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GLOSSARY

CA	Consortium Agreement
D	Deliverable
DoA	Description of the Action
EB	Executive Board
EC	European Commission
GA	Grant Agreement
H2020	Horizon 2020
IPR	Intellectual Property Rights
PM	Project Manager
PC	Project Coordinator
PCT	Project Coordination Team
PO	Project Officer (European Commission)
WP	Work Package
WPL	Work Package Leader

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Market Study and Exploitation Plan
Deliverable 3.6

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1 Executive Summary

Time synchronization is vital to the performance and reliability of networked resources. This is particularly important in networks that underpin our highly inter-connected society. Domains such as energy, position, navigation and timing, trading, finance and mobile telecommunications are particular examples where failure has high societal impact.

As a result, there are established solutions for time and frequency synchronisation and metrology. The convenience of GNSS has made it the default approach for many commercial time and frequency applications but there is an increasing awareness of the over-reliance on this one source and of its vulnerability to accidental or malicious interference. The London Economics report[1] identifies an impact on the UK economy of £5.2B for a five day loss of GNSS. The UK National Risk Register[2] identifies severe space weather (page 33) as a high impact Category D risk which could damage the GNSS constellations (page 10).

An analysis of the market for the highest precision atomic frequency references and atomic clocks shows that these are specialised niche products with sales in low volumes. For example, the long established hydrogen maser sells about fifty units per annum. The Caesium Fountain Clock is the leading primary standard. These are built as custom instruments and maintained by dedicated resources in the top National Measurement Institutes (NMIs). There are only tens of these caesium fountains in the world and the complexity and delicacy of these instruments means that there is no commercial market at this performance level.

The volume market for atomic clocks emerges with caesium beam and rubidium vapour cell clocks and there are a number of industrial suppliers for these products. Since the iqClock offers many orders of magnitude higher precision, the market investigation in this study concentrates on opportunities that need better performance than caesium beam tube atomic clocks.

Research efforts to enhance national standards are concentrated on optical clocks and are establishing performance at two orders of magnitude better than the caesium fountain. Not only does this offer a step change in time and frequency metrology but provides a robust requirement for optical clock technology in the long term. Optical clock performance also opens up new measurement possibilities that create real interest and the key to identifying commercial potential in this capability is to understand its value and its cost. There are good reasons to think that it can deliver high value in some circumstances but the early stage exploitation will come from metrology in the NMIs and lead into fundamental science studies including deployment in space where a variety of science goals can be pursued.

A key factor that will influence opportunity is the networking of optical clocks to confirm performance and to enable their use as distributed and highly sensitive detectors. Again, this is at an early but promising stage with several demonstrations of feasibility and continuing positive progress. It represents a real opportunity for the proliferation of optical clock technology.

In a more visionary sense, the ability to distribute time and frequency with optical clock precision wirelessly to mobile platforms is quite a stretch from anything demonstrated so far, but there are some interesting concepts beginning to emerge and the capability would be transformative.

[1] The economic impact on the UK of a disruption to GNSS, London Economics, Jun 2017

[2] National Risk Register https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/952959/6.6920_CO_CCS_s_National_Risk_Register_2020_11-1-21-FINAL.pdf

2 Time and Frequency Market Overview

The table below gives an overview of the market for time and frequency products. Quartz crystal oscillators are ubiquitous in modern electronic systems from phones to laptops and in professional electronics and sell in huge volume. Higher precision applications depend on atomic clocks. These range from the PCB mounted CSAC to the room sized Caesium Fountains in highly specialised laboratories. They have been ranked in order of decreasing noise floor and consequently, the sales volume reduces significantly as performance improves due to the increasing cost/sales price. The information in the table is drawn from the references in the footnote[3].

Clock type	Price range	Annual value	Noise Floor	Ref
Crystal Oscillators XO	Few$ - $10s	$3.4Bn	1E-08	1
Oven Controlled XO	$10s - $1000s	$170M	1E-10	2
CSAC	$2k-$3k	$90M	1E-11	3
Rubidium clocks	$2k – $10k	$155M	1E-13	4
Cs Beam clocks	$70k -$90k	$50M	1E-14	5
H Maser	$150-250k	$11M	1E-15	5
Cs Fountain	$1.5M-$2M	$3M	1E-16	6

Table 1

The bestselling microwave clocks are based on rubidium vapour cells with a noise floor of 1E-13, a volume of about 1 litre, a power consumption of 10W and a selling price of about $5000. Clocks in this part of the market are known as 'Tactical' and are the common choice for mobile defence applications and as Primary Reference Time Clocks (PRTC) in telecom networks (ref ANSI T1.101)

The next step up is to the Strategic level. These applications demand precision above other considerations and their users will put additional effort into facilities, environmental control and specialised support to ensure performance. Clocks based on the Caesium Beam Tube are the base level strategic clock and serve a wide range of applications from National Measurement Institutes (NMIs) to Telecoms to Defense. The next step is the Hydrogen Maser but the added cost and complexity really restrict its applicability. All of these clocks can be sourced from established manufacturing companies such as Microsemi, Spectratime, Frequency Electronics, Accubeat, Stanford Research and IQD

As of today, there is no commercial supplier of the caesium fountain clocks that are used as the primary frequency standard. NPL will take contracts to build caesium fountains as special projects but there is a very small demand. Clocks at this level require the specialised facilities and level of scientific support that is only available in an NMI.

Beyond the Commercial Market

The official definition of the second was first given by the Bureau International des Poids et Lourds (BIPM) at the 13th General Conference on Weights and Measures in 1967 as: "The second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom." Primary Frequency Standards are based on this atomic reference and are maintained by leading NMIs around the world. The most precise measurements are based on Caesium Fountains which reach an accuracy of 10^{-16}. These Fountain clocks are used to discipline Hydrogen Masers which in turn use the Caesium Beam Tube clocks as flywheels. Many of the smaller NMIs use Caesium Beam Tube clocks directly and a total of

[3]Table references
1) Mordor Intelligence March 2018 Crystal Oscillator market to 2023
2) Daedalus consulting 2014
3) Industry Estimate
4) OY Research 2018 Global Rubidium Atomic Clock Market Research Report Forecast (2017 to 2021)
5) OY Research 4/ 2018 - Global Market Size of Cs Beam & Maser Atomic Clock (2013-2025)
6) Personal communication

450 of these clocks contribute to the International Timescale. For the last twenty years, NMIs and other academic groups have been developing clocks which reference atomic transitions in the optical frequency domain (10^{14} Hz) with mHz linewidth showing stability at <10E-19 level. This makes them the most stable clocks ever built. These optical clocks are large and fragile research instruments. An optical clock occupies an entire specialised laboratory and needs several scientists to operate and maintain it. The accuracy of these optical clocks is remarkable but to exploit the performance commercially, it is essential to significantly reduce size, weight, power and cost so that optical clocks become attractive in comparison to the best microwave clocks.

Scope

The top five to ten NMIs have been developing optical clocks for over twenty years and some of them contribute to the International Time Scale as secondary references. Their performance and reliability is reaching the point where the redefinition of the second is a realistic prospect. We can therefore assume that there will be a long term commitment in the NMIs to the continued development and maintenance of optical clocks as primary reference standards.

We define the scope of this market study as the application space for current strategic atomic clocks plus any new and emerging applications enabled by the higher precision of the optical clock.

