Final Publishable JRP Summary Report for JRP IND55 Mclocks Compact and high-performing microwave clocks for industrial applications

Overview

Atomic frequency standards provide the ultimate source of accuracy and stability for all modern communication, navigation and timekeeping systems. There is a demand from industry for more accurate and stable clocks. Several Rubidium (Rb) based prototype clocks with unprecedented frequency stability have been developed by specialised laboratories using laser sources and innovative techniques to prepare and detect the atoms. In this project, the prototypes are developed and improved to make them suitable for industrial use, commercial production and to transfer frequency standards between laboratories and from laboratories to clock manufacturers. Commercial clock manufacturers want clock technology which reproduces laboratory performance, but with portability, reliability and low power consumption.

Need for the project

A wide range of scientific and technological fields requires stable and reliable frequency standards and timekeeping. Often only atomic clocks can provide these signals with the required level of accuracy and stability. There are three areas which need the development of compact clocks with high metrological features:

1. Technological applications where frequency stability is the main concern (of the order of 10^{-12}-10^{-13} at 1s measurement time), for example, telecommunications, navigation, defence and space. Currently Rb clocks are used, and if the requirement for stability is particularly stringent Rb clocks are replaced by hydrogen masers (H-masers). However, they are bulky, very expensive and only a few laboratories or industries can afford them. The ideal would be a clock combining the performance of an H-maser with the low price, reliability and compactness of a Rb clock. This is required for the European satellite system GALILEO, which currently has on board a performing (but heavy) hydrogen maser and a lower performing Rb clock. Reducing the payload would bring financial benefits for each launch.

2. Applications where size is primary importance (for example a volume of the order of 20 cm^3 and a weight of 50 g). This is important when the clock operates inside measurement instruments, in vehicles or in unmanned devices. They are important role in military applications, especially in GPS-denied environment. In addition, the small size, jointly with a stability of some 10^{-12} (1 hour measurement time), opens the door to new classes of applications such as underwater sensors for seismic research or gas and oil exploration.

3. Advanced applications where stability, accuracy and reduced size, weight and cost are all highly desirable. This is the case in metrological laboratories. Currently, they use an H-maser to optimise the short-term performances and a master Cs clock to optimise the medium to long term behaviour. In addition, most advanced laboratories use a Cs fountain to calibrate the master clock. This rather complicated ensemble could be replaced by a single continuously operated clock exhibiting high stability and accuracy performances. Such a clock could also be used in the ground part of satellite navigation systems or for inertial navigation in submarines.

Scientific and technical objectives

The project reviewed the performance and features of vapour-cell clocks (Rb clocks are a type of vapour-cell clock) including commercial and laboratory prototypes, and evaluated what industry requires now and in the future. The project then characterised and validated two specific types of vapour-cell clock, and examined a third option which is still in the research stage.

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European Metrology Research Programme
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The project had the objectives:

- **To review the microwave vapour-cell clocks**, including both the commercial devices currently available on the market and the most recent clocks exploiting laser pumping techniques. The aim of the review is to identify the limitations of traditional commercial devices to fulfil the increasing demands of some advanced technological and industrial applications and to highlight the need to convert better performing laboratory vapour cell clocks into industrial products. In addition, the review will include input from the stakeholder committee which will address industrial needs and be fed into the project.
- **To develop a vapour-cell clock based on the pulsed optical pumping (POP) principle** with a fractional frequency stability of units of 10^{-13} at 1 s and in the 10^{-15} range at 10^5 s. The clock will be targeted on industrial applications in terms of size, power consumption and reliability.
- **To develop a vapour-cell clock based on cold atoms** with performances comparable to those of the pulsed optical pumping on the short term but with better performances on the long term including a metrological specification of accuracy within an order of magnitude of that of primary standards. The project will identify the compromises required in order to obtain the expected performance while still targeting industrial applications.
- **To investigate alternatives principles, such as coherent population trapping (CPT)** or electromagnetically induced transparency, to study the possibility to realize a clock optimized in terms of compactness and to provide support to the implementation of the previous clocks.

Results

In this project specific solutions were conceived and realised in order to optimize size, weight, power consumption of these new-concept vapour cell clocks, which can match the good metrological performances achieved by laboratory prototypes.

Review the microwave vapour-cell clocks, including both the commercial devices currently available on the market and the most recent clocks exploiting laser pumping techniques.

The aim of the review was to identify the limitations of traditional commercial devices to fulfil the increasing demands of some advanced technological and industrial applications, and to highlight the need to convert better performing laboratory vapour cell clocks into industrial products. For example, there are growing concerns about data integrity and security, an increasing number of applications requiring time stamping, and it is expected that stable frequency references will be increasingly required. In this first phase of activity there was input from the stakeholder committee about industrial needs. This highlighted that the POP clock, Rubiclock and CPT clock exhibit outstanding properties of accuracy and stability and are of interest in an industrial field.

Develop vapour-cell clock based on the pulsed optical pumping (POP)

POP clock components have been designed, realised and characterised. Specifically, researchers from the University of Neuchatel with the collaboration of INRIM developed and successfully characterised quartz cells containing the Rb atoms and a compact laser head for the generation of the pumping radiation. UFC and INRIM developed the low phase noise synthesis chain used to excite the atoms. Characterisation measurements show that both the laser system and the synthesis chain do not contribute to the limit of the clock stability. After the design and the characterisation of the magnetron cavity, the clock was completely characterised. A clock stability of $3x10^{-13}$ up to integration times of 300 s has been reached. In addition, the core of the clock where the atoms are located, known as the physics package, was optimised. In this physics package a conventional cylindrical cavity has been used. This prototype of POP clock demonstrated a frequency stability as low as $2.5x10^{-13}$ at 1s and reaching the value of $2.5x10^{-14}$ at 10000 s.

