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THE IMPACT OF QUANTUM TECHNOLOGIES ON THE EU'S FUTURE POLICIES

Part 1 Quantum Time

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The Impact Of Quantum Technologies On The EU's Future Policies, Part 1 Quantum Time
Abstract

Atomic clocks are a quantum technology, used in national metrology laboratories to define UTC and in various networked infrastructure. Developments in the clocks themselves, and in the distribution of precise time, can be expected to affect several application areas of importance to European policy.

Contents

Acknowledgements

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Executive summary

This report is one of several, produced within a JRC study, devoted to the policy impact of different branches of quantum technology.

Policy context

Quantum technologies in general are the subject of an ongoing initiative to set up a FET Flagship, motivated mainly by the economic potential they are believed to offer. Atomic clocks are one of the better established examples. Although new opportunities may well exist for products such as chip scale atomic clocks, the economic benefit should also come from applications in various forms of networked infrastructure. Ultraprecise time also impacts on various other policies. Timestamping of financial transactions, electronic commerce and geo-referencing of data (INSPIRE) are all affected.

Scientific advances in ultraprecise clocks have led to a highly-developed voluntary international cooperation of national laboratories under the coordination of the BIPM. Almost all EU member states participate and some play leading roles. Coordination of the EU national metrology labs and their contribution to the BIPM is further underpinned by EURAMET. This strong position is, however, not reflected at the level of national legal definitions of time. A rational EU strategic policy goal would be to fully embed the BIPM definition of time in EU law and the laws of member states. Further technological evolution towards a standard based on optical clocks is expected. This would entail the installation of dedicated fibre for coordination of the national standards across Europe, and this infrastructure could also be used to distribute ultraprecise time signals for applications.

A voluntary international cooperation also exists for geodetic height, under the IUGG, and using the relativistic gravitational redshift offers the possibility of a significantly more accurate international system. In this case a harmonized legal definition across the EU already exists, via the INSPIRE directive.

Main findings and key conclusions

Policy areas where precise time is important vary between the highly regulated, with specific EU regulations and directives, to those where effective voluntary harmonization exists through international scientific non-governmental organizations and standards bodies. Coordination of standard clocks between NMI's is well-developed but no EU-wide, harmonized legal definition of time, or system of traceability exists. An application of particular importance is timestamping financial transactions, but the current regulatory regime does not yet adequately meet the needs of modern high speed trading. The continuing evolution of atomic clocks has led to important technological shifts which carry policy implications. Optical clocks, using visible light, are now starting to outperform microwave clocks and fibre optic networks are under development for coordination between NMIs. Together, these offer new possibilities for applications of ultraprecise time, including but not limited to basic research. A more precise geodetic framework may be established on the basis of gravitational redshift, affecting policies which make use of this. Fibre distribution of precise time may lead to it becoming available as a commoditized or free service, not subject to the limitations of GNSS and terrestrial radio sources. At the same time, atomic clocks of more modest precision are becoming smaller and cheaper, which also offers new possibilities for cost reductions in applications in telecommunication networks and smart grids and may help to mitigate risks brought about by technology change (power grids), or malfeasance (GNSS jamming and spoofing).

Related and future JRC work

This is the first subject report from the JRC quantum technology study. One on quantum communications is being prepared. Quantum computing is being addressed in a foresight

exercise and a further report on quantum sensing is planned. Applications of atomic clocks for navigation, not included here, will also be addressed separately.

Quick guide

The report consists of a brief explanation of atomic clocks as used in national metrology institutes and the ways that precise time is distributed, a discussion of applications and relevant EU policies, in finance and commerce, power networks, telecommunication networks and geodesy, and a final note on basic research applications.

1 Background on quantum technologies

This report is part of a study to assess the potential impact of quantum technologies on EU policy, which is being conducted by the Joint Research Centre (JRC) of the European Commission.

Quantum technologies have gained increased interest in the last years as research evolves towards application. The application of quantum physics offers possibilities for completely new approaches to a wide-range of technological problems. Furthermore, in such a new field, advances which are relatively simple scientifically, or have been made as enabling steps for something else, may have high practical impact. It is, however, necessary to be aware of the risks of over-promotion. Just because a novel device or technique is based on a deep scientific insight and can be made to work, it does not follow that it will be competitive with conventional technology.

