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Requirements and Definitions

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Abstract
This document summarizes the requirements for a time and frequency reference system and based on these requirements defines the research services to satisfy the identified needs of the science community.

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1 Executive Summary/Introduction: Requirements of the Scientific Community

1.1 What do stakeholders need?

In the framework of a design study of clock network services (CLONETS-DS) funded by the EU Commission via Horizon INFRADEV-01-2019-2020 from 2020 to 2022, feedback in the form of questionnaires and interviews was collected from 68 organizations representing 13 countries throughout Europe and expertise in the following different fields of research: fundamental physics, metrology (e.g. optical clocks), geodesy, very long baseline interferometry (VLBI), telecommunication, and navigation. The questionnaire, shown in its complete form in Appendix 1, covers a range of topics such as:

1. Which future service or research could be addressed, improved, or eased with better (e.g. better than 1E-16, 1E-18, ...) T/F reference?
2. Which timescales are important (e.g. seconds, days, ...)?
3. Is synchronization with peers required/desired?

The stakeholders were supported in filling out the questionnaire by meeting individually with CLONETS-DS members, who could discuss the stakeholder's future services and research needs in detail. As further support the stakeholders were given a tutorial, on the technical terms of time and frequency and background information on the CLONETS-DS project, in the form of video presentations that could be downloaded from a password-protected site.

In addition to the feedback gained from the questionnaires and interviews, selected stakeholders representing the diverse fields of research were invited to a user workshop from September 13-15th, 2022 to give more detailed input on the design study. This collective feedback from the European stakeholders guided the requirements of the services that CLONETS will offer, as described in Section 3. Furthermore, the stakeholder workshop provided valuable detailed input concerning the need and impact of CLONETS on their fields of research and potential applications. In an iterative process after the workshop, this feedback collected during the workshop was used to critically assess the science areas and create a consolidated list of 5 Science Cases and 16 associated applications with the highest stakeholder need and impact.

Here is the consolidated list of Science Cases and their associated applications:

Science Case 1: Fundamental Science
- Improvement of optical clocks
- Precision spectroscopy to search for beyond standard model (BSM) physics
- Re-definition of the SI unit second

Science Case 2: Quantum Technologies
- Improvement of real-world QKD
- Development of new protocols
- Entanglement distribution beyond QKD

Science Case 3: Earth Observation / Geodesy
- Height system unification
- Satellite gravity mission validation
- Geodetic network consistency

Science Case 4: Astronomy
- Radio interferometry and VLBI in astronomy
- Laser ranging
- Pulsar timing

Science Case 5: Telecommunication and Networks / Position, Navigation, Synchronization, and Timing
- Optical timescales
- Position, navigation & timing, PNT
- Resilience for GNSS
- Supervision of telecommunication networks and synchronization (5G or 6G)

CLONETS can enable scientific advancements for these science cases, not otherwise possible, because, as confirmed by the stakeholders they require:

(1) the comparison of time and frequency signals from multiple sources via a network,

(2) and/or time and frequency signals that exceed the performance that can be realized by single research institutions, despite major efforts and investments into installations of commercial time and frequency products.

We highlight here the high-impact scientific advances that can be achieved in Europe, and are not otherwise possible, by realizing a pan-European optical time and frequency distribution via fiber network (OTFDvFN), referred to throughout this document as CLONETS:

Science Case 1: Fundamental Science

CLONETS can provide absolute frequency references with accuracies at the 10^{-17} level and lower with traceability to the SI second and can therefore be used to perform precision frequency spectroscopy of atomic transitions including hydrogen, anti-hydrogen, exotic atoms and molecules.

Science Case 2: Quantum Technologies

CLONETS can provide synergies with quantum information technologies, where the distribution of quantum entanglement via optical fibers plays a central role. Highly phase-coherent optical references (>> 1000 km of coherence length) and low-jitter (<<100 ps), high-accuracy (10 ps) time references offer the possibility to extend quantum communication link distances, to improve the performance of e.g. existing phase-encoded key-distribution protocols and to support the scalability of quantum communication networks. Open research threads such as time-based authentication protocols, blind computing and more can take advantage of superior CLONETS infrastructure performances, too.

Science Case 3: Earth Observation / Geodesy

CLONETS can provide the infrastructure for measuring gravitational potential differences between clocks located at as needed locations and can therefore be used to measure height differences throughout Europe and establish a unification of Europe's height system und ultimately satellite gravity mission validation and geodetic network consistency.

Science Case 4: Astronomy

CLONETS will benefit areas of astronomy that exploit observations from multiple sites and/or using multiple techniques. A prime example is VLBI for astrometry, where it will allow improved data analysis with a potential for new discoveries and possible improvements to the celestial reference frame. VLBI has stringent requirements for both short-term and long-term Pulsar timing is another well-established area expected to benefit, while there is a potential for applications to other fast-growing topics such as multi-messenger astronomy.

Science Case 5: Telecommunication and Networks / Position, Navigation, and Timing

CLONETS will benefit future routine, reliable and secure dissemination of time and will be a critical infrastructure for developing applications that rely on time transfer. This is because, for example, satellite-based navigation systems can only exploit optical clocks based at ground-stations if the technological capability exists for comparing the optical clocks two orders of magnitude better than their ideal operating levels.

In the next two charts, the time and frequency accuracy/stability requirements of the associated applications of these science cases are plotted. The background shading highlights the border of what is achievable using commercially available technologies and what is achievable only with optical time and frequency distribution via fiber networks (OTFDvFN) in terms of stability and accuracy. Some Science Case applications require only frequency signals and not timing signals or vice versa and therefore not all applications have data points shown in both plots. The stabilities and accuracies shown are the ultimate ones that need to be realized and don't relate to a specific timescale (*e.g.*, stability in 1 s).

As shown in these two charts, the Science Case applications require predominantly time and frequency accuracy/stability at levels not provided by commercial products. In the next section, section 2, the stakeholder requirements in terms of benefit, need, and impact are detailed per Science Case. In order to put the needs and impact of the proposed CLONETS on the above Science Cases better into context with current available technologies, we clarify first how to characterize frequency standards.

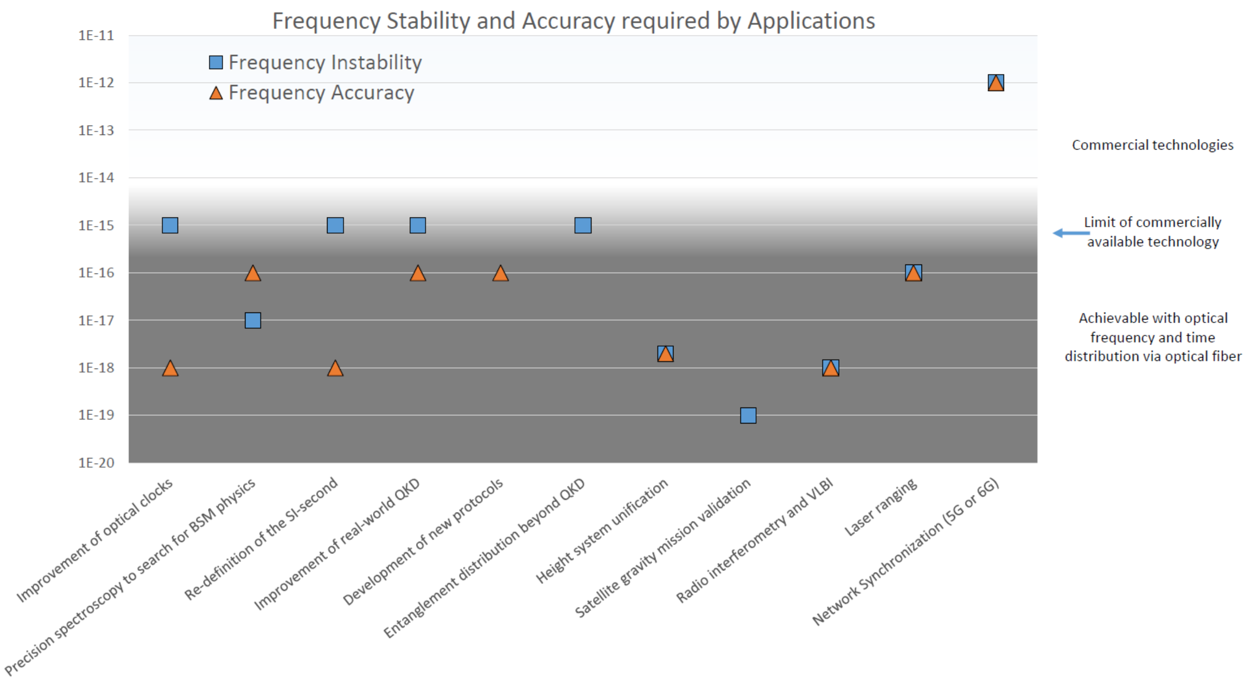

Figure 1: Frequency stability and accuracy requirements of the applications discussed here. The grey shaded area shows that most of these cannot be reached with currently available commercial technologies.

