UNDERWATER ACOUSTIC MODEMS WITH INTEGRATED ATOMIC CLOCKS FOR ONE-WAY TRAVEL-TIME UNDERWATER VEHICLE POSITIONING

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Abstract: *Time synchronization of the nodes of an underwater acoustic network, particularly when the nodes are autonomous underwater vehicles (AUVs) operating in formation, is a necessary prerequisite for the effective use of collected sensor measurements in diverse marine application scenarios. One of the methods adopted to operate AUVs synchronously is to synchronize their clocks at the surface (typically by means of GPS) and then use a low-drift clock for maintaining the desired precision while submerged. This paper presents experimental results on the integration of a chip-scale atomic clock (CSAC) into the processing electronics of an underwater acoustic modem on board the AUVs Medusa and Folaga. Since one of media access modes of the acoustic modem, built upon S2C technology, is based on transmission/reception of Synchronous Instant Messages, the modem with integrated atomic clock becomes capable of precise measurements of one-way signal propagation delay (between signal source and signal recipient), and thus of precise estimation of the propagation distance. The paper describes and discusses experimental results on the CSAC accuracy achieved during multiple field tests, includes practical recommendations for CSAC disciplining and phase synchronization with the source of common time reference (GPS time), and provides experimental results on positioning accuracy of AUVs using S2C acoustic modems for communication and positioning purposes.*

Keywords: *AUV, CSAC, underwater acoustic communication, underwater positioning.*

1. INTRODUCTION

Positioning of AUVs can be based on estimation of one-way propagation time of acoustic signals from AUVs (nodes) [1],[2]. In comparison to two-way ranging algorithms such solution does not require any response from the signal recipient, and thus avoids overloading the acoustic channel with activity of many interrogating devices. Given the scarce available bandwidth, on the order of a few tens of kHz, these savings may have a major practical impact. For example, they may enable larger formations of vehicles, or higher update rates in estimated vehicle positions.

Only two sources, transmitting their positions acoustically can be already enough for silent positioning of all AUVs of a formation (implies availability of pressures sensors in the AUVs and some *a priory* information on geometry of the formation [3].

Such implementation of silent positioning method helps to minimize the time needed for positioning of all AUVs and provides an opportunity to scale the formation to any necessary number of AUVs. Energy efficiency and minimization of acoustic impact onto marine environment (i.e. minimized “acoustic contamination”) are an additional important feature of the solution. This, however, may come at the cost of coarser positioning accuracy and higher sensitivity to perturbations when compared with denser message exchanges between vehicles.

2. SELECTION AND PHYSICAL INTEGRATION OF ATOMIC CLOCK

The development has been done in the scope of the WiMUST (Widely scalable Mobile Underwater Sonar Technology) project, whose specification contains a strict requirement on the accuracy of AUVs’ synchronisation (allowing no more than 50 us time deviation during an autonomous mission of at least 8 hours), as well as a requirement to develop a small size and lightweight solution, having low power consumption, low cost and being commercially available.

Silent positioning of AUVs in the project is based on application of acoustic modems built upon S2C technology [4]. In order to keep the hardware small and compact, the decision was to integrate an atomic clock into the modem electronics and providing also a technical possibility for distribution of time stamps of the atomic clock to other hardware recipients situated in the same vehicle.

Currently only one model of atomic clock is available on the market that meets the equirements mentioned above. The model is Microsemi SA.45s Chip Scale Atomic Clock (CSAC) [5]. According to manufacturer specification, this has two orders of magnitude better accuracy than OCXOs or TCXOs oscillators [6],[7],[8]. It has a power consumption of less than 120 mW, its weight is 35 g, and it requires a volume of only 16.5 cm^3 (4.06 x 3.53 x 1.14 cm). The SA.45s provides 10 MHz and 1PPS outputs at standard CMOS levels, with short-term stability (Allan deviation) of 3E–10 s within a time slot of 1 s. Its typical long-term aging is less than 9E–10 s per month, and maximum frequency change is ±5E–10 over an operating temperature range of 10°C to 70°C. The SA.45s CSAC accepts a 1PPS input that may be used to synchronize the unit’s 1PPS output to an external reference clock with ±10 ns accuracy.