National programmes in quantum technologies have been launched by EU member states, in partnership with commercial companies; the best-known examples are the Netherlands' QuTech and QuSoft programmes (http://qutech.nl and www.qusoft.org) and the UK national quantum technologies programme (http://uknqt.epsrc.ac.uk/). Technology giants such as Google, IBM and Intel (quantum computing), Microsoft (software for quantum technology), Toshiba (quantum communications) with very large total R&D budgets are willing to make the high-risk R&D investment needed. Small research spin-off start-up companies are also appearing. Outside Europe, some prominent initiatives are on quantum communication in China and the US, NIST and associated groups in the US and Quantum Valley Investments in Canada.

The Science and Technology Options Assessment group of the European Parliament has taken a strong interest in the subject, and made quantum optical science and technology the subject of its 2015 Annual Lecture. The possibility of setting up a Future and Emerging Technology Flagship in Quantum Technologies was publicly raised by the European Commission in communication COM 178 of April 2016. A small group of advocates of quantum technology who had been developing this idea released "The Quantum Manifesto" shortly afterwards [de Touzalin et al., 2016], and formally presented it to the Commissioner for the Digital Economy and Society in May. Over 3600 signatories have endorsed it to date. These discussions were welcomed by the Competition Council, and a high-level steering committee (HLSC) of academic and industrial experts was established to guide preparations. Its initial ideas for a governance model and work plan were made public in November, following which the Commissioner updated the Competition Council. The HLSC has recently presented its intermediate report at a workshop organized by the Maltese presidency on 17 February, which includes a proposal for a Strategic Research Agenda.

This activity is mainly motivated by the economic benefits expected from a quantum technology industry, if Europe's very strong position in research in this field can be maintained into the commercialization phase. But quantum technologies may also open new possibilities in cybersecurity, law-enforcement, defence and security and health, which are of direct public policy interest.

In order to understand which policies are most likely to be affected by a potential emergence of such technologies in the next five years and what will be the possible effect, the JRC is consulting selected stakeholders, from both within the EU and outside, in the major application branches of quantum technology. Our aim is to elucidate dispassionately what can be foreseen, over the full spectrum of policy. The study will also consider whether it would be useful for the JRC to take on a role in this field itself.

This present report concerns applications of precise time measurement by atomic clocks: one of the best established quantum technologies.

The report draws on the results of a workshop held at the JRC Ispra on 12th May 2016

The list of organizations that participated can be found in Annex I.

2 The quantum technology of precise time

2.1 Atomic clocks as fundamental time standards

The international time system is maintained by the Bureau International des Poids et Mesures (BIPM) in Paris. All but one of the EU member states are members or associates of the BIPM. European national metrology institutes (NMI's) are also coordinated via the European Association of National Metrology Institutes (EURAMET).

Time signals generated from more than 500 hydrogen masers and caesium clocks in more than 70 metrology laboratories around the world are communicated via satellite to the BIPM and a weighted average is used to produce Echelle Atomique Libre (EAL). This is calibrated against signals from primary and secondary caesium clocks at 11 NMI's, averaged over 1 year and taking into account relativistic corrections, to generate International Atomic Time (IAT). This scheme takes advantage of the superior short - term stability of hydrogen masers and the superior long-term drift of the caesium clocks, the latter being therefore the fundamental standard ([1]). Coordinated universal time (UTC) is produced by adding leap seconds to IAT, where necessary to keep synchronized with the Earth's slowing rotation. The metrology institutes maintain their own versions called UTC(*k*) where *k* is the acronym of the institute, which are used as continuous references for local clock comparison and frequency distribution. Deviations of the UTC(*k*)'s from UTC are published in BIPM Monthly Bulletin "Circular T" ([2])

Atomic clocks using visible light, termed "optical" clocks, are starting to outperform those using microwaves [Poli et al., 2013]. The desiderata for an atomic clock [Ludlow et al., 2015] are: high frequency, narrow line width and long probe time, large number of atoms and long averaging time. Although, therefore, the higher frequency of optical clocks is an inherent advantage, it is only recently that sufficiently narrow spectra lasers for the probe beam, and optical combs for counting and frequency comparison, have become available. A landmark was the precision of 1.6×10^{-18} over a 7-hour period achieved using a ^{171}Yb clock, published on 22 August 2013 by the National Institute for Standards and Technology (NIST) [Hinkley et al., 2013], followed shortly afterwards by a a Sr clock at the same institution with nearly the same performance [Bloom et al., 2014]. Since then metrology institutes in Europe have reported similar achievements [Huntemann et al., 2016].