In order to differentiate from the collection of perhaps 15-25 optical clocks in NMIs, an attractive commercial optical clock will need to be offer benefits in size, weight, power and cost. It needs to be much smaller than the lab-based caesium fountain clock, be relatively portable. Matching the Maser or Muclock (Appendices 4 & 5) would be ideal but is very challenging. The timing performance need not be as good as the ultimate performance of an optical clock in a specialist laboratory environment but it will need to match or better the performance of a caesium fountain or the Muclock.

3 Market Need for Optical Clock Performance

As already stated, the established need for optical clock performance is for improved metrology in the NMIs and in the BIPM. Basing the definition of the second on an optical frequency rather than the electronic transition in caesium is an area of active interest. The re-definition would enable optical clocks to act as the primary frequency standard with a 10-100 times improvement in precision. This research has been continuing for over twenty years and is close to fruition. Setting an international timescale at this level of precision is an extremely attractive goal and will underpin ongoing research and development to maintain the capability in the top NMIs creating a long-term science and technology base for optical clocks.

What does such a clock enable?

Time is the physical quantity that we can measure with the highest precision. So it is useful to think of such a clock not only as a frequency reference but also as a sensor. An optical clock is exquisitely sensitive to a wide variety of variations in its physical environment including gravity and magnetic field.

In fundamental physics, optical clocks would enable the tracking of dimension-less fundamental constants such as the fine structure constant α, the electron to proton mass ratio $\mu = me/mp$, or the quantum chromodynamics mass scale $mq/\Lambda QCD$. Because each clock transition frequency has a different dependence on these constants, their variations imply drifts in clock frequency ratios that can be detected by repeated measurements[4]. Currently, combined optical to optical and optical to microwave clock comparisons put an upper bound on the relative variation of fundamental constants in the 10^{-17}/year range. In addition, existing optical clocks are regarded as sensitive to prospective dark matter events and can serve as a global topological defect dark matter observatory.

Other tests of fundamental physics are also possible with atomic clocks. The local position invariance can be tested by comparing frequency ratios in the course of the earth's rotation around the sun and the gravitational red-shift can be tested with clocks as is planned for the Pharao-ACES mission due to

[4] J. Guéna et al *Improved tests of local position invariance using 87Rb and 133Cs fountains.* Phys. Rev. Lett.,109:080801, Aug 2012.

be commissioned on the ISS in 2021/22. Note that this is a laser cooled caesium clock and that even better precision could be anticipated with an optical clock. Flying an optical clock as an external payload on the ISS is the goal of mission I-SOC.

It delivers a portfolio of fundamental science objectives:

- measuring the Earth's gravitational time dilation at the 2 x 10^{-7} level
- measuring the Sun's time dilation at the 1 x 10^{-6} level
- measuring the Moon's time dilation at the 2 x 10^{-4} level
- enabling world-wide relativistic geodesy at the 1 cm level
- enabling world-wide atomic time distribution
- enabling world-wide clock comparisons at 10^{-18}

In the future, an ensemble of optical clocks in space would create the ultimate master clock for global timekeeping and provide a further means of detecting gravitational waves[5].

Other applications include:

The synchronisation of signals from antenna arrays in Very Long Baseline Interferometry (VLBI). The recent progress on the Square Kilometre Array is instructive on this point. That programme is now placing RFQs for timing equipment and synchronisation system design and implementation. Their chosen timing solution is the Hydrogen Maser from a commercial supplier.

Geodesy and geopotential variation. General Relativity indicates that clocks will tick at a frequency which will have a dependence on the local gravitational potential. Synchronising two optical clocks before transporting one clock to a different location has been shown by a comparison of their frequency to infer the difference in height to an accuracy of <10cm offering new ways of monitoring geological changes due to earthquakes, volcanos, water tables and ice sheets[6]. The possibility of geodesy with accuracies at the 1cm level has been indicated by McGrew et al[7]

Telecoms and related services have an increasing need for precision timing. It is envisaged that improved synchronisation in the network would increase bandwidth and enable new services such as ubiquitous 10cm accuracy navigation services over 5G.

What commercialisation opportunities arise?

The NMIs and a small number of academic organisations will continue to purchase the components and subsystems that are essential to building an optical clock. This is not a large market. However, it does represent an important ongoing demand for optical clock technology and the skills required to maintain it.

Research on the behaviour of fundamental physical constants is very likely to be funded in due course and will be of the character of a one-off big space science project. It is most likely to be resourced from a consortium of academics and institutions supported by specialised technology supply partners or through contract to an established space project prime such as Airbus or TAS and their supply chain.

Astronomy applications in VLBI do result in procurement of precision clocks but these projects are rare and are a long time in gestation. The SKA project has been in preparation for well over 15 years and is now sourcing three Hydrogen Masers for its synchronisation scheme.

Geodesy has some potential and will benefit from the combination of reference optical clocks in NMIs and portable optical clocks as demonstrated by PTB.

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[5] Tino, G.M., Bassi, A., Bianco, G. et al. SAGE: A proposal for a space atomic gravity explorer. Eur. Phys. J. D 73, 228 (2019). https://doi.org/10.1140/epjd/e2019-100324-6

[6] Grotti et al, Geodesy and metrology with a transportable optical clock, Nature Physics, May 2018. DOI: 10.1038/s41567-017-0042-3

[7]McGrew, W.F., Zhang, X., Fasano, R.J. *et al.* Atomic clock performance enabling geodesy below centimetre level. *Nature* **564,** 87–90 (2018). https://doi.org/10.1038/s41586-018-0738-2

4 Distribution of Time and Frequency

As mentioned earlier, the use of optical clocks as sensors to extend the measurement accuracy of certain physical quantities to unprecedented levels opens up new possibilities. It also emphasises the criticallity of combining and comparing optical clocks in a network that preserves the extreme precision of these instruments. The distribution of a time and frequency is therefore a crucial element in developing applications and achieving commercial exploitation and clock technology and distribution technology go closely hand in hand and ultimately enables the market that extreme precision timing can address.

GNSS

The development of GNSS for military position, navigation and timing giving time accurate to billionths of a second and position accurate to a few metres and its public availability as a 'free at point of use' service has made it the most convenient and cost effective time reference and it has become the default for many critical applications. Furthermore, the desirability of a sovereign GNSS for strategic use has led to the introduction of Russian, European and Chinese systems as outlined in the table below. Mass market sensors have already emerged that utilise two or three of these GNSS sources to enhance reliability.

Key Performance Parameters

It's worth noting the key performance parameters that interest a range of GNSS users since they are likely to be reflected in requirements for an optical clock time service. Applications often trade off parameters against each other depending on their requirements. For example, in safety-critical applications integrity is prioritised over accuracy, whilst in mass market applications low power consumption and Time To First Fix are prioritised over integrity.

Availability: the percentage of time that a timing solution can be computed in the coverage area.

- System availability: Values typically range from 95 to 99.9%.
- Overall availability: takes account of receiver and environment. Values vary greatly.

Accuracy: is the difference between true and computed solution. This is expressed as the value within which 95% of samples would fall if measured.

Continuity: is the ability of a system to deliver PNT services with required performance levels. It is expressed as the risk of discontinuity and depends on the timeframe. A typical value is around $1x10^{-4}$ over the course of the procedure where the system is in use.

Integrity: expresses the ability of the system to provide warnings to users when it should not be used.

Robustness: relates to spoofing and jamming and how the system can cope with these issues.

Time To First Fix (TTFF): time between activation of a receiver and availability of a solution. It includes power on self-test, acquisition of signals and computation of the solution.

Latency: difference between the reference time of the solution and the time this solution is made available to the end user (i.e. including all delays).

