THE QUANTUM WORLD: FROM LABORATORY TO INDUSTRY

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Recent advancements in quantum technology mean we can exploit the fundamental properties of atoms and particles and apply quantum mechanics to real world applications. Some of the applications Teledyne e2v are focussing on include quantum gravitational sensors for civil engineering, oil and gas and navigation, space based quantum sensors with applications in Earth observation and quantum clocks for timekeeping resilience across a wide range of use cases. Quantum gravitational sensors offer advantages to existing technologies such as Ground Penetrating Radar (GPR) which are used to map under the ground. Similarly quantum clocks offer many benefits to existing technology, including stability over long periods of time. This paper will give an overview of the quantum technologies being commercialised at Teledyne e2v, an insight into how RF and microwave frequencies are used in the devices being developed and a comparison to existing technologies.

1 INTRODUCTION

Teledyne e2v have three main areas of focus for commercialising quantum technologies; these include ground based quantum sensors, quantum sensors for space and quantum clocks. The basis of each of these areas is to apply the principles of quantum mechanics to everyday applications, bring quantum out of the laboratory, and into the ‘real-world’.

1.1 Cold Atoms as Sensors on the Ground and in Space

Atoms can be cooled to close to absolute zero using lasers, which is fundamental to cold atom sensors. Cold atom sensors have a range of applications from precisely measuring the Earth’s gravitational field to studying the principles of fundamental physics. Measuring the Earth’s gravitational field is useful to aid ground based geological exploration, space based Earth observation and can even be used to augment Inertial Navigation Systems (INS) where the reception of Global Navigation Satellite System (GNSS) signals is degraded or denied.

Cold atom gravity sensors offer huge benefits both on Earth and even in space. On the ground, cold atom gravity sensors (gravimeters or gradiometers) offer potential use in civil engineering applications such as detecting hazards and features under the ground such as pipes, disused mineshafts or sinkholes; other uses include oil and gas exploration. In space, cold atom gravity sensors can be used to carry out Earth observation to detect and understand mass transport processes [5] which could lead to significant breakthroughs in our knowledge of and ability to monitor many key components of the Earth system such as sea level, ice sheet melting and aquifer depletion.

1.2 Quantum Clocks

The precise measurement of time is fundamental to the effective functioning of many of the services we take for granted in modern society, for example the phasing of the national grid, and many forms of communications such as 4G and 5G. Banking also relies heavily on precise timing, for the timestamping of transactional information, and a core part of many computer networks is the accurate timestamping of data packets. This time and synchronisation data is ever increasingly being derived from GNSS provided time signals, which can leave a huge vulnerability if the signal is ever lost, degraded or spoofed, either through natural events, accidental events, state level activity or deliberate spoofing and jamming. There is therefore increasing demand for timing and synchronisation solutions that are GNSS independent, and can perform in a wide variety of 'real-world' use cases and applications.

2 Existing technologies

2.1 Existing Ground Based Gravity Sensors

Existing methods of underground surveying, to determine subsurface structures, range from gravimetry to Ground Penetrating Radar (GPR). Currently the majority of ground based gravity sensors are based on classical physics and include methods such as measuring the extension of a spring with a mass attached to it (Figure 1). GPR on the other hand, sends Radio Frequency (RF) signals into the ground, and detects/processes the reflected signal (see *Figure 2*). Although these techniques have been refined and optimised a great deal, they are reaching the limits of their sensitivity, are prone to drift and are susceptible to manufacturing and maintenance tolerances such as mechanical wear. GPR in particular is limited by the environmental conditions of the ground, for example moisture in soil, and clay can limit ground penetration significantly. Cold atom gravity sensors on the other hand measure the passive 'signal' of gravity to determine subsurface features whereas GPR uses an active signal. Cold atom gravity sensors measure gravitational acceleration which varies based on the subsurface density which can then be used to create a map of what is under the ground.

