NPL REPORT TQE 32

HOLDOVER ATOMIC CLOCK LANDSCAPE REVIEW

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JULY 2024

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ABSTRACT

The vulnerability of the UK's reliance on GNSS has been highlighted in several recent government commissioned reports and features in the National Quantum Strategy, Resilient PNT Policy Framework, and the 2023 National Risk Register. Holdover atomic clocks are accurate local timing sources that can provide resilient precision timing to critical national infrastructure (CNI) in place of GNSS timing signals when these signals are disrupted.

This document presents a summary of holdover atomic clock technology in the UK as a baseline to help support future development of UK sovereign commercial holdover atomic clock manufacturing capabilities. These holdover clocks would serve primarily in UK positioning, navigation, and timing (PNT) applications, including provisions for UK CNI. This document summarises timing requirements and standards across several application sectors (present and future), the current progress on atomic clock development in the UK and the current state of UK supply chains and industrial capabilities. At the end of this report, we describe our view of the essential elements of a coordinated UK Holdover Clock development programme required to enable the necessary provisions for the UKs national timing centre (NTC), future national timing infrastructure and UK CNI end users.

ISSN 1754-2995

https://doi.org/10.47120/npl.TQE32

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KEY DEFINITIONS

- **Atomic (or Quantum) clock** – A system producing a stable output oscillation frequency and / or a time scale based on the absorption of a precise frequency of electromagnetic radiation by an atom or ion. Atomic clocks are comprised of three parts: an oscillator, a frequency reference, and a frequency counter.
- **Frequency standards -** Devices that provide stable and accurate signals at specific frequencies, from which time intervals can be derived with additional equipment. Atomic clocks are often referred to as atomic frequency standards due to their reliance on frequency measurements, however, unlike atomic clocks, frequency standards do not include a frequency counter.
- **Holdover clocks** – Flywheel timing references that are used in applications to retain synchronisation during a period, the holdover time, where the usual timing and synchronisation signal (e.g., through GNSS) is unavailable. These clocks may also be used as standalone timing references.
- **Microwave clocks** – Atomic clocks where the electromagnetic radiation absorbed by an atom or ion is around the microwave region of the spectrum (frequency 0.3 to 30 GHz). The most common microwave clocks use caesium (9.2 GHz) or rubidium (6.8 GHz) atoms, but more advanced systems are under development, for example the ytterbium multi-ion microwave clock, which operates at 12.6 GHz.
- **Optical clocks -** Atomic clocks where the electromagnetic radiation absorbed by an atom or ion is around the UV/visible/near infrared region of the spectrum (wavelength 250–2000 nm / frequency 1200–149 THz). Frequency combs are needed in optical clocks to count optical frequencies, so they can be used to provide timing signals. For example, a strontium optical lattice atomic clock uses a frequency of 429 THz, which is ~50,000 times higher than a caesium microwave clock.
- **Portable clock** – An atomic clock which can be operated reliably during transportation without any appreciable degradation of performance.
- **Transportable clock** – An atomic clock which can be moved relatively easily from site to site but only operated whilst static and deployed in a suitable environment, e.g., commercial cold atom clocks, hydrogen masers, etc.
- **Chip-scale atomic clock** – An atomic clock that can be embedded into electronic devices at the printed circuit board level.
- **Miniature (or compact) clock -** An atomic clock that is turnkey and portable and smaller than a 3U rack-mounted system, e.g., rubidium frequency standards.
- **Primary and Secondary frequency standard** – An atomic clock used to realise the definition of the SI second, usually based at a national metrology institute, e.g., a caesium fountain (primary), or strontium lattice clock (secondary), etc. (These are defined in [10]).
- **Primary reference clocks (PRC)** – Terminology used mainly in the telecommunication networks industry. PRCs are high-precision clocks that conform to accuracy standards set by e.g., the International Telecommunication Union (ITU).
- **RETSI clocks** – These are atomic clocks that are installed as part of the National Timing Centre (NTC) time scale infrastructure. They include, for example, caesium fountains, and in the future, systems based on optical clocks.

- **Time (or Frequency) accuracy** - related to the offset from an ideal time or frequency reference. For example, the difference between a measured on-time pulse and an ideal on-time pulse that coincides exactly with UTC.

- **Frequency uncertainty** – The degree of doubt or error in the estimation or measurement of an oscillator signal's frequency. This should be quantifiable and the associated coverage factor specified.

- **Frequency instability** - The spontaneous and/or environmentally caused frequency change within a given time interval.

GLOSSARY/ABBREVIATIONS

AC	Alternating current
ADEV	Allan deviation
AFS	Atomic frequency standard
AlO_2	Aluminium oxide
ANSI	American National Standards Institute
ASIC	Application specific integrated circuit
AUV	Autonomous underwater vehicle
AVAR	Allan variance
BIPM	International bureau of weights and measures (Bureau International des Poids et Mesures)
BOM	Bill of materials
Ca	Calcium
CAGR	Compound annual growth rate
CNI	Critical national infrastructure
COTS	Commercial-off-the-shelf
CPT	Coherent population trapping
CR&D	Commercial research and development
Cs	Caesium
CSAC	Chip scale atomic clock
DARPA	Defense advanced research projects agency
DASA ESL	Defence and security accelerator engineering Severity Level
DBR	Distributed Bragg reflector
DC	Direct current
DEFSTAN	UK Defence standardization
DFB	Distributed feedback
DLR	German aerospace centre (Deutsches Zentrum für Luft- und Raumfahrt)
DoS	Denial of service
DR	Double resonance
DSAC	Deep space atomic clock
DSIT	Department for science, innovation and technology
Dstl	Defence science and technology laboratory
EAR	Export administration regulations
ePRTC	Enhanced primary reference time clocks
ESA	European space agency
EU	European union
GEO	Geostationary orbit
GNSS	Global navigation satellite system
GPS	Global positioning system
GSTP	ESA General support technology programme
HCF	Hollow-core fibre
IEEE	Institute of Electrical and Electronics Engineers
IP	Intellectual property
ISCF	Industrial strategy challenge fund
ITAR	International traffic in arms regulations
ITT	Invitation to tender
ITU	International telecommunication union
JPL	Jet Propulsion Laboratory
JTIDS	Joint Tactical Information Distribution System
LAN	Local area network
LEO	Low Earth orbit
LISA	Laser interferometer space antenna
MAC	Miniature atomic clock
MEMs	Micro-electromechanical systems

MEO	Medium Earth orbit
MHM	Microchip hydrogen maser
MOD	Ministry of Defence
MOT	Magneto-optical trap
MRL	Manufacturing readiness level
MTIE	Maximum time interval error
MTTF	Mean time-to-failure
NATO	North Atlantic Treaty Organization
NGGM	Next generation gravity mission
NIST	National Institute of Standards and Technology
NMS	National measurement system
NPL	National Physical Laboratory
NPL-CsF2	NPL's caesium fountain primary frequency standard
NQCC	National Quantum Computing Centre
NQTP	National Quantum Technologies Programme
NTC	National Timing Centre
NTP	Network time protocol
OCXO	Oven-controlled crystal oscillator
PFS	Primary frequency standard
PLL	Phase-locked loop
PMU	Phase measurement unit
PNT	Positioning, navigation, and timing
PPS	Pulse per second
PRC	Primary reference clock
PRTC	Primary reference time clock
PSFS	Primary and secondary frequency standards
PTP	Precision time protocol
QTFP	Quantum technologies for fundamental physics
R&D	Research and development
RAFS	Rubidium atomic frequency standard
Rb	Rubidium
Rb POP	Rubidium pulsed optical pumping
RETSI	Resilient enhanced time scale infrastructure
RF	Radio frequency
ROI	Return on investment
RTO	Research and technology organisation
SBRI	Small business research initiative
SFS	Secondary frequency standard
Si	Silicon
Si_3N_4	Silicon nitride
SiO_2	Silicon oxide
SME	Small and medium sized Enterprises
Sr	Strontium
STFC	Science and Technology Facilities Council
SWaP	Size, weight, and power
SWaP-C	Size, weight, power, and cost
Ta_2O_5	Tantalum pentoxide
TAI	International Atomic Time
TCXO	Temperature compensated crystal oscillator
TDEV	Time deviation
TDMA	Time division multiple access
TFF	Time-to-first-fix
TRL	Technology readiness level
TTSF	Time-to-subsequent-fix
UAV	Unmanned aerial vehicle

UHV	Ultra-high vacuum
UK	United Kingdom
UKRI	United Kingdom Research and Innovation
UoB	University of Birmingham
US	United States of America
UTC	Coordinated Universal Time
UTC(NPL)	Physical realisation of UTC maintained by NPL (i.e., the UK time scale)
UUV	Unmanned underwater vehicle
VCSEL	Vertical cavity surface emitting laser
Yb	Ytterbium

EXECUTIVE SUMMARY

Precise time and frequency signals are used across critical national infrastructure (CNI) and other key sectors including secure navigation, telecommunications, energy, finance, and transport. Global Navigation Satellite Systems (GNSS) are used worldwide to access and distribute these signals, the accuracy of which are determined by on-board satellite atomic clocks and their periodic synchronisation with ground-based clocks that are linked to Coordinated Universal Time (UTC) [1]. The precise timing signals offered by GNSS are vulnerable to disruption, either through intentional (e.g., jamming, spoofing, physical infrastructure attacks) or unintended means (e.g., severe space weather events, equipment failure, human error). With a 7-day GNSS outage estimated to cost the UK economy £7.64 bn [2], there is a growing concern around the UK’s near complete reliance on GNSS, and an urgency to mitigate the risk. GNSS-related disruptions are also highlighted in the UK’s National Risk Registers since 2012, and most recently in the 2023 edition with societal impact ranging from moderate to catastrophic [3].

An atomic clock is an oscillator system that continuously observes the constant energy states of atoms (or ions) to maintain a stable oscillation frequency of a local oscillator (e.g., a quartz crystal or laser). Atomic clocks, such as the NPL Caesium Fountain (shown below), serve as the basis for the International System of Units (SI) definition of a second and underpin the timing and synchronisation capability that lies at the heart of our digital infrastructure.

The 2016 Blackett review of quantum technologies [4] identified vulnerability to GNSS denial-of-service attacks as a priority area for UK strategy and recommended the sovereign development and use of atomic clocks and inertial navigation systems as a mitigation. This was further highlighted in the 2018 Blackett review on satellite dependencies [5]. Resilience against disruption to timing networks has also motivated significant Government investment into the National Timing Centre (NTC) R&D programme [6]. This investment is aimed at the development of a distributed network of highly stable and robust clocks to provide and disseminate a more resilient source of time for the UK. In due course this new time scale will take over from existing infrastructure as the source of UTC(NPL), providing signals traceable to the global time scale UTC.

Holdover atomic clocks are an essential component of a robust and resilient timing network. They are atom-based accurate local timing references that can provide resilient precision timing to critical national infrastructure (CNI) in place of GNSS timing signals when disruptions occur. To mitigate against the threat of loss of GNSS signals, the UK's defence and CNI need to have reliable holdover clocks in place.

UK customers are currently dependent on non-UK companies supplying holdover atomic clocks and related timing equipment for positioning, navigation and timing (PNT) and other important infrastructure. There is currently a lack of diversity in the global supply of holdover atomic clocks and UK customers have limited options, both in the type of clocks available and the supplier. This poses several problems for UK customers, ranging from supply issues to a widespread lack of knowledge in the subject of timing and synchronisation.

In this report, a summary of holdover atomic clock technologies in the UK is presented with a view to help support the development of sovereign commercial holdover atomic clock manufacturing capabilities. These clocks will serve primarily in UK PNT applications, including provisions for UK CNI. Timing requirements and standards are also presented across several application sectors (present and future), along with the current progress of atomic clock development in the UK and state of UK supply chains and industrial capabilities.

The UK has excellent capabilities around holdover atomic clocks development. Existing UKRI/SBRI funded programs are designed to produce holdover atomic clock demonstrators up to TRL5, but there is currently no strategy in place to support the manufacturing and commercialisation of these demonstrators. To bring these devices successfully to market, more focus is needed on applications requirements, market size, technology feasibility, supply chains, and production feasibility. There is also a clear need to support technologies in the so-called “valley-of-death” (TRL 4-7) stages of development. A clear government strategy and directive around timing requirements for UK CNI and defence applications, which builds on the 2023 DSIT PNT announcement [7], together with identified future commercial needs, would provide industry-based consortia with a better understanding of which technologies and supply chains to prioritise.

Manufacturing atomic clocks in the UK would provide greater resilience in the supply chain for UK holdover clocks with improved performance, giving UK customers greater assurances of both the technology and supply. UK manufactured clocks would have greater resiliency against ITAR/other import restrictions associated with procuring key components from non-UK based companies and provide UK manufacturing companies access to a market projected to be worth £1 bn in 2033 [8, 9], with additional opportunities across the supply chain, and greater return on investment (ROI) with the anticipated sales and export potential. It would also leverage the considerable sunk investment in quantum technologies, supporting UK businesses to establish new capabilities, adding new highly skilled people to the workforce in timing and manufacturing industries, with much needed skills improved upon across many areas of PNT.