Power consumption at the receiver: Typically tens of mW. This will vary depending on available signals and data. For example, GNSS chips use more power on cold start than when computing a position.

Limitations in the Practical Use of Time Distribution

When it comes to timing applications where users can get a clear view of the sky, a roof mounted antenna and some cabling can provide high precision timing signals at modest cost. As a result, military, government and commercial organisation have become almost entirely reliant on GNSS to deliver a wide range of critical services including power, transport, communications, finance, security and so on. However, the GNSS signal at the ground is extremely weak and receivers are susceptible to interference from multiple reflections, reflected signal leakage from adjacent GNSS atennae and increasingly to intentional jamming or spoofing. Additionally, the satellites are potentially at risk from unexpected solar events or other space hazards. The vulnerability of the GNSS-reliant infrastructure to accidental or malicious catastrophe has been receiving increasing attention since the publication of the RAE report in March 2011[8] and the consequent economic and societal impact was highlighted in the recent London Economics report[9]: *The economic impact to GNSS-reliant present-day UK of a loss of GNSS has been estimated at £5.2bn over a five-day period, comprised of £1.7bn in lost GVA and £3.5bn in lost utility benefits. Applications in road, maritime, and emergency and justice services account for 67% of all impacts*. Further weight was added in the Blackett report[10] of January 2018.
As a result, regulatory pressure on robustness and holdover has increased and is driving market demand for local clocks with extended holdover. Reports of an increased demand for HP5071 clocks are consistent with this short term demand. In the longer term, there is a strong interest in robust alternative methods of time distribution to obviate the risk of service loss.

Market Opportunity on GNSS satellites

The opportunity for high precision clocks on satellites for GNSS arises from the timing references on-board the satellites themselves rather than the ground-based references. Each satellite in a MEO GNSS constellation uses an ensemble of 3 or more clocks for improved stability and redundancy so the opportunity size for the major constellations is about 300 clocks.

There may be as many as 180 satellites in total so the maximum installed base will be in the region of 600 clocks. Of course, the desire for sovereign independence is a very strong driver for national sourcing so an accessible market is more like 100 clocks in total. The clock Average Selling Price (ASP) is likely to be in the region of $1M. Once the constellation is complete, the satellites will be replaced at a rate of about 2 per annum or 6 clocks per annum. In other words, a very small but highly specialised, knowledge intense, research, development and production facility requiring strong government support is likely to be the form that such manufacturing takes.

Network Timing

Alternative means of time distribution is already in place for telecom networks and solutions exist in both TDD and PTP protocols that meet the ITU requirements for synchronisation. Communication spectrum is the most valuable resource in telecom markets and there will be ongoing commercial pressure to improve performance to allow operation closer to the spectrum band edges and to synchronise adjacent networks so that interference is reduced and handover is improved. The emergence of 5G will not change the picture very much except in high population areas where the need to 'densify' the network channels will lead to the introduction of 26 GHz femtocells to cope with bandwidth demands at railway stations, entertainment venues and other areas that are likely to experience heavy loading or high peak demand. However, such cells will not need the very high precision of a next generation commercial frequency standard and the telecomm requirements for high precision will remain much as they are today with a relatively small number of precision clocks in the core and higher strata of the network.

[8] Global Navigation Space Systems: reliance and vulnerabilities, RAE, Mar 2011

[9] The economic impact on the UK of a disruption to GNSS, London Economics, Jun 2017

[10] Satellite-derived Time and Position: A Study of Critical Dependencies, Blackett review, Jan 2018

Optical clock networks

In recent years, research activities[11] have produced optical clocks which can reach absolute accuracies better than 10^{-18}. A physical network of optical timescales, derived from these clocks, could enable dramatic improvements in precision navigation and timing, phased sensor arrays, testing special and general relativity, clock-based geodesy, and searches for dark matter. These possibilities have driven scientific interest and government funding to develop time transfer methods over optical networks to develop the required infrastructure. At present, the continuously-operating time and frequency links between National Metrology Institutes (NMIs) and other precise timing centres depend on two satellite-based methods [TiFoon Ref1]. One employs two-way exchanges of microwave signals between institutes via a geostationary communications satellite, and the other is based on simultaneous reception of signals from Global Navigation Satellite System (GNSS) satellites. However, the best time transfer accuracy that can be achieved using these methods is around 1 nanosecond, and their frequency transfer capability does not support comparisons between optical clocks at the levels of accuracy now being achieved by the clocks themselves. The performance of optical transfer has exceeded standard microwave methods and provides a means of comparing optical clocks and networking them together. The approach requires non–standard bidirectional channels and amplification throughout the optical backbone network which is neither straightforward nor cheap. The operation of these channels is still far from routine, requiring frequent intervention by experienced staff. As an indication of what's possible, the target for novel methods of time transfer over fibre is sub-picosecond accuracy.

The ideal would be to share fibre infrastructure with standard IP traffic and it has demonstrated feasibility. However, the technology challenges are high and the commercial fibre networks will need strong evidence that the addition of Time and Frequency signals does not disrupt their normal data traffic. Even with the use of a commercial network, the cost of access is high and is driven by the increasing demand for data transfer capacity. The rule of thumb for fibre usage charges is 1€/metre/year.

However, when it becomes possible through initiatives like the GEANT CLONETS-DS (design study) then an interconnected network to link national research centres and enable a Europe-wide optical clock network for time and frequency dissemination will create the opportunity for an array of extreme sensitivity sensors for a variety of science and commercial uses.

Global Network and Space Optical Clocks

The situation in Europe benefits from the relatively close proximity of a large number of research centres which makes the optical network relatively cost effective. The situation in the USA is quite different with many thousands of miles separating major centres and the likelihood of implementation of a dedicated national optical clock fibre network is low. Until the point at which Time and Frequency can be distributed over commercial fibre, the US will continue to rely on microwave links and satellite transmission and are likely to push research in free-space optical and microwave transfer techniques.

The relevance of this network aspect for the market for high precision clocks is yet to be fully understood but commercial organisations are making enquiries about the possibility of linking to the scientific network to derive a robust and reliable frequency and time reference. In fact, Orange Polska is already connected to the Polish timing network. It is fairly safe to speculate that the commercial use of optical distribution of time will increase and come to underpin the criticality of optical clocks in NMIs and the viability of the network that connects them. The different geography of the US will lead to different solutions to achieve similar goals. Ultimately, it will be desirable to connect continental infrastructures and it is likely to lead in due course (10-20 years) to a satellite element to enable inter-continental distribution of time. In fact, the use of an optical clock on the ISS will establish the benefits of a space based master clock and demonstrate the means to link it to ground networks.

The impact of optical time distribution on the timing market will therefore not be immediate but it will influence the opportunity size in a 5-10 year timescale by, on the one hand, reducing the need for independent high precision clocks that are occasionally referenced to national standards but also

[11] S Brewer et al., Phys. Rev. Lett., 2019, [https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.033201]

providing a small but ongoing demand for high precision clocks in holdover applications through the network.

Two key areas for development focus

There are two key areas of focus to help drive these opportunities towards commercial exploitation.

The first is the cost of the optical clocks which needs to be significantly reduced compared to the prototype clock. An alternative approach might be to use an optical clock to discipline other clocks and enhance their performance as networked sensors. This emphasises that there is a price/performance point for the optical clock that will facilitate its adoption. Defining that point is complex at this stage but will be a major consideration as the programme matures.