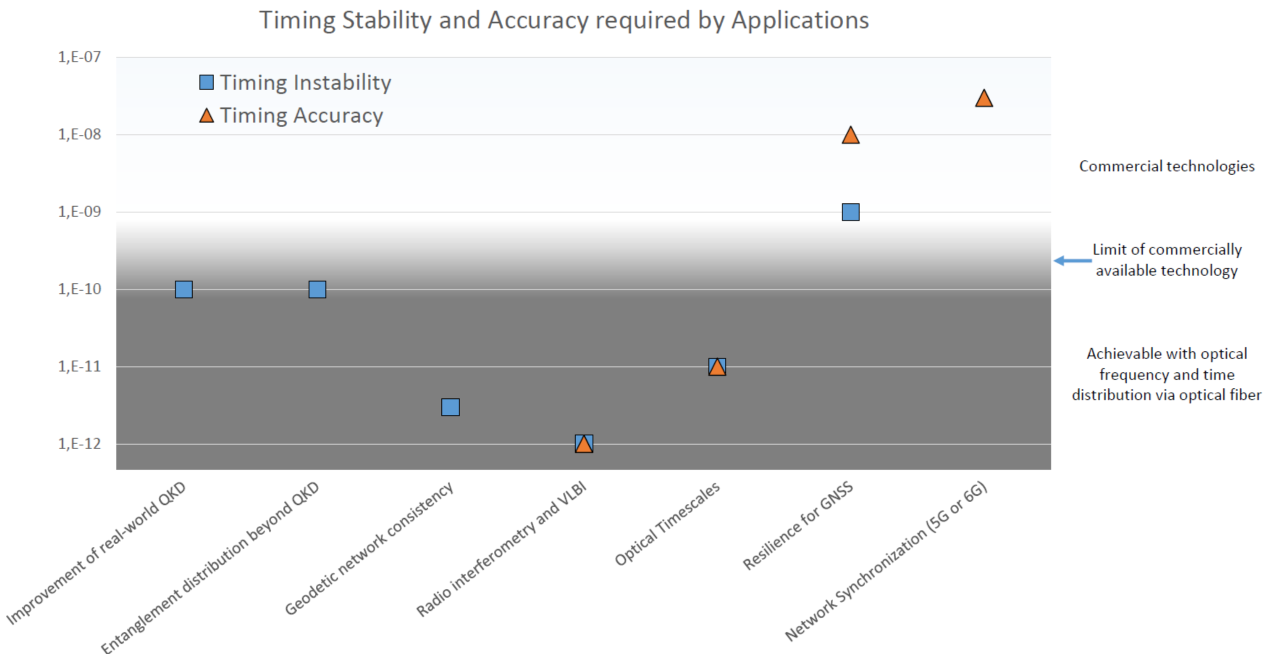

Figure 2: Timing stability and accuracy requirements of the applications discussed here. The grey shaded area shows that most of these cannot be reached with currently available commercial technologies.

1.2 Technical Background of Frequency and Timing Requirements

Explain the difference between stability and accuracy and the relevance to different applications.
It is necessary to understand the characterization parameters of frequency standards, in order to appropriately assess the need and impact of CLONETS for advancing European science. Namely, we must make clear what is meant by the terms "stability", "accuracy" and "precision", which are the terms used in describing a frequency standard's or an oscillator's quality. Furthermore, we must make clear what improved performance CLONETS offers compared to current commercial solutions.

Here are shown 4 bullseye patterns distinguishing stability and accuracy:

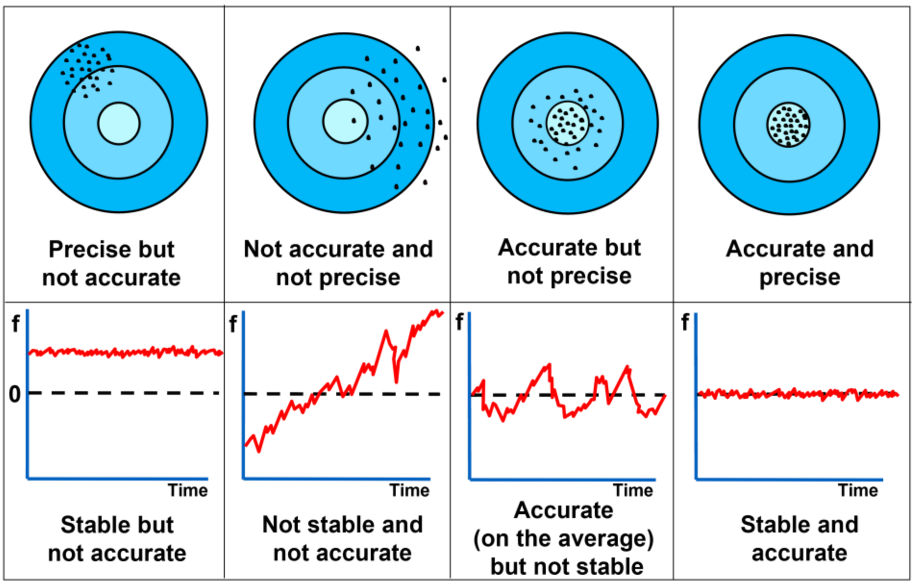

Figure 3: Diagram showing the difference between precision and accuracy.

Stability refers to the reproducibility of a measurement or the average of a series of measurements. If the number of separate values obtained is sufficiently large and their distribution is found to satisfy certain criteria, well-known statistical methods can be applied in order to calculate the contribution of the observed scatter to the final error; one can then also express the precision in some conventional form, such as standard deviation, in order to indicate the reproducibility of that particular measurement. Stability is quantified by what is known as the statistical uncertainty, σ, of a frequency standard or clock.

Accuracy: refers to the relation of the observed result to some "absolute" correct value.
Usually in the measurement of physical magnitudes, the correct value is unknown, so the accuracy is often judged by guessing the likely limits of systematic errors (usually optimistically) or by the "precision" of the measurements based on consideration of the values obtained from laboratory to laboratory and from time to time. Accuracy is quantified by what is known as the systematic uncertainty, u, of a frequency standard or clock.

It's important to note that accuracy differs from stability since it is not random and can be corrected for. In typical applications a clock's accuracy will be regularly corrected, i.e. calibrated, by compensating for these systematic errors and/or steering the clock using a reference time scale.

Reference: Characterization Parameters of Frequency Standards	
Term	**Definition**
Accuracy	Closeness of agreement between a measured quantity value and a true quantity value of a measurand (a quantity intended to be measured). The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.
Stability	Property of a measuring instrument, whereby its metrological properties remain constant in time.
Uncertainty	Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.
Reproducibility	Two standards built in the same manner shall have the same frequency.

To better understand the relationship between the statistical and systematic uncertainties of a frequency standard and the frequency of the oscillator signal let us consider the following:

A higher resonant frequency of the oscillator leads to lower statistical uncertainty (σ) of a frequency measurement in fixed time and therefore a higher stability since $\sigma \sim 1/\nu_0$. This is because in a fixed time more measurements can be made - there are more wavelength cycles available – and the signal to noise ratio is increased.

A higher resonant frequency of the oscillator also leads to a higher accuracy and a lower systematic uncertainty $u(\delta E) \sim 1/\nu_0$ in the case of characteristic perturbations δE, such as external electric and magnetic fields.

This range of performances of various clocks versus oscillator frequency is shown here in this plot from Claude Audoin and Bernard Guinot's book "The measurement of time" [1]. On the left side of the plot is shown the time discrepancy or total clock offset accrued after one day of clock operation.

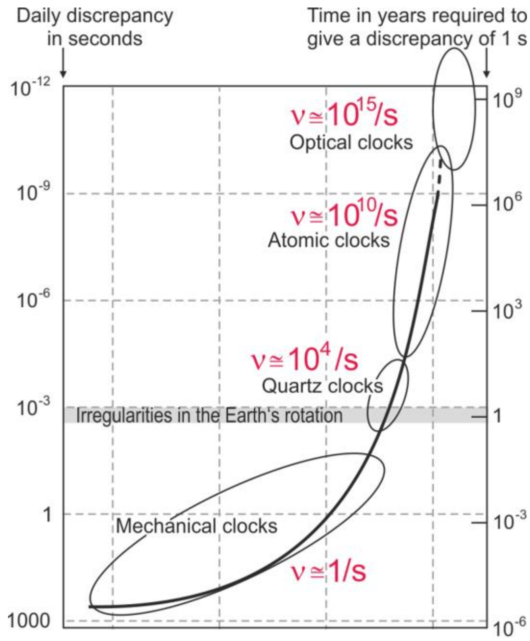

Figure 4: Improvement of clocks over the centuries.

Mechanical or quartz clocks by our bedside tables and throughout our houses, have irregularities which will lead to offsets in time of nearly 1000 seconds to 100 microseconds every day. Atomic clocks, in comparison, which operate with oscillator frequencies in the microwave range, have irregularities that lead to offsets in time of 10s of microseconds to nanoseconds each day.
For reference, the International System (SI) of units for time and frequency (the second and Hz, respectively) are obtained in laboratories using so-called primary frequency standards. A primary standard operates at a frequency calculable in terms of the SI definition of the second*: "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133". *XIIIth General Conference of Weights and Measures, Geneva, Switzerland, October 1967

We exploit this timekeeping capability of atomic clocks, and particularly Cs as a primary frequency standard, in our everyday lives for many applications, as they underpin international time and frequency infrastructure. For example, timing signals, underpinned by atomic clocks are provided by and exploited in modern day society via radio transmitters, the internet, a fixed-network telephone service and Global Navigation Satellite Systems (GNSS) links for enabling electricity distribution, telecommunications, all modes of transport and internet transactions. GNSS, such as GPS, GLONASS, Galileo, or more recently BEIDOU, provides today the most ubiquitous access to the highest-performance time and frequency signals.

Optical clocks have since roughly 2005 surpassed atomic clocks, such as the Cs atomic clock, in achieved frequency stability and accuracy; that is clocks with oscillator frequencies in the optical range instead of the microwave range. Despite the superior performance of optical clocks, no current commercial technologies can provide this improvement in accuracy and stability for the average stakeholder. Optical time and frequency distribution (OTFD) of such reference signals via a fibre network (vFN), outperforms satellite-based technology by orders of magnitude over continental scales with significantly reduced measurement time and unprecedented uncertainty, as shown in the following plot.