In section 12 of this report, we describe our view of the essential elements of a coordinated UK Holdover Clock development programme, should the government decide to initiate such a strategy.

1 INTRODUCTION

Atomic clocks serve as the basis for the International System of Units' (SI) definition of a second. They underpin the timing and synchronisation capability that lies at the heart of our digital infrastructure. Atomic clocks enable global navigation satellite systems (GNSS), such as the European Union's Galileo Program, and the United States' Global Positioning System (GPS), where each GNSS satellite has at least two portable space-grade atomic clocks on-board. The timing capability of the GNSS system is dependent both on the performance of these on-board clocks, and their periodic synchronisation to ground segment clocks [11]. GNSS offers unprecedented access to precise time and consequently underpins many critical dependencies, with ubiquitous use across key sectors including secure navigation, telecommunications, energy, finance, and transport. Precise time offered by GNSS is vulnerable to disruption, either through intentional (e.g., jamming, spoofing, physical attacks) or unintended means (e.g., weather events, solar flares, space debris, human error), with a 7-day GNSS outage estimated to cost the UK economy £7.64 bn [2, 12]. There is a growing concern around its reliance and an urgency to build risk mitigation. Accordingly, the 2016 Blackett review of quantum technologies [4] identified vulnerability to GNSS denial-of-service attacks as a priority area for UK strategy and recommended the sovereign development and use of atomic clocks and inertial navigation systems as a mitigation. This was also highlighted in the 2018 Blackett review on satellite dependencies [5]. Resilience against disruption to timing networks has also motivated significant Government investment into the National Timing Centre (NTC) research and development (R&D) programme [6]. This investment is aimed at the development of a distributed network of highly stable and robust clocks to provide and disseminate a more resilient source of time for the UK.

The UK quantum roadmap highlights atomic clocks as a key technology for providing synchronisation and holdover for future networks [13, 14]. Holdover clocks are important components used locally to retain timing synchronisation by acting as flywheel timing sources across a period where the primary timing signal is unavailable. They can therefore be used to de-risk reliance on GNSS timing signals by offering provision during disruption to GNSS. Holdover clocks can also enable stable timing signals to be used where GNSS signals cannot be accessed, such as undersea or underground. Holdover clocks are necessary back-up tools for many national defence and critical national infrastructure (CNI) applications. The performance requirement for holdover clocks depends on the expected duration of the holdover periods and the acceptable time deviation (TDEV) or maximum time interval error (MTIE) from a reference, therefore timing solutions vary significantly depending on application. There has been a steady growth in demand for holdover clocks over the past decade, particularly with the rollout of 5G telecommunications and the need for increased resiliency of PNT infrastructure. Currently the atomic clocks market is served by a small number of manufacturers globally offering a range of commercially available holdover clocks. Recent reports indicate that the global atomic clocks market will reach more than £500 million per annum by 2028, and more than £1 billion per annum by 2033 [8, 9].

The increased global demand, compounded by global supply chain challenges, has created significant procurement issues for UK customers in acquiring atomic clocks, with exceedingly long lead times reported, and a risk of further de-prioritisation with suppliers as international supply chains focus on needs at home. This situation is likely to continue well into future decades. A sovereign UK capability for the development, manufacture, and supply of atomic clocks and time distribution infrastructure is needed to secure UK CNI and defence sectors, as well as commercial logistics. In response, a small number of UK-based manufacturing companies have embarked on R&D projects to develop new commercial atomic clocks, largely through the UK National Quantum Technologies Program [15]. Many of these atomic clocks are currently at low technical maturity levels (<TRL4), with key components still under development and supply chains for key components not yet available.

This document outlines the current landscape of the UK's holdover clock capability to inform the development and growth of a UK-based manufacturing industry in support of current and future UK CNI and defence sector needs.

2 TECHNICAL OVERVIEW

2.1 ATOMIC FREQUENCY STANDARDS, ATOMIC CLOCKS, AND TIMING NETWORKS

Any clock can generally be viewed as a system of three parts: an oscillator, a frequency reference, and a frequency counter. Strictly, atomic clocks are oscillator systems that exploit an atomic transition within an atom (e.g., caesium, rubidium, strontium) or ion (e.g., calcium ion, strontium ion, ytterbium ion) as the frequency reference, to steer a microwave or optical oscillator (such as a quartz crystal resonator or a laser) which is then counted to determine a time interval from which a time scale is created. An atomic frequency standard (AFS) consists of only the first two elements but can be used as a calibration tool for synchronising other atomic clocks and oscillators with lower accuracy. In practice, atomic clocks will normally provide a reference clock signal (typically 10 MHz as the industry standard) and a 1 pulse-per-second (1PPS) time interval reference (other frequencies can be generated by using external phase-locked loops (PLLs)). Another distinction is often made based on the availability of the clock output, with time scales relying on uninterrupted 24/7 timing signals for periods of several months/years, whereas AFSs may only be required on demand for short periods where synchronisation between oscillator systems can typically be achieved in a few minutes or hours. It should be noted that the phase noise performance of an atomic clock or AFS at short timescales (up to 10 seconds) is typically defined by the oscillator performance and is not improved by the atomic reference.

Atomic clocks can be steered periodically by an AFS with superior accuracy. For example, telecoms transceivers use atomic clocks to maintain synchronisation between network nodes; These atomic clocks may be disciplined (phase-locked) to GNSS time signals which are synchronised to Coordinated Universal Time (UTC), or in direct comparison to high performance primary or secondary frequency standards (PSFS) via infrastructure maintained by national laboratories such as NPL. This architecture relaxes the performance requirement on the atomic clock at the point of use.

An example of a high accuracy AFS is a Primary Frequency Standard (PFS) housed at a national laboratory, such as the NPL Caesium Fountain (NPL-CsF2), which provides a realisation of the SI second. Examples of microwave atomic clocks[1] include commercially available caesium beam tube clocks, rubidium vapour cell clocks, and hydrogen masers, which are turn-key standalone systems designed to operate uninterruptedly for very long durations (typically several years), sometimes in varying environments.

Within communications networks a hierarchy is implemented according to 'Stratum levels', with Stratum 0 typically referring to a GNSS satellite clock or another accurate atomic clock traceable to UTC. Stratum 1 devices, sometimes referred to as primary reference clocks (PRCs), primary reference time clocks (PRTCs) or grandmaster clocks, have a direct connection to Stratum 0 clocks and distribute time synchronisation signals via network servers. These use either Network Time Protocol (NTP) capable of synchronising clocks to 1 ms over local area networks (LANs), or newer Precision Time Protocol (PTP) (introduced in

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[1] The terms "Atomic Frequency Standard" and "Atomic Clock" are often used interchangeably within the timing R&D community. The "Cs Fountain clock" is a good example, as most implementations of atomic fountain systems fit the definition of a frequency standard. Additionally, lab-based "optical clock" systems may not include frequency combs, and whilst referred to as "clocks", they are defined as frequency standards.

2002) which supports synchronisation to better than 1 µs over LANs, better than 100 ns over networks designed to early IEEE-1588 standards [16, 17], and approaching 1 ns for networks specialised to the latest IEEE 1588v2.1 standard. Stratum clock and oscillator requirements are defined up to 15 levels but communications networks typically operate to a depth of 3 levels (i.e., Stratum 2), where very good double oven-controlled crystal oscillators (OCXOs) or Rb oscillators are used, or Stratum 3 where a wider range of crystal oscillators suffice.

2.2 MICROWAVE VS OPTICAL ATOMIC CLOCK SYSTEMS

Atomic clocks come in many different forms. The different frequency ranges of the atomic frequency reference require alternative system technologies for their realisation as either microwave or optical clocks. These distinctions may not be noticeable to most end-users, who often treat atomic clocks as ‘black-boxes’, however, there are certain pros and cons associated with each system, including implications in performance, and size, weight, power and cost (SWaP-C).

Microwave clocks use a local oscillator (LO) which oscillates typically in the range of a few GHz and can be counted directly using conventional electronics. Optical clocks use a LO which oscillates at frequencies close to 100,000 times higher, in the range of a few hundred THz, and require an optical frequency comb (or optical “gearbox”) to generate countable signals. For example, a caesium atomic clock uses the hyperfine separation of the ground state as a frequency reference (9.192 GHz) and is accessible using conventional microwave technologies, whereas a strontium ion clock operates at 444.779 THz and requires laser light to access this transition which must be counted via an octave spanning, self-referenced, optical frequency comb. Optical clocks generally offer superior accuracy and short-term frequency stability over microwave clocks owing to higher achievable quality-factors of the derived atomic signal, but this comes at the cost of requiring additional parts and added complexity. Depending on the application requirements, microwave systems may offer a simpler, more efficient, or lower SWaP-C route.

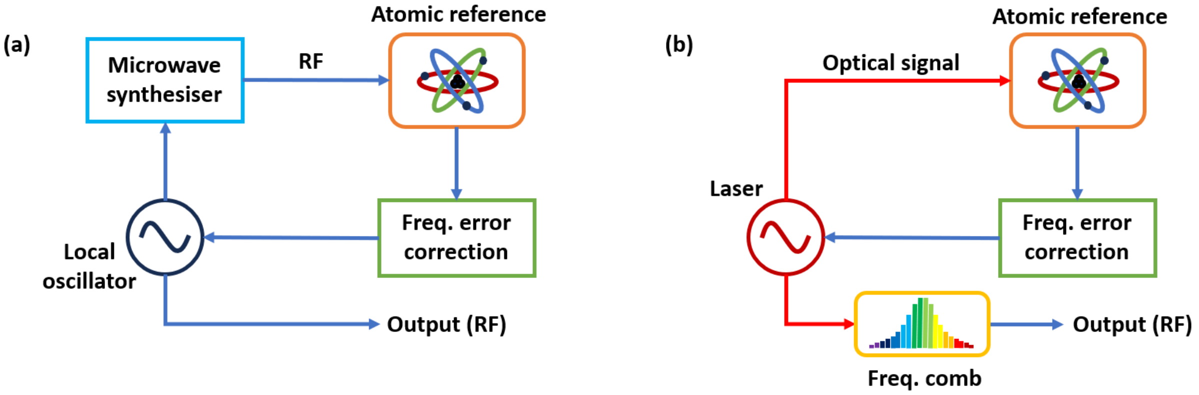


Figure 1. Block diagram schematic configuration of (a) microwave atomic clock and (b) optical atomic clock.

Commercially available microwave atomic clocks are comprised largely of off-the-shelf low-cost components, e.g., microwave oscillators, telecoms-grade lasers or lamps, and vapour cells. Many are based on components used in telecoms and radar systems which have seen costs driven down by extremely large volume production. On the contrary, many optical atomic clocks currently fit the definition of an AFS, requiring human intervention to address environmental effects which can cause system outages (e.g., lasers out of lock) or systematic frequency shifts at environmental sensitivity levels which may compromise the desired performance. In present high accuracy optical clock systems, the “clock laser” (laser targeting the specified “clock transition” in atoms) can suffer outages over short to medium periods; automatic operation to prevent or mitigate these issues will be a key requirement for any future commercial portable optical clock. Despite these challenges, research efforts are underway to develop turn-key optical clocks that can operate with minimal human intervention. Optical clocks are built using highly bespoke and expensive laboratory-grade components and more effort will be required to convert these into reliable low-cost and portable technologies.

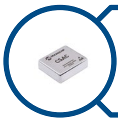
The performance (accuracy and frequency stability) of atomic clocks is also influenced by their sensitivities to ambient environmental changes. Whilst most high accuracy atomic clocks are tested in relatively stable laboratory conditions, actual use cases “in the field” can cause undesirable output frequency excursions, e.g., vibrations, or rapid thermal changes inducing frequency shifts. There are many other physical effects on the various components that can affect the frequency stability of an atomic clock. These can be reduced through judiciously considered engineering solutions (both in hardware and software). In general, the complexity of an atomic clock system determines the level of challenges required to be addressed (e.g., reliability, production uniformity, lifetime) to maintain the clock’s stability over long periods, particularly if the system is operating in an uncontrolled environment. It is therefore a considerable engineering challenge to translate a lab-based AFS into a self-regulated turn-key 24/7 operational atomic clock system that can manage the various sensitivities which induce both major and subtle frequency drifts over time.

Continued research into new microwave and optical clock technologies is needed to realise current lab-based state-of-the-art performance in field-deployed settings. At present, industrial and academic researchers across the world are considering both microwave and optical atomic clock systems as next generation portable atomic clocks for a multitude of purposes. Section 9 of this document provides a summary of several promising state-of-the-art and next-generation holdover atomic clock technologies being developed outside of the UK. There are clear pros and cons associated with both microwave and optical clocks around complexity, SWaP limitations, reliability, availability of components, supply chains and cost. Ultimately, the decisions on the types of atomic clocks to develop in the UK should be guided by applications and end-user requirements that can then be translated into atomic clock systems requirements.