Additionally, the total cost of ownership compared to other solutions needs to be minimised. The clock control system needs to move towards a turnkey approach to reduce the need for skilled intervention as much as possible.

As the technology moves towards product status, considering these issues early will significantly reduce risk and delay and maximise the chance of successful commercialisation.

5 Conclusion

The redefinition of the second based on an optical frequency is in prospect. It will enable significant improvements in time and frequency metrology. The top five or more NMIs will support an enduring interest in optical clocks and in the science and technology that underpins their operation.

It is important to note that there is no competing technology that delivers optical clock performance and that this performance opens up new capabilities that will have a commercial value. Distribution of this new level of capability is crucial and the combination of optical clock and distribution system are combined will determine the shape and size of the market in years to come

Technology development in the next five years and beyond should concentrate on packaging optical clock capability in a way that delivers value and meets customer’s needs. Size, weight and power need to match the hydrogen maser.

We can assume that the question of performance has already been answered as Yes. The next step is cost reduction. The iqClock is in development status and current costs are inevitably much higher than for regular production or even for small batch production. Identifying means and opportunity for cost reduction in the current technology is a key next step. Also very important is the innovation in the science scheme which will take longer to mature but has the potential to be really transformative.

Beyond the progress on clock technology directly, the bigger potential for commercial exploitation is in the use of optical clocks as distributed frequency references and sensors. Work is already in progress to link clocks together over long distances via fibre networks giving the potential to utilise high precision clocks in metrology laboratories as master clocks driving simpler optical clocks distributed across the network. It will be very important to consider optical clock development in the context of a network of distributed clocks since it is in that scenario that they can bring real value to sensing, navigation, time and frequency services, geodesy and so on.

Looking further into the future, the concept of optical clocks in a robust network becomes even more valuable if the master clock ensemble is space-based. Combined with flexible network distribution technologies including free space, this could bring about a transformation in global sensing, positioning and timing capabilities that would underpin a wide variety of economically significant services.

6 Historical Clock Technology Commercialisation

The ability to measure time has been a key requirement of human societies going back to the dawn of civilisation. The deep understanding of atomic physics that developed in the 20th century coupled with the electronics revolution has enabled advances in precision timing to the point that clocks are now amongst the most accurate instruments in the world and will soon find application in fundamental physics experiments on gravity, dark matter and so on. This revolution in clock precision began with Isidor Rabi's work on atomic beam magnetic resonance in the 1930s and resulted in the emergence of an atomic clock based on ammonia in the US in 1949. NPL in the UK claimed the first caesium beam clock in 1955. Further refinement followed and in 1967, the 13th General Conference on Weights and Measures defined the second on the basis of oscillations in the caesium atom. For the first time, the world's timekeeping system no longer had an astronomical basis. Caesium continues to be the atomic frequency standard to the present day with a global ensemble of caesium fountain clocks, hydrogen masers and caesium beam tube clocks in national measurement institutes forming the basis of the international time standard administered by the BIPM.

Technology Evolution

The state of the art in caesium microwave atomic clock technology has progressed considerably in national measurement institutes over the last 60 years. Present day Caesium microwave fountain clocks using laser-cooled atoms and a cryogenic local oscillator can achieve stabilities of $3x10^{-14}\ \tau^{-1/2}$ and thus reach limiting uncertainties of ~ $2x10^{-16}$ in a day. Such clocks are large (in the region of 2000 litres) and immobile and require a high degree of support for the intended use. They have not been commercialised although it is worth noting Muquans introduction of a cooled rubidium fountain clock as a commercial offering. It's too early to say if it is achieving commercial success. By contrast, the small, rack-mounted thermal caesium beam clock (HP5071A) demonstrates stability of ~ 10^{-12} at 100 second averaging times, reaches a stability floor of ~ 10^{-14} after 5 days and achieves uncertainties of $\pm 5x10^{-13}$.

That the science from the academic research base transferred rapidly into national measurement institutes with a focus on maintaining and refining a traceable standard is hardly surprising. However, the emergence of a commercial atomic clock was close behind and the caesium beam tube clock remains the dominant commercially available frequency standard used today (i.e. in contrast to the lab instrument caesium fountain clocks) with a market share estimated at 80%. In summary, the caesium beam tube technology is well understood and has over thirty years of excellent heritage. It has established modest but steady sales in the region of 500 per annum at a $70k price point. The technology is at its performance limit and offers no significant opportunities for reduced size and cost. In order to move commercial time standards forward to new demands and new challenges, an alternative fundamental approach is needed. That approach could be the optical clock.

There is currently no alternative technology that can match its performance. The key question for optical clocks is will they remain as a large, complex, fragile instruments in NMIs or will the iqClock consortium help lead them to successful commercialisation?

7 Exploitation Plan

The Unique Selling Point

Optical clocks are being established as the primary frequency reference for an International Time Scale with about two orders of magnitude improvement in accuracy. There is no commercially available clock at optical clock performance levels. The extreme accuracy and stability of optical clocks enables new measurement capability which can become the unique selling point for this technology.

The Optical Clock as a product

The product mindset should be adopted even at this stage so that a customer perspective, in so far as it is available or can be inferred, begins to guide the direction of development. Probably the best approach is to take a lead from existing clocks that do have customer requirements and use cases to address. Their product data sheets will give a useful indication of important performance parameters to consider as long as specifics related to optical clock operation are kept in mind. The Appendices 4, 5 and 6 include data sheets for the i3000 Hydrogen Maser from T4 Science, the Muclock from Muquans and provisional data for an optical clock from M Squared Lasers.

Optical Clock technology

This is already built into the iqClock programme but it is worth emphasising that succesful technology innovation arising inside and outside the programme needs to be worked through to understand both the positive impact and the risk. A top level product description and a block diagram should be created and regularly reviewed.

Supply Chain and Cost

A crucial consideration for novel product development is the availability and sustainability of the supply chain for critical technologies.

Obsolescence of electronic components needs to be borne in mind by system designers but the important issue in this early stage development is to understand the status of the technically innovative elements. There is a danger that performance, cost and availability assumptions are based on very small samples that may not be repeatable or that may suffer from poor yield. Other considerations include special selection of components to meet a demanding specification, reliance on unspecified parameters that are not subject to test nor guaranteed by the manufacturer, evolution of processes to new standards, time consuming tuning of components requiring specialised skills and so on.

It is also necessary to understand the commercial landscape for the component or sub-system in question to see if there are other markets for the product. Other markets are helpful in increasing volume and thereby reducing price but they may also become dominant and influence the specification or availability. The product development planning process needs to take account of these issues and monitor the changing situation to inform design decisions or mitigations to be addressed.

Reviewing these various inputs as related to the top level block diagram should be conducted on a regular basis.

Roadmap

The programme will benefit from a technology and cost roadmap to help inform plans to progress the optical clock to commercial exploitation.

Product Innovation

A formal process for the regular identification and progressing of IP generation and protection should be foundational to the exploitation plan for the iqClock. Not only does strong IP provide protection against competition and encourages investment partners it also provides a stronger position to negotiate cross licencing in the event of the need to use external IP.

The use of iqClock as a transportable time and frequency reference increases its options for exploitation and, once again, useability will be very important in maximising this benefit.

Technology Landscape Monitoring

The consortium already covers this through published papers, conferences and exhibitions. The process should be formalised as part of a regular review and needs to cover the Optical Clock; Clock Comparison Methodologies: Microwave, Fibre, Astronomical, Transportable; Time Distribution via Microwave TWTTS, Dedicated Fibre, Commercial Fibre, Free Space Optical and Microwave; and Optical Clock Networks.

