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Why do we need a Polish miniature time reference for space and military applications?

Abstract: The paper presents an overview of atomic clock solutions developed in leading scientific and commercial teams of the world. The construction of a Polish atomic clock is proposed, giving the names of scientific units that can participate in it.

Keywords: Polish atomic clock

The applications of precise time and frequency references are extensive. The first of these is telecommunications, where the development of successive technologies (4G – 5G, etc.) is only possible through the use of atomic references. These enable bandwidth narrowing (increased data capacity) and faster transmission. Additionally, they allow the use of data encryption based on signal encoding in the time domain, which is more effective compared to mathematical encryption algorithms. Currently, every base station of mobile network operators is equipped with an atomic reference (or a temperature-stabilised quartz reference – the latter are being replaced), and these users represent the largest market for this product.

The second most important application is precise navigation. Accurate time measurement is crucial for the precise determination of object positions. For example, commercially available car navigation systems use quartz frequency references (10^{-6} s/s), allowing for location estimation with an accuracy of ± 10 m. The use of temperature-stabilised quartz references (10^{-8} s/s) improves the positioning accuracy to ± 2 m. In contrast, the use of atomic references (10^{-11} s/s) increases precision to ± 1 cm. This is because precise navigation requires very accurate measurement of the travel time of a radio beam from a device on the ground to a satellite (or often several satellites) and back to the ground device. Errors in time estimation result in inaccurate navigation.

It is therefore evident that precise navigation systems are utilised in military solutions, which constitute the third application area. It must be clearly stated that every modern weapons system uses an atomic time reference.

From another perspective, the possession of a miniature time and frequency reference enables the development of advanced and precise systems for navigation and communication in the space and military domains.

The component in the form of a miniature time and frequency reference is thus a critical component in system construction. Existing manufacturers (available solutions: Israel, USA) may not be willing to share this critical technology, thereby limiting the potential for technological growth in Europe. This situation has been recognised by the EU (see EU report) and the European Space Agency (ESA), as reflected in ESA's announced tenders for the development of miniature time and frequency references (ESA NAVISP-EL1-032 project; start date: 01/03/2020; duration: 18 months (Neuchatel & EPFL)

ESA project entitled: “Ceramic Miniature Atomic Clock (C_MAC)”; Contract 4000114436/15INLIMM, started in 2015), including the latest tender for CSAC (Title: TIME REFERENCE FOR PORTABLE TERMINALS USED IN SECURE COMMUNICATIONS (ARTES 4.0 4S SPL 7C.078) - RE-ISSUE, Activity Number: 1000037324). Currently, ESA is

conducting several dozen procurement processes for solutions for the Galileo satellite navigation system and secure satellite and ground communications systems.

At this point, it is important to clarify the subtle difference between Miniature Atomic Clock (MAC) technology and Chip-Scale Atomic Clock (CSAC) technology. In MAC solutions, microwave excitation of rubidium atoms is used. For this reason, MAC is synonymous with a rubidium oscillator. The key component of MAC is a cell filled with alkali metal vapour, with dimensions suited to the size of the microwave cavity—the cell dimensions are approximately 1 cm³. These cells are most commonly produced using the traditional glass-blowing method. Due to the size of the cell and the method of atom excitation, MAC solutions have a power consumption of around 450 mW.