3 COMMERCIAL LANDSCAPE

The first commercial atomic clock was the Atomichron caesium beam standard available in 1956, funded by the Office of Naval Research and US Signal Corps [19]. Since then, commercial atomic beam standards developed rapidly and there are now a range of microwave atomic clocks available from a small number of manufacturers around the world. Current commercially available atomic clocks can be summarised into four categories: (i) **chip-scale**, (ii) **tactical**, (iii) **strategic**, and (iv) **space**. The typical outputs of these atomic clocks are a 10 MHz sine wave and 1 pulse per second (PPS) TTL signals (note that other microwave frequencies can be generated using a PLL). These clocks can be calibrated using a 10 MHz or 1PPS input from a higher-accuracy reference clock or AFS. This section provides an overview of each category along with a table summary.

There are several types of holdover atomic clocks that are required for PNT infrastructure. These can be summarised with four categories:



Chip-scale - low cost and compact, can be embedded into electronic devices at the printed circuit board level.

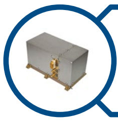
Typical: 1 μs holdover period of 1 day.

Tactical - having physical cable connectors and a form-factor <30,000 cm^3.

Typical: 1 μs holdover period of 3 - 5 days.

Strategic - typically designed as either rack-mounted or free-standing systems

Typical: 1 μs holdover period of 10+ days.



Space - “space-hardened” tactical/strategic clocks that are usually built-to-order.

Typical: 1 μs holdover period of 10+ days.

3.1 CHIP SCALE ATOMIC CLOCKS

Chip-scale atomic clocks are the cheapest and most compact atomic clocks available. They are typically provided as board-level components that can be embedded into electronic circuit boards. They can provide a holdover of 1 μs timing accuracy at up to 1 day (a particularly good chip-scale OCXO can typically achieve this in no more than 1 hour). Chip-scale atomic clocks are amongst the simplest types of atomic clock architectures with the fewest internal components. Current commercially available chip-scale systems use one of two well-known atom interrogation techniques: coherent population trapping (CPT) or double-resonance (DR) interrogation. Much of the functionality lies within an electronic microcontroller which extracts and interpolates key information from the detected atomic signal to correct deterministic systematic frequency shifts. Chip-scale atomic clocks are usually the most ruggedised atomic clocks, with typical product specifications meeting military grade standards in operating temperature, shock, and vibration.

3.2 TACTICAL ATOMIC CLOCKS

Tactical atomic clocks offer 1 μs accuracy holdover for several days (typically between 3 to 5). They are characterised as having physical cable connectors and a form-factor smaller than 3U rack-mounted atomic clocks, or <30,000 cm^3. Current commercially available systems are based on the DR interrogation technique although some CPT clocks have been developed as tactical clocks. The rubidium DR technique has some advantages over CPT, e.g., to potential use of a lamp rather than a laser, which improves reliability and ageing, as lamp-based clocks typically have a longer mean time to failure (MTTF). In NTP-based telecoms networks, tactical clocks may be used as Stratum 1 or 2 holdover clocks.

3.3 STRATEGIC ATOMIC CLOCKS

Strategic atomic clocks are designed as either rack-mounted or free-standing systems. Some technologies, such as cold atom systems, are required to be completely static during use as motion may perturb the derived atomic signal and cause abrupt frequency shifts. While strategic atomic clock systems are not usually designed for extreme MIL-spec (US DoD standards for tools, materials and weapons used by U.S. Armed Forces) or certain DEFSTAN (UK equivalent) environments, they offer the best accuracy and frequency stability performance of all commercially available atomic clocks. In PTP-based telecoms networks, strategic clocks may be used as Stratum 0 or 1 clocks (e.g., network PRCs).

3.4 SPACE ATOMIC CLOCKS

Space atomic clocks are “space-hardened” and usually built-to-order (e.g., manufacturers will receive invitations to tender (ITTs) from international space agencies to deliver atomic clocks to certain specifications). GNSS satellites typically house four atomic clock systems that are periodically synchronised to UTC via ground segment clocks. Currently, GPS (block III) satellites carry three rubidium-based clocks (RAFS), with one providing redundancy as a spare [20]. Galileo satellites have two rubidium systems and two passive hydrogen masers with the same redundancy strategy [21]. The typical MTTF of a RAFS space atomic clock is >15 years [22, 23]. These are ruggedised against various forms of radiation and able to survive rocket launches. As a result, space atomic clocks are considerably more expensive than terrestrial atomic clocks.

Microchip (US) have recently developed a ‘space hardened’ chip-scale atomic clock (SA.45s) designed for operation in Low Earth orbit (LEO) satellites. Microchip and other atomic clock suppliers are in the process of developing “Space” versions of chip scale and tactical atomic clocks for PNT-enabled LEO satellites.

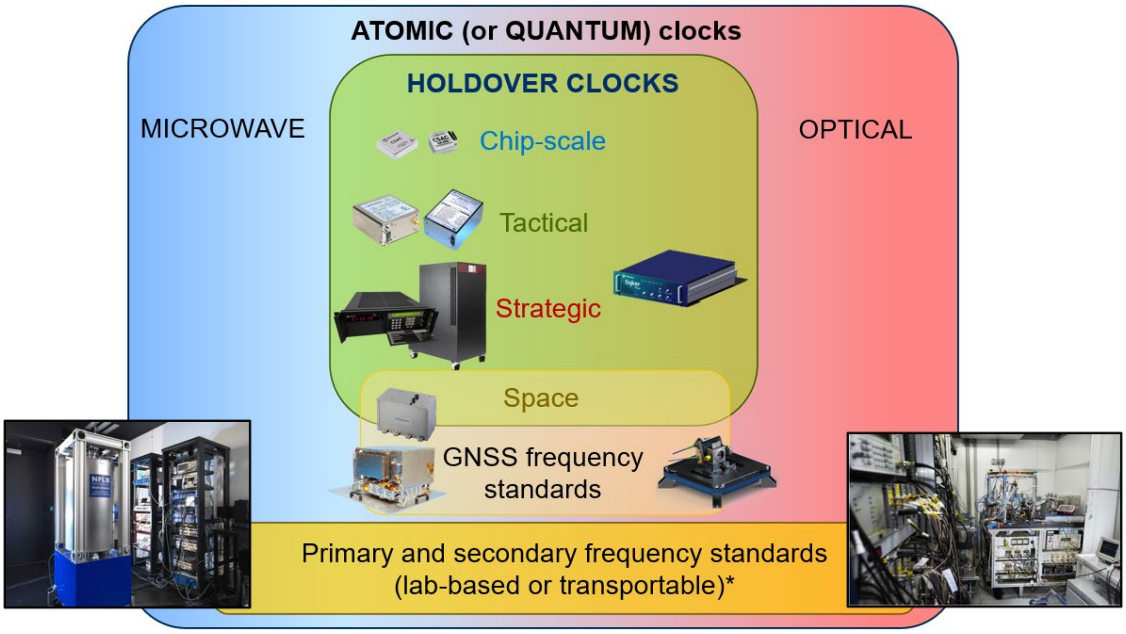


Figure 2. Schematic Venn-like diagram delineating the various types of atomic clocks. *Note that strategic clocks such as Cs Beam clocks and H-Masers can be used as part of time scale infrastructure.

Table 1. Commercial atomic clock global supply summary.

Atomic Clock	Category	Technology	Size (cm^3)
*Typical "good" OCXO	OCXO	Crystal osc.	6
Microchip SA.65 (CSAC)	Chip scale	CPT	17
Teledyne TCSAC	Chip scale	CPT	17
Accubeat NAC1	Chip scale	CPT	17
Quartzlock E10-CPT	Chip scale	CPT	17
Chengdu CPT	Chip scale	CPT	17
Microchip SA.55 (MAC)	Chip scale	CPT	46
Quartzlock E10-MRX	Chip scale	Rubidium DR	40
SAFRAN mRO	Chip scale	Rubidium DR	50
Chengdu XHTF1031	Chip scale	Rubidium DR	65
Stanford PRS10	Tactical	Rubidium DR	393
SAFRAN LPFRS	Tactical	Rubidium DR	213
SAFRAN mRO-50	Tactical	Rubidium DR	393
Accubeat AR133-00	Tactical	Rubidium DR	150
Accubeat AR133-03	Tactical	Rubidium DR	296
Quartzlock E10-MRO	Tactical	Rubidium DR	189
Quartzlock E10-LN	Tactical	Rubidium DR	211
Rakon HSO-13	Tactical	Crystal osc.	161
Rakon HSO-14	Tactical	Crystal osc.	827
Oscilloquartz OSA 3300	Strategic	Caesium beam	30 000
Microchip 5071A	Strategic	Caesium beam	29 500
Microchip 5071B	Strategic	Caesium beam	29 500
Chengdu TA1000 OPC	Strategic	Caesium beam	44 600
muQuans muClock	Strategic	Cold Rubidium	682 000
Spectradynamics cRb-Clock	Strategic	Cold Rubidium	39 000
Microchip MHM	Strategic	H-Maser	374 000
Vremya VCH-1003M	Strategic	H-Maser	390 000
T4Science iMaser-3000	Strategic	H-Maser	436 800
**NPL Cs Fountain	Strategic	Caesium Fountain	800 000
Space CSAC SA.45	Space	CPT	17
SAFRAN mini-RAFS	Space	Rubidium DR	380
SAFRAN RAFS	Space	Rubidium DR	3148
FEI RAFS	Space	Rubidium DR	4901
Excelitas RAFS	Space	Rubidium DR	4179
FEI Cs	Space	Cs beam	--
Perkin Elmer	Space	Rubidium DR	--
Leonardo ASSD PHM	Space	PHM	22 203
Leonardo ASSD mini-PHM	Space	PHM	26 250
Microchip	Space	Cs Beam	--

*An OCXO is not an atomic clock but is used here for reference
**These are built-to-order by NPL. Other national metrology laboratories around the world may also offer high performance atomic clocks that are made-to-order.

Existing commercially available atomic clocks are listed in Table 1. A comprehensive review of commercially available atomic clocks can be found in [18]. Manufacturers are often improving upon existing products to remain competitive and address new market requirements. The most widely used chip-scale and strategic atomic clocks are developed by Microchip (based in US). In 2017, Microchip embarked on a major multi-year program with a goal of maintaining production of the ubiquitous caesium beam clock - the 5071A (originally developed by Hewlett-Packard in the 1990s) - through to at least 2035 [24]. A new model was subsequently released by Microchip in 2023 - the 5071B - with updated electronics including microprocessors to ensure continuity of supply over the next decade and achieve RoHS compliance [25]. A 10-year timeframe was considered based on Microchip's perceived overall industry trends for alternative technologies and predicted likely mass-market acceptance of the alternate solutions. At present, researchers at Microchip, and other manufacturers are considering alternative technologies to serve in future PNT applications, such as trapped ion microwave clocks and pulsed Rb microwave atomic clocks. Other start-up companies in the US are developing new types of optical atomic clocks, largely enabled by the new fibre frequency comb product, FFC-100, manufactured and supplied by Vescent Technologies in the US [26]. An overview of these next generation atomic clocks is shown in a section 9 of this document.

4 SOVEREIGN NEED

The need for UK sovereign manufacturing of atomic clocks centres mainly on defence and CNI security requirements and "assured" supply (reliable and trustworthy technologies and suppliers). There are issues around global supply and priority for UK customers due to various factors including: sovereign interests of other states, global components supply chain issues, and other commercial reasons.

To date, numerous funding opportunities provided by the UK National Quantum Technologies Program and MOD/Dstl for holdover atomic clock development have enabled a variety of systems to reach low TRL (4 or less). Initial research on these systems has largely been carried out by NPL and/or UK academia with some transfer of knowledge to UK industry via UKRI funding.

The current level of knowledge on PNT requirements in the UK, and specifically timing needs for next generation defence and CNI applications, has limited UK industry's ability to determine which atomic clocks and other instrumentations are needed. There are some examples of relatively low TRL technologies without necessary supply chains that have been/are being investigated by companies in the UK, which are at risk of not maturing towards higher TRL/MRL (technical/manufacturing readiness levels) or production.

A clear government strategy and directive around timing requirements for UK CNI and defence applications, which builds on the 2023 DSIT PNT announcement [27], together with identified future commercial needs, would provide industry-based consortia with a better focus and understanding of which technologies and supply chains to prioritise. This will also, lead to better business justifications and a greater industry pull.

5 HOLDOVER CLOCK REQUIREMENTS

Timing and synchronisation system architectures can determine both the ultimate accuracy performance and holdover durations. Many application requirements are met through a cascade of hierarchal timing and synchronisation technologies. Developing holdover clocks with improved performance within a given SWaP-C bracket can increase the quality of service, particularly where timing or synchronisation is limiting, and potentially maintain quality with simplified more resilient timing architectures.

This section outlines the need for atomic clocks across various sectors and applications. The need for UK sovereign manufacturing of atomic clocks centres mainly on defence and CNI security requirements and “assured” supply (supply chain assurance). Some users require confidence in the security of the underlying technologies (e.g., non-hackable firmware, etc.), particularly for defence applications.

5.1 CRITICAL NATIONAL INFRASTRUCTURE

5.1.1 Power and energy

Energy grids use GNSS timing with microsecond synchronisation and timestamping for sensor data across the energy network. The UK grid typically has equipment and networks for which timing equipment is used for fault location, frequency measurements, disturbance monitoring, bulk metering, and phase syncing. AC phase synchronisation is important to improve power efficiency and minimise disruptions to the power network. Synchrophasers comprised of phasor measurement units (PMUs) are used across the energy grid to enable monitoring across specific locations in the network and understand dynamic and transient grid events over a wide geographical area [28].