Customer Engagement

It is too early to say that there are customers for optical clocks but it is possible to identify prospective users. NMIs are interested parties and their opinion on opportunities to commercialise the technology would be useful especially if they see themselves as providers to large projects such as space programmes. iqClock partners are useful sources of information on potential customer requirements from their existing contacts. The space agencies and ESA in particular are already well advanced on defining requirements for optical clocks and will be a source of useful information.

For all of the opportunities, the user requirements and use cases should be explored to understand how the characteristics of the optical clock operation meet the user needs. For example, is operation continuous or intermittent and how does this impact the availability of the frequency reference or time signal. Continuity of operation is baseline in commercial frequency standards. Reliability will also become very important. An optical clock product will need to meet or exceed current products which warranteed for several years and expected to operate for 5-10 years. Robustness is important, especially for transportable clocks. A detailed understanding of specialised facility requirements will be an important factor influencing the willingness of the customer to adopt an optical clock solution.

Competition Monitoring

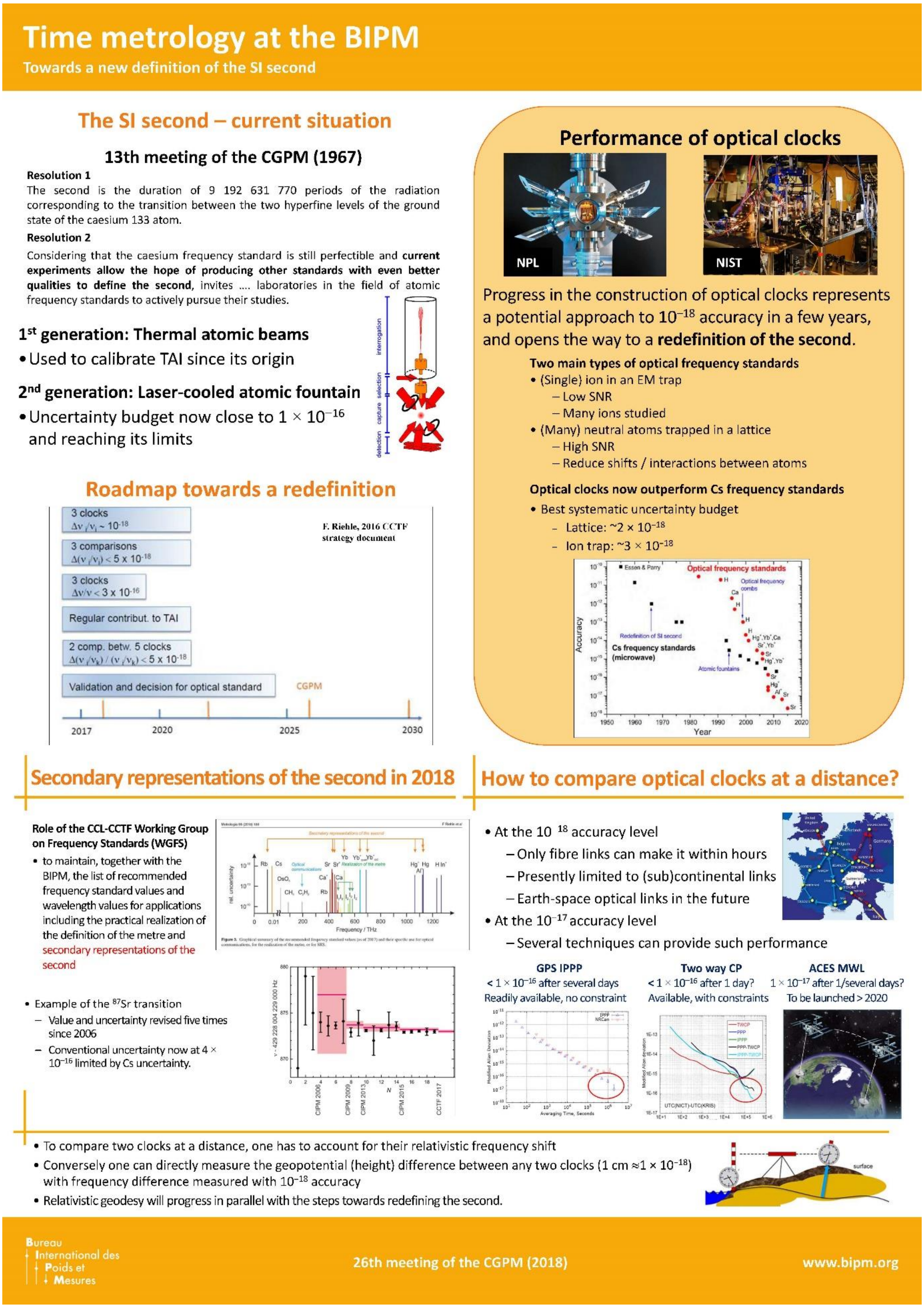
The programme should actively monitor competitive technologies both in optical clock technology providers and in adjacent technologies that could offer immediate benefit to users and may therefore become the embedded solution.

Another competitive threat will come from ongoing developments of microwave clocks. The Table below gives a list of possible contenders drawn from recent publications and conference presentations. It captures the broad picture and would benefit from a more detailed and systematic review. Note that some of these projects have limited information in the public domain but keeping their progress under review is important.

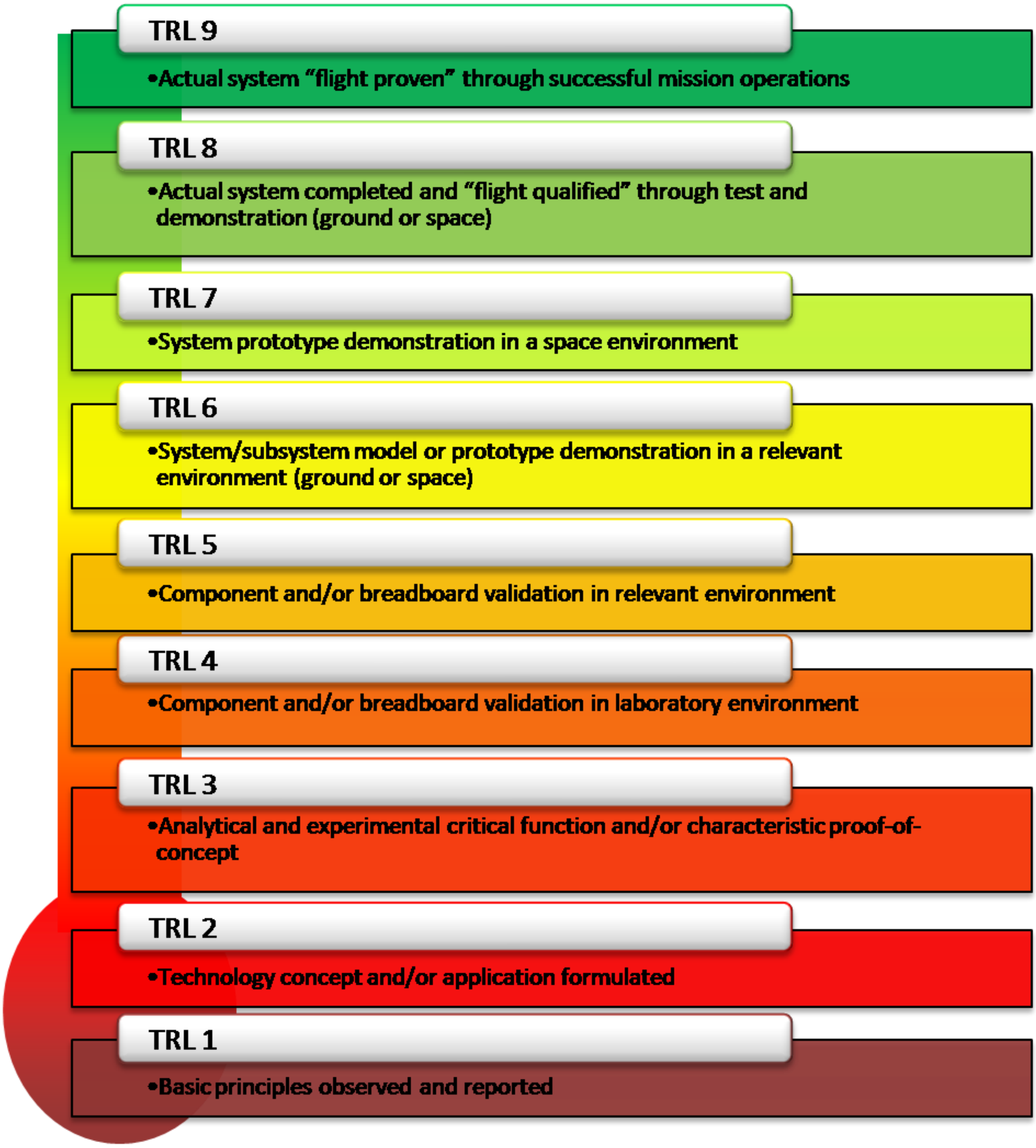
Next Generation Clock Technologies		
Technology	Organisation	Researcher
Ytterbium ion buffer gas cooled single (blue) laser	Sandia/JPL; Microsemi	
Cold Atom Caesium (852nm) 2D MOT single laser	NIST	John Elgin
Two photon Rubidium compact optical	NIST	Zachary Warren
CPT POP	FEI licence?	
Blade Trap Ion Clock – Honeywell	Honeywell	
Mercury Ion lamp driven DSAC	JPL	
Pulsed Rubidium	INRIM	Michel Izio