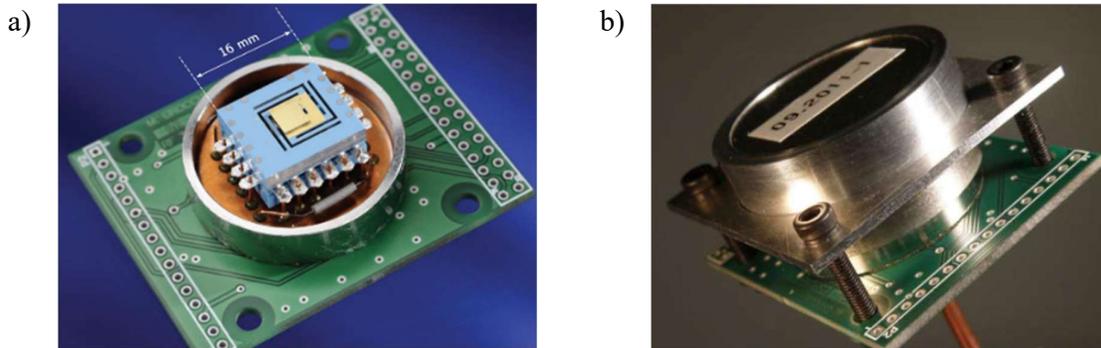
CSAC solutions are alternatively referred to as "optical atomic clocks" because the excitation of atoms is carried out by laser light modulated at high frequency. Both rubidium and caesium atoms can be used, and the cells are smaller, produced using MEMS techniques. As a result, CSAC consumes around 120 mW, though CSAC solutions are technically more complex than MAC.

The first model of CSAC was introduced by Dr John Kitching from NIST in Boulder, Colorado (USA) in 2004. Subsequently, the US established the DARPA programme, aimed at developing a product that would enable the creation of new solutions in telecommunications, computing, and the broader military industry. The first prototype of CSAC, ready for implementation, was presented in 2011. It should be emphasised that Kitching's work (funded with several million dollars) and the subsequent implementation efforts at Symmetricom (now Microchip) were financed through DARPA programmes. Between 2011 and 2013 alone, Symmetricom received at least ~20 million dollars to support the implementation of CSAC. Between 2004 and 2012, parallel work on CSAC was undertaken in several centres (Israel, Russia, China, and the EU). Some of these efforts led to the development of domestic MAC or CSAC solutions, although the results are not clearly reported in the literature.

According to an analysis by the European Commission [1] (The EU report references and refers to the research of Dr Paweł Knapkiewicz, citing the article: Knapkiewicz Paweł, *Technological Assessment of MEMS Alkali Vapor Cells for Atomic References*, *Micromachines* 10(1), 2019; doi:10.3390/mi10010025), as well as my own, currently available rubidium resonator (MAC) solutions originate from Israel (one supplier) or the United States (five suppliers). In Europe, the only solution is offered by the Safran group. Available MACs are characterised by short-term stability (depending on the solution) in the range from $1.5 \cdot 10^{-11}$ to $6 \cdot 10^{-11} = 1$ s.

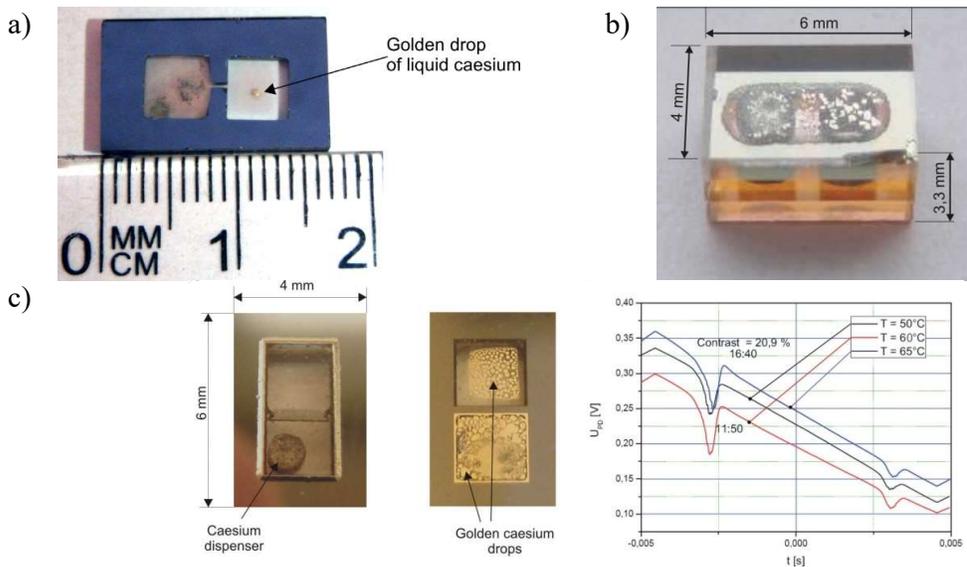
Microchip (USA, formerly Symmetricom / Microsemi) is the only company in the world that offers CSAC for sale on a continuous basis, under the trade name SA65 (successor to SA45). Europe does not have its own CSAC solution.