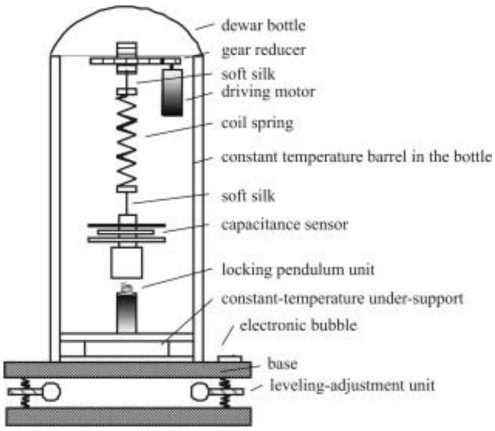

***Figure 1** schematic of a borehole gravimeter based on classical physics which involves observing a mass on a spring for variations in the gravitational field Figure from [7].*

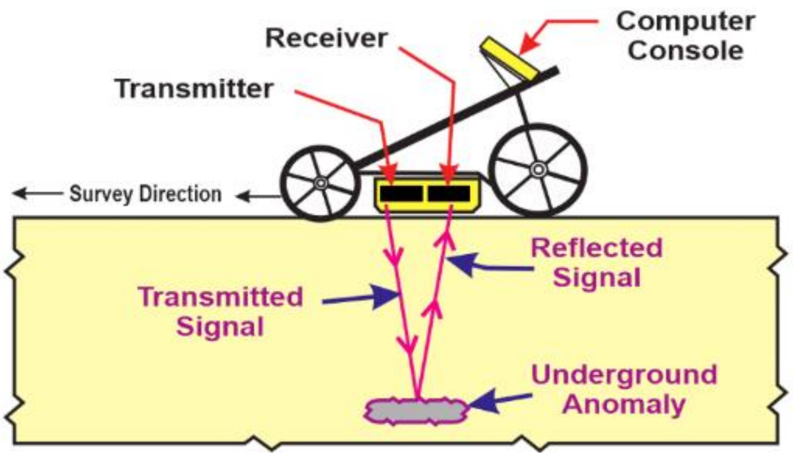

Figure 2 *Schematic showing the basic principle of Ground Penetrating Radar [11].*

Some of the existing methods of ground surveying are listed in *Table 1*. The key benefits of a cold atom gravity sensor can be seen, such as good mobility, high accuracy and very short cycle times. The reduction in the cycle time for a cold atom gravimeter can be a huge advantage as it saves a lot of time when carrying out surveys of large sites.

Table 1 *Comparison of different gravimeters and their performance [8]*

Gravimeter	Method	Precision **(g/sqrt(Hz))**	Drift rate **(g/day)**	Accuracy (g)	Cycle time (s)	Mobility
Mass on a spring	Relative	1×10^{-10}	3×10^{-8}	NA	~15	Good
Superconducting gravimeter	Relative	$< 1 \times 10^{-12}$	2×10^{-10}	NA	~15	No good
Falling Corner-Cube: optical interferometer, free-falling retroreflector	Absolute	5×10^{-8}	-	2×10^{-9}	~10	No good
Atom Interferometer: cold atom, laser cooling and trapping	Absolute	4.2×10^{-9}	-	3×10^{-9}	~1.3	Good

2.2 Existing Space based Gravity Sensors

Quantum gravity sensors in space offer applications such as Earth observation and monitoring of the Earth's mass transport processes. Under microgravity conditions cold atoms do not fall a great distance which increases the available measurement time [4]. As sensitivity increases with the square of the measurement time, increasing the measurement time by 10 times improves the sensitivity by 100 times, making space an ideal environment for gravity sensing [4].

Previous missions such as NASA's GRACE mission, which used microwave ranging technology and ESA's GOCE mission, which used an Electrostatic Gravity Gradiometer (EGG) to measure the gravity field of Earth, have provided invaluable advancements in Earth observation. The GRACE mission was able to show that one of the contributing causes of sea level rise is due to large ice sheets of Greenland and Antarctica losing mass [5]. The GOCE mission has been instrumental in understanding the surface of the geoid (global mean sea level) from information about the Earth gravity field, resulting in providing a globally uniform level of zero height [5]. Although there have been huge improvements in the information provided from such missions, there is a need for a next generation of instruments to provide information with higher spatial resolution and measurement sensitivity [5].