Table 6

Appendix 1 Redefinition of the second



Appendix 2 Technology Readiness Levels



Appendix 3 Jet Propulsion Lab's DSAC

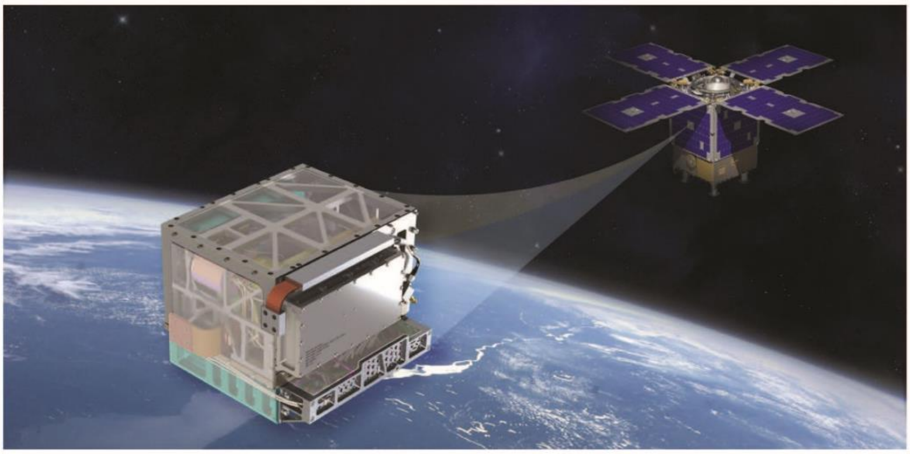
The DSAC is shown in the fact sheet below. It was launched in June 2019 and has been operating successfully and beyond expectation. The details are given in a conference paper from August 2019.[12]

National Aeronautics and Space Administration

NASAfacts

Deep Space Atomic Clock

A New Frontier in Ultra-Precise Space Navigation



JPL's Deep Space Atomic Clock will fly aboard General Atomics' Orbital Test Bed satellite as a hosted payload. It will launch as part of the Department of Defense's Space Technology Program 2 (on a SpaceX Falcon Heavy rocket).

Know Your Place in Space Via Time

Since nautical ships first carried spring-wound chronometers, accurate timekeeping has been an essential part of navigation. Exact measures of time are especially critical for spacecraft, which journey far into the solar system. The Deep Space Atomic Clock, designed and built at NASA's Jet Propulsion Laboratory, represents an enormous advance towards improving deep-space navigation.

It's Atomic!

Since the 1950s, the gold standards for timekeeping have been ground-based atomic clocks. They are also the cornerstone of deep-space navigation for most space missions because of their fundamental role in navigation measurements. These clocks measure very stable and precise frequencies of light emitted by specific atoms, using them to regulate the time kept by more traditional mechanical (quartz crystal) clocks. This results in a clock system that can be ultrastable over decades. The new Deep Space Atomic Clock timepiece will use mercury ions to provide a measure of time that is stable to better than one microsecond per decade.

Making It Portable

Ground-based atomic clocks are phenomenally accurate, but their designs are too bulky, power-hungry and sensitive to environmental variations to be practical for spaceflight. They need to be miniaturized and toughened in order to venture off our planet. Deep Space Atomic Clock greatly enhances the performance of current space clock designs, and can virtually eliminate spacecraft clock errors. Deep Space Atomic Clock will enable a shift to a more efficient, flexible and scalable clock architecture that will benefit future navigation and radio science.

The new clock design will enable safer and more precise navigation to Mars and beyond.

---

[12] Deep Space Atomic Clock Mission Overview, August 2019, AAS/AIAA Astrodynamics Specialist Conference

The Deep Space Atomic Clock Demonstration Unit (shown mounted on a plate for easy transportation).

Deep Space Atomic Clock mercury ion trap housing with electric field trapping rods seen in the cutouts. This is where Deep Space Atomic Clock interrogates and measures the mercury ion resonance that is used to discipline a quartz crystal clock.

Launch in 2019

The Deep Space Atomic Clock is a demonstration unit and payload that is being hosted on the Orbital Test Bed spacecraft provided by General Atomics Electromagnetic Systems of Englewood, Colorado. It will launch in June 2019 to Earth orbit aboard the SpaceX Falcon Heavy rocket. NASA's Deep Space Atomic Clock will operate for at least a year to demonstrate the clock's functionality and utility for space navigation.

Key Facts

- Promises to be the most precise atomic clock ever flown in space — stability of better than one microsecond in a decade.
- Uses mercury ions (fewer than the amount found in two cans of tuna fish) to create a clock that is orders of magnitude more stable, while being less sensitive to magnetic fields and temperature changes than its predecessors.
- Will provide vastly improved navigation for traveling to and landing on other worlds.
- Accurate enough to measure the effects of gravity and relativity of other worlds — can measure the effects of Jupiter's massive gravitational pull on its moons in much less time than required by current approaches.
- Enabling device for onboard radio navigation for future exploration of our solar system by astronauts.