To make sure that the atomic clock in our application provides accuracy required in the project, a series of tests were carried out during and after redesign of the modem electronics, as well as after integration of the modems into AUVs during at-sea tests on AUVs ranging (and thus time synchronisation) accuracy.

3. INVESTIGATION OF THE ATOMIC CLOCK (DISCIPLINING AND SYNCHRONISATION)

Each atomic clock has an individual drift of its oscillator frequency mainly determined by two factors: aging and retracing [9]. Therefore, even if 1PPS signal phases of several atomic clocks are synchronous at a given instant, their individual drifts can cause increasing deviations of the clock's 1PPS signals over time. In CSAC frequency differences between devices may be around 10^{-7}-10^{-8} %. The problem can be solved by means of adjustment of each oscillator frequency using an external 1PPS signal source, for example, the 1PPS output of a GPS receiver. The process of conducting such adjustments is called "disciplining".

In general, GPS receivers are able to accurately maintain their internal clocks in order to accurately calculate their geographic coordinates (internal clocks of GPS receivers are permanently synchronized with GPS time to satisfy high accuracy requirements). Even if they can be relatively noisy in short-term, their averaged 1PPS output is stable [10].

Because of short-term noise in the GPS 1PPS output, we had to experimentally estimate and specify (at least for GPS receiver models used in our tests) a sufficiently large disciplining time constant to average out the noise. Another parameter we had to estimate and specify was an acceptable level of phase error threshold, which can be used for deciding if the disciplining procedure has been successfully finalised. According to the documentation on the CSAC, if the phase difference between the 1PPS outputs of the GPS receiver and the atomic clock during a specific time interval is less than the given threshold, the disciplining procedure is considered as successful [9]. The specific time interval is understood as the disciplining time constant. This constant can be different for diverse sources of the reference 1PPS signals. Therefore, depending on the GPS receiver mode l installed in the AUV, the disciplining time constant has to be estimated and specified in documentation for a customised equipment setup and used for correct mission preparation later by the user. The default threshold is usually set to 20 ns, though the atomic clock interface allows for adjusting the threshold to different values.

The experimental material of this subsection contains information on disciplining atomic clocks. Atomic clock investigation has been carried out in a series of tests with estimations of the clocks offsets and skews in different scenarios. The setup consisted of:

- two atomic clocks, type CSAC SA.45s,
- two types of GPS receivers, Sparkfun Venus with JavaD GrAnt antenna, and Ashtech MB100 with Hemisphere A21 antenna,
- individual 12VDC batteries, Panasonic CF31 computer running Debian Linux, USB hub, cables.

The schematic of the equipment setup and corresponding hardware are given in Fig. 1.

Each GPS receiver can operate independently from any other providing phase-synchronized 1PPS outputs, which can be used to attain approximately equal disciplining and phase synchronization results on separate AUVs. This supports the idea of carrying out the disciplining procedure independently on each AUV, which has its own GPS receiver, shortly before the mission (when AUVs remain on the surface). This idea was simulated and tested.

In the tests we used an Arduino-based board to measure the phase difference between CSAC and GPS 1PPS outputs during and after disciplining. This setup was built for all necessary tasks with atomic clocks: for disciplining the atomic clocks using different GPS

1PPS outputs, for synchronizing CSAC 1PPS phase with GPS 1PPS, as well as for simulating a several-hour mission of two vehicles after disciplining.

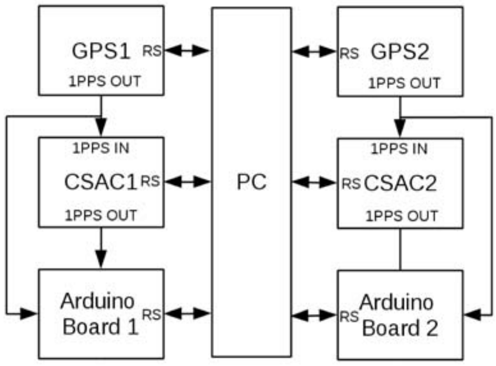


Fig. 1. Schematic of the equipment for disciplining/investigations of atomic clocks

All the data from CSAC, GPS and Arduino-based measurement units have been logged in each test and used for subsequent analysis. Fig. 2 and Fig*.* ***3*** demonstrate the process of SCAC disciplining: when using Sparkfun Venus GPS (Fig. 2) and Ashtech MB100 GPS (Fig. 3). In general, Sparkfun Venus GPS turned out to be noisier than Ashtech MB100 GPS (note the difference in vertical scales). Nonetheless, in both cases after approximately 15-20 minutes, the disciplining and synchronization results were already sufficiently accurate as required by a WiMUST system.

