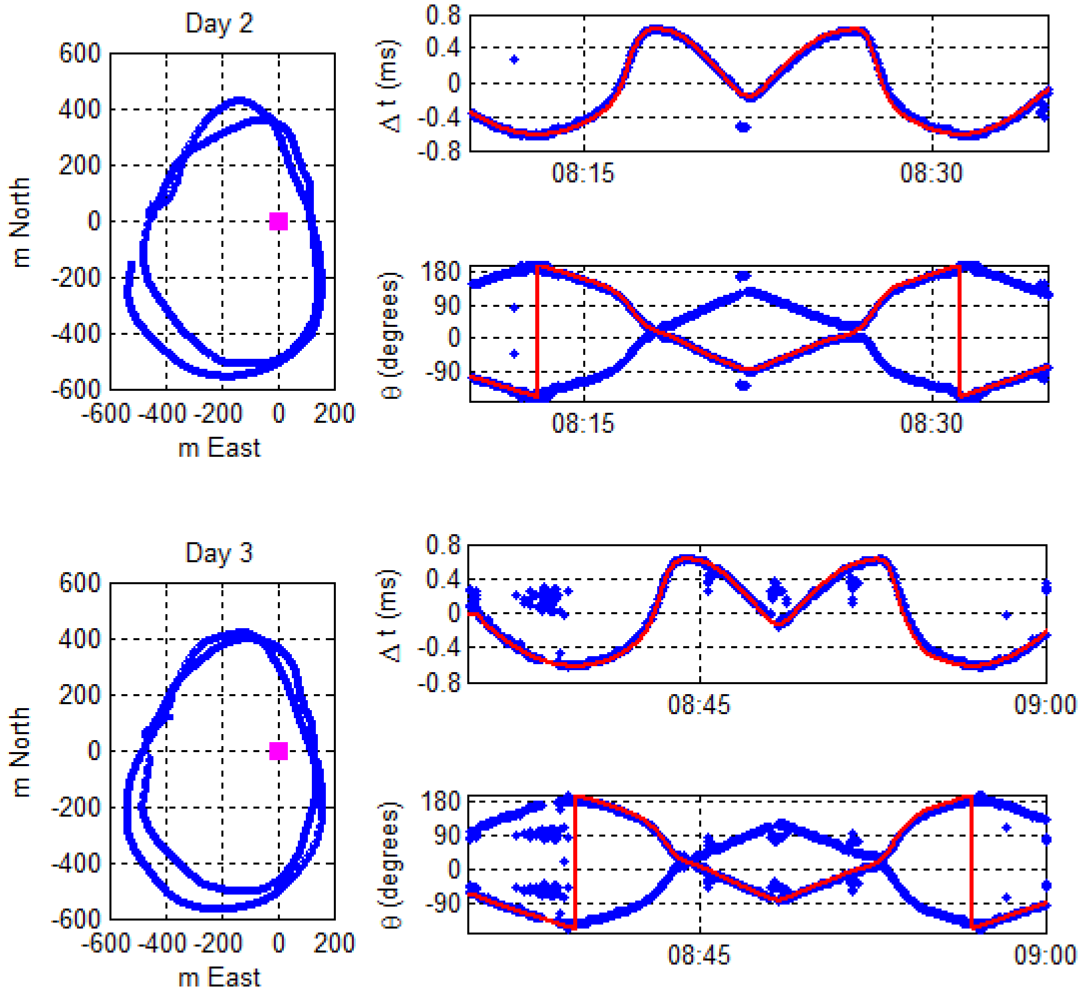

Figure 3: Results from second (top) and third (bottom) experiment day. See caption of Figure 2 for further explanation.

4. CONCLUSIONS

We have presented an experiment which demonstrates that it is now possible to coherently combine data from independent battery-powered non-wired acoustic sensors. This capability can pave the way for new ways to utilize combinations of multiple acoustic sensors.

We saw no deterioration in sampling coherence over the 48 hours the sensors were deployed, and expect coherent sampling to be maintained for a longer time: If the clock accuracy is 0.05 ppb and the acoustic sampling rate is 32 kHz, we will stay synchronized to within a sample for a week. The amount of time offset between units that can be tolerated will depend on the application, but for reference we note that in the experimental setup of this paper a time offset of one sample would lead to a bearing offset of 3° at broadside. Recall that this experiment was designed to be tough on synchronization requirements, while longer and more realistic baselines would lead to smaller sensitivity to residual time offsets. Also, the inaccuracy is mostly manifested as linear drift (see Sec. 5.6 in [4]) that can be relatively easily compensated for.

REFERENCES

[1] **R. Lutwak, A. Rashed, M. Varghese, G. Tepolt, J. LeBlanc, M. Mescher, D. K. Serkland, K. M. Geib, G. M. Peake, S. Römisch,** The Chip-Scale Atomic Clock – Prototype Evaluation, In *39th Annual Precise Time and Time Interval (PTTI) Meeting*, Long Beach, CA, USA, pp. 269-290, 2007.

[2] **E. Fischell, T. Schneider, and H. Schmidt,** Design, Implementation, and Characterization of Precision Timing for Bistatic Acoustic Data Acquisition, *IEEE J. Oceanic Engineering,* 41 (3), pp. 583-591, 2016.

[3] **D. Tollefsen, S. E. Dosso,** Source Localization with Multiple Hydrophone Arrays via Matched-Field Processing, *IEEE J. Oceanic Engineering,* Early Access, 2016.

[4] **P. Thorød**, *Firmware for synchronizing Chip-Scale Atomic Clock to GPS – Enabling precise and accurate synchronization, and timekeeping, in distributed underwater sensor networks,* M.Sc. Thesis, Chalmers University of Technology, Göteborg, Sweden, 2015.