Holdover atomic clocks can be placed alongside PMUs as a source for timing and synchronisation to enable network monitoring and phase stabilisation. In the US, alternative precision timing measures are being researched for the national power grid [29]. As well as existing energy grid infrastructure, there are new developments in smart grid technologies. The European Metrology Network (EMN) considers time distribution to be one of the main metrology challenges for smart electricity grids [30]. The European Global Navigation Satellite Systems Agency (GSA) are working with Galileo and EGNOS teams to ensure smart grids have added resiliency to GNSS signal interference, as well as jamming and spoofing attacks [31].

5.1.2 Communications (data/telecoms)

A Stratum hierarchy is used throughout commercial telecommunication networks with Stratum 1 clocks generally reliant on synchronisation to GPS/GNSS Stratum 0 UTC traceable clocks. Stratum 1 clocks (often referred to as PRCs, PRTCs, or grandmaster clocks within PTP networks), strictly require 1×10^{-11} long-term fractional frequency accuracy with 10 ns holdover at 15 minutes and 100 ns at 3 hours capability. This is relaxed for Stratum 2 clocks at 1.6×10^{-8} long-term accuracy and 1×10^{-10} holdover accuracy at 1 day. PRTCs have their own range of classifications that go beyond Stratum 1 with PRTC Classification A required to be within ±100 ns of UTC, PRTC Classifications B within ±40 ns of UTC, and the enhanced PRTC (ePRTC) classification requiring ±30 ns of UTC. ePRTCs generally consist of a well calibrated GNSS receiver and a pair of caesium atomic clocks to mitigate against GNSS DoS [32].

4G cellular networks place a maximum of ±1.5 µs on the network timing error, which has been moved forward into 5G timing requirements, though certain use cases require much more stringent timing accuracy. The IEEE 1588 standard (now v2.1) for a precision clock synchronisation protocol for networked measurement and control systems (i.e., PTP) is now widely adopted across 5G networks and supports synchronisation better than 1 µs over LANs, better than 100 ns over networks designed to early IEEE-1588 standards [16, 17], and approaching 1 ns for networks specialised to the latest IEEE 1588v2.1 standard. In extreme use cases, a White Rabbit network, which aims for fully deterministic Ethernet-based communications, can achieve sub-ns time transfer using PTP in combination with Layer 1 synchronisation and an enhanced PTP timestamp which accounts for measurements of phase delay in the network [33].

The International telecommunications union (ITU) recommendation, ITU-T G.8272, identifies two types of primary reference time clocks PRTCs suitable for time, phase and frequency synchronisation in packet networks dependent on location. The more stringent 103 PRTC-B specification is intended for locations where it is possible to guarantee optimised environmental conditions (e.g., indoors), and PRTC-A is for non-optimised environmental conditions. Under locked operating conditions the time output of the PRTC-A should be accurate to 100 ns compared to an applicable primary standard (e.g., GNSS). The corresponding PRTC-B figure is 40 ns. More detailed specifications are given in [34, 35].

6G, currently in the planning phase, targets extreme use cases with short range (<10 m) 100 Gbps per-user wireless access communication (10 Gbps over 100 m ranges), high-accuracy localisation at up to 1 cm over 10 m range, and sensing with 10 cm distance accuracy and 0.04 m/s velocity accuracy over a range of 50 m using monostatic and bi-/multi-static radar-like mapping arrangements [36]. The synchronisation requirements range from 100 ps to 10 ns for the various segments within the network; This may require an overhaul of timing equipment across the network.

5.1.3 Financial trading

In the financial sector, trading algorithms rely on precise synchronised time to determine temporal relationships between trades. Accurate timestamps are needed to demonstrate that transactions take place in the proper sequence. In Europe, all market participants are required to use the same precise synchronised time. MIFID II RTS 25 regulations require financial organisations achieve traceability of high-frequency trades to within 100 µs of UTC [37, 38]. In practice the Network Time Protocol servers (NTP) used by many finance companies can achieve better than 1 ms in local area networks under ideal conditions via reference to GNSS; This is adequate for non-high frequency trading (1 ms maximum divergence from UTC). GNSS timing has traditionally been used for time stamping such transactions, although mitigation against non-compliance in the event of GNSS outage has moved some financial trading exchanges in the UK towards more resilient timing solutions such as NPL*Time*®, which achieves these timing requirements via fibre-optic-based transfer of timing signals from NPL with a service level agreement of 1 µs [39].

5.1.4 Underwater applications

Underwater and undersea applications requiring precision cannot access GNSS signals, and therefore employ OCXOs, chip scale atomic clocks, and tactical atomic clocks for enabling precision timestamping, synchronisation, and navigation. Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) typically use tactical atomic clocks, for more precise navigation and sensing applications [40].

Undersea sensing methods such as reflection seismology benefit from precise timing [41]. Oil exploration firms use atomic clocks to assist in locating and monitoring natural resources under the seafloor. Accurate timestamping also enables better data post-processing, providing more accurate information on the location and nature of the detected samples. Multiple sensors typically deployed in a grid across a large area, include a hydrophone, a geophone, and a chip scale atomic clock to timestamp data. As underwater applications typically run with finite battery generated power, ruggedised low-SWaP atomic clocks are sought after in these applications.

5.1.5 Other terrestrial CNI applications

All aircraft and airliners are equipped with GNSS receivers to enable pilots and ground staff to know their location. Air traffic controllers use atomic clocks for precise and accurate measurements of time between aircraft. There have been causes for concern recently due to potential GNSS spoofing hacks enabling pilots to be misled as to their location. Safety-critical applications such as aircraft landing systems and rail signalling require the greatest level of resilience [4]. During aircraft take-off and landing, local ground-based beacon radars are used to track the aircraft. Holdover clocks may be used as a mitigation tool in ground-based augmentation systems (GBAS), if GNSS signals and ground beacons are disrupted.

The use of GNSS for navigation and tracking on land, sea and in the air has become commonplace. Until 2020, there was an expectation that air traffic would grow and put pressure on the existing air traffic management technologies. New systems, SESAR in Europe [42] and NextGen in the US [43] are being developed in which different stages of flight use GNSS together with different forms of augmentation. However, GNSS is not used for landing commercial aircraft which requires sub-metre accuracy with a very fast update rate. There are a wide range of parameters to consider to determine the positional accuracy of different forms of transport, such as the vehicle’s speed, required positional accuracy, and achievable update rate (based on available timing equipment), e.g., for an aircraft travelling at up to ~300 m/s, a positional update rate of (ideally much less than) ~3 ms is needed to obtain a ~1 m positional accuracy. More information is required to determine the best type of timing infrastructure for these applications.

The UK emergency services communications network currently requires GNSS timing. The positioning and navigation aspects of GNSS available in computer-aided dispatch technologies assist in many areas including managing fleet vehicles, locating accidents, etc. Existing systems communicate using mobile phone and “TETRA” radio networks and every vehicle has its own communication platform based on a GNSS receiver. A new emergency services communications network based on 4G will address some of these limitations. Holdover atomic clocks could also be used to provide more resiliency to these applications.

Intelligent road transport systems are now in widespread use. Best journey route algorithms are based on GNSS for in-vehicle satnav, as is the tracking of dangerous goods and road tolls monitoring. Food supply chains depend on GNSS-based PNT to ensure timely delivery of produce.

Railways rely on timing and navigational aspects of GNSS via the synchronisation of the rail telecom networks, station clocks and passenger information systems. Freight rail transport is expected to substantially increase across Europe putting more pressure on systems dealing with timing and logistics. More efficient usage of the existing infrastructure can be achieved with intelligent traffic management and control systems. These new automation systems have a dependency on GNSS.

Commercial shipping is dependent on GNSS for navigation for applications include search and rescue, port operations and dredging and cable laying. At sea there is little chance of masking or multipath problems, but these can be a problem nearer to shore and in harbour. Surface vessels, from fishing boats to container ships to deep-water oil rigs, depend crucially on GNSS signals for navigation, station keeping, and surveillance. They are an important maritime navigation aid and as sea-based transport vehicles become more autonomous, the trend is toward increased reliance on GNSS.

Several other civil applications requiring resilient timestamping via holdover clocks can be found in [5].

5.2 SECURITY AND DEFENCE

Secure GNSS signals are used to provide accurate timing to various defence applications, such as military communications and navigation. The UK defence sector seeks to acquire alternative means to navigate and communicate securely and reliably without reliance on GNSS signals. The armed forces rely on access to dependable and accurate timing signals, e.g., for handheld receivers for military personnel, navigation systems for vehicles (manned or unmanned), etc., the timing requirements of which are discussed in this section.

5.2.1 Military radios / receivers

Military radios and handheld/backpack receivers typically use TCXOs or OCXOs to provide initial timing acquisition and reacquisition following signal loss (potentially in a jammed environment), system integrity monitoring, and performance when in view of less than four satellites (i.e., when there are insufficient measurements to resolve timing error). If the received signal is weak, timing uncertainties in the receiver can result in a signal search which requires more processing power and longer durations depending on the amount of time offset. This period is known as the time-to-subsequent-fix (TTSF) [41, 44]. An oscillator warm-up time affects TTSF while the power requirements and size of the oscillator affect the radio/receiver's battery life, mission duration, and weight. Chip-scale atomic clocks are an alternative to TCXOs and OCXOs and offer advantages in reducing the TTSF, and therefore the receiver processor's power consumption. They also improve jamming and spoofing resistance. Chip scale holdover clocks can allow receivers to maintain accurate time for longer, compared to OCXOs, enabling faster reacquisition of GNSS positioning after longer periods of signal outage.

5.2.2 Positioning and navigation

For navigation, a 1 µs timing error can result in a ~300 m position error. Quartz oscillators are currently used in receivers to ensure timing precision at the nanosecond level, allowing position errors at <1 m, but this is only maintained in the short-term if they are not periodically synchronised to a stable and accurate timing reference [45].

5.2.3 Radar systems

Radar systems depend on very low phase noise oscillators. Problems arise when oscillators on-board radar systems experience turbulence (e.g., in missiles, aircraft, or ships) which can generate phase noise. Reducing or suppressing oscillator phase noise can minimise detection anomalies and errors. Current doppler radars have specific phase noise requirements which are largely met by commercial crystal oscillators [46]. Components within radar systems which are mounted on agile platforms like missiles or UAVs must tolerate greater demands in performance and stability. Improvements can be made by using carefully tuned PLLs between oscillators which have different environmental sensitivities.

Atomic clocks can offer greater resistance to environmental effects for certain military applications in harsh environments, although SWaP and warm-up times remain a concern for some end-users. In bistatic radar systems, strategic/tactical clocks containing low-phase noise oscillators could be used at the transmitter to synchronise chip-scale atomic clocks at the receivers, offering significant improvements in coherent signal processing and radar performance [47].

For distributed sensors and multi-static radar systems, and other wide area network applications, integrated GNSS receivers are currently the most efficient method of synchronising oscillators and atomic clocks. Employing better holdover atomic clocks (i.e., suitably environmentally ruggedised with longer holdover durations) that are phase locked with suitable low phase noise oscillators in such systems will provide greater resiliency when GNSS signals are disrupted.

Academic researchers in the UK are investigating the potential of extremely low phase noise transportable optical atomic clocks with the aim to remove all GNSS dependency from radar systems [48]. The aim is to replace existing oscillator technology with superior frequency-stabilised laser-based oscillators in certain fixed multi-static radar nodes, providing precision detection of slow-moving objects such as drones over longer distances and across noisy cluttered environments. The project, led by the University of Birmingham (UoB), is still in its early stages but could be rolled out to cover much wider areas.

5.2.4 Military communications

Atomic clocks are used in military communication systems to reduce network latency and provide resilience to spoofing/jamming. Portable military satellite communications benefit from having improved network acquisition times due to reduced time uncertainty from onboard atomic clocks. Time-division-multiple-access (TDMA) communication systems can also benefit from better time-gated synchronisation between transceivers, enabling faster data rates and communication speeds. The accuracy of atomic clocks affects other important communication system performance parameters such as spectrum utilisation and autonomy period. The Joint Tactical Information Distribution System (JTIDS), which is part of the Link 16 network used by NATO, involves frequency hopping over 51 frequency bins spaced 3 MHz apart at a rate of around 77,000 hops per second over the L-band [49]. This defines the permissible frequency tolerances in both the transmitters and receivers. Phase noise may also affect these tolerances, and atomic clocks can alleviate phase noise anomalies caused by environmental changes provided the PLL is adequately tuned [41].