The key result was that high performance was reached by locking the laser on the same cell used for clock operation, without the need of an external cell. This greatly simplified the clock which is particularly important for an industrial and commercially use. The size of the POP clock was reduced by using a magnetron cavity, rather a traditional cylindrical microwave cavity. Also, a reduced size (less than 1 dm^3) laser head was designed and successfully tested.

Develop vapour-cell clock based on cold atoms (also known as Rubiclock)

OBSPARIS studied the possibility of using a light induced atomic desorption (LIAD) system for an atomic clock for the first time. OBSPARIS and the University of Neuchatel designed a system to tune the Rubiclock microwave cavity easily. All the Rubiclock apparatus has been successfully tested in a zero gravity environment. After the studies on the fine tuning of the device and preliminary stability measurements, activity was focused on the full metrological characterisation of the clock. Studies related to short and long term frequency stability have been done, as well as studies to investigate possible frequency shifts that could limit the clock's accuracy. A clock stability as good as 4.2×10^{-13} at 1s up to 2×10^{4} s has been measured. The drift has been also measured and cured using a new glass borosilicate coil used to generate the magnetization quantization field. Cavity pulling has been recognised as one of the possible effect limiting the clock's accuracy. It is expected that in the future Rubiclock can be tested in other zero gravity campaigns.

The key outcome was that for vapour-cell clocks based on cold atoms (Rubiclocks), a system was devised to tune the cavity easily, this simplifies the use of the clock, both in terms of cost and time. Moreover, a compact laser system based on commercially available telecom lasers was implemented.

Investigate alternatives principles, such as coherent population trapping (CPT)

All partners contributed to the delivery of the CPT clock specification and a study of CPT resonance in an open lambda system has been also been completed. UFC and INRIM have realised the synthesis chain for the CPT clock and a preliminary characterisation of the synthesis chain was done. The work was mainly devoted to completing the new physics package and the optical setup. After completing the clock, in the last six month the work concerned the clock characterization. A frequency stability of 2 x10-^{13} up to 100 s has been measured. The main effects limiting the clock stability in the medium-long term have been studied and recognized. They are the temperature fluctuations (related to the buffer gas) and the light shift.

CPT clocks have the potential for very small applications since no microwave cavity is required. A system to modulate the laser phase easily to generate CPT was done and a specific atomic interrogation was studied to increase the signal to noise ratio. This technology is still in the research stage, but the prototypes developed demonstrated the potential.

Actual and potential impact

Dissemination of results

The project outputs have been shared widely with the metrology community and instrumentation and clock manufacturers; 26 papers or posters have been published and 14 papers have been published in peer-review journals. A website has been established to promote the activities of the project and it includes e-training lectures. There is a stakeholder area where presentations can be uploaded so that members can disseminate information about the project activity. A tutorial presentation on vapour cell clocks was presented at the European Frequency and Time Forum (EFTF 2014), and 8 works (oral and posters) were presented.

The project was also presented at the workshop “Atomic clocks for Industry” together with EMRP project (IND14) *New generation of frequency standards for industry*. The project has been also presented to three EURAMET meetings. Results from the project have been presented at the Joint Congress EFTF-IFCS (Denver, April 2015), IEEE Workshop on Metroaerospace (Benevento, Italy, June 2015), the International Astronautical Congress (Jerusalem, Israel, 2015), the 8th Symposium on Frequency Standards and Metrology (Potsdam, October 2015) and at the EFTF congress (York, April 2016).

Impact

The innovative techniques and/or solutions have been presented to European clock manufacturers and space agencies. Demonstrating the technology and commercial potential of the new technologies will promote their use by clock makers and industry. The results will be useful to many institutes or companies whose activity is related to accurate and stable time and frequency signals, including those wanting to have stable and high performing which are cheaper and more compact than at present.

The pulsed optically pumped clock developed in this project will provide frequency stability comparable to passive Hydrogen masers, but from an instrument with much reduced volume and power consumption, and potentially low price than existing solutions. In addition, the cold atom vapour-cell clock can provide excellent frequency accuracy as a potential replacement of today's commercial Cs beam atomic clocks.

Commercial impact

The sensor company Muquans will adopt the device developed in the project to tune the cavity in their commercial clocks more easily. Another company is starting a collaboration with UFC for the industrial development of a miniaturised CPT clock.

Partially exploiting the results of the project, INRIM is undertaking a technological transfer to Leonardo Company for the realisation of an Engineering Model of the POP clock for space applications. The project is funded by ESA under a GSTP programme: GSTP6.2 AO7935: Rubidium POP (co-funded by Leonardo Company).

Potential impact

The outcomes of this project may impact also on metrology, fundamental research and dissemination of the SI second. A wide range of key European industries, including navigation, telecommunication, defence and precision instruments producers may experience significant benefits from the results of the present work. One of the main goals is therefore to disseminate frequency standards technology and capabilities that are now mainly located in European NMIs or research institutes, to stakeholder and end-users and European clock manufacturer companies.

List of publications

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