2.3 Existing Timing and Synchronisation

Existing clocks use crystal oscillators as a time reference, these drift over short periods of time due to temperature variations. These crystal oscillators are usually manufactured to oscillate at a target frequency at room temperature, but will decrease if the temperature increases or decreases from room temperature. Each clock will have a factor by which it will age dependent upon the oscillator used, Table 2 shows how each of the timing references compared to each other. Caesium atomic clocks and Global Positioning System (GPS) have the best values for aging over a period of 10 years and for accuracy compared to the other oscillators. However relying on global Navigation satellite systems (GNSS) is a risk as they are susceptible to denial and spoofing, providing a need for a reliable time reference for critical every day applications.

***Table 2** Comparison between timing references and their performances over time.*

Oscillator Type	Accuracy	Aging / 10 year	Power	Weight (g)
Crystal oscillator (XO)[9]	10^{-4} to 10^{-5}	10-20 PPM	20 µW	20
Oven controlled crystal oscillator (OCXO) [9] - 5 - 10 MHz - 15 to 100 MHz	5 x 10^{-7} to 2 x 10^{-8}	2 x 10^{-8} to 2 x 10^{-7} 2 x 10^{-6} to 11 x 10^{-9}	1 - 3 W	200 - 500
Rubidium atomic frequency standard (RbXO) [9]	10^{-9}	5 x 10^{-10} to 5 x 10^{-9}	6 - 12 W	1500 - 2500
Caesium atomic frequency standard [9]	10^{-11} to 10^{-12}	10^{-12} to 10^{-11}	25 - 40 W	10 000 - 20 000
Global Positioning System (GPS) [10]	4 x 10^{-8} to 10^{-11}	10^{-13}	4 W	340

3 TECHNICAL BACKGROUND

3.1 Measuring gravity with atoms - Atom Interferometry

At room temperature atoms are energetic. Once they are cooled down, atoms can be used as sensitive test masses and the environmental effects felt by the atoms can be measured, this includes the effects of gravity. One of the techniques used to cool down atoms is known as a magneto optical trap (MOT) (See Appendix A for more information). Once a MOT has been created the cold atom cloud can be used to carry out atom interferometry. Typically atom interferometers use three laser pulses, the first is used to separate the atom cloud in two, the second pulse inverts the separation and finally a third pulse is used to recombine the atoms again. From this an interference pattern can be observed. If one half of the atoms experience different conditions to the other interference fringes will be visible [3]. As atoms are extremely sensitive, the effects of any perturbation such as from fundamental forces (like gravity) are easily detectable. When the two parts of the atom cloud recombine the interference of the clouds provides a measure of gravity. The process of atom interferometry is illustrated in Figure 3. As gravity varies across the Earth due to subsurface structures, mountains and even buildings, this variation in gravity when detected can give an indication of what is under the surface of the Earth.

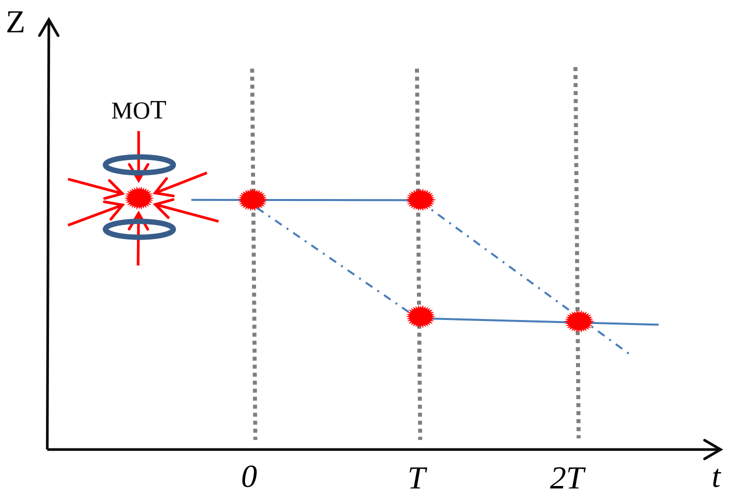

Figure 3 *Schematic showing atom interferometry. The dashed grey lines represent the laser pulses that split and recombine the atom cloud and the red circles are the cold atom clouds. Once a MOT is achieved the cloud is subject to the first pulse which separates the cloud in two, the second pulse then inverts the separation and the final pulse combines the atoms.*