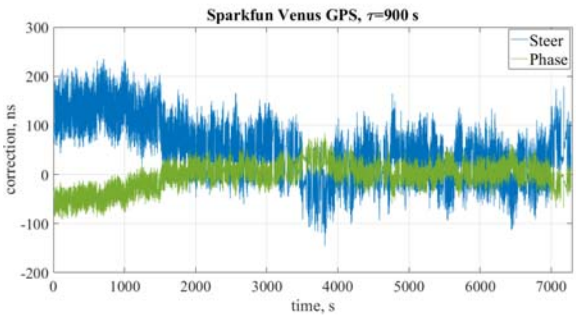


Fig. 2. Disciplining of CSAC by means of Sparkum GPS.

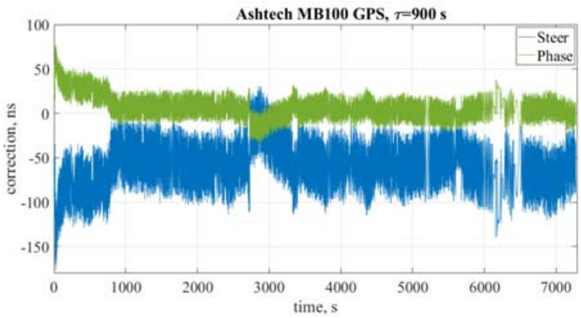


Fig. 3. Disciplining of CSAC by means of Ashtech GPS

Due to noise jitter of some GPS receivers that can lead to phase mismatch (between GPS 1PPS and CSAC 1PPS) of higher than 20 ns, the decision about disciplining of the atomic clock can be negative (20 ns was defined by manufacturers as a default parameter for automatic decision about successful disciplining). Since the project goal can aslo be achieved with initial phase synchronisation accuracy coarser than 20 ns, during development the SCAC firmware has been updated to provide an opportunity to adjust the phase threshold parameter by the user (a corresponding utility has been developed and tested). The values that there were practically observed during different tests with different GPS receivers were about 30 ns. The threshold of 30 ns has been finally set up as a recommended value and used later during testing at sea.

The outcome of the CSAC disciplining procedure – determination of the parameter called “steer value” – can be saved to non-volatile memory of the clock. Immediately after disciplining, the CSAC can be used for accurate time referencing of the AUVs. The accuracy of the time referencing is within tens of nanoseconds in the beginning of the mission, and was observed in the simulation of an autonomous mission to have an order of several microseconds after 8 hours of autonomous operation.

However, after some days/months so-called aging effect leads to degradation of the clock accuracy. E.g. in a month after disciplining, the usage of the atomic clock can already be too inaccurate for WiMUST missions: tens of microseconds per hour can be an approximate value of atomic clock deviation during an autonomous mission.

Moreover, because of switching the CSAC unit off and on, the so called retrace error introduces an additional shift in the reference frequency resulting in further performance degradation of the clock. Moreover, if power-cycled repeatedly the retrace error can even accumulate. The retrace parameter specifies the change of frequency of an oscillator after off/on-switching the clock (e.g. ±5e-10 s after 48 hours off). According to the information of the manufacturer, the atomic clock can move outside its retrace specification during continuous or discontinuous operation for *2*5e-10*(3600 * 8) = 28.8 us* (worst case). In fact, in our internal CSAC tests, after disciplining and off/on-switching the power (for several minutes) we observed about 6 us time drift (between 1PPS from GPS and CSAC 1PPS) after an 8-hour operation.