Despite this progress, it is likely to be at least some years before a revision of the standard for the second is viable [Gill, 2016]. One reason is that there is currently no universally agreed best candidate. Systems based on several different isotopes are being researched, some well-studied ones are ^{87}Sr, ^{88}Sr$^+$, ^{171}Yb$^+$, ^{174}Yb and ^{199}Hg$^+$. It may not necessarily be best to standardize on the most accurate clock; how well studied it is and how easy to realize must also be taken into consideration. Another constraint on revision of the SI standard second is that it must be approved by the General Conference on Weights and Measures, which is held only every four years. The earliest reasonable opportunity would be 2026.

A more concrete difficulty preventing refinement of fundamental time standards is that it is not possible to synchronize clocks via satellite much beyond the existing accuracy. One alternative is to make the standard optical clocks transportable and physically bring them

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([1]) The international definition of the second, 9 192 631 770 periods of the radiation from the transition of the two hyperfine levels of the ground state of ^{133}Cs, has not changed since 1967 [BIPM 2006, 2014]. In 2006, secondary representations were adopted based on ^{87}Rb, ^{88}Sr$^+$,^{87}Sr, ^{199}Hg$^+$ and ^{171}Yb$^+$.

([2]) http://www.bipm.org/en/bipm-services/timescales/time-ftp/cirt.html#nohref
The table shows the institutes contributing to the system and the differences between UTC and UTC(*k*). In the column uA, the uncertainty originating in the standard, at the time of writing there was one entry, at PTB, at 0.1ns, one, at the US Naval Office, at 0.2ns and several at 0.3ns. Further details, including a list of the contributing clocks, may be found in the BIPM annual report at
http://www.bipm.org/en/bipm/tai/annual-report.html

together for comparison [Cao et al., 2016], [Koller et al., 2017], which may be the only possibility for intercontinental comparison. Several projects within Europe, though, have centred on synchronization of fixed clocks via dedicated fibre-optic lines [Gibney, 2015].

Optical fibre links for frequency transfer are in operation between SYRTE(France), PTB (Germany) and NPL (UK). These phase compensated links reach an ultimate resolution of one part in 10^{20} in less than one day of measurement, allowing for the best comparisons between remote optical clocks, as was achieved in June 2015 with the comparison of Sr clocks in SYRTE and PTB. The NPL-SYRTE link was made over fibre belonging to the GÉANT research network, under the ICOF project.
http://www.geant.net/opencall/Optical/Pages/ICOF.asp

Distribution of the Italian national time standard from INRiM in Torino by fibre-optic link is being progressively extended through the peninsula and into France in the project "Link Italiano per la Frequenza e il Tempo (LIFT)" [Levi et al., 2013].

In the EURAMET EMRP project SIB02 NEAT-FT, new techniques were investigated for phase-coherent comparison of remotely located optical clocks, separated by distances of up to 1500 km using optical fibre links.

In April 2015, SGF, a BIPM Study Group on optical Fibre links for UTC, was established, under the CCTF Working Group on Coordination of the Development of Advanced Time and Frequency Transfer Techniques (WG-ATFT). SGF will focus on the developments and achievements in the field of frequency and time transfer using optical fibres, aiming at the comparison of atomic clocks, the comparison of timescale, the dissemination of time and frequency standards and of UTC to users.

The project "CLONETS – CLOck NETwork Services: Strategy and innovation for clock services over optical-fibre networks" began in January 2017, funded under the H2020 INFRAINNOV-02-2016 Call, linked to telecommunications companies and GÉANT. It aims to prepare the transfer of precise time over fibre technology to industry, to strengthen the coordination between research infrastructures and the research and education telecommunication networks. The end goal is a sustainable, pan-European network, providing high-performance clock services to European research infrastructures, compatible with a global European vision of time and frequency distribution over telecommunication networks including lower precision services.

It may therefore be said that the first links in a European fibre network for dissemination of ultraprecise time have been built and it is expected and hoped that it will be progressively extended. It will have applications in fundamental and applied physics, geodesy and astronomy; see below.