5.3 ADDITIONAL DRIVERS

5.3.1 Space applications

Atomic clocks are used onboard geostationary satellites for timing and synchronisation. There are also atomic clocks being considered for deep space navigation. NASA's Deep Space Atomic Clock (DSAC) developed at Jet Propulsion Laboratory (JPL) is a lamp-based mercury ion microwave clock with in-orbit demonstrated fractional frequency instability of 3 x 10^{-15} at 23 days, maintaining time to within 4 ns over a similar period. Further along the performance bracket, NPL is actively engaged in multiple projects supported by ESA contracts and funding from the UK Space Agency, to integrate optical atomic clocks and ultra-stable laser technology into upcoming ESA/UK Space Agency programs e.g., [50, 51], spanning fundamental science, Earth observation, and navigation initiatives. In particular, the viability of incorporating optical clocks and cavity-stabilised lasers into LEO and MEO satellite navigation constellations is being considered. This approach aims to facilitate faster updates to MEO constellation clocks while diminishing reliance on atmospheric constraints and data uploads from ground stations. Similar technologies could be deployed to improve GNSS on Earth or implement new planetary guidance systems e.g., to support a Mars colony.

LEO space satellites are often ‘smallsats’, with a rapidly growing list of applications across communications, scientific experiments/observations, and defence. Increasingly, these require better SWaP-C timing solutions. Better timing capabilities on-board LEO satellites can enable RF geolocation/earth observation, interferometry, satellite ranging/cross-linking, and provisions for holdover timing to ground based applications when GNSS is unavailable/disrupted, leading to assured PNT capabilities [52].

5.3.2 Chronometric levelling

The exceptional performance of optical clocks and in particular the stability offered by optical lattice clocks, which exceeds $4 \times 10^{-17}/\sqrt{\tau}$ fractional frequency instability for synchronous comparisons, enables the observation of gravitational time dilation at the millimetre height scale around the geoid, showing promise to replace classical methods of gravimetry, spirit levelling, or GNSS-based altimetry and gravimetry to determine global geopotential models. A network of high-performance optical lattice clocks compared at the 1×10^{-18} level would currently enable centimetre level chronometric levelling with sub-hour temporal resolution, providing a rich dataset for Earth observation sciences. Currently, this application is in an early demonstration phase and is being considered by the International Association of Geodesy (IAG) and the Global Geodetic Observing System (GGOS). Key innovations in clock architecture are likely needed to see the required performance of optical clocks in a field-deployed setting for the eventual widespread adoption in geodesy. With the potential for timing resolution to exceed practical classical measurements of geopotential – transforming timing networks into space-time networks – future universal terrestrial time scales will suffer distortions due to gravity, prompting the development of reference systems outside the influence of the Earth’s dynamic gravitational environment (master clocks in space).

5.3.3 Quantum computing

Quantum state engineering, entanglement, high-fidelity coherent control, long coherence times, low-noise state detection, and isolation from the environment are all desirable properties for both atomic clocks and quantum computing systems. Platform technologies based on electrically trapped ions or optically trapped neutral atoms are commensurate with both application areas, and so many challenges to develop and scale these systems are shared. The huge investment in quantum computing, including in the UK’s National Quantum Computing Centre (NQCC), is expected to drive new market opportunities for clocks owing to cost reduction in shared component supply chains.

5.3.4 Redefinition of the SI second

State-of-the-art optical clocks currently operate with estimated fractional frequency uncertainties over 100 times lower (i.e., better) than that of Cs fountains which realise the SI second (e.g., NPL-CsF2). Consequently, a case and roadmap for a redefinition of the second to an optical atomic transition or ensemble of transitions [53] has been set out by the metrology community [54] with a CCTF target date of 2030. The most stringent realisations of the SI second will then fall to optical systems and a new market for primary optical atomic frequency standards is expected to emerge. An expansion of the NTC RETSI is a primary candidate for initial uptake of turn-key state-of-the-art optical atomic frequency standards. NPL leads the UK effort to support a redefinition of the SI second and develops and operates the UK's only fully evaluated optical atomic frequency standards, based on trapped Yb^+, Sr^+, and neutral Sr. Implementation of these systems, or similar, into the UK's national time scale UTC(NPL) will deliver immediate improvement in time scale stability. Prototype optical time scales have already been demonstrated at NPL and a new high-availability autonomous Yb optical lattice clock is under development with intent to establish the first continuous UK optical timing infrastructure.

5.3.5 Fundamental physics

Comparisons of state-of-the-art atomic and molecular clocks offer sensitivities for exploring a rich set of physical theories, including possible time variation of fundamental physical quantities such as the fine structure constant and electron-to-proton mass ratio [55], relativity [56], and dark matter models [57]. Over time, these measurements help to refine a wide range of fundamental physics theories beyond the Standard Model and help to achieve a better understanding of the nature of matter in our universe in the direction of answering big questions in modern physics, such as reconciling differences in the theories of gravitation and quantum physics. Several proposals [58, 59] exist for the detection of gravitational waves and tests of gravitational redshift [60] using space deployment of cavity-stabilised lasers in the first instance (e.g., the NASA/ESA LISA programme) and follow-on optical clock space missions. The application of state-of-the-art optical atomic clocks to fundamental physics is a big driver of their progress with unbounded requirements on performance. Several novel clock systems with emphasis on fundamental physics are being developed within the UK the Quantum Technologies for Fundamental Physics (QTFP) programme, funded by STFC as part of the UK NQTP.

5.4 REQUIREMENTS SUMMARY

In CNI applications such as telecommunications there are established protocols (e.g., IEEE 1588 and ANSI T1.101) and standards for holdover requirements. Many applications require time accuracy of ~1 μs of a primary time reference. Some applications use an ensemble of holdover clocks (e.g., two Rb-based tactical clocks and a Cs-based strategic clock) to provide additional assurance. A deeper understanding of the timing requirements and education about the risks associated with GNSS loss are needed across all sectors to help fully mitigate those risks.

In figure 3, several application timing requirements for PNT have been captured and summarised and split into three sections: (1) timing requirements across a range of application domains, (2) time dissemination protocol specifications, and (3) approximate holdover capabilities for different types of atomic clock. The right-hand side of the x-axis indicates the most stringent timing requirement or capability, and better clock holdover. An estimation of how certain commercial clocks maintain accuracy after 1 day (blue trace) and

30 days (orange trace) is shown. This is a useful tool for understanding which type of holdover clock is appropriate for each application. For example, one can infer that a commercial tactical clock cannot provide adequate accuracy performance for certain CNI applications beyond a day of holdover. However, more detail is required to understand each CNI sector and infrastructure needs in order to implement adequate timing holdover measures.

For certain applications, placing high-performance clocks at the point of use could remove costly requirements for characterisation and minimisation of latency in clock dissemination networks, e.g., in distributed computing within and across datacentres [61]. Incremental advancements in commercial atom clock SWaP-C will continue to improve the cost-to-performance ratio of CNI and security and defence applications, while commercial atomic clocks incorporating next-generation technologies will offer unprecedented performance with potential to disrupt existing industry practices and bring about use in new application areas. Continued research into new microwave and optical clock architectures will be critical to realising current lab-based state-of-the-art performance in field-deployed settings.

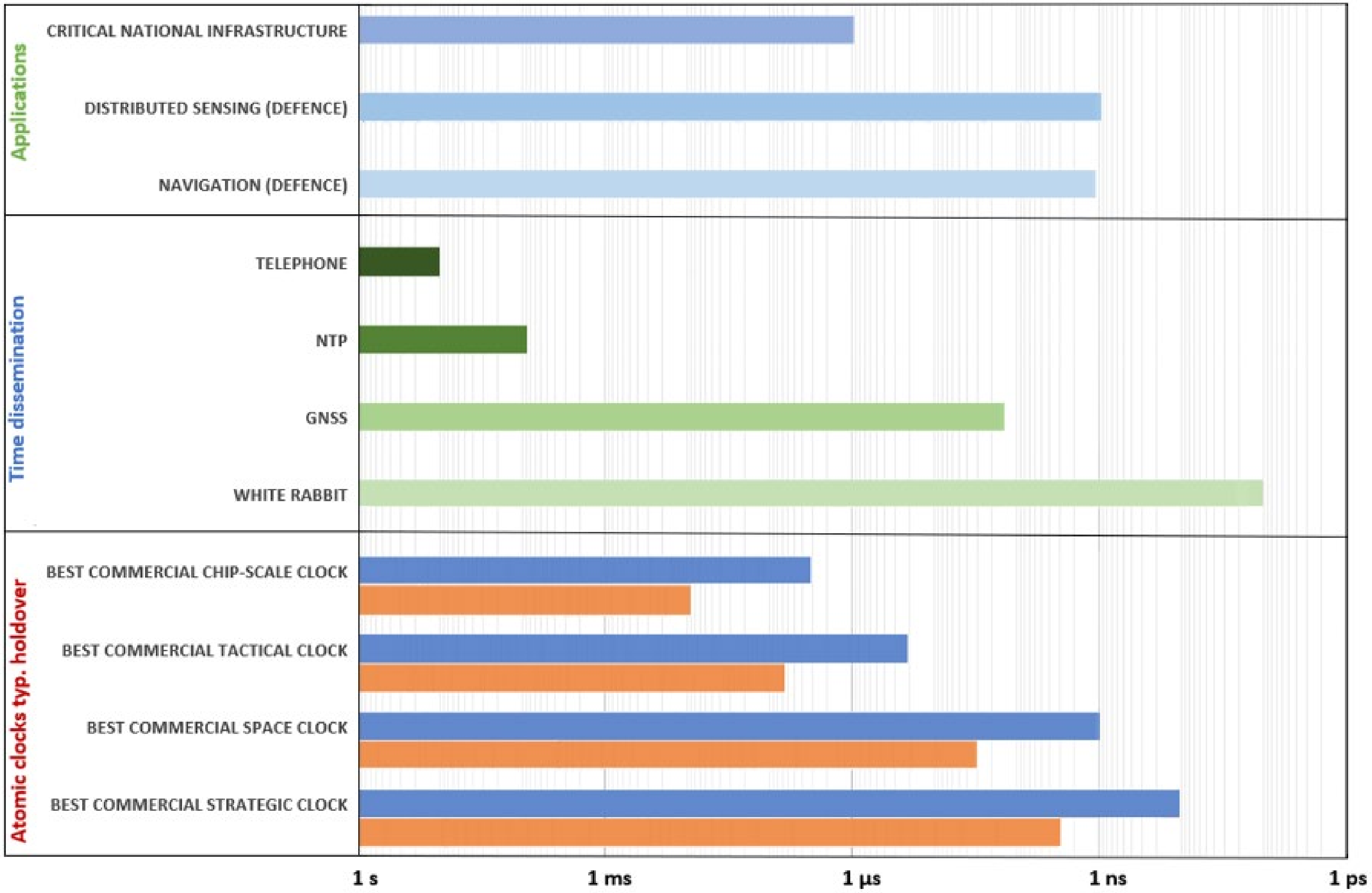


Figure 3. Condensed timing accuracy requirements for certain application areas, time dissemination techniques and associated timing accuracy thresholds, and the holdover capabilities of existing atomic clock systems (blue bars: 1 day holdover, orange bars: 30 days holdover). More applications and details are included in the main text.

6 END-USERS

There are a large number of end-users in the UK who require atomic clocks for timing purposes and frequency references. These users are primarily situated in defence, CNI, and space related sectors. Other companies, e.g., in the telecommunications sector, rely on systems which have atomic clocks embedded (e.g., a GPS-disciplined Rb oscillator). Some users are not aware that their system contains an atomic clock as timing systems are installed and maintained by external contractors. In general, many end-users have a poor understanding of atomic clocks, both in terms of being able to interpret their performance and in defining their needs and requirements. Most end-users, particularly those in the telecommunications sector, understand TDEV or MTIE requirements, as these are defined by established networking protocols. Atomic clocks researchers, manufacturers and suppliers instead use Allan variance/deviation (AVAR/ADEV) to determine a clock's holdover capabilities. Better dialogue and training are required for end-users and manufacturers to bridge their understanding of atomic clocks and timing requirements.

Table 2 shows a list of several end-user sectors identified in the UK. In general, end-users have expressed a preference for:

(1) A reliable UK-based supply of atomic clocks with holdover performance at least as good as those currently available on the market.
(2) Improved atomic clock ruggedisation (several end-users in the defence sector, have pointed to the "UK Defence Standardisation" (DEFSTAN) to use as a general guide.
(3) Better atomic clock holdover performance for increased resiliency against prolonged denial of access to GNSS signals.

Table 2. Summary of atomic clocks interests from several end user organisations.

Sector	Consolidated needs*
Military/Defence equipment contractors	Various needs for better holdover clocks (from chip-scale to strategic) across different locations and use-cases (e.g., comms, radar, navigation, etc.). Particular interests in "Quantum Navigator" instruments for GNSS independent navigation.
Radar systems specialists	Interests in holdover clocks for frequency synchronising network of low-phase noise oscillators and secure comms.
Transport	Looking into future digital infrastructure. Time synchronisation important but not yet certain about infrastructure requirements.
Telecommunications network providers / infrastructure	Future telecoms systems need better holdover clocks, particularly at base stations. Some interest in developing timing distribution network using fibre infrastructure. Key customers of Rb clocks for EU tele/data coms networks. Currently buying COTS.
Oil and gas, other energy suppliers	Low power timestamping equipment required for underwater sensors, with improved holdover times.
UK-based wholesalers of Rb clocks and oscillators	Wholesale UK distributors of crystal oscillators and various portable atomic clocks, amongst other timing equipment. Have key info about market and user-specific requirements.
Financial sector infrastructure contractors	Interests in holdover clocks for finance sector for improved resilience in time synchronisation and timestamping.
Technical R&D consultancy and contractors	Interests in integrating UK holdover clocks in bespoke systems requiring precision timing.
Defence and Space technologies	Interested in clock systems in space for future precision timing and navigation, incl. across LEO, MEO and GEO satellites and deep space.
Construction industry supplier	Interested in high spec oscillators and potentially clocks for surveying applications.
Electricity energy distribution	Employs third party contractors to install timing infrastructure.