Mission Specifics

MISSION NAME:	Deep Space Atomic Clock Technology Demonstration Mission
LAUNCH DATE:	June 2019
MISSION DURATION:	One year
MASS OF INSTRUMENT:	16 kg/35 lbs
SIZE OF INSTRUMENT:	29 cm x 27 cm x 23 cm / 11 in x 10 in x 9 in

The Deep Space Atomic Clock project is sponsored by the NASA Space Technology Mission Directorate and managed by NASA's Jet Propulsion Laboratory in Pasadena, California.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

For more information about the Deep Space Atomic Clock, visit:
www.nasa.gov/mission_pages/tdm/clock/index.html

JPL 400-1636 Rev. 1 6/19

NASA Facts

Appendix 4 T4 Science Active Hydrogen Maser Datasheet

T4 Science
iPRECISION MASER SOLUTIONS™

38 YEARS OF LEADERSHIP IN MASER CLOCK TECHNOLOGY

iMaser 3000™

SMART ACTIVE HYDROGEN MASER CLOCK

State-of-The-Art Performance & Features

Swiss Quality & Technology

- Ceramic Cavity technology for lowest thermal sensitivity (<$8\cdot10^{-16}$/°C)
- Sensitivity in temperature change technology for higher stability performance
- Durable Teflon & Bulb Coating technology for over 20 years lifetime
- Remote Distance control & monitoring for higher reliability & maintenance-free operation

Ultra High Frequency Stability

- Allan deviation (1Hz bandwidth):

1 s	**$6\cdot10^{-14}$**	*(UST option 2020)*
1'000 s	$2\cdot10^{-15}$	
10'000 s	$1.2\cdot10^{-15}$	
Long term	$2\cdot10^{-16}$	

Low Phase Noise (5MHz)

- **-132** dBc/Hz @ 1Hz *(UST option 2020)*

High Electromagnetic Compliance

- CE compliance per ISO 17025,
- EN 55022 Class B, EN 55024 & EN 61326-1

Advanced Features

- Auto cavity SmarTuning™ capability
- Distance control, monitoring & self-diagnostics

Warranty

- 2 years, extendable to 5 or 7 years

Lifetime

- >20 years

Key Applications

- VLBI
- SLR
- Ground space stations
- Navigation
- Frequency reference source
- Time keeping & precision time scales
- GNSS satellite monitoring & geodesy

iMaser™ 3000 Specifications

FREQUENCY STABILITY

Allan Deviation				
1Hz bandwidth	Standard*	Option LN*	Option ST	Option UST*
1 s	$1.3\cdot10^{-13}$	$1\cdot10^{-13}$	$8\cdot10^{-14}$	$6\cdot10^{-14}$
10 s	$2\cdot10^{-14}$	$2\cdot10^{-14}$	$1.8\cdot10^{-14}$	$1.5\cdot10^{-14}$
100 s	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$4\cdot10^{-15}$	$4\cdot10^{-15}$
1 ks	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$1.5\cdot10^{-15}$
10 ks	$2\cdot10^{-15}$	$1.5\cdot10^{-15}$	$1.2\cdot10^{-15}$	$1\cdot10^{-15}$

PHASE NOISE

Output	5 MHz		10 MHz		100 MHz	
Hz	Standard [dBc/Hz]	Option LN/ST/UST	Standard [dBc/Hz]	Option LN/ST/UST	Standard [dBc/Hz]	Option LN/ST/UST
1	-118	-130/-131/-132	-112	-124	-92	-102
10	-135	-142/-142/-144	-129	-136	-105	-113
100	-145	-152/-152/-153	-139	-147	-115	-125
1k	-152	-156/-156/-157	-146	-151	-125	-148
10k	-155	-156/-158/-159	-149	-153	-145	-154
100k	-155	-156/-158/-160	-149	-153	-145	-155

ENVIRONMENTAL

	Standard	Option	[unit]	Option code
Temperature sensitivity [/°C]	$<5\cdot10^{-15}$	$<8\cdot10^{-16}$	/°C	HCB
Phase sensitivity to temperature between sine outputs	<10	<2	ps/°C	HCB
Magnetic sensitivity	$<5\cdot10^{-14}$	$<1\cdot10^{-14}$	/G	MS
Frequency sensitivity to vibration	$<1\cdot10^{-9}$	$<5\cdot10^{-10}$	/g	LN/ST/UST
Power source sensitivity.	$<1\cdot10^{-15}$	$<1\cdot10^{-15}$	/V	

OUTPUTS

	Standard	Option	Option	Option code
5 MHz	2			
10 MHz	0	2	4	O2/O4
100 MHz	2			
1 PPS	1	2	4	PPS2/PPS4

5 / 10 / 100 MHz			[unit]	
Level (50 Ω)	+13	±1	dBm	
Isolation	>	85	dB	
Spectral purity	<	-45	dBc	2nd harm.
Spurious	<	-70	dBc	

1 PPS TIMING	Output	Sync Input	[unit]	Rem
Amplitude	>2.3	>2.3	V	50 Ω/TTL
Pulse width	100 µs	>100	ns	
Rise/fall time	<2 ns	<1	µs	
Jitter	<40 ps	<1	µs	Between 2nd output
User settable		40	ns/step	

POWER

	Nominal		[unit]	Rem
AC	110-220	85-135 176-264	V	50-60Hz
DC	24	22-30	V	3 A typical
Power	100	30-220	W	Standby-Operation Warm up
Battery	24V	0.25	hours	BATi
Battery pack	24V	15	hours	BAT1
2nd pack	24V	32	hours	BAT2

ADVANCED FEATURES

- Remote Ethernet monitoring: LAN HTTP, FTP, open source thru Windows, Linux or Mac (RE)
- Remote Distance Ethernet controls & distance maintenance (DC)
- Auto cavity Tuning™, Long term drift: $2\cdot10^{-16}$/day** (CT)

*Achieved with the advanced LowSensitivity™ in temperature change technology, providing an ultra-low temperature sensitivity of up to $-8\cdot10^{-16}$ /°C
** Typically achieved within ±0.1 °C/day ambient temperature or with ±0.5 °C/day the HCB ultra-low temperature sensitivity and CT SmarTuning options after a long period of continuous, undisturbed operation.

CONTROL

- Frequency resolution $6.4\cdot10^{-15}$ $2\cdot10^{-17}$ (CT)
- Frequency tuning range $\pm 3\cdot10^{-8}$

ELECTROMAGNETIC COMPLIANCE

- CE compliance per ISO 17025,
- EN 55022 Class B, EN 55024 & EN 61326-1

MECHANICAL

- Size (WxDxH) 60x80x91 cm
  23.7x31.5x35.9"
- Weight 100 kg / 220 lb
  40 kg / 88 lb per battery pack

WARRANTY

- 2 years on site
- Extendable to 5 or 7 years (W5 / W7)

LIFETIME

- >20 years

ORDERING information

- Instructions iMaser3000 / xx/ xx / xx

Options

(xx – option codes)

LN/ST/UST	Low Noise OCXO/(Ultra) best Short Term
HCB	Active Heater-Cooler-Box (climatic chamber)
MS	Extra Magnetic shield
O2/O4	2/4 10MHz outputs
PPS2/PPS4	2/4 x1PPS outputs
BATx	Battery pack (IATA Approved)
CT	Cavity tuning
RE	Remote Ethernet control
DC	Remote Distance control &maintenance
Wx	Extension of warranty

Examples: iMaser3000/BAT2/O4/ST/RE/W5

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Data is subject to change without prior notice. V20/06/23

Appendix 5 Muquans Muclock Datasheet

μQUANS
PRECISION QUANTUM SENSORS

MuClock

A high-performance frequency standard based on cold atoms

MuClock is the first commercially available atomic clock based on laser-cooled atoms. This unique solution is the result of more than 15 years of research conducted by our academic partners: LP2N and LNE-SYRTE, the French National Metrological Institute for time and frequency and one of the major international experts in the field of frequency standards.