Improvements in atomic clocks will in future drive a revision of the definition of the second. Well-established arrangements to manage this process exist via the NMI's, EURAMET and the BIPM. The change will be small, will directly affect only specialist scientific users and is unlikely to occur before 2026. It should not have a high impact on policy directly, but it may have indirectly because, to overcome the limitations of satellite synchronization so that improved primary clocks can be fully exploited, fibre-optic networks are being built in Europe. These networks will enable better traceability of ultraprecise time which will also benefit applications.

2.2 Dissemination of precise time

It should be understood that receiving the fibre-distributed ultraprecise time signals described above requires a small optical laboratory with skilled staff. Much more development is needed to make it into a user-level service or "precise time from the wall socket". Other methods are currently used to disseminate precise time from NMI's.

2.2.1 Dissemination by terrestrial radio

Several EU member states disseminate their UTC(*k*) by terrestrial radio (see Annex 2 for list of transmitters). Typically the time signal is transmitted with microsecond precision but this reduces to milliseconds for reception in less favourable locations. Terrestrial radio dissemination is very well suited to lower cost, lower precision applications, because the signals can easily be received on consumer-grade radio-controlled clocks.

2.2.2 Dissemination on GNSS

Global navigation satellite systems (GNSS) determine position on a time-of-flight principle, using atomic clocks mounted on the satellites. In the EU's Galileo system, this is achieved by means of passive hydrogen masers and rubidium clocks. In the US Global positioning System (GPS) most of the satellites have rubidium clocks and some are also equipped with caesium clocks. Russian GLONASS satellites now use caesium clocks, although rubidium was used in some of the original satellites in the 1980's and was considered for the more recent GLONASS K satellites. Chinese Compass/Beidou satellites use rubidium clocks. A detailed discussion may be found in [Malette et al., 2010]. http://www.esa.int/Our_Activities/Navigation/How_the_Galileo_atomic_clocks_work

The International GNSS service (IGS) provides, on an openly available basis, the highest quality GNSS data, product and services in support of the terrestrial reference frame, Earth observation and research, positioning and timing, and other applications. IGS Clock Products provide global sub-nanosecond time transfer, jointly with the BIPM. http://www.igs.org

The clocks in all the GNSS constellations are synchronized to UTC, which is therefore available from GNSS signals as a by-product, and is such a convenient source of precise time that its use has become ubiquitous, and possibly entrenched. "GPS disciplined oscillators" (GPSDO's) sell for a few hundred Euro, or even less than 100 Euro. Managers of computer networks or large infrastructure may not even be aware that their systems depend on a time reference from satellites.

Some GPSDO's are quartz oscillators which are steered to GNSS time, others do also contain their own rubidium clocks. Vendors usually specify a hold over accuracy versus time, for when the GNSS signal is lost. GNSS time has the inherent vulnerabilities that the signal might be jammed or spoofed, blocked by space weather or switched off for a security alert. Hold over capability provides no protection against undetected spoofing.

EU Policy

On 15 December 2016 Galileo started offering its initial services to public authorities, businesses and the general public. It is a flagship project of the recently published Space Strategy for Europe – see http://ec.europa.eu/growth/sectors/space_en. It is expected that, in the coming years, Galileo services will be widely used in Europe. However, non-EU GNSS services, especially GPS and GLONASS, are now also important, and will continue to be.

Galileo services are governed by Parliament/Council Regulation (EU) 1285/2013 on the implementation & exploitation of European Satellite Navigation Systems.

There are potential safety and security risks in using GNSS time in critical systems and infrastructure, which might demand a policy or legislative response for specific cases.

2.2.3 Dissemination on computer and telecommunication networks

Computer networks usually carry time information and telecommunication networks often do so, modern ones may indeed use the same protocols. Often, although they may also contain local atomic clocks, computer and telecommunication networks are synchronized to GNSS, and so can be used as a source of UTC. The precision is dependent what protocols are implemented and on what hardware. It can be as low as 10ms but some types of network have precision better than 10ns. More detail is given in Chapter 3.

2.3 Legal Time

It is important that time is legally defined, with an accuracy which reflects the requirements of modern society, so that there is a basis to settle disputes and issue judgments in cases for which the time at which some event occurred is critical. But a study conducted by EURAMET in 2009-2010 showed that, of 34 EURAMET countries surveyed, 16, including 13 current EU member states, did not have a legal definition of time [Lapuh, 2011]. In 8 of these, the NMI's were lobbying for one.