*consolidated knowledge from discussions with ~20 companies across different sectors.

7 UK ATOMIC CLOCK MANUFACTURING

Several UK-based companies have attempted to develop pre-production prototypes of various atomic clocks, partially funded through the UK NQTP / MOD, and supported by NPL. This section provides a summary of those projects.

Table 3. Pre-production prototypes of commercial atomic clocks under development by UK manufacturers.

Category of clock	# Companies	# Clocks under development	Optical / Microwave	1 μs *** Holdover period	Current TRL
Chip scale	1	1	Microwave	2 - 5 days	3
Chip Scale*	2	2	Microwave	2 – 5 days	2
Tactical*	1	2	Microwave	5 - 10 days	6
Tactical / strategic**	1	1	Microwave	30 – 100 days	3
Tactical / strategic**	1	1	Optical	30 – 100 days	3
Strategic	2	2	Microwave	30 - 100 days	2
Strategic	1	1	Optical	100+ days	2
Strategic*	1	1	Optical	100+ days	2
Space	1	1	Microwave	30 – 100 days	2

*These industrial atomic clock development programs have ceased due to insufficient funding, resource, or perceived ill-defined market.
**Atomic clocks that are initially developed as Strategic (i.e., larger form-factor) clocks, but through supply chain maturity and reduction in SWaP over time, could meet criteria of Tactical clocks.
***1 μs holdover period used as this covers most CNI application requirements for timing accuracy.

Many of these technologies are progressing towards functional demonstrations. In some cases, the initial R&D was conducted by NPL and/or UK academia with transfer of knowledge to UK industry via UKRI/SBRI government funding. Only one program to date reached TRL 6 but has now ceased. At least three other low-TRL development activities have also ceased due to insufficient funding and resource.

A government strategy and directive around timing requirements is needed for UK CNI and defence applications, which builds on the 2023 DSIT PNT announcement. Better business justifications with clearly defined markets and customer requirements, would provide industry with better understanding of which technologies and supply chains to prioritise. There is also a clear need to support technologies through the so-called “valley-of-death” (TRL 4-7) stages of technology development.

8 UK BASED SUPPLY CHAINS AND DISTRIBUTORS

The UK has a strong photonics, semiconductor, and quantum community, comprising several companies. There are also several research groups situated within UK universities and research organisations. This makes it possible for the UK to establish sovereign capabilities in several areas of holdover atomic clock development. There are, however, limitations with certain key technologies such as RF components and microcontrollers and chipsets, which are often procured from non-UK suppliers. This section provides a summary of holdover atomic clock activities in the UK and highlights the key capabilities in the UK which could enable sovereign UK atomic clock products.

8.1 SYSTEM INTEGRATORS

Several companies in the UK are seeking to develop and manufacture holdover atomic clock products as part of an existing portfolio of electronic hardware products. These range from new start-ups and SMEs to large scale system integrators. These companies are all relatively new to the field of timing and require significant support with evaluating the market, requirements definition, technology demonstrator development, systems engineering, production engineering, and test and evaluation, amongst other key areas.

In the UK there are five SMEs and three large companies that have developed / are developing atomic clock manufacturing capabilities, largely through UK grant funding. One of the SMEs is a well-established UK manufacturer and supplier of Rb clocks and other timing related instruments, which has seen demand in their products rise in line with recent market report accounts.

8.2 MECHANICAL AND OPTOELECTRONICS PACKAGING

Packaging components is a critical part of atomic clock development. The quality of the design and materials used for packaging atomic clocks, particularly the physics package, can have a huge impact on the quality of the end-product. There are key companies in the UK who have demonstrable capabilities in highly-ruggedised and even space qualified packaging techniques. Many of these companies have experience with optoelectronics and laser packaging, including hermetic sealing capabilities, which can help improve performance and longevity of the product.

There are four companies known to be capable of packaging atomic clock sub-system modules in the UK (three SMEs and one large company), mostly specialising in optoelectronics and microelectronics for various sectors including space.

8.3 QUANTUM RESEARCH AND TECHNOLOGY ORGANISATIONS

Research and Technology Organisations (RTOs) play an important role in the National Quantum Technologies Programme, providing specialist expertise across several technology areas. RTOs typically have dedicated R&D equipment and facilities to support UK industry establish new product and services.

There are four RTOs involved in atomic clocks components R&D in the UK offering wide-ranging services such as new laser technology prototyping, optoelectronics packaging and assembly, modelling and design for various environments including space. These organisations have experienced personnel and are conducting new research and occasionally catalysing novel technologies to support new product developments in the UK.

8.4 ATOMIC CLOCKS SUB-COMPONENTS

Holdover atomic clocks require some bespoke components that require certain expertise to develop. Fortunately, the UK has several SMEs with these skills, some of whom play an active role in the UK's National Quantum Technology Program. Whilst many relevant developments are still maturing, many of these companies are demonstrating promising early prototypes and the capacity to support a sovereign UK holdover atomic clocks capability.

The UK has a range of manufacturing companies specialising in key areas such as crystal oscillators, MEMs vapour cells, laser and optoelectronics components, Mu-metal shields, and vacuum equipment. There are also specialist engineering consultancy companies that can support new hardware prototyping.

8.5 SEMICONDUCTOR COMPONENTS

The UK has a strong semiconductor industry, with particular expertise in III-V and silicon semiconductor platforms [62]. There are several semiconductor growth and fabrication capabilities in optoelectronic device manufacturing, which is relevant to the development of new photonics and laser technologies. These technologies play an important role in both current and future atomic clocks, which often require bespoke laser and chip-based components. Many companies in the UK have successfully developed state-of-the-art prototypes of new components for quantum technologies [63].

There is one large scale semiconductor wafer growth company, and several (seven identified) SMEs specialising in laser diode developments, and micro and nano fabrication facilities. These companies also have design experts, adaptable high volume production capabilities and accredited testing capabilities.

8.6 TIMING REQUIREMENTS DEFINITION

There are several outfits in the UK which specialise in time and frequency related components and equipment. Many of these companies both use and sell (as UK distributors), and in some cases install timing equipment, including atomic clocks, for UK end-users. These companies can play an important role in supporting requirements definition activities as well as performing field-trials of prototype atomic clocks that are made in the UK.

There are five companies in the UK that have been identified to support activities around requirements definition of next-generation atomic clocks. Three are SME consultancy firms or suppliers of timing equipment. Two large companies are involved in telecommunications and defence.

9 RESEARCH AND DEVELOPMENT

Several new holdover atomic clock technologies are being developed in the UK, with most development projects funded through the NQTP. This section provides an overview of atomic clock related research in the UK, followed by an overview of leading systems under development around the world. A scaling system is introduced first to provide better understanding of the important metrics to help determine the best candidate atomic clock technologies for certain applications.

9.1 ATOMIC CLOCK TECHNOLOGY SCORING SYSTEM

NPL has adopted the specially-tailored scaling system shown in Table 4 to indicate seven important metrics to help qualify and categorise each clock technology. The scale uses numbers 1 to 9 to represent the various levels of progress and maturity within a specified representative range. Each metric is scored independently, and a low score does not always reflect negatively on a clock technology, e.g., a commercial hydrogen maser costs ~£500k per unit (score 4) with a current market size of ~10 – 100 per annum (score 3 - 5), yet it is a crucial timing instrument used in CNI applications.

This tool can be useful to help determine which atomic clocks are most appropriate for development in the UK. It can help differentiate atomic clock technologies that have near-term commercial prospects over those which are in the early stages of research. The scoring system can also improve understanding of timescales to production for each clock, with supply chain factors included. It is also a helpful tool for end-users and customers to determine the suitability of each clock for a given application, with information on anticipated SWaP, production volume and cost.

Table 4. Scaling system used to score and categorise various new atomic clock systems under development.

	1	2	3	4	5	6	7	8	9
Maturity Level (TRL/MRL)	Basic principles observed	Technology concept formulated	Technology proof of concept (using e.g., benchtop equipment)	Validation in lab (not using benchtop equipment)	Validation in relevant environment (e.g., env. chamber)	Demo in operational environment	Pre-production systems	Product Qualification Pilot	Full rate assembly and production
Complexity of technology (Complexity scale)	24 or above	21 - 23	19 - 20	16 - 18	13 - 15	10 - 12	7 - 9	4 - 6	3 or less
Supply chain availability	Supply chain unidentified	Supply chain identified but not associated	Supply chain agreed to CR&D	Supply chain at MRL3	Supply chain at MRL4	Supply chain at MRL6	Supply chain at MRL7	Supply chain at MRL8	Supply chain at MRL9 at required scale
Performance	Holdover of 1 us for up to 6 hours	Holdover of 1 us for 1 day	Holdover of 1 us for up to 3 days	Holdover of 1 us for up to 10 days	Holdover of 1 us for up to 30 days	Holdover of 1 ns for up to 3 days	Holdover of 1 ns for up to 10 days	Holdover of 1 ns for up to 30 days	Holdover of 1 ps for up to 30 days
SWaP and portability	Lab	Portable container - static operation; 50 kg+; 50 W +	Portable container - moving operating; 50 kg+; 50 W +	Portable trolley (12U) - static operation; 35 kg +; 50 W +	Portable trolley (12U) - moving operation; 35 kg+; 50 W +	4U (rack mounted); < 20 kg; < 40 W	1000 cc (Rb clocks); < 5 kg; < 20 W	50 cc (CSAC); < 0.5 kg; < 2 W	System on a single chip; < 0.1 kg; < 1 W
Unit cost	> £5 M	£1 - 5 M	£500 k to £1 M	£100 - 500 k	£50 - 100 k	£20 - 50 k	£5 - 20 k	£1 - 5 k	< £1 k
Market size (units per annum)	< 1	1	2 to 12	13 to 30	31 to 100	100 s	1000 s	10,000 s	100,000 s

The ‘complexity of technology’ score within this table uses a grading system adapted from a 2019 Dstl presentation [64] and is summarised in Figure 4. To rationalise this grading scheme, three areas were selected to represent the general complexity of an atomic clock system:

(i) The type of vacuum needed within the system, with a score of 1 representing no “active” vacuum system components, e.g. a vapour cell with buffer gases raising the pressure to almost an atmosphere; a score of 2 representing a high vacuum (HV) system, such as a hermetically sealed caesium-beam tube chamber; and a score of 3 representing a more sophisticated vacuum arrangement required to reach ultra-high vacuum (UHV) levels (<1e-10 mbar), e.g. those used for cold atoms and ion traps.

(ii) Atomic sources are ranked similarly, with a score of 1 representing a thermal system, e.g., warm alkali vapour or caesium beam; a score of 2 indicating the need for cold atoms/ions; and a score of 3 for anything else, e.g., sympathetic cooling, radioactive sources (i.e., nuclear clocks), Fullerene cages, etc.

(iii) Finally, the number of lasers (or lamps) used, as each laser requires careful tuning and optimisation; certain types of lasers may require additional redundancy measures.

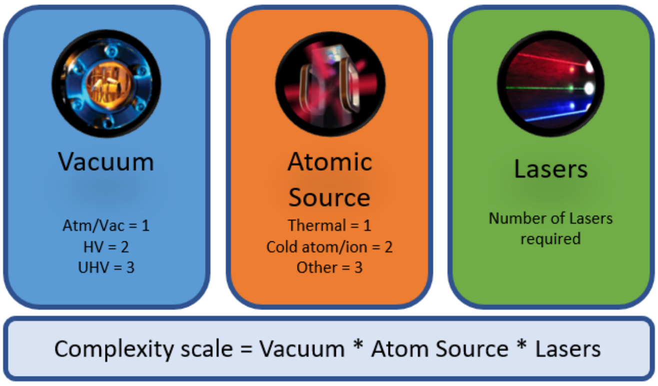


Figure 4. 1Representations and equation used in the ‘complexity scale’ as a simple means to determine the complexity of an atomic clock system (adapted from [64]).

The scaling methods set out above can be applied to each atomic clock described in the following sections of this report, and the current levels of progress charted (blue bars), overlaid with projected progress after 5 years from now (orange bars) and 10 years (grey/red bars) assuming adequate resourcing is provided for the full duration. An example chart is shown in Figure 5.