3.2 Quantum Atomic Clocks – Frequency references

Every clock has a frequency reference which it uses to keep time, in a mechanical clock the reference is a pendulum, wrist watches use a quartz crystal and atomic clocks use the transition of excited electrons within the atom as a reference. The frequency of a caesium atomic clock is very precise and of very narrow linewidth allowing extremely high precision in the frequency reference. It is at least three orders of magnitude better than a quartz oscillator.

The Basic Atomic Clock:

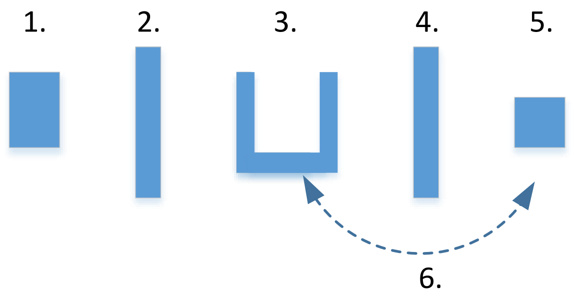

Figure 4 *Schematic showing the basic set up of an atomic clock where the numbers are as follows 1. Source of atoms, 2. Filter A, 3. Microwave cavity, 4. Filter B, 5. Detector and 6. Feedback loop*

The operation of an atomic clock is shown in *Figure 4*, the basic sequence of an atomic clock is as follows:

1. Caesium atoms are sprayed in high vacuum from the source to filter A
2. Filter A allows only one type of atom (Cs-133 in its ground state) to enter the microwave cavity
3. Microwaves at the right frequency cause a hyperfine quantum change (excitation) in the atoms

4. Filter B allows only changed atoms to reach the detector and be counted
5. This frequency, the atoms' natural hyperfine transition frequency, is counted to determine the length of a second
6. The feedback loop uses the detector signal to adjust the microwave frequency until it sees the most changed atoms

The microwave generator which is usually a crystal oscillator, is tuned to the exact frequency causing the maximum number of hyperfine transitions. As quartz crystal oscillators are affected by environmental changes, causing the frequency of the oscillations to change, an Oven Controlled Crystal Oscillator (OCXO) is used. The OCXO maintains the temperature of the quartz crystal to prevent frequency variations due to temperature change. As the atomic transition within caesium-133 oscillates at 9,192,631,770 Hz, this determines when 1 second has passed. In order to maintain this frequency a feedback loop is critical, if the detector does not detect enough atoms that have changed state to maintain the correct frequency (9,192,631,770 Hz) of the microwaves, it alters the frequency of the crystal oscillations respectively.

4 Case Study 1: REVEAL- Ground Based Gravity Sensor

The presence of sinkholes, mineshafts and other buried objects under construction sites is a huge problem in civil engineering. These underground openings are a risk to the health and safety of people working on the site. They are also a risk after construction work has been completed as they can move and increase in size over time and may open up causing a building; a road or a bridge to subside or collapse with devastating effect. Teledyne e2v in collaboration with the University of Birmingham, RSK and Gooch & Housego, are developing a quantum gravimeter which can be used for subterranean surveying to identify underground objects before construction takes place. This reduces the risk for people working on the site and allows remedial work to be carried out before building takes place, decreasing the risk of future structural problems. Figure 5 shows a CAD model of the gravity sensor being developed at Teledyne e2v. The sensor will be portable and use atom interferometry to carry out surveys of what is under the ground.