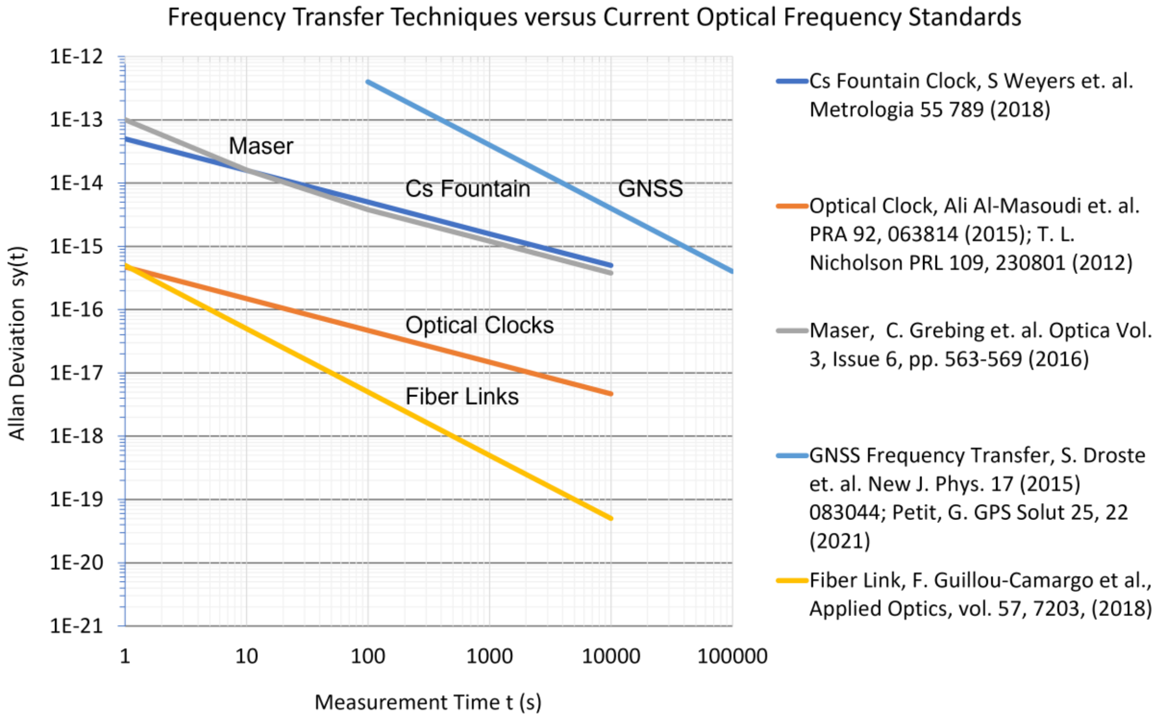

Figure 5: Performance of frequency transfer techniques over a range of timescales (seconds to days) compared to current optical frequency standards.

It is in fact only technologically possible to achieve a pan-European distribution of time and frequency with instabilities at the level of optical clocks/frequency standards at any time internal via optical fibers. Optical fibers give users, needing time uncertainty less than nanoseconds and/or frequency uncertainty better than 10^{-12} (Hz/Hz), access to signals providing this performance, that have so far only been available at national metrology institutes or a few laboratories worldwide. This excellent performance of time and frequency dissemination via optical fibers has already demonstrated outstanding results for a variety of novel applications in fundamental research. European science stands to benefit greatly from access to the time and frequency signals underpinned by optical clocks by taking advantage of OTFDvFN provided by the proposed CLONETS. These European Science Cases and their associated applications are detailed next in Section 2.

In conclusion of this section, we provide the following summary:

- Optical clocks are superior to the best Cs atomic fountain clocks, aka primary frequency standards with regards to stability and accuracy.
- Improvements of the optical clocks will continue for at least the next decade.
- Satellite mediated frequency comparisons lack the performance required for distribution of time and frequency signals derived from optical clocks.
- Optical frequency and time distribution (OFTD) methods are needed to realize the full potential of optical clocks.
- Demonstrated instability / uncertainty of optical fiber networks are well below that of the best optical clocks.

2 Benefits, Needs, Impact and Locations of CLONETS per Science Case

2.1 Science Case 1: Fundamental Science

Optical clock research and the redefinition of the SI-unit “second” are a driving force of time and frequency links between remote laboratories. Since optical clocks based on various species of atoms (e.g. Strontium lattice, Ytterbium-ion, and many more) are still being researched worldwide, it is critical to analyze their behavior at the highest level via clock comparisons based on frequency ratio measurements. For non-metrological and smaller-scale laboratories it is challenging to invest in the sufficient know-how and facilities required not only to develop optical clocks but furthermore, to carry out these necessary comparisons between optical clocks. CLONETS would enable and encourage new stakeholders to research and develop optical clocks with improved access to the stable clock laser signal derived from CLONETS’ signals and diverse optical clocks to carry out comparisons.

Furthermore, the ultra-precise reference frequencies derived from an increased dissemination of optical clocks via CLONETS will greatly benefit tests of fundamental physics, since to a large extent the necessary measurements rely on frequency measurements using atomic clocks as superior references. In particular the search for beyond standard model physics such as tests for possible violations of the equivalence principle of General Relativity [2], a Lorentz symmetry breaking while the Earth rotates around the Sun [3], or for a possible time variation of the electron-to-proton mass ratio or the fine structure constant [4,5], stands to benefit from CLONETS. For example, current precision spectroscopy being performed at CERN on anti-matter are nearly at the limit of commercially available frequency sources such as masers and Cesium clocks. Therefore, a time and frequency network with absolute frequencies at levels several orders of magnitude better than these atomic clocks would allow much higher precision in the spectroscopy as needed to confirm theories.

Many other fields and applications would benefit from CLONETS’ distributed general reference frequencies although they will not require the ultimate performance at 10^{-18} levels, but rather will need improved availability at the level of the current realization of the SI unit, i.e. 10^{-16} level, and/or need 10^{-16} level in less than one day of integration time. These include lower-level applications such as laser frequency calibration, length interferometry, atmospheric sensing and greenhouse gases, and remote wavelength standard calibration or synchronization and timing of accelerator facilities.

2.1.1 Improvement of optical clocks

Currently the best optical clocks reach uncertainties better than 10^{-18} [6]. The validation of their performance requires the identification of systematic shifts, their dependence on external parameters, and finally a comparison with a similarly performing clock. Usually this is done by means of a second, locally available clock. However, good practice requires verification against an independent clock, preferably in another institute or location. Thus, the need arises to compare distant clocks in such a way that the contribution of the comparison becomes negligible with respect to the systematic uncertainties of the clocks. This means that the contribution of the comparison should be at least a factor of ten below that of the clocks, i.e. $<10^{-19}$.

As the relative frequency uncertainty scales with the transition frequency, recent research aims to extend the operation frequency of future clocks into the ultraviolet and soft x-ray domain. Potential novel candidates are based on highly charged ions [7] or heavy nuclei [8,9] where a few γ transitions are known at energies of 1 keV and below. Development of such clocks, their characterization and validation will require a clock network to perform frequency comparisons significantly below the 10^{-19} level. These requirements exceed even the best clocks available today and will make frequency comparison techniques even more demanding. CLONETS can meet these demanding needs and ensures that optical clocks will continue to be researched and developed not just by select metrology institutions, but the wider scientific community throughout Europe.

2.1.2 Precision spectroscopy to search for beyond standard model (BSM) physics

i. Test of QED (hydrogen spectroscopy)

Status and state-of-the-art for this application

Prof. Theodor Hänsch at the Max-Planck-Institute for Quantum Optics (MPQ) was the first to use an optical frequency comb to measure the extremely narrow optical resonances in cold atoms with high resolution [10]. These high precision measurements on the 1S-2S transition in hydrogen, accurate to a few parts in 10^{-15}, led to the Nobel Prize in Physics 2005 being awarded to Prof. Hänsch.

To further improve the accuracy of the measurements of the 1S-2S transition in Hydrogen, a more accurate reference than the hydrogen maser and cesium clock at the institute were necessary. In a ground-breaking experiment with a 920 km fiber link between the Physikalisch-Technische Bundesanstalt (PTB) and MPQ, the optical clock signal from PTB could be transferred to MPQ for a more precise determination of the 1S-2S transition frequency [11].

Today, advances in precision spectroscopy on other transitions in hydrogen and muonic hydrogen have allowed confirmation or in other cases further specification of fundamental physics theories. For example, fundamental constants such as the proton radius can now be determined with ever higher precision [12]. However, these frequency measurements are now often limited by the reference used (e.g. hydrogen maser or cesium clock) and require more stable and more accurate references such as optical clocks down to the 10^{-18} level.

ii. Matter/antimatter comparison

Status and state-of-the-art for this application

Precision spectroscopy is not limited to atoms commonly found on earth. Recent experiments at CERN have investigated and measured the 1S-2S transition in antihydrogen with astonishing accuracy [13]. Measurements on antimatter allow insights into any kinds of asymmetry in the laws of physics that may exist. The Standard Model requires hydrogen and antihydrogen to have the same spectrum. To confirm this to a higher degree, soon the limits in the measurements will once again be the radio frequency reference used. Reaching an accuracy on the 10^{-15} level and beyond currently requires a full metrology laboratory, or an optical link from a metrology institute.

Long-term accuracy of 10^{-18} is required for molecular antihydrogen ion spectroscopy, but even short-term stability is highly relevant. Future particle physics experiments may need a higher short-term stability over times of microseconds, which can be reliably averaged over minutes to months, to yield a good long-term stability and accuracy of < 10^{-13}-10^{-15}, for example in the antiprotonic helium experiments of the ASACUSA collaboration at CERN.

iii. Search for dark matter

Status and state-of-the-art for this application

Multiple approaches are being pursued for dark matter detection. In fundamental physics, it is critical to find out more about this since the mass density of the universe is dominated by dark matter. Theory says that galactic dark matter could be an ultralight bosonic field. Such scalar fields look like temporal (spatial) variation of fundamental constants. There are several possible detection modes: slow drift, which requires clock comparisons as aided by CLONETS; "glitch" patterns for topological dark matter like domain walls; as well as fast oscillation of fundamental constants up to 100 MHz with $Q > 10^6$.
Recently, optical atomic clocks have been used in the search for dark matter [14]. A network for comparison of multiple clocks at different locations is critical and CLONETS is the only viable solution for realizing such a networked comparison of optical clocks. Furthermore, projects such as the Global Network of Optical Magnetometers to Search for Exotic Physics (GNOME) are currently using GPS-synchronization but will require better synchronization through a fiber-based time and frequency network, such as CLONETS, in the future [15].

iv. Search for drifts in fundamental constants

Status and state-of-the-art for this application

The search for variation of fundamental constants depends on the comparison of as many different transitions in atoms, ions, or molecules of different nature (hyperfine, electronic etc.) as possible at the highest possible level. Naturally, optical clock candidates are good targets, but also Hydrogen, Anti-Hydrogen, molecules, exotic atoms, and the like are important targets.