Some states define their legal time to be UTC or the local UTC(*k*). One or more disseminations of UTC, by terrestrial radio, satellite radio, telephone network or data network can also be used, and the EURAMET survey shows various combinations. For example, Germany uses the DCF77 terrestrial radio signal, based on UTC(PTB) as its legal time (Annex 2), and it is also incorporated into the legal definition of time in the Netherlands and, informally, Denmark. Most EU member states recognize computer network or GNSS disseminations for legal purposes. Limited precision and possible vulnerabilities to loss of signal or malfeasance mean that none of these methods provide a comprehensive solution.

When an electronic signal is used to timestamp an event with a legal character, such as a transaction, one of the most important requirements is that the signal is traceable. This is another driver for fibre-distribution of precise time, distinct from synchronization, because fibre is much less vulnerable to spoofing and jamming than radio distribution. Fibre is not completely invulnerable, however, and encryption of time signals may also be needed.

There is a possible need for a harmonized European system of protocols and standards for interfaces for distribution of ultraprecise time. Chips able to handle different protocols might obviate the need for strict uniformity.

The lack of an EU-wide system of legal time is a significant weakness and carries risks for the future. Progress in making atomic clocks and online sources of precise time cheaper, more readily available, traceable, interoperable and protected from malfeasance can contribute to resolving this.

2.4 Lower precision stand-alone atomic clocks

Atomic clocks have applications in power generation and transmission, computer networks, fixed line and mobile telecommunication, financial trading and even high-grade audio systems, where temperature controlled quartz crystal oscillators are considered insufficient. Stand-alone clocks are used where there is a motive to be independent of GNSS.

Rack-sized atomic clocks with an Allan deviation ([3]) $<2\times10^{-12}$ (100 s) are sold commercially for a few thousand Euro. Chip-scale atomic clocks (CSAC's) : micro-engineered devices of a few 10's of grams, are now available for applications where greater mobility or lower power consumption is needed e.g. military and petroleum exploration [Zhong, 2014]. A commercially available version claims an absolute frequency offset on shipping $< 5 \times 10^{-11}$ and an Allan deviation $< 3\times10^{-11}$ (100s). Small portable instruments based on CSAC's are also available. The wider availability and reduced price of CSAC's may open new possibilities for network synchronization (see Chapter 3).

US origin CSAC's can be restricted by the International Traffic in Arms Regulations (ITAR), which is applied by the US much more widely than might be inferred from its name alone. However vendors are now offering ITAR-free CSAC's.

There is a possible future need for standardisation of CSAC's.

([3]) The Allan deviation, which is the usual measure of clock stability, is the root mean square difference between two values of the slope in the time reading, over a specified time interval [Allan, 1987].

3 Principal applications and associated policies

3.1 Computer networks

Time synchronisation is almost always used in computer networks, to avoid possible errors caused by data carrying inconsistent time information e.g. an email received before it was sent. Achieving adequate precision and reliable time synchronization in a computer or other electronic communication network is a complex engineering task which depends on the existence of agreed protocols. The real performance achieved depends on the protocol and the details of the hardware implementation.

Relatively modest precisions may be enough for a network to function well, providing the protocol is very robust. Network Time Protocol (NTP) is a standard for synchronisation of computer networks, set by the Internet Engineering Task Force, an open community. NTP is long established and widely used. It is implemented on the internet protocol (IP) layer, i.e. in software. Several different time signals can be received by each computer and compared to remove outliers but, since most IP routers introduce substantial delays, variable from packet to packet, ordinarily only millisecond precision can be achieved on local networks, and tens of milliseconds on wide area networks.

NTP also has known security vulnerabilities. Latest information about these, and fixes, can be found at
http://support.ntp.org/bin/view/Main/WebHome#NTP_Security_Information.

The IEEE 1588 Precision Time Protocol (PTP) is an Ethernet-layer protocol which can achieve higher precision in networks without routers, containing special switches which measure and allow for the transit time. It is considered the first choice for modern telecommunication networks and, while most Ethernet networks being deployed today are capable of supporting it, legacy networks in Europe mostly are not. If PTP is implemented on a routed network the precision is likely to be less than that achieved with NTP, which has better algorithms for coping with packet arrival-time noise.