Figure 5 *CAD model of gravity sensor being developed at Teledyne e2v for subterranean surveying.*

5 Case Study 2: Cold Atom Space PAyload

5.1 Project Overview

Project CASPA involves designing, building and testing a prototype of a 6U cube satellite (CubeSat) with a cold atom space payload on-board. The project is led by Teledyne e2v in collaboration with the University of Birmingham (science lead), XCAM, Clyde Space, Covesion, Gooch & Housego, and the University of Southampton. The aim of project CASPA is to build a system capable of cold atom trapping of rubidium (Rb) atoms autonomously in the space environment. The key challenges include achieving autonomy, compactness, thermal control and low power consumption while meeting the stringent environmental requirements of launch and the space environment. The selection of materials that are suitable for use in space is also a major constraint on the system design.

5.2 CASPA Design

The cold atom space payload being developed pushes the boundary on the Size Weight and Power (SWAP) of cold atom systems. The entire 4kg payload has been designed to fit into a 4U envelope within a 6U CubeSat structure. The satellite consists of four main subsystems designed to interface together to generate a MOT in low Earth orbit (550km altitude); these include the optical subsystem, physics package subsystem, electronics and imaging subsystem and the satellite platform. The layout of the subsystems within the 6U structure can be seen in Figure 6. The payload will be powered by battery power generated by the solar panels and has been designed to function with a peak power consumption of 40W.

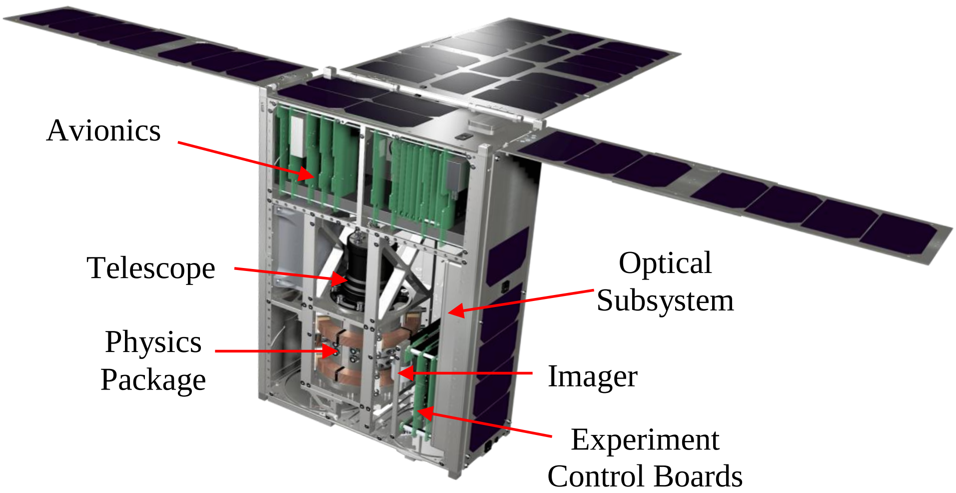

Figure 6 *CAD model showing the basic layout and design of the 6U CubeSat showing the solar panels once they are deployed.*

A photograph of a MOT achieved during the experiment concept phase can be seen in Figure 7.

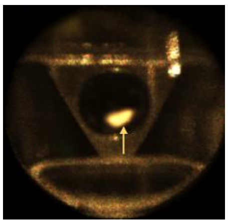

Figure 7 *Image of a MOT captured using an XCAM camera, during the experiment concept definition phase of the project. The cold atom cloud is indicated by the yellow arrow.*

5.3 Early Modelling and Testing

As the key objective of CASPA is to raise the Technology Readiness Level (TRL) of cold atom systems and prepare them to be used in space applications, a significant amount of time and effort is being spent on environmental analysis and testing. The prototype model will have environmental tests carried out on it, including vibration testing and basic radiation tests.

Modelling has been a key part of the early design process for CASPA and has been fundamental to producing rapid design iterations prior to manufacturing. The prototype CASPA design has been through finite element analysis (FEA) to allow rapid design iterations to improve the physical robustness of the system under vibration and shock. The results of one of the vibration analyses can be seen in Figure 8; the conditions used in the model were as specified in the General Environmental Verification Specification (GEVS) standard as recommended by the CubeSat standard.