The many degrees of freedom of molecules make them complementary to atoms for testing new physics and exploring the limits of the standard model. High precision molecular spectroscopy is increasingly being used to test fundamental symmetries [16], to provide stringent tests of quantum electrodynamics [17,18,19] or to measure fundamental constants or their variation in time [20,21,22], to search for fifth forces or extra dimensions at the molecular scale [20,23] or look for signatures of dark matter [24]. Precise molecular spectroscopy enables us to improve the modelling of molecular internal vibration and rotation and thus calculate the absorption lines of increasingly complex molecules. As an example, precision spectroscopy on trapped HD+ has been used to measure the proton-to-electron mass ratio at a record 2×10^{-12} level [20,21] and to test molecular theory including QED, improvements to 10^{-14} are on the way, requiring a frequency reference at the 10^{-15} level. Similar requirements are found for molecules of astrophysical interest such as ammonia, water, carbon monoxide [25], and methanol [26]. This is required for improving our understanding of interstellar or protostellar physics and chemistry.

Another topic of interest is new physics with isotope shifts. The investigation will also require stable frequency dissemination between remote sites. Atomic spectral lines for different isotopes are shifted, revealing a change in the properties of the nucleus. For spinless nuclei isotope shifts for two distinct transitions are expected to be linearly related, at least at leading order in a change of the nuclear mass and charge distribution. Looking for a breaking of linearity in so-called King plots was proposed as a novel method to search for physics beyond the standard model.

Other future fundamental physics applications of interest include nuclear gamma spectroscopy (ELI-NP, GF at CERN etc) [27], Thorium nuclear clock for fundamental physics [28], tests of relativity such as the one-way speed of light [29], and Spectroscopy 2.0 (a novel approach to complex spectra) [30].

2.1.3 Re-definition of the SI unit second

One of the central challenges of time and frequency metrology today is to redefine the unit second in the international system of units, the Système International (SI), so that it is based on an optical frequency standard, since they achieve superior stabilities and accuracies compared to the current Cs frequency standard. The most promising candidates on which to base the new definition of the unit second are those optical frequency standards currently recognized [31]. and already contributing to Coordinated Universal Time (UTC) and International Atomic Time (TAI), respectively [32]. The current roadmap adopted by the CCTF [33] outlines that a redefinition could take place in 2026, but the CCTF is currently discussing and drafting a new roadmap, which foresees that a redefinition is more likely in 2030 or 2034.

The current roadmap adopted by the CCTF makes it clear that the ability to compare distant optical frequency standards without any significant loss in accuracy or stability is a prerequisite for a possible redefinition of the SI second as expressed in [34] and put forward by the CCTF in its recommendation [35]. Comparisons need to be made at the $<10^{-18}$ level. As of today, only fiber links have been shown to achieve the necessary accuracy over the long distances required for international comparisons. In fact, the performance of fiber links surpasses current satellite-based solutions by orders of magnitude.

As discussed in Science Case 5, the fiber links will not only be needed to realize a redefinition of the unit second, but furthermore, fiber links with consistent, long-term availability are mandatory to realize and disseminate the prospective optical SI second [3].

2.1.4 Relevant Locations

Vienna (AT), Bern (CH), Geneva (CH), Villigen (CH), Prague (CZ), Braunschweig (DE), Darmstadt (DE), Düsseldorf (DE), Garching (DE), Hannover (DE), Jena (DE), Mainz (DE), Stuttgart (DE), Cadiz (ES), Besancon (FR), Marseille (FR), Paris (FR), Zagreb (HR), Florence (IT), Torino (IT), Amsterdam (NL), Delft (NL), Krakow (PL), Torun (PL), Istanbul (TY), London (UK).

2.2 Science Case 2: Quantum Technologies

Describe the overall benefits of CLONETS for this science case
Quantum technology is a rapidly developing field of physics and engineering. Quantum technology broadly includes research that exploits and controls the quantum nature of light and matter to achieve new measurements with unprecedented sensitivities and unique quantum advantages. A good example is the exploitation of quantum light sources for achieving quantum-enhanced spectroscopy [36,37], quantum cryptography [38,39] and quantum information processing [40, 41]. Other examples to be noted include the development of quantum sensors like gravimeters, accelerometers, and optical clocks, which are making huge advancements in academic research as well as commercial applications [42, 43, 44]. Research and development of all of these examples of quantum technologies stand to benefit from better time and frequency references than are currently commercially available and would therefore benefit from the proposed CLONETS.

Not just research and development of quantum technologies will benefit from CLONETS but also large-scale proposed infrastructures like a quantum internet and distributed sensing. To realize these new infrastructures, it is necessary to implement readily accessible optical phase references as can be provided by the proposed CLONETS. The distribution of a highly coherent, phase-stable optical reference via the optical fiber network of CLONETS would in many cases eliminate the need for maintaining local ultrastable cavities. Similarly, the high-accuracy and low timing jitter reference signals, distributed by CLONETS, would be readily available to the users of quantum communication and eliminate the need for additional, dedicated solutions. Furthermore, both of these benefits of CLONETS can support scalability and improved performances e.g. in terms of relevant distances in phase-encoded quantum communication protocols.

Finally, some new cryptographic primitives (e.g. in blind computing), as well as applications such as time-based authentication, hybrid protocols or loophole testing in entanglement distribution, take advantage of superior phase coherence, making a stable fiber network for optical time and frequency distribution (OTFD) an advantageous and effective tool.

2.2.1 Improvement of real-world QKD

Major investments in Europe and internationally are already being made to establish quantum communication fiber networks for transferring quantum secure information and to prepare what is generally known as the quantum internet. It is therefore important to consider how and if clock network services can coexist with quantum communication networks, as this has far-reaching consequences for this proposed clock network services design study.

We outline some of the current European quantum communication networks either in planning or already established as of June 2021. In June 2019 a quantum communication infrastructure project was launched; Belgium, Germany, Italy, Luxembourg, Malta, the Netherlands and Spain explored the development and deployment of the necessary infrastructure [45,46]. In June 2018 the UK launched the UK Quantum Network (UKQN) that links four nodes for dedicated research. An additional link UKQNTEL was added in March 2019 that functions as a quantum secure network for transmitting encrypted data [47]. The project MuQuaNet in Munich, Germany will interconnect 5 research campuses [48]. A link between the Ludwig Maximillian Universität and the DLR in Munich is supported by QComm. The network will potentially be extended to Erlangen and Berlin. In Lower Saxony, Germany there are plans to use the dark fiber links between PTB and the Leibniz Universität Hannover for testing entanglement distribution. In Italy, there is a well-established so-called Quantum Backbone, which provides atomic clock dissemination services to scientific and commercial users of the country. The Italian quantum backbone has been used for demonstrating common-clock very long baseline interferometry [49] and more recently for demonstrating the distribution of quantum secure information [50].

The recent work of C. Clivati and co-workers in Italy [50] demonstrated very nicely that clock network services not only can but should coexist with quantum communication networks in order to realize real-world quantum communication. They employed the path-length stabilization techniques established in optical time and frequency distribution via fiber networks (OTFDvFN), to reduce the quantum-bit-error-rate due to channel length variations to less than 1%. Their work established experimental requirements of QKD networks for realizing reduced quantum-bit-error-rates due to path length fluctuations and also the necessary synchronization of lasers and detectors via optical signals and timing signals. These requirements are three-fold and are summarized here:

a. optical signal for phase-locking multiple lasers via frequency combs or directly to create a coherent (in-phase) quantum information network of (indistinguishable) photons.

b. clock (timing) signals to realize coherent synchronisation of the lasers and detectors with <100ps timing jitter, 1PPS, 10 MHz or 100 MHz
c. Phase (delay) adjustment based on path length stabilization (adjustment in e.g. 10 ps steps)

CLONETS would provide several clear advantages for existing quantum communication network techniques in need of local and distributed precision frequency control. Furthermore, CLONETS is the only current viable solution for providing absolute time-delay calibration between different nodes in a QKD network, which will greatly simplify existing methods and will thereby make it easier to set up new nodes. We also anticipate that latency in a network could be reduced if users exploit the absolute timing information that would be provided by CLONETS, since the users wouldn't have to wait for coincidence events in the quantum transmission.

2.2.2 Development of new protocols

We anticipate three emerging areas of development of new protocols where CLONETS would enable innovation.

1. Clocks exceeding a certain level of accuracy could authenticate the link.
2. New cryptographic primitives (for example in blind computing) could take advantage of superior phase coherence, which would be provided by CLONETS.
3. Hybrid protocols (DV and CV) could be supported by the distribution of an ultrastable optical phase reference.

As a first case, we address the issue of authentication. Nowadays, common techniques for authentication of users are based on different protocols, but in particular there is a large distribution of One-Time-Passwords (OTPs). Use of an OTP, i.e. a one-time authorization code or dynamic password, is a password that is valid for only one login session or transaction, on a computer system or other digital device. OTP-generation algorithms typically make use of traditional cryptographic techniques. To improve this technique, Internet Engineering Task Force (IETF) has adopted the standard RFC 6238, an algorithm that makes use of the performance of a time reference derived from a user device, also known as the Time-based OTP (TOTP). Improving the accuracy and stability of the available time reference directly enhances the security realizable with this algorithm. This is because TOTP codes are not only single use but also only valid for a limited time. Due to this limited time window in which TOTP codes are valid, attackers must proxy the credentials in real time, and in general attackers would need access to a time reference with an accuracy and stability at the level of the user. CLONETS will offer high-performance timing signals that would be not available to common attackers.