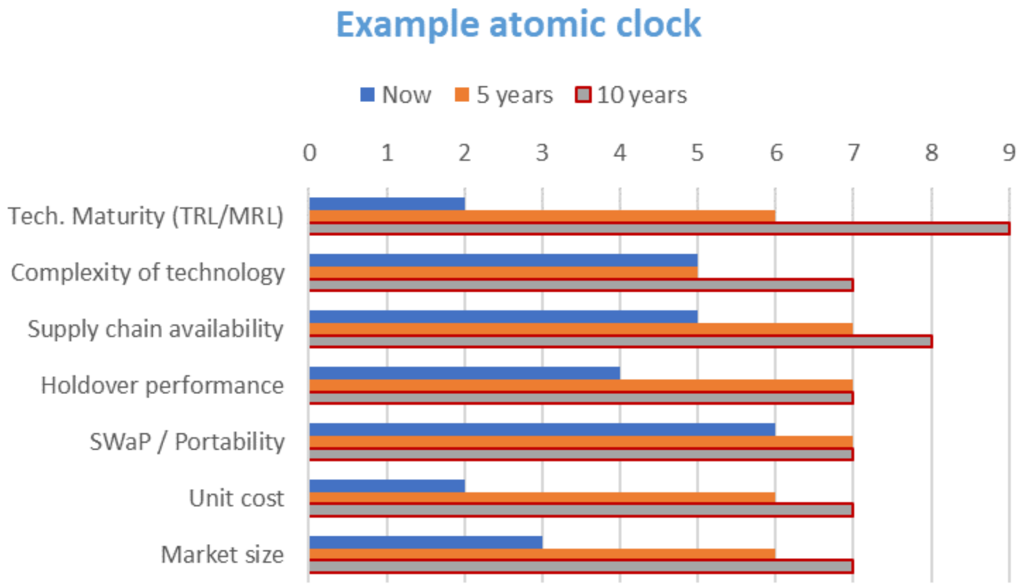


Figure 5. Example scaling system applied to represent seven important metrics, as per the proposed scaling system shown in Table 4.

9.2 ATOMIC CLOCKS AT NPL

In the NPL Time and Frequency department, over 90 scientists and engineers are working on the development of innovative atomic clock systems and time dissemination technologies and services. It is the largest single entity within the UK that has expert atomic clock development capabilities and is internationally recognised as a leading institute in the field.

The atomic clocks under development at NPL range from compact chip-scale systems to state of the art primary and next-generation secondary frequency standards that contribute to the realisation of national and international time scales. NPL has been working closely with industry collaborators to secure supply chains for some of these technologies. These activities are largely funded through UKRI sponsored collaborative R&D projects, direct DSIT quantum funding in alignment with the UK NQTP, and ESA contracts. Recently (mid 2023), NPL was awarded funding to participate in several UK-based atomic clock projects (leading one) as part of the EPSRC and SBRI related PNT-themed funding calls.

In addition to these, there are nine next-generation holdover atomic clock technologies of varying types and maturity levels that are being developed at NPL (this does not include the primary and secondary atomic clocks used to define UTC).

9.3 ATOMIC CLOCKS AT UK UNIVERSITIES AND OTHER RESEARCH HUBS

There are several atomic clocks being developed at UK universities and a defence research laboratory. The university research is funded by EPSRC and UKRI, mostly as part of the NQTP. To date, none of these atomic clock activities have yet reached significant clock performance characteristics and remain at low TRL. While some of the technologies employed are novel and have potential, more effort is needed to increase maturity before manufacturing feasibility can be considered. The projects do however provide significant training of postgraduate and post-doctoral candidates available to take up careers in the UK quantum and time and frequency industries' research communities. There are nine known atomic clocks being developed at different UK research institutes, mostly fitting in the tactical and strategic categories.

9.4 WORLD STATE-OF-THE-ART HOLDOVER ATOMIC CLOCKS

Over the past twenty years, some governments around the world have each invested the equivalent of several £100s of millions worth of funding in holdover clocks for sovereign capability in safeguarding national assets and CNI. Many of these commercially available clocks will continue to serve in existing applications and create new and sizeable markets for portable atomic clocks as end-users move to reduce/eliminate the use of GNSS signals. This section highlights several identified best next-generation candidate technologies from around the world.

Table 5. List of state-of-the-art holdover atomic clock systems (non-UK) across chip-scale, tactical, strategic, and space categories. The list aims to be representative and not exhaustive.

Org.	Clock Technology	Category	Optical / Microwave	Ref.
NIST/Col Uni/Georgia Tech (US)	**MEMs based Rb Beam**	Chip scale	Microwave	[65]
Neuchatel University (Swiss)	**Rb DR**	Chip scale	Microwave	[66]
Infleqtion (US)	**2-photon Rb**	Tactical / Strategic	Optical	[67]
Peking University (China)	**Ca Beam**	Tactical / Strategic	Microwave	[68]
JPL/NASA (US)	**Hg+ (*terrestrial)**	Tactical	Microwave	[69]
CAS Wuhan (China)	**RAFS**	Tactical	Microwave	[70]
INRIM (Italy)	**Pulsed Rb**	Tactical / Strategic	Microwave	[71]
FEI Inc	**Pulsed Rb**	Tactical	Microwave	[72]
DLR (Germany)	**Iodine thermal cell**	Strategic	Optical	[73]
DFM (Denmark)	**Acetylene thermal cell**	Strategic	Optical	[74]
Vector Atomic (US)	**Iodine thermal cell**	Strategic	Optical	[75]
Microchip (US)	**Buffer gas cooled Yb+**	Strategic	Microwave	[76]
JPL/Sandia (US)	**Laser cooled Yb+**	Strategic	Microwave	[77]
Riken University (Japan)	**Sr optical lattice**	Strategic	Optical	[78]
PTB (Germany)	**Yb+ optical**	Strategic	Optical	[79]
NIST Yb lattice (US)	**Yb optical lattice**	Strategic	Optical	[80]
JPL / FEI (US)	**Hg+ ***	Space	Microwave	[81]
CNES (France)	**Cold Rb**	Space	Microwave	[82]
Key Labs / CAS (China)	**Cold Rb**	Space	Microwave	[83]
FEI (US)	**"Digital" Rb**	Space	Microwave	[84]

*There are two versions of the Hg+ clock being developed: A tactical version for terrestrial use, and a space clock currently used in deep space navigation trials.

10 GAP ANALYSES

While the UK has developed a wide range of competitive lab-based holdover atomic clock technology, several key components are either undeveloped or too immature to support a sovereign UK atomic clocks capability. Some NQTP projects have enabled the creation of new quantum component expertise in the UK; however, whilst creating new skills and capabilities, the lack of market pull has limited industry uptake, and to date, many of these components remain at low TRL and MRLs. It is important to address the supply of components for next-generation atomic clocks to avoid frequent revalidation and requalification exercises. Having supply chains established early can improve business justifications for companies and provide better technical focus for atomic clocks development. It also greatly reduces technical and commercial risks. This section highlights some of the key components in need of targeted support to enable the production of next generation atomic clock technology in the UK.

10.1 FREQUENCY COMBS

A frequency comb is a key component for optical atomic clocks. It enables the stabilised optical frequency (the several 100s THz laser oscillation frequency stabilised to the atom source) to be translated to other optical frequencies (such as 1.5 µm) or down-converted to a much more accessible microwave frequency to provide end-users with a useful clock output (most commonly 5, 10 or 100 MHz, or a 1 PPS signal). Without a frequency comb, end-users will have only an optical signal as the output from the optical atomic clock, which is unsuitable in most timing and synchronisation applications predominantly in the RF and microwave domain. However, it is also noted that timing applications and metrology are increasingly associated with photonic platforms centred around fibre optical communications in the 1.5 µm region, and capable of expanding to wider optical / infra-red bandwidths with recent advances in hollow core fibre technology.

There are several activities across the UK to develop portable microcombs for optical atomic clocks. NPL is providing consultancy support and test and evaluation services to some UK-based fibre frequency comb projects. Whilst the fibre-based comb technology is more mature, several researchers in the UK are looking at much more compact and scalable (high volume manufacturing potential) techniques using micro-ring resonators. These come mainly in one of three forms: ring shaped glass rods, semiconductor (Ta_2O_5 or Si_3N_4) waveguides, and micro-toroid structures. In general, microcombs are an attractive technology which should enable much lower SWaP optical atomic clocks, but a more convincing demonstration of the technology is required before it is considered a viable component in future compact optical atomic clocks. In addition to NPL's research into fibre, microring and glass rod resonators, there are four university-based research teams that are looking into semiconductor microring resonator technologies, two UK companies looking into fibre-based frequency combs and one RTO developing an interest in the area.

10.2 COMPACT ULTRASTABLE CAVITIES

Compact bulk optical cavities are required for more advanced optical atomic clocks (e.g., cold atom/ion-based systems) and serve to reduce the frequency noise of the laser that is subsequently stabilised to the atom source [50]. In the UK, NPL is currently the only research organisation working on developing high-performance portable optical reference cavities for stabilising lasers. NPL has a number of ESA-funded cubic cavity and clock projects underway across a variety of ultrastable laser and clock applications, including synchronisation and navigation, Earth observation, fundamental science, quantum computing, and high-resolution spectroscopy. NPL has licensed the patented cubic cavity technology to a few commercial technology firms in Europe, the US, and UK.

Compact semiconductor microring resonators may serve in place of bulk optical cavities in future portable optical atomic clocks, but this technology is still at an early stage of maturity. More work is needed in the UK to expand and mature technologies in this area. NPL is actively looking at ultrastable cavities and compact microrings and have considerable know-how and an important patent in this area.

10.3 LASERS AND LASER SYSTEMS

The UK has a particularly strong photonics industry with several laser manufacturers. Many of these laser manufacturers have been participating in the NQTP and have developed several new laser technologies for quantum applications. The NQTP has enabled UK laser companies to grow and develop new manufacturing capabilities, establishing new product prototypes for quantum applications, however more effort is needed to increase TRL and MRL, and ultimately drive down cost. One of the key challenges on cost is that quantum applications, both in the UK and abroad, are yet to demand any considerable volume of these lasers, compared with, e.g., tele/data communications sectors, where laser diode manufacturing companies typically supply volumes exceeding 1 million laser diodes per annum. There are some overlaps in requirements between telecoms and quantum lasers, e.g., in the 1.5 µm region where COTS telecoms lasers can be frequency doubled to access Rb transitions in certain quantum systems.

Atomic clocks, with the exception of some lamp-based systems, require lasers that have challenging specifications, particularly in the required wavelengths for particular atoms or ions and the narrow linewidth needed for the clock laser. Device lifetimes and MTTF are also critical. The atomic transitions that need to be targeted with lasers have certain requirements that are often non-standard for the laser industry. For example, the cooling transition for the Sr atom requires a laser at 461 nm; there are very few low SWaP-C solutions available at this wavelength, and those which are available often suffer from reliability issues. More work is needed to mature the laser technologies required for integration in future atomic clocks.

In the UK, there are three universities known to be active in laser technology development (diode and solid-state). There are three semiconductor laser manufacturing companies who can develop key lasers for atomic clocks. There are six other companies who specialise in solid-state laser technologies, including one which specialises in lasers for atomic clocks.

10.4 VAPOUR CELLS

There are several vapour cell development capabilities in the UK, however none are mature enough for production, currently. One of the key challenges to address with vapour cell-based systems is sourcing the appropriate type of glass, specifically to address helium permeation which affects long-term stability. Aluminosilicate glass is widely considered to be suitable however there are few suppliers of this type of glass, and the main suppliers found do not appear to offer small volumes for R&D purposes. A potential solution being explored in existing R&D projects is the use of glass coatings to reduce He-permeation, such as SiO_2 or aluminosilicate. Another issue is the lack of scientific glassblowers in the UK with the skills required to manufacture the vapour cell glassware. Sourcing certain isotopes and buffer gases have also caused issues in current CR&D projects. These challenges need to be addressed for high quality and sufficiently low-cost vapour cells to be suitable for clock integration.

In the UK there are several organisations that can develop vapour cells. There are four companies known to be capable in developing MEMs based vapour cells, and two universities with similar abilities. There are two companies that have developed / are developing glass blown vapour cell capabilities, by means of technology transfer from NPL.

