Publishable JRP Summary Report for JRP IND14 Frequency
New generation of frequency standards for industry

Overview

Global high technology sectors such as telecommunications, aerospace, navigation, defence and security all rely on timing synchronisation between accurate time and frequency references. Frequency standards with stability and accuracy at the level required for these industrial applications already exist in well-controlled laboratory environments. European national metrology institutes (NMIs) have spent many years developing both microwave and optical frequency references, with the best of these today being capable of fractional frequency reproducibilities equal to or better than 10^{-15}, significantly beyond what is required for most industrial applications. These laboratory frequency standards are generally bulky, have high electrical power consumption and can only be operated by highly trained personnel. They are also not designed for extended operation in demanding industrial environments such as space, aerospace, ground-based mobile communications and base stations, where temperature fluctuations and vibration levels are likely to be at least an order of magnitude worse than in a typical laboratory environment. Developing industrial versions of high performance time and frequency standards will always involve a trade-off between NMI lab performance and size, weight and power (SWaP) requirements for operation in relatively hostile environments and conditions.

The project went beyond the current state-of-the-art of industrial technologies, and to a lesser extent beyond NMI capabilities, by researching emerging alternative technologies to transform the NMI-based frequency standards technologies towards compact, robust and turn-key standards that can be well-suited for operation in industrial environments. Space and defence qualification of these systems is not explicitly targeted as the associated expense is outside the EMRP budget scope, nevertheless the technology developments undertaken represent an important step in this direction.

Need for the project

The overall aim of the project was to convert accurate and stable frequency standards technology, developed in the well-controlled laboratory environments, into formats suitable for use industrial applications in space, aerospace, defence and optical and microwave communications. Such applications include the requirement for improved time & frequency capability and associated synchronisation between distant clocks in mobile and non-perfect conditions, especially in instances where for example GPS is denied, and for improved synchronisation that is becoming necessary for transferring ever-increasing volumes of data as communications systems move to 5G and beyond.

<u>Optical frequency standards</u>

For the most accurate optical frequency standards in the 1.5 µm telecommunications band, NMIs use frequency-stabilized lasers based on acetylene gas cells, which are generally designed and constructed by NMI personnel. Such NMI-designed standards are typically reproducible at the 10^{-11} level however commercially available turn-key alternatives are typically only stable at the 10^{-8} level. These commercial systems are not based on molecular or atomic references and are susceptible to long-term frequency drift and require periodic re-calibration. Industry needs more stable turn-key optical frequency standards for spectral purity in telecommunications and gas sensing. This will allow more accurate narrow channel characterisation of wideband multiplexed fibre communication systems leading to more efficient DWDM channel control and calibration, and faster analysis and higher resolution of trace gas spectra in sensing applications.

<u>Optical local oscillators</u>

The best commercially available optical local oscillators (lasers) have linewidths in the sub-kHz region over timescales of a few milliseconds. Future high accuracy optical atomic clocks will need lasers with sub-Hz linewidths over timescales of 1-100 seconds for both optical and down-converted microwave applications in satellite navigation, deep space ground stations, multi-telescope arrays such as the Square Kilometre Array and high resolution radar. This will allow improved and more resilient position, navigation and timing data

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availability in these high technology areas. This performance has so far only been demonstrated in extremely well controlled laboratory environments and needs to be demonstrated in harsher industrial environments such as space, aerospace and mobile defence arenas to be useful in future space science & earth observation missions, satellite navigation programmes, and in rapidly expanding high-data-rate communications.

Microwave local oscillators:

The best commercially available microwave local oscillators are based on ultra-low-noise quartz crystals with frequency stabilities of around 8×10^{-14} at 1s. This stability limits performance in some leading-edge applications such as radar for the aerospace and defence sector. Higher-stability alternatives to quartz, such as cryogenic sapphire, are available but are unacceptable due to high maintenance costs associated with their fragility and large size and therefore compact and robust microwave local oscillators need to be developed.

Microwave frequency standards:

Many middle-range-accuracy time and frequency standard applications involving time synchronisation between remote antennae (e.g. telescope arrays for very long baseline interferometry) or synchronisation of remote data systems, employ high performance quartz oscillators or commercial rubidium atomic clocks, which are referenced to an external signal such as GPS. However, for industrial autonomy the frequency standard should ideally provide an accurate and stable reference independent of the external reference signal over extended periods. These medium capability clocks and timing systems that are synchronised to higher accuracy remote timing systems such as GPS are fine whilst they have the GPS access. However, loss of access to the GPS signal, due to intentional jamming or difficulties in achieving direct line of sight to the satellites eg in high-rise urban areas, requires that the local clocks have sufficient accuracy and stability to maintain timing synchronisation during these GPS-denied periods. Currently quartz oscillators only give good short-term stability and do not provide an accurate reference over extended periods. There are industrial stand-alone rubidium and caesium atomic clocks available, the caesium systems providing the better accuracy, but these tend to be expensive rack-mounted systems, whereas there is a need for low-SWaP (size, weight and power) portable atomic clocks for use in mobile communications in defence, aerospace and telecoms.