As a second case, let's consider blind computing. Commercial applications rely heavily on distributing calculations to remote systems to provide remote users enhanced computation capacity. There are, however, security concerns with this common practice, for example because of the use of untrusted hardware. Encryption and authentication can be used to protect distributed calculations. Another approach is blind quantum computation (BQC), which provides a way for a client to execute a quantum computation using one or more remote quantum servers while keeping the structure of the computation hidden [51]. Effective protocols are, however, an issue in the implementation of BQC [52]. For example, a promising protocol [53] is limited in that the privacy of the computation is maintained only for short periods. Synchronization of servers via high-performance OTFDvFN can support the efforts to test and implement such protocols and make the computation private over longer periods.

As a third case, we address hybrid protocols in QKD, mixing Discrete Variables (DV) and Continuous Variable (CV) techniques. To overcome the limitations of both DV and CV - QKD protocols, it is proposed to simultaneously perform discrete modulation-based encoding for a CV-QKD subsystem and time-phase encoding for DV-QKD, by transmitting such hybrid-encoded pulses with an optimized average number of photons per pulse [54]. For this class of hybrid protocols, phase control, synchronization and measurement accuracy are all relevant. CLONETS would also in this case enable more ubiquitous use of optical phase control.

2.2.3 Entanglement distribution beyond QKD

Entanglement distribution beyond QKD is another possible application of CLONETS. Entanglement implies the existence and creation of correlations between non-local systems that cannot be explained in classical, causal relationship terms. Entanglement distribution is associated with high fidelity transport of quantum information over short and long distances where the fragile phase of quantum superpositions at the single or multi particle level plays a central role, e.g. in developing quantum memories [55] and establishing long-reach quantum communication [56]. From a fundamental point of view, active research is pursued e.g. to test the violation of Bell inequalities in comprehensive ways [57,58], or with different quantum systems [59], or to check against loopholes in practical implementations [60].

In all such applications, timing plays a crucial role as soon as in-field implementation is concerned: it enables the synchronization between distant nodes, ensures a common time-base between remote time-tagging modules [59,61] as well as stable visibility of coincidence counts between interfering photons that travelled via connecting fibers. In some foundational tests, the accuracy of timing is critical to put limits on superluminal influences that could explain entanglement in the framework of existing theories [60].

Phase wandering and delay-changes in deployed optical fibers is so-far addressed similarly to what is done in quantum key distribution, i.e. sending narrow-linewidth light [[61]] and/or a clock signal in the form of laser pulses [59] as phase and timing reference respectively, or by measuring the fiber delays by post-processing. Very recently, polarization-based entanglement distribution over a record length of 248 km was supported by GPS-disciplined time-taggers, whose timing drift, on average 13 ps/s, limited the length of temporal acquisitions over which a sufficient visibility could be obtained [62]. In general, established dedicated systems in this community reach synchronization capabilities at the level of ~100 ps.

The pan-European availability of CLONETS' both ultrastable optical signals (>> 1000 km of coherence length) and absolute, highly accurate time references (unc. <<100 ps) could be exploited in these applications, removing one of the most significant degrees of freedom and reducing associated uncertainties.

2.2.4 Relevant Locations

Olomouc (CZ), Hannover (DE), Mainz (DE), Munich (DE), Stuttgart (DE), Ulm (DE), Vienna (AT), Innsbruck (AT), Barcelona (ES), Besancon (FR), Torino (IT), Matera (IT), Firenze (IT), Roma (IT), Milano(IT), Napoli (IT), Delft (NL), all 27 European members states of the Europe Communication Infrastructure (EuroQCI).

2.3 Science Case 3: Earth Observation / Geodesy

The field of geodesy has become interested in continuously operating ultrastable clocks, since these have reached the 10^{-18} level of accuracy domain, which means that the gravitational redshift of a 1 cm difference in physical height can be measured in the gravitational potential of earth. Capturing the variable part of the gravity field is a key element for insight into mass transport processes on Earth. Many of these large-scale mass transport phenomena (ground water levels, rise of sea water level, melting of ice sheets) are secondary measurements of climate change.

Stable frequencies distributed via fiber network are very suitable for important applications such as height system unification in Europe. As of today, even neighboring European countries do not have a unified height system with the same zero-level. Classical optical leveling is still commonly used and suffers from progressive error accumulation. Absolute height measurements and a unified system would eliminate these problems. Furthermore, satellite gravity missions that measure the geoid could be verified and improved greatly with a sufficiently dense grid of ground truth measurements. These measurements supply the shape of the geoid and are critical for the monitoring of climate change as well as sea-level variations.

At this point in time, all of the measurement techniques of space geodesy rely on clocks, but they do not use time nor frequency in an absolute sense. Due to redundancy either with respect to the number of observations or the number of observed targets, parameters for specific clock corrections are computed in a non-linear least-squares adjustment process. A good example for this process is the precise point positioning (PPP) procedure, which enables determination of terrestrial positioning with errors as small as a few centimeters under good conditions, as compared to the few meters typically achieved using conventional consumer GNSS methods. The PPP procedure exploits products of the International GNSS Service (IGS), provided by the International Association of Geodesy (IAG), based on continuous observation of a network of more than 200 globally distributed GNSS stations, so-called ephemerides. Although such processes for clock corrections work remarkably well, a closer look at the established clock corrections, reveals that these adjustment parameters are also absorbing a certain amount of technique-inherent systematic measurement errors in the residual smoothing adjustment process, which strongly indicates that there is still room for an improved accuracy.

We outline this rather typical situation with a comparison of two H-masers, one located at the geodetic observatory in Matera (Southern Italy) and the other in Wettzell (Southern Germany). The figure shows the result of a two-week observation campaign in 2017, where the VLBI systems have been operated continuously in addition to the GPS receivers, which were referenced to the respective maser of each station. In order to account for offsets in the maser frequency, a quadratic term has been removed from the measurements.

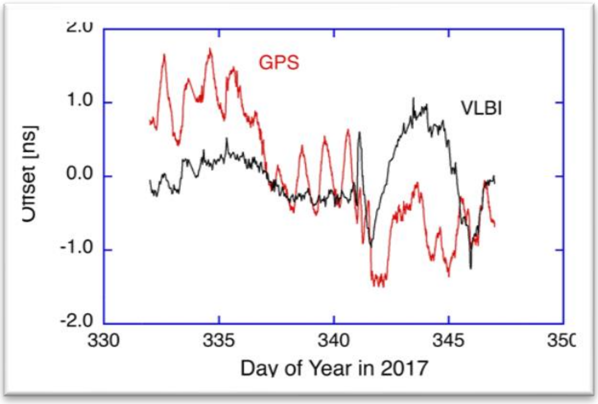

Figure 6: Clock comparison between masers located in Wettzell (Germany) and Matera (Italy).

This clock comparison illustrates how systematic errors specific to each measurement technique are acting on VLBI and GPS differently. Neither of the clock comparison techniques can reproduce the clock behavior that would be observed, if the two masers were compared in the same location side by side. Some of the apparent systematic error contributions shown in the figure originate from variable instrumentation delays and some of them relate to deficits in the established propagation delays.

2.3.1 Height system unification

National height systems in Europe have their own datums, usually related to tide gauges. The agreement between different systems can reach 10 to 20 cm. Within national systems, errors introduced by spirit levelling reach 2-5 cm, causing slopes [63] or distortions. These uncertainties do not suffice for the definition of the International Height Reference System [64] (IHRS). Chronometric levelling, realized by stationary optical clock comparisons in a pan-European network, will be a valuable new technique for the unification of different national height systems. In order to improve currently existing height systems, clock comparisons will have to be performed at the level 2-3 cm in terms of stability as well as accuracy, translating into the requirement of 2-3 x 10^{-18} fractional frequency difference. Ultimately in view of the IHRS, a slightly higher performance level of 1 cm (10^{-18} fractional stability and accuracy of the clock) is desired. For the initial establishment of the height system, it is enough to obtain these measurements once. In order to capture variations over time, repetitions on a regular (e.g., annual) basis in areas of particular interest would be desirable. For the purpose of a network densification of the height system, transportable optical clocks with similar stabilities and accuracies are required. Each measurement campaign with a comparison to the optical clock network would yield a new contribution to the pan-European height network as a result.

This challenging application is not available without the proposed CLONETS. It builds critically on two building blocks, namely the general availability of highly resolving accurate clocks and a lossless distribution system for the comparison of these accurate frequencies.

This application would allow the definition of a flawless IHRS, at least over the region of Europe. Such a height system would provide valuable large scale ground truth and consequently enhance satellite gravity missions.

2.3.2 Satellite gravity mission validation

Nontidal gravity field variations of the Earth are monitored by the satellite gravity mission GRACE Follow-On (GRACE-FO). While the satellite mission and potential successors always yield spatial gravity potential changes, point-wise measurements from clock comparisons can be employed to complement or validate the results [65]. Clock comparisons would have to be conducted at the 10^{-19} level of stability on spatial scales below 300 to 400 km. The optical clock network would ideally have to operate permanently, and to achieve the desired spatial resolution, clocks would need to be distributed at distances of at most a few 100 km. Since the interest here lies in the time-variable potential, constant offsets in the fractional frequency differences between the clocks are irrelevant.

CLONETS will provide a network of reference points for Earth-observing satellite missions that map the contour of the gravity field. Such a stable reference frame is not yet available, but highly desired for the decade-long observations that aim to quantify the temporal evolution of gravity fields on spatial scales of a few 100 km. The topics of interest are related to the anthropogenic climate change and include changes in groundwater levels, melting of ice sheets, and rise of sea water levels.