10.5 PHOTONICS AND INTEGRATED OPTICS

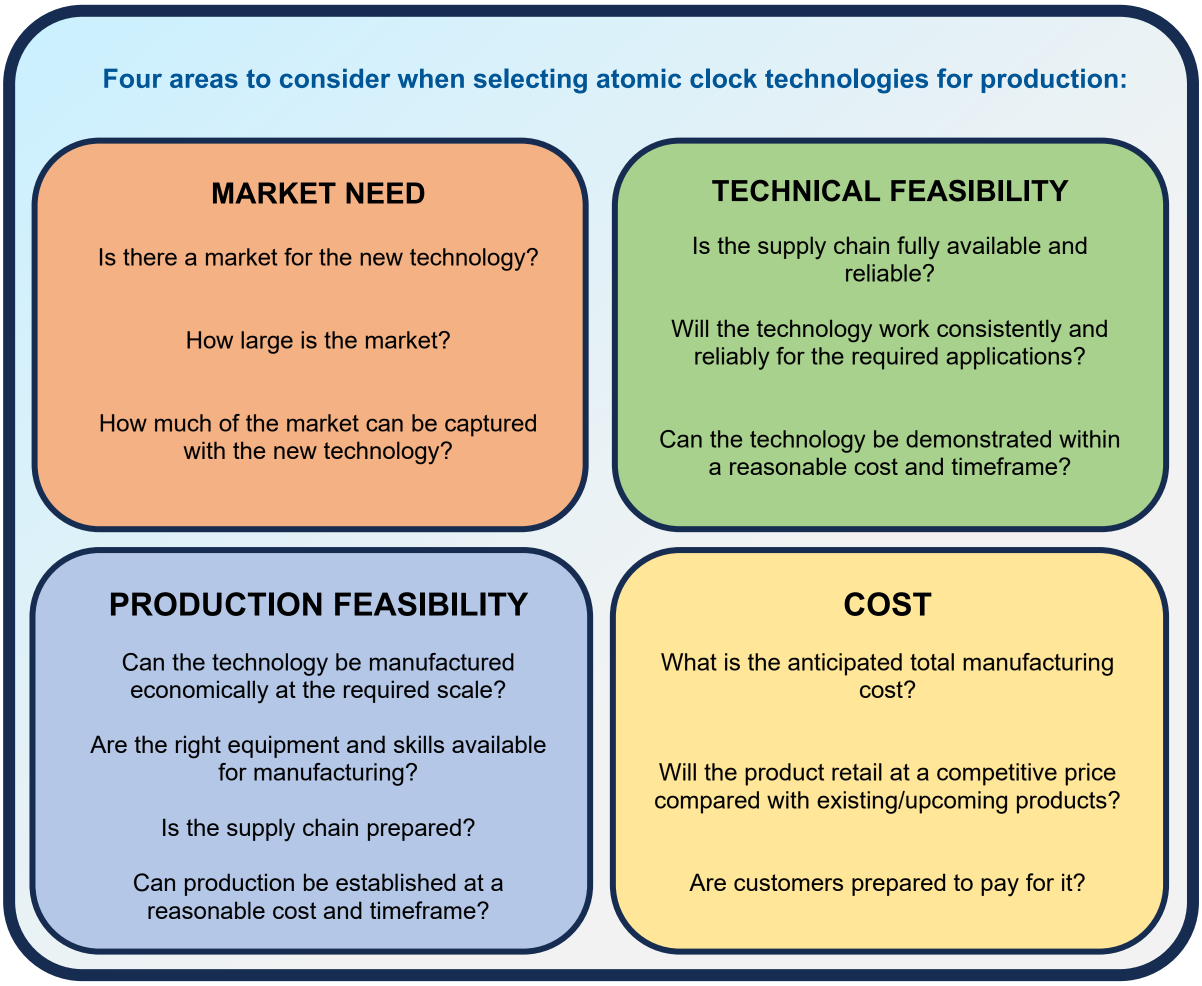
Over the past few decades, research institutes have been looking at the integration of several optical system components onto robust, scalable, and manufacturable platforms. Approaches include bulk optics packaging, optical fibre integration, micro-benching, and on-chip photonic integrated circuits based on various platforms such as silicon and silicon nitride.

Photonics integrated circuits (PICs) are rapidly approaching the point where they converge with applications involving atom-based quantum devices, though the cost of manufacture makes this approach currently prohibitive in all but the largest of markets. UK capability in PICs targeting quantum areas is growing with several university research activities and spinouts specialising in the area. This area has its own distinct landscape and would need more investigation to accurately convey UK capability.

11 PRODUCTION CRITERIA

The market success of a commercial atomic clock system depends on the strengths and weaknesses of the underlying technology weighed against market values. For example, the popular 5071A caesium beam clock (now by Microchip) is based on robust technology that has been demonstrated to work reliably and with an adequate cost-to-performance-ratio across a range of applications, resulting in a product that is still selling in high volume. In contrast, commercially available cold-rubidium clocks offer better accuracy and short- to medium-term stability than the caesium beam clock, are somewhat less successful owing to considerably higher cost (~5 times more than a caesium beam clock), reduced product lifespan (5 years compared to >10 years) and with tighter restrictions on its operating environment (i.e. can only be used in applications where the clock must remain completely static during use). The new cold-rubidium clocks are yet to make any considerable impact on the market.

There are several new atomic clock technologies being developed in the UK and around the world. It is reasonable to consider that few of these technologies will lead to sufficiently high TRL / MRLs such that the technology is available as a product. In order to determine which clocks have the best potential to reach production, four important factors should be considered as per figure 6:



Four areas to consider when selecting atomic clock technologies for production:

MARKET NEED

Is there a market for the new technology?

How large is the market?

How much of the market can be captured with the new technology?

TECHNICAL FEASIBILITY

Is the supply chain fully available and reliable?

Will the technology work consistently and reliably for the required applications?

Can the technology be demonstrated within a reasonable cost and timeframe?

PRODUCTION FEASIBILITY

Can the technology be manufactured economically at the required scale?

Are the right equipment and skills available for manufacturing?

Is the supply chain prepared?

Can production be established at a reasonable cost and timeframe?

COST

What is the anticipated total manufacturing cost?

Will the product retail at a competitive price compared with existing/upcoming products?

Are customers prepared to pay for it?

Figure 6. Four areas to consider when selecting atomic clock technologies for R&D and production.

12 FUTURE OUTLOOK

12.1 MARKET SIZE AND OPPORTUNITY

The latest global market reports provide information of the market size: ~£400M cumulative sales in 2022, and surpassing £420M in 2023 [8, 9]. Over the forecast period 2024 to 2033, demand is expected to exhibit a 7.0% compound annual growth rate (CAGR), with key opportunities in telecommunications (primarily 5G rollout), data communications, CNI, and defence, as well as some new application areas, e.g., LEO sats, distributed sensing, etc. Tactical and chip-scale clocks are the largest segments of the global atomic clock market and likely to remain so over the next decade. Annual sales are anticipated to cross £1 bn per annum by the end of 2033. The size of the UK market is currently unclear, but a figure of between 1 and 5% of the global market is considered a reasonable estimate.

Currently, UK industry is addressing <1% of the global market, mainly with Quartzlock Rb-based atomic clock products; these are also sold under other brand names. It is anticipated that alternative (equivalent or better) holdover clocks manufactured in the UK can capture up to 20% of the total global market (i.e., >£200M sales per annum from 2033).

Despite the UK leading in some areas of R&D (e.g., prototype developments at NPL), currently the UK have produced no new atomic clock products on the market, largely due to relatively low levels of investment (~£10M total, compared with several £100Ms invested in US and China). It is reasonable to expect the UK to capture a significant share of this market with various novel and disruptive technologies, however, a considerable and commensurate uplift in investment is needed to mature these technologies through both TRLs and MRLs.

12.2 OUTLINE FOR A UK HOLDOVER ATOMIC CLOCKS DEVELOPMENT PROGRAM

Several recent UK government policy and strategy announcements point to a need for the UK to establish sovereign capability in Holdover Atomic Clocks manufacturing. The National PNT Policy Framework announced in October 2023 includes the aim to strengthen timing infrastructure resilience and points to the development of an assured supply of holdover atomic clocks to be of strategic interest for CNI and defence applications [7]. Within the National Quantum Strategy, launched in March 2023, quantum clocks are envisioned to provide greater resilience in timing and navigation [15]. This outlook was reinforced with the launch of a new “Quantum Mission” in November 2023 aimed at developing deployable quantum navigation systems (including clocks) by 2030, providing next-generation accuracy for resilience that is independent of satellite signals.

For a UK atomic clocks manufacturing capability to be realised, we suggest there are five areas that need to be addressed:

- Clarity and guidance are required to select which types of holdover clocks to develop in the UK and the sovereign and global market opportunity for each clock type.
- There are considerable skills gaps in areas such as atomic clocks engineering, systems engineering, and manufacturing/production engineering in the UK, and these must be addressed.
- UK atomic clock technologies selected for development must offer end-users distinct SWaP, performance, ruggedisation, extended operational lifetimes and/or cost advantages over incumbent technologies that can already be procured.
- A dissemination structure that enables easy access for commercial clock systems to achieve traceability to national reference standards e.g., primary and secondary frequency standards (both microwave and optical) and UTC(NPL).
- UK holdover clock manufacturers require a clear vision of the future market to set up appropriate production capabilities to meet market demand.

To achieve these, we propose that any UK Holdover Atomic Clocks development program should include the following elements:

- Preparation of a comprehensive application-based timing requirements review to better understand holdover clock needs for each UK defence and CNI sector, e.g., SWaP and cost requirements, performance target, ruggedisation, market size, etc. with a view to establish clear specifications for priority holdover atomic clock systems to be developed.
- A national coordinated research and development program focussed on producing manufacturable atomic clocks of all required categories (chip-scale, tactical, strategic, and space) and establishing associated supply chains (vertical and horizontal, where appropriate) in the UK. The program should have a longer-term outlook than previous programs and include adequate provisions to support UK industry through the “valley-of-death” (TRL 4-7).
- Creation of a holdover clocks training program to support technology transfer to UK industry, with inputs from quantum clock specialists, systems engineers and experts in manufacturing and volume production engineering, where applicable.
- Establishing a holdover clocks early-adopter programme consisting of end-users in CNI and defence to perform field trial tests to evaluate the efficacy of holdover atomic clock prototypes and provide feedback.

12.3 THE RISKS OF NOT MANUFACTURING ATOMIC CLOCKS IN THE UK

UK customers are currently dependent on non-UK companies supplying holdover atomic clocks and other related timing equipment for PNT and other important infrastructure. At present there is a lack of diversity in global supply of holdover atomic clocks, and UK customers have limited options for supply of holdover atomic clocks, both in the type of clocks available and the supplier. This poses several problems for UK customers, ranging from supply issues to widespread lack of knowledge in the subject of timing and synchronisation. A summary of the risks associated with not pursuing UK manufacturing capabilities in holdover atomic clocks is as follows:

- UK customer orders are often treated as low priority with non-UK suppliers as they are forced to prioritise needs at home (e.g., US Executive Order 13905).
- Many end-users, including those in CNI, have reported lead times in procurement of holdover clocks > 12 months and in some instances, several years. Supply problems, such as long lead times, delays and quality issues can create challenges in establishing PNT resiliency in the UK.
- Continued dependency on non-UK holdover atomic clock suppliers; UK customers may need to arrange agreements in place for technology and supply assurances.
- Compatibility issues – UK customers buying from a few suppliers may have to redesign entire systems based on change of clock due to e.g., potential disruptions to the supply chain.
- Some UK customers may procure additional holdover clocks for contingency/spares as mitigation to above risks; this could amplify the supply issues.
- UK defence will continue to disclose requirements to non-UK suppliers.
- ITAR/EAR/other import restrictions could lead to procurement challenges.
- Remote technical support and product maintenance/servicing/repairs may be challenging – this may cost UK customers more in the long-term.
- Relinquishing all capability to date for establishing sovereign capabilities. Cutting edge UK-based holdover clock/supply chain technologies may be replicated/superseded at non-UK establishments and thereby result in the loss of any potential UK commercial advantage.

- Some UK manufactured clocks may emerge on the market as a result of current UKRI funded activities but these are unlikely to compete globally without investment to improve production infrastructure and capacity.
- Many UK customers lack understanding in time and frequency requirements as they procure COTS solutions without appreciation for the specifications being delivered. As a result, customers are not making the effort to learn about timing and synchronisation in their applications, and potential other use-cases for timing equipment.

13 SUMMARY AND CONCLUSIONS

Holdover atomic clocks are atom-based timing references used as precision timing tools in many national defence and CNI applications. To mitigate against the threat of loss of GNSS signals, the UK's defence and CNI sectors need to have reliable holdover clocks in place.

UK customers are currently critically dependent on very few non-UK companies for supplying holdover atomic clocks and timing equipment for PNT and related infrastructure. There is a lack of diversity in the global supply, and limited option in type of clocks available. This poses several problems for UK customers, ranging from supply issues to a widespread lack of knowledge in the subject of timing and synchronisation.

A summary of holdover atomic clock technologies in the UK was presented with a view to help support the development of a sovereign commercial holdover atomic clock manufacturing capability. These clocks would target service in all critical UK PNT applications, including provisions for UK CNI and the NTC. Timing requirements and standards were also discussed across several application sectors (present and future), along with current progress on atomic clock developments in the UK, and the current state of UK supply chains and industrial capabilities, highlighting critical gaps.

The UK has excellent capabilities around holdover atomic clock development. Existing UKRI/SBRI funded programs are designed to produce holdover atomic clock demonstrators up to TRL4/5, but there is currently no strategy or clear roadmap in place to support the commercialisation of these demonstrators. There is a need to support technologies in the so-called “valley-of-death” (TRL 4-7) stages of development. More focus is needed on applications requirements, market size, technology feasibility, supply chains, and production feasibility. A clearer directive around timing requirements for UK CNI and defence applications, which builds on the 2023 DSIT PNT announcement, together with identified future commercial needs, would provide industry-based consortia with better understanding of which technologies and supply chains to prioritise.

UK manufactured holdover clocks would enable greater resilience of supply chain for UK PNT and give UK customers greater assurances of both the technology and supply. UK manufactured clocks can offer greater resiliency against ITAR/other import restrictions associated with procuring key components from non-UK based companies. With new atomic clock products, UK companies could access a market projected to be worth £1 bn in 2033, and further opportunities across the supply chain, with greater ROI with sales and export potential. This would also leverage the considerable sunk investment in quantum technologies, supporting UK businesses to establish new capabilities.

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