MuClock features within a single device unmatched performances in terms of short and long-term frequency stability, as well as accuracy and predictability. It therefore offers a very interesting alternative to usual H-Maser / Cs clocks ensembles for the generation of highly stable time scales, among others. Originally inspired by the atomic fountains developed at LNE-SYRTE, our product is based on several technological innovations which allow to propose a compact and robust, turnkey and fully automated system. MuClock provides a new solution that brings the performances of cold atom frequency metrology, in a stand-alone, easy-to-use equipment.

The approach developed by Muquans relies on the laser manipulation of cold atoms. The principle of operation is based on the microwave interrogation of a large atomic cloud, cooled down with laser beams to a temperature of a few μK. This unique atomic medium shows an exceptional stability over time, independent of the external conditions. This technique offers the possibility to perform over months spectroscopy measurements with an exceptionally high signal-to-noise ratio and a remarkable stability.

General view of Muquans's cold atom frequency standard. The lower racks contain all the electronics, control units, and laser systems. The upper part visible inside the frame is a magnetic shield containing the atomic resonator.

Muquans - Institut d'Optique d'Aquitaine, Rue François Mitterrand, 33400 Talence - FRANCE - + 33 (0)5 57 01 73 50 - www.muquans.com

Key Technologies

▸ Isotropic Laser Cooling

The general idea behind the system design is to prepare the cold atom cloud inside the microwave cavity and interrogate the atoms at the same place. This is achieved with isotropic laser cooling (ILC). ILC utilizes the reflections on the inner surface of the microwave cavity to produce a well-controlled laser field for efficient cooling of the atoms. The preparation of the atomic cloud is quickly followed by its microwave interrogation. This measurement sequence is repeated at a 10-Hz repetition rate. With this approach, we therefore obtain performances close to atomic fountains with a significant weight and volume reduction and improvement in compactness, ease of use, and robustness to the environment.

▸ Telecom-based, entirely fibered laser technologies

The laser system developed by Muquans is based on the utilization of an amplified seed laser operating at 1560 nm, which is then frequency-doubled to generate the required wavelength of 780 nm. This approach therefore gives access to a wide variety of high performance fibered optical components, originally developed for high-bit-rate optical communications systems. Thanks to the technological effort conducted over the last 20 years by the telecom industry, these components present unique features:

- All-fibered components: no optical alignment required
- Extreme optical and electrical performances
- Compliance with Telcordia qualification procedures (extended temperature range)
- High reliability (lifetime > 50 000 h)

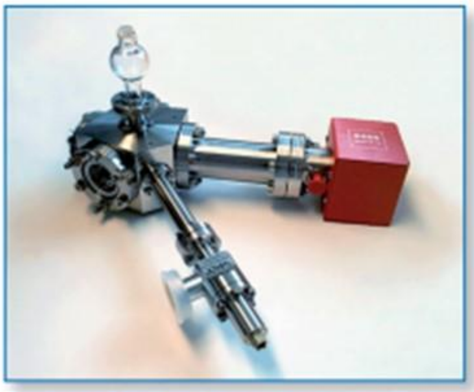
Specifications

▸ Frequency stability

1 s	≤ 3.0 10^{-13}
10 s	≤ 9.5 10^{-14}
100 s	≤ 3.0 10^{-14}
1000 s	≤ 9.5 10^{-15}
10000 s	≤ 3.0 10^{-15}
1 day	≤ 2.0 10^{-15}
Flicker floor	≤ 2.0 10^{-15} (@ 10 days)

▸ Phase noise

Offset (Hz)	5MHz Output
1	-121 dBc
10	-151 dBc
100	-163 dBc
1,000	-168 dBc
10,000	-176 dBc
100,000	-178 dBc



The heart of MuClock is a vacuum chamber. The low pressure Rubidium vapor inside is laser cooled in the spherical glass cell, and interrogated thanks to a spherical micro-wave cavity surrounding it (not on the picture).

▸ Accuracy

High predictability: low noise floor and accuracy of a few 10^{-15}

▸ Available outputs

Output frequencies: 5, 10 and 100 MHz
Synchronization options: PPS input & output

▸ Power

Operating power	200 W
Peak power	250 W

▸ Physical characteristics

Dimensions

Height	155 cm
Width	55 cm
Depth	80 cm
Weight	135 kg

References

- Esnault et al, Advances in Space Research **47**, 854-858 (2011)
- Guéna et al, Contributing to TAI with a secondary representation of the SI second. Metrologia 2014, **51**, 108-120
- BIPM, Recommended values of standard frequencies for secondary representations of the definition of the second, CIPM (2015) www.bipm.org/utils/common/pdf/mep/87Rb_6.8GHz_2015.pdf

μQUANS

Contact

Should you have any inquiry regarding our products or our technologies, please feel free to contact us.

sales@muquans.com
www.muquans.com

Appendix 6 M Squared Optical Clock Outline Specification

Strontium Optical Lattice Clock

Our strontium lattice clock project aims to create the world's first commercially available fully integrated optical frequency atomic clock. The clock will be compact, transportable, easy to use and based on optical lattice technology enabled by the SolsTiS. The strontium lattice clock will achieve frequency uncertainties below 10^{-17} , a level unprecedented on the global market.

APPLICATIONS

- Remote Frequency Comparisons
- Time and Frequency Dissemination
- High Frequency Financial Trading
- Power Grid Management
- Global Navigation Satellite Systems (GNSS)
- Satellite-Free Navigation
- Relativistic Geodesy
- Time-Variation of Fundamental Constants
- Tests of General Relativity
- Gravitational Wave Detection

FEATURES

- Target frequency uncertainty < 10^{-17} level – more than 4 orders of magnitude better than the world's best commercial microwave clocks.
- Blue MOT atom number > 10^6
- A compact permanent magnet Zeeman slower.
- Designed to easily switch between cooling and trapping ^{88}Sr and ^{87}Sr.
- Sub-Hz linewidths via optical reference cavity lock.
- Fully customisable experiment timing and sequence control using the FPGA-based Ice Bloc DCS.

SPECIFICATIONS

BLUE MOT SUBSYSTEMS	
ATOMIC SPECIES	Neutral ^{88}Sr or ^{87}Sr
ZEEMAN SLOWER ATOMIC BEAM LONGITUDINAL VELOCITIES	Final velocity of 50 m/s for initial longitudinal velocities 60 m/s to 240 m/s
MOT BEAM CONFIGURATION	Single beam
OUTPUT POWER 461 nm (BLUE MOT)	1.5 W
LINEWIDTH 461 nm	sub-MHz
OUTPUT POWER 679 nm (REPUMPER)	25 mW
LINEWIDTH 679 nm	sub-MHz
OUTPUT POWER 707 nm (REPUMPER)	25 mW
LINEWIDTH 707 nm	sub-MHz
ADDITIONAL SUBSYSTEMS	
OUTPUT POWER 689 nm (RED MOT)	25 mW
LINEWIDTH 689 nm	sub-kHz
OUTPUT POWER 813 nm (LATTICE LASER)	5 W
LINEWIDTH 813 nm	sub-kHz
ATOM NUMBER IN OPTICAL LATTICE	$> 10^4$
OUTPUT POWER 698 nm (CLOCK LASER)	25 mW
LINEWIDTH 698 nm	sub-Hz
CLOCK TYPE	Neutral ^{87}Sr optical lattice clock
TARGET FREQUENCY UNCERTAINTY	Below 10^{-17}