The importance of highly accurate and well-validated data to monitor the effects of climate change cannot be underestimated. A ground-based reference network will greatly increase the value of satellite missions already operating or planned.

2.3.3 Geodetic network consistency

Systematic measurement errors still cause limitations on the ultimate resolution and stability of the geodetic reference frames. As the instrumentation is rather bulky and complex and involves moving large telescopes in the case of the Very Large Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) technique, the systematics are hard to identify and to mitigate. Furthermore, geodetic measurement techniques are based on time (GNSS, VLBI) and time intervals (SLR), which makes them vulnerable to unintentional time delays accumulated at various steps in the measurement process and these extra delays are very hard to extract from the measurements. Time coherence in the fundamental stations [66] of the geodetic network is the best way to address this issue. This enables error correction based on closure measurements [67]. The ideal scenario for a geodetic core site would be an accurate optical clock, where the clock transition provides direct access to the gravitational potential. The same clock when tied to a delay-compensated local time and frequency distribution system provides a rigid link to the measurement systems with a constant offset and without the introduction of signal-delay-related systematic errors. The measurement systems in turn are tied to the external celestial reference frame (quasars and satellites) by the measurement processes facilitated by VLBI, SLR and GNSS. Regular high resolution time transfer (free space or via optical fibers) between such geodetic core sites would give access to a physical height system via clock comparisons, while VLBI provides Earth rotation parameters. On top of that, all the techniques contribute significantly to the instantaneous figure of the Earth by providing station coordinates and accurate baselines between the observatories.

The techniques of space geodesy are rather advanced, but they are hitting a hard limit, which is given by systematic measurement errors, which are shifted around between the established coordinates, the clocks/time and signal propagation delays. A clear separation of errors with respect to their origin will improve the quality of the derived products, the long-term stability and in particular the accuracy. Adding continuously available stable and accurate clocks to the core observatories of space geodesy, offers the outstanding opportunity to integrate gravity into the otherwise separate geometric techniques i.e. VLBI, GNSS and SLR.

2.3.4 Relevant Locations

Bonn (DE), Wettzell (DE), Browiec (Poland), Herstmonceux (UK), Potsdam (DE), Grasse (F) Onsala (S), Zimmerwald (CH), Matera (I), Medicina (I), Ny Alesund (N), Metsahovi (FIN), Graz (AT).

2.4 Science Case 4: Astronomy

Multi-site and multi-technique observations are very important in astronomy and are expected to benefit from CLONETS. A prime example is VLBI for astrometry, which defines the celestial reference system, in complement to its geodetic applications. This requires extremely high accuracy, as well as short-term and long-term synchronization between the remote observing sites, such as can be provided by CLONETS, and first experiments have already been conducted by consortium members [68]. Another important application for CLONETS is pulsar timing, where improved links both between sites and to future optical clock timescales can be expected to improve the sensitivity of network analyses to new physics, both in the source objects themselves and along the signal propagation paths.

2.4.1 Radio interferometry and VLBI in astronomy

Radio telescopes and interferometers, including VLBI, are used to capture high resolution images of astronomical sources. Their operation requires high-stability frequency references, and in the future, they may have advantages in obtaining such references through CLONETS.

A more immediately compelling application for CLONETS is the use of VLBI for astrometry, i.e. for very high precision measurements of the angular positions of sources, in particular the positions of distant quasars which constitute the International Celestial Reference Frame (ICRF). VLBI observations also provide the instantaneous rate of rotation or Length of Day (LoD) of the Earth, as well as the instantaneous orientation of the Earth's rotational axis with respect to the ICRF, and the rotation angle of the Earth about this axis. These data contribute to international timekeeping through the role of the offset UT1 – UTC in the definition of UTC.

The VLBI observing method is based on measuring the group delay of broadband noise emitted from remote quasars. From the observed time delay between the telescopes of the observing stations, the pointing direction towards the respective quasar is obtained. During the observation, the telescope timescales are not synchronised. By sacrificing some of the observations, the clock offsets from each station with respect to an arbitrarily chosen reference station are determined. In order to remove systematic errors, VLBI processing infers piecewise linear "clock corrections" for every 2-hour interval of observation. These corrections combine, in an unknown way, errors due to the lack of coherence of the involved clocks in the widely separated stations, and to the limiting coherence of the atmospheric propagation delay. With the increased bandwidth of the VGOS 2, 14 GHz instead of the current S- and X- band windows, there is already pressure for an improvement.

The path forward is not yet fully evident; however, a significant improvement would be achieved if phase delay measurements could be realized between distant telescopes. CLONETS can make an important contribution to this by providing very high accuracy synchronisation between the distant observing sites, at least within Europe. These applications of VLBI are of course complementary to and intimately entwined with the geodetic applications which are presented in Science Case 3, and the same synchronisation requirement of 1 – 100 ps applies here.

Similarly, to the discussion in Science Case 3, CLONETS will provide very high-performance synchronization between distant observing sites within Europe, allowing clock errors to be essentially eliminated. The elimination of clock errors will in turn open the possibility to better investigate other sources of fluctuations such as the atmosphere. This can be expected to lead to improvements in VLBI data processing and improved accuracy of the results. It may also lead to the discovery of previously inaccessible signals in the data.

2.4.2 Laser ranging

Laser ranging methods are used to measure the distances to satellites (Satellite Laser Ranging, SLR) and nearby celestial objects, a prominent case being the Moon (Lunar Laser Ranging, LLR). These measurements are used for geodesy, contributing to the ITRF, for linking the ITRF to other reference frames, and for tests of the equivalence principle. SLR is sensitive to the geocenter and therefore defines the origin for the terrestrial reference frame.

SLR is the only technique in the toolbox of space geodesy, which only uses a single clock, because it is a two-way time-of-flight measurement technique. That means that both the transmit and receive signal is timed on the same clock. Therefore, clock related biases are cancelling out as common mode effects. SLR depends on the clock frequency for scale though. A deviation of one part in 10^{12} from the SI second is sufficient to ensure a range resolution of 1 mm even at lunar distances. A common frequency source provided by CLONETS user for optical time transfer, based on SLR and stable orbiting clocks in common view of SLR stations, could enable time transfer and synchronization between well-defined geodetic markers at the level of a ps. This is an important ingredient for future relativistic space-time geodesy.

Clock offsets, also known as time bias errors, which affect the epoch of measurement, are usually acceptable up to several µs for applications such as precise orbit determination, altimetry and gravimetry. They are usually determined in post processing. Other applications, such as thermosphere density estimations, benefit from smaller errors in measurement epoch, i.e. from better clock synchronisation, as would be provided by CLONETS.

2.4.3 Pulsar timing

Long-term radioastronomy measurements of the times of arrival (dating) of pulsar pulses give access to the physics of the sources, tests of general relativity, search for low-frequency stochastic gravitational wave backgrounds, and pulsar timescales. A stable and accurate frequency reference is needed for these observations, with short-term characteristics of 10^{-11} at 1 s to 10^{-13} at 1 d. In the long term, the objective of comparing pulsar time scales with atomic clock-based time scales implies the need for an appropriate OTFD link between the two, i.e. providing a frequency uncertainty of 10^{-16} for measurement durations of 1 to several years, for the current Cs-based time scales. In the future, comparisons with optical clock-based timescales would require links that provide an improvement of two orders of magnitude. For the analysis of data of networks such as the European Pulsar Timing Array, the sites should be synchronised at the ns level.

CLONETS represents a unique opportunity to improve the frequency references available to European pulsar observation sites and the synchronization of these sites. Fiber links are the only available method for reaching the performance levels needed in the future.

The connection of pulsar timing observation sites to CLONETS can be expected to lead to improvements of the measurements requiring the highest sensitivities, such as the comparison of pulsar time with optical clock-based time, providing the potential for new discoveries.

2.4.4 Relevant Locations

Graz (AT), Zimmerwald (CH), Effelsberg (DE), Potsdam (DE), San Fernando (ES), Kirkkonummi (FI), Grasse (FR), Grenoble (FR), Nancay (FR), Medicina (IT), Noto (IT), San Basilio (IT), Matera (IT), Ventspils (LV), Westerbork (NL), Borowiec (PL), Onsala (SE), Cheshire (UK), Herstmonceux (UK).

2.5 Science Case 5: Telecommunication and Networks / Position, Navigation, Synchronization, and Timing

The most common way of transmitting time or frequency information today is based on exchanging microwave signals between ground stations and satellites [69]. One established satellite time transfer technique is two-way satellite time and frequency transfer (TWSTFT). TWSTFT relies on the path reciprocity of the transmitted signals. However, it is well known that nonreciprocal variations of the delay times are caused by (a) residual satellite motion, (b) by drifts of the signal delay times in the electronic components in the ground stations and in the satellites, and (c) by the difference between the uplink and downlink frequencies in combination with the propagation delay introduced by the troposphere, the ionosphere and multipaths. An assessment of the performance of any T&F comparison technique requires separating the signal contributions of the fiber links from the signals of the compared clocks. This is possible by operating two stations side-by-side connected to a common clock or delivering a common clock signal to the remote stations via optical fibres. In this way the proposed European fibre infrastructure CLONETS will contribute to an improvement of the well-established T&F transfer techniques based on satellites.

CLONETS will also benefit the development and establishment of future dissemination of time as well as future position, navigation and timing (PNT). Satellite-based navigation systems can only exploit optical clocks based at ground-stations if the technological capability exists for comparing the optical clocks two orders of magnitude better than their ideal operation at the 10^{-18} level. Such OTFD between ground stations interlinked via a fiber network, would also serve as a backup to GNSS especially in low visibility environments e.g. for navigation on the sea, by transmitting very precise time signals from the ground for triangulation and crucial navigation.

For high-speed telecommunication both time and frequency from a single source is compulsory. With ever-increasing data rates and transmission for 6G and beyond, the requirements are getting more stringent. Traceability to UTC is also required in most cases. Since it is a service provider, telecommunication requires high reliability, robustness, resilience, management, and operability. The immediate use of a time and frequency network would be the supervision of the current synchronization network.