Anyway, even ignoring the retrace parameter, the aging can strongly affect the accuracy of the atomic clock. This means that atomic clocks have to be re-disciplined fairly often and if possible remain switched on. Of course, an effort for maintaining a swarm of AUVs in permanent readiness for deployment can be large and maintaining the clocks in powered state can be unpractical. Therefore, one of the alternatives can consist in performing only phase synchronization of the clock (after switching it off and on) with an external 1PPS source, i.e. without time consuming steer calibration. In this case, the accuracy of the atomic clock immediately after deployment can be high (tens/hundreds of nanoseconds), but will noticeably degrade during a long mission.

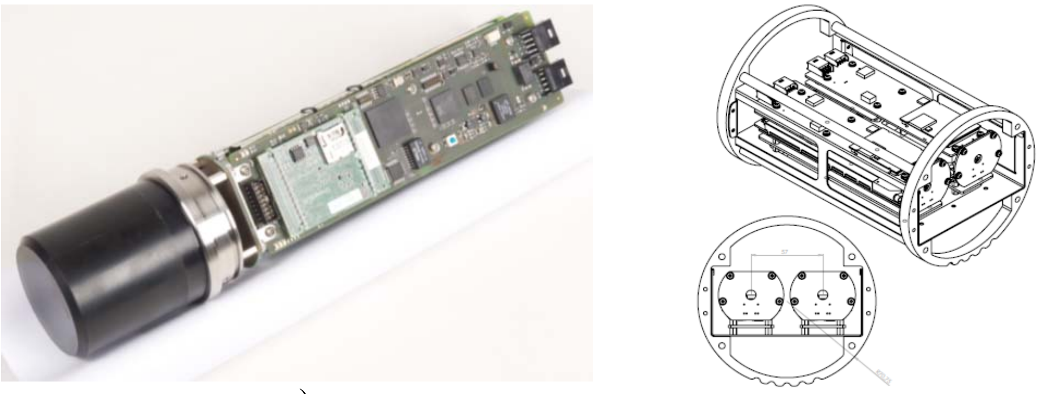
Another alternative can consist in performing the phase synchronization and a short disciplining of the clocks with GPS 1PPS. (A relatively short disciplining procedure can be performed before each mission, while the vehicles are still on the surface and able to receive GPS signals.)

During the tests we experimented with various short disciplining periods (time constants), with available GPS receivers and figured out that the time constants between 300 s and 900 s are good enough for CSAC disciplining and can be recommended for WiMUST practical applications. Such short disciplining results into sufficiently accurate steer parameter and accurate phase synchronisation estimates.

4. INTEGRATION OF THE ATOMIC CLOCK INTO THE MODEM ELECTRONICS

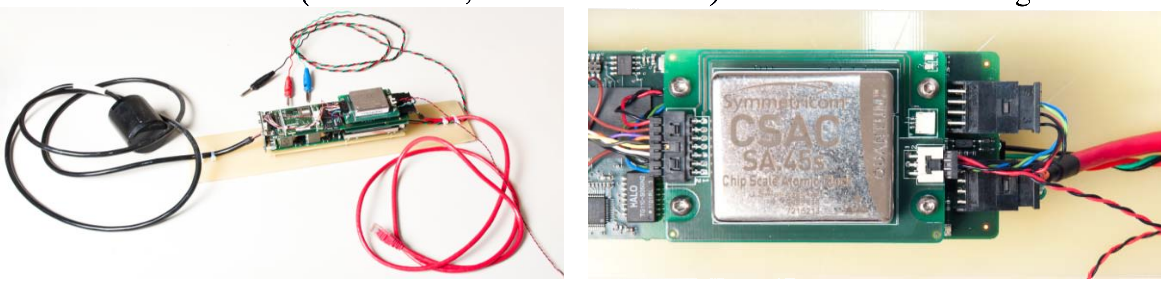
Fig. 4a shows the electronics of the conventional modem S2CM18/34 OEM. Integration of the atomic clock accounted for strong geometrical limitations of AUV sections: the modems had to be placed inside Medusa and Folaga AUVs, namely, two modems of different types in each of the AUVs. An installation model of these two modems inside a Medusa AUV is shown in Fig. 4b. Fig. 5 depicts the solution with atomic clock integrated into the S2CM18/34 OEM modem electronics.