PTPv2, is an industrial evolution of PTP that better defines protocol devices cases and results in significant improvements in time synchronization. Ethernet networks usually do not have a single synchronizing clock, but one can be added using the ITU Synchronous Ethernet protocol (SynchE), defined by ITU recommendations G.8261, G.8262 and G.8264. By combining PTPv2 with SyncE, the time information and frequency is distributed to all the nodes.

White Rabbit is a commercially available, fully deterministic Ethernet-based network for general purpose data transfer and synchronization. It is a system variant of PTP developed by a consortium including CERN and the GSI Helmholtz Centre for Heavy Ion Research, for networks of limited size. It can synchronize over 1000 nodes with sub-ns accuracy over fibre lengths of up to 10 km. It can also be implemented on standard optical networks, to precisions which are now being pushed to below 10 ns. http://www.ohwr.org/projects/white-rabbit.

Two other approaches being taken are using hardware-timestamping with NTP, and using routers which recognize PTP packets and forward them with controlled delay.

IT networks using precise modern methods for synchronisation do generally rely on an atomic clock of some description. Commercially available “grandmaster” clocks for PTP use GNSS time but some are available with optional rubidium clocks or caesium CSAC’s for hold over. So it may be said that while activity to improve timing in computer networks is focused on protocols and on switching and routing hardware, atomic clocks already have a place. Stand-alone atomic clocks will be used more in IT networks if their cost goes down.

3.2 Telecommunication Networks

3.2.1 Background

Precise timing is required for a number of important technologies in telecommunication networks: synchronisation of timeslots in time division multiple access (TDMA) networks, network time protocol (NTP) in satellite communication (both space and ground segment), and for handovers between base stations in professional mobile radio (PMR) and Cellular Networks, and time of day, traffic timing and time slot management in PSTN (public switched telephone networks).

The parent body for this sector is a UN agency: the International Telecommunications Union (ITU). All EU Member States are voting members of the ITU and the European Commission is a non-voting sector member. ITU recommendations are non-statutory but are generally followed in the EU. The European Telecommunications Standards Institute (ETSI) is the recognized regional standard European Standards Organization (ESO) dealing with telecommunications, broadcasting and other electronic communications networks and services, and supports European regulations and legislation through the creation of Harmonized European Standards.

As telecommunication networks have evolved to transport higher data capacity, the plesiochronous digital hierarchy(PDH) technology, in which data rates for European variants were specified generally only to an accuracy of 50ppm, has been superseded by the SDH (synchronous digital hierarchy) technology with 4.6ppm accuracy ([4]). In networks using PDH transport typically every higher order multiplex requires a higher clock accuracy than the primary rate multiplexers, switches and cross connects (see the ITU recommendation ITU-T G.705), whereas SDH networks are usually run with comprehensive network synchronization and timing distribution. The SDH standards do allow a non-synchronized mode, but the need to meet jitter and wander specifications, interfacing requirements at international boundaries and specific needs of digital voice networks have led to synchronized operation being preferred. Commercial timing equipment for SDH networks is, in practice, offered with master clocks referred to GNSS or with caesium clock references. PSTN networks generally have stand-alone atomic clocks and use GNSS as backup [EGA, 2015].

SDH is now starting to be superseded. Many new installations use Carrier Class Ethernet, WDM (wavelength division multiplexing) or optical transport network (OTN) technologies transporting mainly IP packet-based data. These networks in themselves do not need synchronization, but the data they carry may be time-dependent, so the considerations discussed in section 3.1 apply. They may also need to be synchronized in order to facilitate operation together with synchronized SDH networks.

3.2.2 EU Policies

Commission Staff Working Document, SWD (2016) 313 of 14 Sep 2016, "evaluation of the regulatory framework for electronic communications accompanying the document 'Proposal for a directive of the European Parliament and of the Council establishing the European Electronic Communications Code' ", explains the current status of technical standards for telecommunications in EU law.