2.5.1 Optical timescales

It is anticipated that the existing time-scale architectures will increasingly incorporate optical frequency standards in the future. A time scale that incorporates optical clocks, even intermittently in a hybrid optical-microwave time scale architecture, can significantly improve the accuracy in timekeeping towards the sub-nanosecond level as was demonstrated by PTB, Germany, NICT, Japan and NIST, USA [70, 71, 72]. A hybrid optical-microwave time scale architecture does not require that an optical frequency standard runs continuously as a clock, provided that they can be operated reliably in combination with conventional microwave atomic clocks, that act as a flywheel to bridge the dead time of their optical counterparts [70]. Simulations show in fact that “to achieve the same performance of a continuously operating Cs-fountain time scale, we find that it is necessary to run an optical clock 12 min per half a day, 1 h per day, 4 h per 2.33 day, or 12 h per week.” [73]

In the future, the combination of fiber-linked networks and optical frequency standards (OFSs), such as in CLONETS, will further increase the reliability of optically steered time scales because various optical standards in separate laboratories linked by fibers can serve as independent fly wheels. To this end, there is active international collaborative work to incorporate optical clocks into time scales and to link optical frequency standards to the current Cs realizations of the unit second, which also includes advancing new satellite methods of clock comparisons [65, 66]. The aim of current efforts is to achieve frequency transfer at the level of 10^{-18} and time transfer at a few picoseconds level [12]. The only current viable solution for realizing these frequency and time transfer parameters is optical time and frequency distribution via fiber networks, as would be realized in the proposed CLONETS. In this regard CLONETS would have a major long-term impact on the development, realization and dissemination of future optical clock-based time scales.

2.5.2 Position, Navigation & Timing, PNT

From long-term climate observation, to monitoring of critical infrastructure like dams, bridges, or nuclear power plants, to modern georeferenced services like automated machine guidance or car sharing; accurate positioning, navigation, and timing (PNT) plays an ever-growing important role for modern daily life. Global and local reference frames, the backbone of many of the satellite-navigation based applications, are based on geodesy. By nature, many of these services and activities are organized in international societies, like the International Association of Geodesy (IAG) and its services, namely the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service (IVS), the International DORIS Service (IDS) and the International Earth Rotation and Reference System Service (IERS). Other entities like the FIG, EUREF, or EPOS also rely on these basic services for more specific applications. We have to remind ourselves that the reference frames of space geodesy are required to be stable in the long-term. At the same time, they have to provide high-resolution in the short-term.

Therefore, we can state, that the traceability chain in PN is highly complex. It includes time and frequency transfer and synchronisation, but also contributions of the propagation of electromagnetic waves through (uncontrolled, maybe even turbulent) media or dimensional measurements in 3D. Available commercial instrumentation in this sector has achieved a remarkable performance in terms of achievable standard deviations. A rigorous assessment of the achievable uncertainty to the SI definition, however, is often highly complex and therefore missing.

SI-traceable timing directly impacts the field of GNSS concerning:
1. electromagnetic propagation through turbulent air

- High-level sensor and antenna verification
  - Dealing with the optical index of refraction
  - Turbulence measurement and modelling
  - Beam propagation modelling
  - Space weather and
- Height correlations
- UTC traceability of Galileo

- Uncertainty assessment of GNSS PNT solutions
- Autonomous driving
- …

2. earth-bound long-distance measurements
   - Provision, maintenance, and improvement of primary distance measurement standards
   - Establishment of a reference baselines network
   - Maintenance of reference sites for GNSS based positioning and distance monitoring
   - Verification and traceability improvement for terrestrial laser scanning and ranging

3. the field of long-term climate observation
   - Transfer of recent technology developments in optical distance metrology to this field
   - Provision of terrestrial baselines of sufficient extension with SI-traceable references

CLONETS offers the general opportunity to provide time and frequency with a traceability to the respective SI units. Furthermore, it would provide a solution for linking geodetic core stations to a common clock. Simulations based on the GNSS technique show, that this would have the most significant impact in the range between 1 and 100 ps in terms of clock instability. Since VLBI is also based on the microwave technology, it is fair to expect that such a common clock would provide a similar effect on linked observatories. With this said, it needs to be pointed out, that VLBI is most sensitive on the long intercontinental baselines, which would currently not be covered by CLONETS. A network architecture as envisaged by CLONETS-DS is a great opportunity and will make novel analysis concepts both necessary and possible.

2.5.3 Resilience for GNSS

Time keeping is critical for GNSS because timing errors translate into position errors with the speed of light, 0.3 m per ns. Positioning, using Europe's satellite navigation system, Galileo, will be accurate to the m range. Beyond pure performance, many applications are concerned by their dependencies on GNSS systems and potential threats to it [74].
A critical issue will occur when a few-days long failure of GNSS happens, e.g. due to a solar event.
In addition to solar events, timing accuracy can be completely disabled by transmitting interference noise from aircrafts equipped with special devices or destroyed by anti-satellite (ASAT) missiles [75, 76].
In many countries a problem of too much dependence on GNSS is being observed. Work has been started at ANSI/NIST and IEEE concerning the resilience in positioning, navigation and timing (PNT). This topic is currently very active, with many works available. 3rd Generation Partnership Project (3GPP), the organization for standardizing mobile phone networks is going to specify a full PNT backup for customers based on 5G network.

The resilience of optical fibers against electromagnetic interference navigation systems, defense systems, and telecommunication systems is important for providing an alternative time and frequency dissemination system. One prominent case is the supervision of GNSS based services (GALILEO) and ground clocks.

All GNSS providers operate reference clock stations. For GPS this is handled by USNO (United states Naval Observatory), for Galileo there are two stations (PTF, precise timing facility), one in Oberpfaffenhofen, Germany and one in Fucino, Italy. They provide Galileo system time. DLR KN is currently establishing their own reference clock station as composite clock.

Reference frame realization involves the synchronization of geodetic observatories (common clock) with an uncertainty of 10^{-17} (1 ps / day). It requires synchronization of clocks at measurement precision of 1 ps, and traceability to UTC would be nice to have (the requirement on the reference frame is 1 mm accuracy and 0.1 mm stability globally).

Navigation on sea as a backup to GNSS could be very useful – in particular for highly precise navigation requirements near coasts and harbours. Here synchronization of reference stations along the coast with 1 ns timing stability between them would allow careful and precise navigation of a ship into the harbour as backup to GNSS – even e.g. in foggy and bad weather conditions.

Fiber-based time and frequency dissemination technology along with mature optical atomic clocks and an SI second tied to optical standards, as discussed in application "Optical Time Scales", could enable significantly more stable international time scales and more accurate local realizations. Fiber-based time and frequency dissemination technology would make monitoring and oversight of primary reference clocks in telecommunication networks or of ground clocks for GNSS such as the Galileo Precise Timing Facility possible. Optical time scales with timing errors at the 10 ps-level would eventually enable navigation towards cm-level accuracy and if made as ubiquitous as GNSS, would enable a back-up solution [77] and completely new perspectives.

2.5.4 Supervision of Telecommunication networks and Synchronization (5G or 6G)

Any telecommunication network requires synchronization to allow data exchange between network nodes and the users. A dedicated infrastructure is used to deliver the synchronization signals (usually 10MHz and 1PPS derived from the same source) to any device taking part in the data exchange process. This forms a complex chain of hierarchically connected devices where the top-most ones, being the sources of synchronization signals, have the highest accuracy and stability requirements. Currently, the synchronization infrastructure is based on so-called primary reference time clock – PRTC, or enhanced PRTC, or network coherent PRTC, exploits cesium clocks and GNNS technology. The most recent requirements related to the synchronization network are published and regularly updated by international standardization bodies, like Telecommunication Sector of International Telecommunication Union (ITU-T).

Telecommunication network needs both time and frequency (usually 10MHz, 1PPS) derived from a single source. The latest synchronization recommendations require traceability to a known standard, usually UTC. So the CLONETS network may work as a means to provide traceability to UTC, or even to be a source of synchronization signals in some cases.

Operating complex network architecture requires a suitable system that can continuously monitor synchronization quality and identify potential problems early. For the future monitoring of selected points in such networks, optical time transfer (OTT) using optical fiber links exceeds by far the requirements agreed by the International Telecommunication Union (ITU-T) for 5G networks. Such a pilot system operates currently in Deutsche Telekom, where ELSTAB technology is used to connect a few selected main synchronization telecom nodes with PTB time laboratory. OTT allows time scales to be transmitted to any location via optical fibers; thus, it also enables network synchronization with an uncertainty on the order of 50 ps and the time instability of less than 30 ps for averaging periods between 10 s and 10^6 s. Thus, OTT is perfectly suited for constant supervision of the ePRTCs performance within a network. In the long-term CLONETS could contribute to similar, European-wide, synchronization supervision/distribution systems, improving the reliability of telecom networks.

2.5.5 Relevant Locations

Braunschweig (DE), Bremen (DE), Frankfurt (DE), Paris (FR), Amsterdam (NL), Warsaw (PL), all UTC(k)/NMI locations.

An additional point related to telecom may be that telecom operators may be willing to serve as providers of metrological signals to interested clients. This is in some sense a natural evolution of telecom industry that is devoted to supply people with services they needed. Telecom operators have access to optical fibers and can play a role allowing to extend users of CLONETS signals.

3 Required Services

3.1 What services will CLONETS provide to meet the stakeholders' needs for these science cases?

Based on the needs of these respective science cases, we have deduced details on the requirements and specifications of the future CLONETS research infrastructure and present these details in this section as comprehensive research services, which should be provided by CLONETS. The research services and the associated requirements and specifications on the CLONETS research infrastructure serve as the basis for the actual design work in WP2.