The accuracy of the atomic clock’s 1PPS output was measured during several all-day tests in laboratory conditions and sea trials. After disciplining and phase synchronisation of the clocks with accuracy of 30 ns, the deviation of the clock’s 1PPS output from the 1PPS output of a GPS receiver stayed always under 20 us. This accuracy would only slightly influence the range measurements during WiMUST AUV missions. Particularly, ranging errors attributed to the atomic clock deviations would remain under 3 cm.



a) b)

Fig. 4. Electronics of the modem S2CM18/34OEM: a) the modem photo, b) installation of two modems (S2CM18/34, S2CM42/65 OEM) inside an AUV housing



a) b)

Fig. 5. Modem electronics S2CM18/34OEM: a) modem photo with all components, including atomic clock SCAC SA.45, b) detailed view of the atomic clock placed on the modem electronics

To estimate the ranging error in practice, range measurements were carried out during sea trials with multiple AUVs operating together and simulating a cooperative mission. Results of the sea trials are presented in the subsection below.

5. AT SEA TESTS WITH AUVS (WITH MODEMS EQUIPPED WITH ATOMIC CLOCK)

Since one of the main reasons of atomic clock integration was to achieve the possibility of accurate range-only based positioning/navigation of the AUVs, several directed tests have been carried out with multiple AUVs executing relatively long missions.

In the scope of WiMUST, the tests were conducted in November 2016 at Sines, Portugal. All the vehicles operated at the surface, but the acoustic modems were submerged, which made it possible to have the acoustic positioning/navigation scheme working and, at the same time, to have high precision RTK GPS fixes for ground-truthing. This strategy was helpful to evaluate the ranging performance obtained acoustically by the AUV.

Fig. 6 shows a series of AUV poses, representing the navigation architecture. For the sake of simplicity, successive time instants are represented by integer numbers without dimensions. In the description ASV_1 and ASV_2 denote the vehicles shown in the top and bottom paths in the figure (these AUVs can play the role of surface vehicles when necessary). The AUV estimated ranging information from one-way-travel-time of the acoustic signals coming from ASV_1 and ASV_2, and combined it with available depth data and GPS coordinates (embedded in the acoustic messages from ASV1 and ASV2) to estimate of its own geographical position.

At time t=1, the AUV received a range measurement from ASV_1, r_1, and data with ASV_1 position, $p'_{1,1}$. Some time later, t=2, the AUV has moved to another location and received a range measurement from ASV_2, r_2 , and data with ASV_2 position, $p'_{2,2}$. After a while the AUV has obtained a collection of n distance measurements r_1 to r_n , acquired at times t_1 to t_n , and a set of n GPS coordinates that include its own fixes, denoted as $p_{1,1}$ to $p_{1,n}$ as well as those of the two ASVs. In this test the goal was to estimate ranges, $r_{[1:n]}$ and compare them with ranges obtained from GPS positions of the ASVs and the AUV, $p'_{1,[1:n]}$, $p'_{2,[1:n]}$ and $p_{1,[1:n]}$.

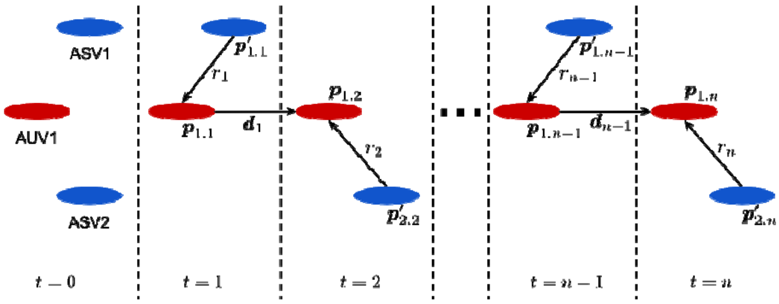


Fig. 6. Timeline of poses of the AUV and the USVs.

Precise time was available onboard in all the nodes equipped with acoustic modems directly from the atomic clocks: the modems output precise PPS time to other systems, in particular the AUV/ASV computer and the GEO acquisition system.