Scientific and technical objectives

The project addressed the needs detailed above with the following scientific and technical objectives:

1. **To develop a new generation of robust, compact, portable and turn-key optical frequency standards instrumentation operating in the near-infrared, with a fractional accuracy of better than 10^{-10}.** The aim was to use recently developed hollow-core-fibre (HCF) or speciality photonic crystal fibre technology to replace large bulk gas or vapour cells, eliminating problems associated with misalignment of bulk optics. Such fibres are likely to degrade stability slightly, compared to that achieved with gas cells, but it was anticipated that reproducibilities at the 10^{-10} level are attainable, representing significant improvement on current commercially available turn-key systems. The operating wavelengths of these standards will be targeted on industrial applications such as telecommunications and gas sensing.
2. **To develop a compact, vibration-insensitive and transportable optical local oscillator with a fractional frequency instability below 5×10^{-15} for averaging times from 1–100 s.** The target was to achieve these performance levels over an extended temperature range (10–40ºC), in an environment that is subject to vibration levels that are an order of magnitude higher than those typically experienced in a laboratory environment-, and even in the presence of significant ground-borne noise. This should show that such lasers are capable of operating in industrial environments or even (ultimately) in the harsh environment of space.
3. **To develop a robust and relatively compact microwave local oscillator providing ultra-low phase noise microwave signals based on a femtosecond comb stabilized to the transportable optical local oscillator**. The aim was to produce a prototype system with performance exceeding that of the best commercially available microwave sources, meeting industrial requirements in the aerospace and defence sectors. Improvements to phase noise of the derived microwave signal at high Fourier frequencies is highly desirable.

4. **To develop atom-referenced microwave frequency standards for industrial applications that require autonomous operation free of the requirement for an external reference signal.** Two technologies were investigated to meet medium- and high-performance industrial requirements, corresponding to clock stability and accuracy in the 10^{-10} – 10^{-12} and 10^{-12} – 10^{-13} range respectively. In both cases compactness and low power consumption are a significant objective. For medium performance, such as is required in mobile communications for defence, security and aerospace, Cs-filled hollow-core fibre standards were investigated. For higher performance systems to provide synchronised master clocks such as those needed for telecommunications networks and satellite navigation systems with performance in the 10^{-13} range, the project investigated a trapped Cs cold atom clock on a chip (TACC).

Results

Optical frequency standards

New gas-filled hollow core fibre (HCF) prototype standards have been produced in partnership with industrial partners and collaborators, including NKT Photonics, who produce a range of hollow core fibres, and Agilent (now Keysight technologies), who provide wavelength standards for the optical communications industry. Novel HCF-to-single mode fibre (SMF) splicing techniques for sealing the acetylene-filled hollow core fibre have been achieved, offering opportunities for integration of gas-filled HCF into standard optical fibre communication technology. These include a compact bulk glass cell design for sealing hollow core fibres which has good long term pressure stability, and improved gas-tight connector adapters using standard connector and ferrule techniques to produce a low-reflection butt-coupling between the HCF and single-mode fibre. Linear C_2H_2 absorption signals from sealed high pressure HCF cells were compared with bulk cells by the industrial partner, and showed comparable results, demonstrating the suitability of the HCF cells for optical spectrometers. Narrow-linewidth saturated absorption spectra at 1.5 μm have been achieved for sealed HCF filled with low pressure acetylene in the region of 12 Pa. The observed pressure increase within the sealed HCF is ~ a few Pa per year, demonstrating the potential as industrial optical frequency standards with extended lifetimes. Fibre lasers have been stabilised to these saturated absorption spectra in HCF cells, demonstrating fractional instabilities at the 10^{-11} level. Designs for laser stabilisation to the sealed HCF cells using FPGA-based electronics have also been demonstrated. The applicability of HCF cells for standards at other wavelengths was investigated by study of the HITRAN database to select appropriate gases, and which pointed to e.g. methane and carbon dioxide as suitable references for diode lasers in the 1300 nm – 2000 nm region. A 2.05 μm diode laser locked to a carbon dioxide-filled fibre has been demonstrated.

Optical local oscillators:

Novel local oscillator architectures using both small cubic optical cavities and fibre spool interferometers have been designed and built. Measurements of the vibration insensitivity performance of the fibre spool interferometers show improved performance, important for deployment in the field and collaboration with a European SME, for take up of this technology, has been established. Frequency stability measurements on the prototype ULE cubic cavity-stabilised YAG laser show ~2 x 10^{-15} at 1 s, within the 5 x 10^{-15} specification. A new cavity – vacuum housing design has been built and the 1064 nm cavity mirrors exchanged for a set at 1.55 μm. Vibration sensitivities for the cubic cavity mounted within the new vacuum chamber give values of 7.0 x10^{-11} /g, 2.4 x10^{-11} /g, and 0.9 x10^{-11} /g parallel and orthogonal to the cavity axis, demonstrating its ability for operation in vibration environments encountered in industrial applications. The complete cavity, mounted within the new vacuum chamber, was shown at the industrial workshop at Neuchatel in June 2015. Subsequent to this, a license arrangement for the cubic cavity has been agreed with a European SME. The FPGA-based stabilisation electronics for the fibre-stabilised lasers show 20 ms lock-in times and have been tested against an iodine-stabilised laser and demonstrated stabilities of 4.1x10^{-12}, limited by the iodine system.