As outlined in the proposal, the results of WP1 have been passed onto WP2 in an iterative process to allow for adjustments based on the feasibility of implementation of the research services. The potential CLONETS research services were discussed in detail between members of WP2 and WP1 and the result of these discussions was presented at the Stakeholder Workshop in month 12. Additionally, the initial results of WP1 concerning the relevant science cases and their requirements on the CLONETS research infrastructure were provided at the Stakeholder Workshop in month 12 in the form of write-ups and presentations.

As a result of intensive discussions with stakeholders and between the members of WP1 and WP2, we have identified 4 types of services, which can be organized:

- in terms of requirements for timing and frequency signals or
- with respect to absolute (traceable) and relative (free running) signals.

For *relative* signals the measurements between scientific users (SU) can be performed such that the signals provided by the network are considered as transfer signals that drop out of any measurement between two SUs.

In contrast to the relative measurements, traceability to the SI-unit of the signals provided by the planned international core network (ICN) CLONETS is mandatory for any *absolute* measurement performed by SUs. This traceability is assured by referring the signals to at least one NMI or UTC(k) laboratory. Thus, the network must provide not only signals but also data that:

1. provide information to the user on the received signal,
2. provide traceability from source to usage.

Which of the four services is needed, depends on the specific user application. Thus, CLONETS has to provide all of the previously described types of service.

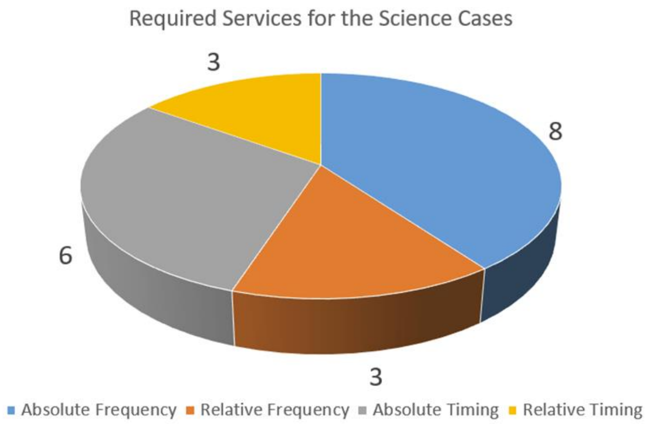

Figure 7: Overview of the required services for the different science cases divided into absolute frequency, relative frequency, absolute timing, and relative timing.

The core network needs an interface at its boundary, either because it meets another core network, or it interfaces to a secondary layer. At the interface, interoperability between networks is ensured if an accurate enough phase measurement between the two metrological networks is made. The required accuracy depends on the scientific application covered by the secondary layer.

In summary CLONETS will provide four core services to interconnect dedicated laboratories and measurement facilities throughout Europe and to equip them for performing collaborative and coordinated research only possible via the professionally maintained CLONETS research infrastructure: (a) relative frequency services, (b) absolute frequency services, (c) synchronization services and (d) absolute timing services. The relative frequency services and synchronization services depend on maintained ultra-stable optical carriers, disseminated timestamps and the measurement or calibration of network delays. CLONETS can also provide absolute frequency and timing services due future to agreements between CLONETS and the European National Metrology Institutes, which serve as an external provider of Universal Coordinated Time and the best performance optical clocks. These services provided by CLONETS exceed the time and frequency capabilities that research institutions can achieve without dedicated staff and funds for a metrology laboratory.

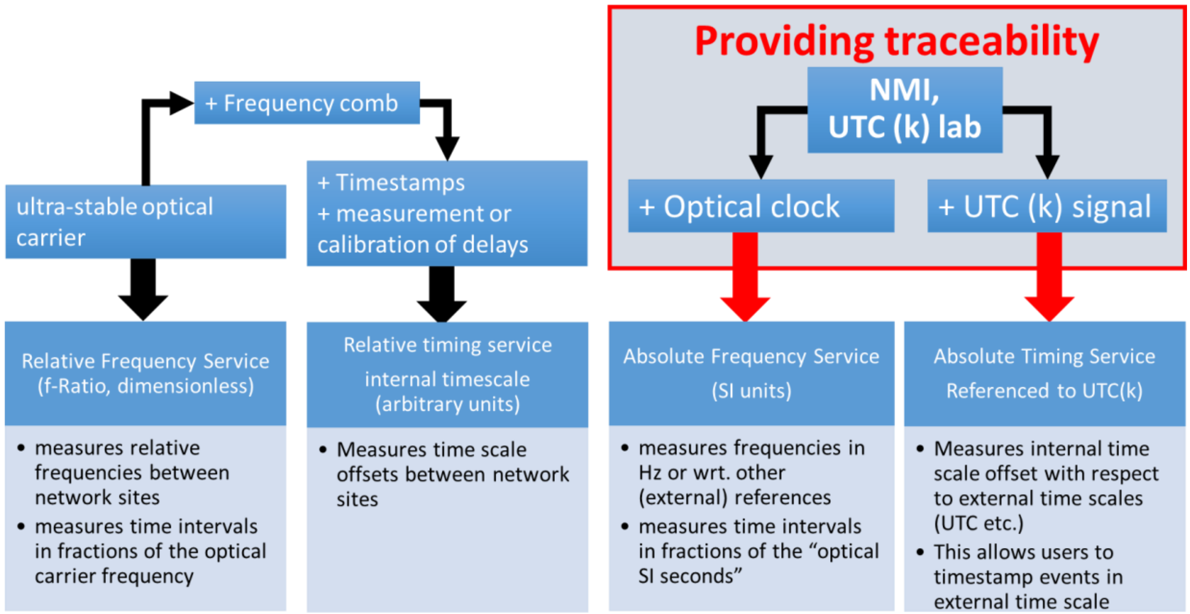

Figure 8: Schematic showing the suggested CLONETS setup to provide relative and absolute timing and frequency services to nodes.

4 Conclusions

4.1 What is the expected impact of CLONETS?

Interconnection of EU infrastructure, highlight technology transfer, job creation

CLONETS will have additional societal and economic impact in Europe beyond the high-impact scientific advancements achieved across the diverse science cases. For example, one of the achievements enabled by CLONETS will be the establishment of a reference system for time and frequency, which will have a global impact on geodesy and navigation, and the future of everyday applications. CLONETS will also achieve widespread technology transfer by making the time and frequency capabilities available today only at select metrology laboratories, available to a large user community across Europe. Furthermore, via dedicated training on how to apply the CLONETS time and frequency signals, CLONETS will create an advanced job force that can benefit a large range of technological sectors that depend on time and frequency such as telecommunications, navigation, power grids, finance, defense and security.

Appendix A Stakeholder Questionnaire

CLONETS-DS – CLock NETwork Services Design Study

User Requirements Questionnaire

The EU-project CLONETS-DS aims at designing a sustainable, pan-European, ultra-precise time-and-frequency reference-system available to the European research community. This research infrastructure considers user needs, designs the required architecture, engineering models and roadmaps, and develops a sustainability model for the future service, thus strengthening the European research area.

The contact person for this questionnaire is ...

1. **General information**

1.1 Contact person:

1.2. Institute:

1.3 Main field of research:

2. **Envisioned research plans**

2.1 Which future service or research could be addressed, improved, or eased with better (e.g. better than 10^{-16}, 10^{-18}, ...) T/F reference?

3. **Time & frequency desiderata**

3.1 Currently used time and frequency reference; performance parameters:

3.2 Which stability would be required/desired (e.g. 10^{-18})?

3.3 Which timescales are important (e.g. seconds, days, ...)?

3.4 Which accuracy would be required/desired?

3.5 Traceability to SI-second required/desired?

3.6 Additional remarks or requests?

4. **Synchronization**

4.1 Is synchronization with peers required/desired?

4.2 Which instability/jitter is required/desired?

4.3 For timestamping: (quasi) real-time or offline processing?

4.4 Additional remarks or requests?

5. Implementation

5.1 Time or frequency signals?

5.2 Preferred format of time signals?

5.3 Preferred wavelength?

5.4 Availability of the reference (continuous, periodic, …)?

5.5 Additional infrastructure available on-site (GPS, masers, clocks…)?

5.6 Additional remarks or requests?

6. Recommendations on other organizations requiring advanced T/F services

6.1 Are you aware of any other research field or group that might benefit from an optical T/F reference?

currently in use										
			INSTABILITY (ADEV)				Accuracy		remarks
Reference frequency		Yes/No	@ 1s	@ 1h	@ 1d	@ 10d	absolute	relative	
optical	e.g. 194 THZ	No							
rf	e.g. 10 MHz	Yes	10^{-13}	10^{-14}	10^{-15}	10^{-15}			
Time	e.g. 1 pps	Yes	10^{-13}	10^{-14}	10^{-15}	10^{-15}			
Potential future use case: please specify									
		required	INSTABILITY (ADEV)				Accuracy		remarks
Reference frequency		Yes/No	@ 1s	@ 1h	@ 1d	@ 10d	absolute	relative	
optical	e.g. 194 THZ								
rf	e.g. 10 MHz								
Time	e.g. 1 pps								

Glossary

CLONETS	Clock Network Services
CLONETS-DS	Clock Network Services Design Study
vFN	via Fiber Network
OTFD	Optical Time and Frequency Distribution
BSM	Beyond standard model
QKD	Quantum Key Distribution
VLBI	Very-long-baseline Interferometry
PNT	Position, navigation and timing
GNSS	Global navigation satellite system
SI	International System of Units
GNOME	Global Network of Optical Magnetometers to Search for Exotic Physics
UTC	Coordinated Universal Time
TAI	International Atomic Time
CCTF	Consultative Committee for Time and Frequency (BIPM)
PPP	Precise point positioning
IGS	International Association of Geodesy
IAG	International Association of Geodesy
SLR	Satellite Laser Ranging
ICRF	International Celestial Reference Frame
LoD	Length of Day
LLR	Lunar Laser Ranging
T&F	Time and Frequency
PRTC	Primary Reference Time Clock
ITU	International Telecommunication Union
ICN	International core network

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