Nodes at the surface obtained GPS fixes at a high enough rate to allow them to estimate their positions very accurately, so that the position estimates that they send to the AUV can be considered unaffected by errors.

For this specific test, three MEDUSA vehicles, provided by IST-ID, were used. Fig. 7 shows the race-track trajectory of the AUV obtained over the entire mission.

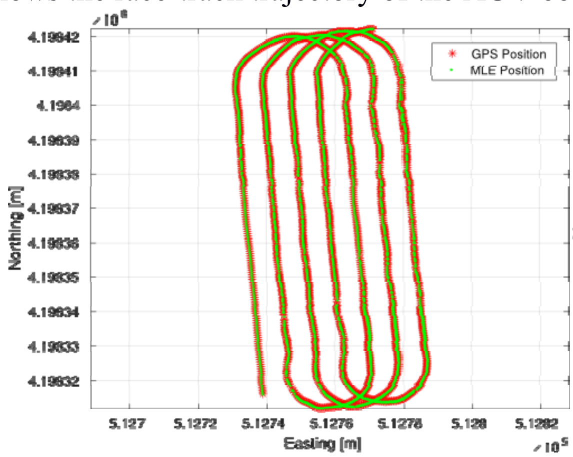


Fig. 7. Race-track trajectory of the AUV.

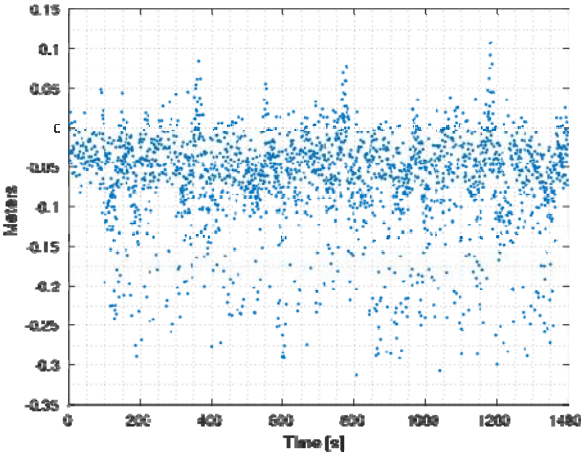


Fig. 8. Residuals in range measurements.

Fig. 8 shows the residuals in range measurements during the mission, i.e. the difference between measured acoustic ranges and the calculated distances using GPS positions (ground-truth). As one can see, the residuals are slightly biased, with a mean of -4cm and standard deviation of 9 cm. There is no significant skew between atomic clocks of the vehicles (less than 3 us per hour). Still, these results are preliminary and a number of factors remain to be compensated in the current implementation, such as lag in the GPS positions of the surface agents when they are broadcast to the AUV, sound speed variations during the day (especially close to water surface). Compensation of such factors should help to further reduce e.g. the slight measurement bias, doing positioning/navigation results even more accurate.

Anyway, the current status already speaks emphatically in favour of using atomic clocks for supporting acoustic range-only based positioning – very accurate even during long autonomous missions – as selected for implementation in the scope of the WiMUST project.

6. CONCLUSIONS

A small-size atomic clock has been successfully integrated into the electronics of an Evologics S2C acoustic modem to replace commonly used quartz clocks, and provide additional important capabilities: 1) to perform one-way-travel-time ranging of the interrogating devices, thus supporting silent positioning/navigation of underwater vehicles with high accuracy, as well as 2) to distribute 1PPS timestamps to other devices installed in the same vehicle.

The paper validates practical recommendations for atomic clock disciplining and phase synchronization with the source of common time reference (GPS time). It also provides experimental results on positioning accuracy of AUVs using S2C acoustic modems with integrated atomic clock (CSAC) for communication and positioning purposes. In practice, the range measurements, based on one-way-travel-time estimation, demonstrated centimeter-level rms accuracy during a half-hour mission, with rough estimation of atomic clock skews less than 3 us per hour. This result fully meets the requirements the WiMUST project, , and the approach can also be recommended for various practical applications of AUV formations requiring high positioning/navigation accuracy during extended autonomous missions.

7. ACKNOWLEDGEMENTS

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