Among the CSAC projects completed, special attention should be given to the MAC-TFC project (Miniature Atomic Clock for Time and Frequency Measurements), initiated by the European Community under FP6. Led by FEMTO-ST, the project was carried out between 2008 and 2014 by an international consortium involving research centres and companies from France, Poland, Switzerland, and Germany. The project was successfully completed, resulting in a miniature caesium atomic clock (CSAC) with short-term stability of $5 \cdot 10^{-11} = 1$ s (Figure 1).



1. CSAC – outcome of the MAC-TFC project: the so-called physics package a) before and b) after hermetisation

In the MAC-TFC project, a unique technique was employed to produce the so-called MEMS optical cell, filled with a precisely controlled amount of caesium and buffer gas. An innovative method of laser-based caesium release from the so-called caesium dispenser was used, developed at FEMTO-ST based on a concept by the Polish-French team (Dziuban, Walczak, Górecki) [2]. This method became the technological foundation for the European CSAC, and in the MAC-TFC project, the caesium MEMS optical cell was developed under the leadership of the Polish project partner (Wrocław University of Science and Technology, Dziuban, Knapkiewicz, Figure 2) [3-7].



2. Caesium MEMS cells produced at Wrocław University of Science and Technology: a) a meso-scale silicon-glass cell, b) a fully glass miniature cell, c) a silicon-glass miniature cell before and after caesium dispensing, along with laser absorption spectroscopy measurements showing two characteristic absorption peaks for caesium

The implementation of the project’s outcomes took place in Switzerland, where over the next 15 years, a team from UniNE’s Time-Frequency Laboratory (LTF, Neuchâtel – the same team that executed the MAC-TFC project), in collaboration with CSEM and Orolia Switzerland SA, developed a commercial version of the rubidium atomic clock. The first mention of this product being market-ready occurred in 2022. Currently, this product, under the trade name mRO-50 (Atomic Clock / Ruggedized versions), is part of the Safran group’s product portfolio, as mentioned earlier.

Based on an analysis of the CSAC solutions market, it can be concluded that Microchip holds an absolute monopoly. According to official data published by the company, Microchip sold 95,000 CSAC units between 2011 and 2020, while also estimating that by 2029, the demand for CSAC will reach one million units annually. Microchip's estimates align with another analysis (ReportLinker, 15 December 2022), which forecasts the CSAC market value to reach 745.79 million dollars by 2028.

A competitiveness analysis indicates that Microchip's competitors in MAC products could be the Israeli NAC1 (by Accubeat) or mRO-50 (by the Safran group).

The challenge of building a CSAC is not trivial, as evidenced by 20 years of technological development and the significant financial resources invested, primarily in the USA and Europe.

The team from Wrocław University of Science and Technology participated in the MAC-TFC project (2008-2011), which aimed to develop the first European atomic clock. The project was successfully completed, but the results were not implemented. Our subsequent efforts to generate interest in this topic in Poland were unsuccessful. Given that CSAC is a critical component for secure data transmission and precise navigation systems (a dual-use technology), having CSAC production capabilities in Poland would allow for technological independence in the field of miniature time and frequency references, including the development of modern and secure telecommunications networks (including satellite) and advanced weaponry.

This goal is achievable and requires “only” a bold and decisive decision to establish a CSAC development programme in Poland. It should be emphasised that Poland already possesses all the necessary competencies to develop CSAC: the know-how and technological infrastructure for producing caesium/rubidium MEMS cells (Wrocław University of Science and Technology, Faculty of Electronics, Photonics, and Microsystems), a time laboratory (the Space Research Centre of the Polish Academy of Sciences, Borowiec branch near Poznań), growing expertise in optoelectronics production, and companies capable of using CSAC to build satellite and military systems.

Source materials

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