"Under the regulatory framework, the Commission is required to establish a list of non-compulsory standards in order to encourage the harmonised provision of electronic communications networks and services and associated facilities and services. Such a list was set up under Decision 2007/176 as amended by Decision 2008/286/EC. The Commission can also ask standardisation bodies (CEN, CENELEC or ETSI) to draw up standards. Member States are furthermore encouraged to use those standards. If

([4]) North American telecommunication practice is different in the technical details. In Europe, the 32 channel form of PSDH called "E1" was used, in the USA, a 24 channel signal called "T1" was used whose data rate was specified to only 130ppm. In the USA and Canada, instead of SDH, a similar but not identical standard called Synchronous Optical Network (SONET) is used, with data rates specified to 20 ppm.

compliance with specified standards at EU level is encouraged, this would be done to ensure interoperability in the single market. The Commission is also given the power to adopt implementing measures in order to render specifications and standards compulsory." However, it has not done so and adherence to telecommunication standards in the EU remains voluntary and market-driven. The Commission has also made little use of its statutory power to mandate the standardisation bodies to draw up standards. SWD (2016) 313 does conjecture that the possibility that standards could be made compulsory may have helped to encourage their voluntary adoption.

ETSI Guide 201 793 V1.1.1 (2000) lists the various ETSI and ITU standards and explains synchronization needs for PDH, SDH and GSM. Among these, especially relevant is the series EN 300-462 "Transmission and Multiplexing (TM); Generic requirements for synchronization networks".

ITU recommendations are also non-statutory but are generally followed in the EU. Especially relevant are the following. ITU-Recommendation G.811 specifies that the long-term accuracy of the Primary Reference Clock (PRC) should be maintained at 1 part in 10^{11} or better, with verification to UTC. A PRC may be an autonomous clock or a non-autonomous clock disciplined by UTC-derived precision signals received from a radio or satellite system. G.811 also specifies performance for wander and jitter. Further ITU recommendations specify how time signals are applied. G.812 covers requirements of slave clocks suitable for use as node clocks in PSTN and in SDH. G.813 specifies characteristics of slave clocks just for SDH.

Atomic clocks are already widely used in telecommunication networks. Development of the technology, especially cost reduction, may be expected to have positive impact on the sector, possibly making them a future key enabling technology.

The EU legal framework allows technical standards for telecommunication to be made compulsory, but this has so far not been found necessary.

A trend towards convergence of telecommunication and computer network protocols may require a concomitant convergence of policies.

3.3 Financial transactions

3.3.1 Background

Trading in various types of security on financial markets is more and more done by computers running special algorithms. Companies seek to profit by removing the human element to achieve more objective decision making, and to place transactions more quickly than their competitors. Reliable timestamping of transactions conducted at very high speeds is therefore essential ([5]). This means that the timestamp must be both sufficiently precise, and traceable.

Currently, timestamping is achieved by local atomic clocks, GNSS and/or computer networks. As well as the source of precise time, the hardware and software implementation on the local network and machine must be adequate. See [Whibberley and Lobo, 2016] for an account of both regulatory and technical issues.

NPL provides a commercial service called NPLTime® which disseminates UTC traceable time over managed fibre links using PTPv2, to the City of London financial district. NPLTime® is certified by NPL itself.

INRiM began providing UTC traceable time over fibre to the Milan financial centre in January 2017.

3.3.2 EU policies

Parliament/Council Directive 2014/65/EU on markets in financial instruments (MiFID II) requires the timestamping of every transaction in the financial industry across all of the European Union. Moreover the directive requires that the clocks of trading venues and their customers be synchronized, standardizing the recorded time for post-trade data, transaction reporting and order event auditing. Article 50 of Directive 2014/65/EU sets requirements on synchronisation of business clocks and defines the responsibilities of the member states, the European Securities Markets Agency (ESMA) and the Commission in this regard as follows:

"1. Member States shall require that all trading venues and their members or participants synchronise the business clocks they use to record the date and time of any reportable event.

2. ESMA shall develop draft regulatory technical standards to specify the level of accuracy to which clocks are to be synchronised in accordance with international standards."

Power is delegated to the Commission to adopt the standards that ESMA submits to it.

ESMA's Regulatory Technical Standard 25 (RTS25) was accordingly adopted as a Commission Delegated Regulation on 7 June 2016. It sets the following requirements:

([5]) Whether or not this trend to high frequency trading is macro-economically advantageous is contentious but, whatever the conclusion of this debate, the need for timestamping of transactions conducted at very high speeds will remain. See [UK Government Office for Science, 2012] for discussion.