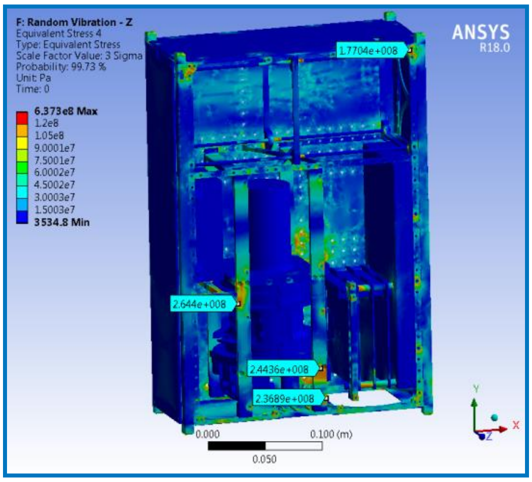

Figure 8 *ANSYS modelling of stress in the structure under GEVS vibration.*

6 Case Study 3: MINiature Atomic Clock (MINAC)

Teledyne e2v are developing a family of atomic clocks for precise timing holdover and synchronisation, providing a product in a number of performance levels and form factors that have widespread application in a large number of use cases; precision timing for mobile base stations, network servers for financial services, broadcasting, data centres, national power distribution networks, air traffic control systems and many more. These atomic clocks, designed, developed and built in the UK (with all key components such as the OCXO and Atomic Vapour Cell also developed in the UK) are focussed on low Size, Weight, Power Cost (SWAP-C) as well as the ruggedness and environmental resistance to perform in harsh environments, including temperature extremes, and high vibration and shock.

As part of this family of atomic clocks Teledyne e2v have been developing a miniature atomic clock (MINAC) to address the need for an accurate, stable timing source independent of GNSS timing signals. In partnership with the National Physical laboratory (NPL) Teledyne e2v have been translating laboratory technology into a commercially viable product. The majority of existing timing and synchronisation systems are only suitable for use in the laboratory, as shown in Figure 9. The aim of MINAC is to develop a caesium clock that fills a gap in the market as shown in

Figure 9 and build a clock that can be used outside the laboratory.

The production of MINAC will benefit from in-house glasswork for the caesium cell development, as well as testing, validation and verification of mechanical and optic components. In addition the design and development will revolve around producing a robust clock that can survive and operate in harsh environments. As well as developing the hardware Teledyne e2v are also carrying out software development which is key to ensure a smooth user interface with the clock.