Microwave local oscillators:

Low-noise microwave generation has been demonstrated by a number of different simple techniques for femtosecond comb-based optical-to-microwave conversion. An improved Yb:tungstate miniaturised femtosecond laser with 1 GHz repetition rate and 190 fs pulse duration has been constructed that avoids Q-switching instabilities and gives an average power of 1.4 W, in excess of current state-of-the-art, offering future possibilities for a super-continuum pump source. A design for a simple and cost-effective interface between the transfer oscillator module has been developed and demonstrated. Experiments with balanced optical-microwave phase detectors (BOM-PDs) have shown an amplitude-to-phase (AM-PM) noise conversion of 60 dB below the single-sideband relative intensity noise of the laser. This is an improvement by a factor of approximately 60 – 300 (dependent on frequency) compared to the previous state-of-the-art. These various approaches have been integrated into a report of "toolbox techniques" for low noise microwave synthesis, and also presented at the Neuchatel industrial workshop.

Microwave frequency standards:

The trapped atom on a chip has demonstrated a short term stability of < 6×10^{-13} at 1 s. Long term stability has been improved, and now reaches 6×10^{-15} at 30 000 s (~0.3 day), which outperforms the targeted performance at one day by a factor 3. A preliminary error budget on the clock accuracy has been evaluated, which is the first-ever accuracy evaluation of a miniature microwave clock with cold trapped atoms, but further work is needed to reduce uncertainty due to cold atom temperature. The parallel activity targeted on miniature Cs-filled clocks in hollow-core fibre has concentrated on developing effective means to fill 80-μm core diameter HCF with the alkali vapour. This operation has added complexity over filling HCF with e.g. acetylene, due to Cs saturated vapour pressure considerations and condensation of the vapour in the HCF. However, the strong optical absorption at the Cs D2 line in a 20-cm fibre has led to the observation of Doppler-free saturated absorptions signals due to co- and counter-propagating photons in the HCF at the Cs 852 nm D2 line. The results show saturated absorptions features with narrow linewidth and signal contrast equivalent to or better than Doppler-free features obtained in a bulk Cs-filled cell. CPT signals have also been observed in small cells.

Actual and potential impact

The project's outputs were disseminated to the metrology, scientific, industrial time & frequency communities by various routes. The project so far has contributed 15 publications and 59 presentations. A presentation on the results of project was made to the IEC TK86 Swiss Committee concerned with fibre optics, with the goal of making people aware of the new coming technologies that may impact the photonics community. In addition a presentation to UK Ministry of Defence stakeholder group on optical and microwave micro-clocks was given. The technologies developed in the project were demonstrated at the industrial showcase event in Neuchatel late June 2015, with over 80 participants.

The industrial take-up and eventual industrial impact on all these parallel developments rests upon the further refinement of system and device designs, and the evaluation of frequency stability and drift. Some of the early work by partners on robust cavity designs and low-noise microwave generation has resulted in EU and national funded collaborations being set up between separate partners and MenloSystems GmbH, a major femtosecond comb supplier. Further, activities on hollow core fibre systems for both IR optical reference standards and microwave clocks are contributing to ESA and defence-related applications respectively. In the former case, ESA is interested in small IR wavelength standards at ~ 2 μm as on-board reference for satellite monitoring of atmospheric carbon dioxide concentrations. In the latter, there is interest in small clocks with suitable accuracies for use in mobile defence scenarios. Finally, significant activity by some of the partners on the development of robust optical cavities is contributing strongly to ESA technology development of space versions of these cavities, as was demonstrated in the ESA design studies of the cosmic vision STE-Quest mission proposal, a mission designed to answer a range of questions in fundamental physics. There has also been significant take-up of the optical oscillator cubic cavity design in an ESA engineering model build of a high stability laser stabilised to the cubic cavity, as an integral part of the development of space equipment for gravity mapping from space. As mentioned above, the cubic cavity development has also led to licensing discussions with an industrial SME for the provision of high resolution spectroscopic instrumentation. In all these cases, it is necessary to demonstrate increased technology readiness levels (TRLs) for prototype systems before full industrial take up can be fully implemented. Achieving high TRL levels for space and defence applications inevitably requires substantial and costly development outside the scope of EMRP projects, especially for equipment destined for space, aerospace, defence and telecoms.

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