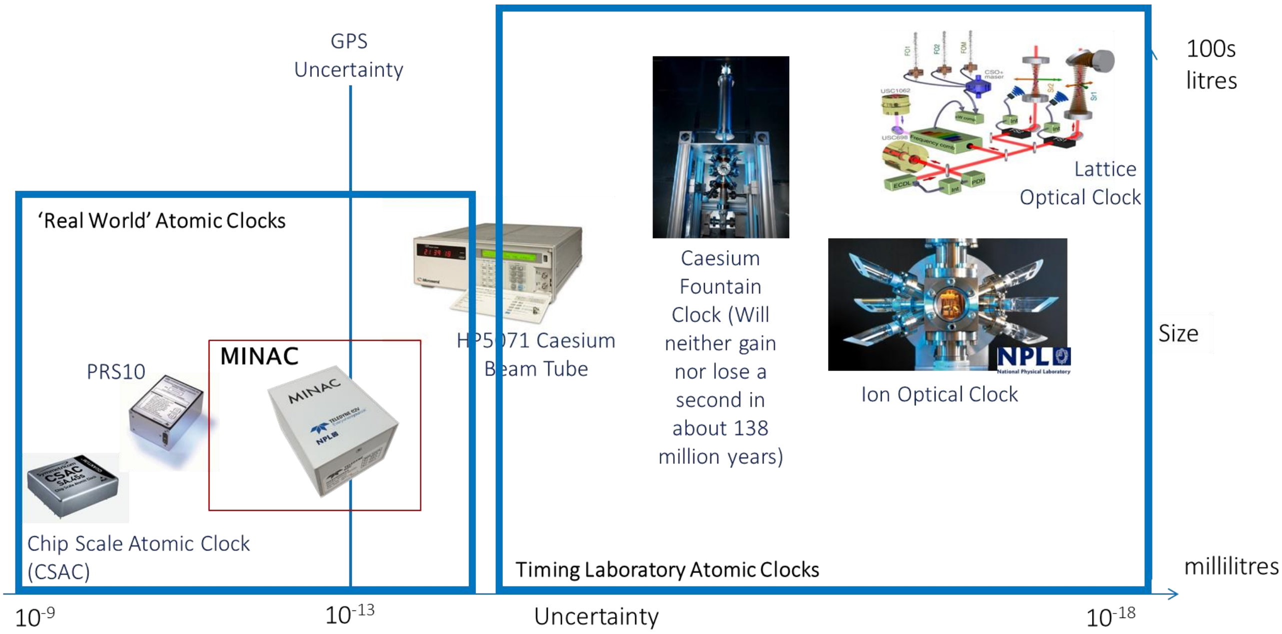

Figure 9 *Graph showing size vs uncertainty of existing clocks, highlighting where the MINAC clock fits in.*

6.1 Applications

The potential applications for MINAC include:

- Aerospace & Defence — C4I, Communications Systems, ECM, Situational Awareness & Radar
- Air Traffic Management
- Autonomous Systems
- Banking/Financial Markets
- Critical National Infrastructure (CNI) Protection
- Cyber Security
- Energy Distribution
- Fixed & Mobile Communications Networks (including 5G)
- Oil & Gas Exploration
- Science & Technology
- Transport Infrastructure Networks
- Utilities

7 CONCLUSION

There exists a well-defined user need for quantum sensors and clocks with improved performance to provide real time Earth observation, higher precision underground mapping and enable new high reliability precision timing. It is important to note that microwave generation is a key part of a large number of next generation timing, sensing and computing instruments being developed to provide ground breaking advancements. Although there are challenges associated with translating quantum technology into useful products, by building on existing science and data and using a structured systems engineering approach Teledyne e2v is bringing these technologies out of the laboratory and into industry.

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9 APPENDIX A - Magneto Optical Traps

To create a Magneto Optical Trap (MOT) a set of six orthogonal, counter-propagating laser beams are required as well as a magnetic field. The laser beams cross at the zero point of the magnetic field and the atoms are subject to a velocity-dependent force, which cools them, and a position-dependent force, which traps them [1].

The basic set up of a MOT can be seen in Figure 10. The lasers are all equal in energy and the photons from the laser beam are absorbed by the atoms and re-emitted by random spontaneous emission [2]. Each of the six laser beams supplies momentum to the atoms in one direction [2] and the magnetic field provides the position dependence confining the atoms to the centre of the zero point of the magnetic field. To ensure the atoms are slowed down and not accelerated, the laser frequency is tuned to ensure that atoms are only on resonance with a laser beam (and hence only absorb photons) when they are travelling towards it (due to the Doppler shift effect) [1]. For a basic introduction to how cold atoms are used to carry out atom interferometry please refer to Appendix **Error! Reference source not found.** (atom interferometry).

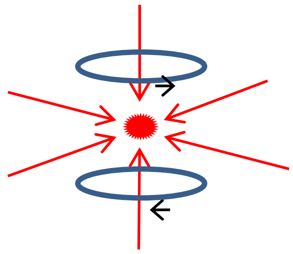

Figure 10 *Schematic of a MOT set up. The red arrows represent the counter propagating laser beams; the magnetic field is produced by a pair of anti-Helmholtz coils (represented by the blue circles, black arrows show the direction of the current in coils). The red circle in the centre is the atom cloud which is created at the zero point of the magnetic field.*

Once a cloud of cold atoms is formed, the 'trap' is switched off and the atoms begin to fall under acceleration due to gravity, by probing the cloud of atoms with a laser beam and observing the interference it is possible to measure gravity.