Table 1. Level of accuracy for operators of trading venues

Gateway-to-gateway latency time of the trading system	**Maximum divergence from UTC**	**Granularity of the timestamp**
> 1 millisecond	1 millisecond	1 millisecond or better
=< 1 millisecond	100 microseconds	1 microsecond or better

Table 2. Level of accuracy for members or participants of a trading venue

Type of trading activity	**Description**	**Maximum divergence from UTC**	**Granularity of the timestamp**
Activity using high frequency algorithmic trading technique	High frequency algorithmic trading technique.	100 microseconds	1 microsecond or better
Activity on voice trading systems	Voice trading systems as defined in Article 5(5) of RTS2 ([6])	1 second	1 second or better
Activity on request for quote systems where the response requires human intervention or where the system does not allow algorithmic trading	Request for quotes systems as defined in Article 5(4) of RTS2	1 second	1 second or better
Activity of concluding negotiated transactions	Negotiated transaction as set out in Article 4(1)(b) of Regulation (EU) No 600/2014.	1 second	1 second or better

The precision of 100μs for timestamps required by RTS 25 is unsatisfactory from a functional forensics and audit point of view. The practical need of regulators to prevent malfeasance is 1μs, which is technically achievable using existing methods.

A much higher precision of 1ns was proposed during the discussions for the regulation but was rejected as unachievable; reasonably enough, since UTC(k) itself is only precise to about 10ns . Furthermore, 1ns is beyond the precision of GPSDO and PTP and at the limit even for White Rabbit.

There is a strong case for tightening the regulatory requirement on the precision of timestamps for high speed trading on financial markets, moving to 1μs in due course.

([6]) RTS2 is a regulatory technical standard for bonds and other non-equity instruments, which is also intended to be adopted as a Commission delegated regulation.

3.4 Electronic identification and trust services for electronic transactions

3.4.1 Background

Electronic commerce now part of everyday life for the general public and has become a critical element of the modern economy. From an EU regulatory standpoint, it is considered to be one example of a trust service, along with things such as electronic government services. The time at which a transaction takes place can be significant legally, for example, in the event of a dispute over bids for an item or over whether a buyer was entitled to a special offer.

For the most part, individual transactions in electronic commerce do not take place at very high frequency, timestamps of e.g. 1 second precision are often sufficient. Legislation and standards focus much more on the cybersecurity aspects than on the technical issues of timing.

3.4.2 EU Policies

Regulation No 910/2014 on electronic identification and trust services for electronic transactions in the internal market, sets the overall EU policy in this area. Article 42 on requirements for qualified electronic timestamps states that they are to be based on UTC. Currently, no further detail about what this means is given in the regulation or the implementing legislation.

An ETSI technical specification (TS) covers the same topic:

TS 102 023 V1.2.2 (2008-10) Electronic Signatures and Infrastructures (ESI); Policy requirements for timestamping authorities

It gives much more detail about UTC, e.g. concerning handling leap seconds.

The ETSI TS also points out that, even if the timestamping authority has excluded liability in its contract, statutory law may impose it, according to the Unfair Contract Terms Directive 93/13/EEC and its corresponding national implementations, which may be stricter than the directive itself.

3.5 Electric Power Networks

3.5.1 Background

There are two issues of interest in synchronizing power networks. The first is source synchronization in order always to transmit the maximum power possible and the second is the timestamping of phase measurements which are conducted for monitoring purposes. Time-synchronization measurement and its application for protection, control etc. both at the transmission level, and increasingly at the local distribution level for smart grids, are topics of current research. While not new, they are gaining importance.

European power grids are coordinated by the European Network of Transmission System Operators for Electricity (ENTSO-E), making it responsible for the world's most extensive phase synchronized power transmission network.

A consequence of the advent of a more diverse electric power generation mix, with many low-power renewable sources, is that a substantial part of the energy in the grid has not been generated by traditional, massive, steam turbine generators, whose angular momentum provided a degree of automatic phase stability and the ability to respond to rapid changes of demand ("spinning reserve"). Instead, electronic control must be used.

While it is true that careful monitoring of grids is vital to guard against instabilities, and loss of synchronization on a continental scale can be disastrous, this does not require the use of ultraprecise clocks. Continent-wide blackouts, such as that of 4 November 2006 [Bundesnetzagentur, 2008], involve gross mismatches of frequency, of the order of 1Hz.

Normally, the purpose of phase monitoring is to avoid more local disruption, or to increase efficiency, especially when diverse generating sources are contributing. Precise time measurement can also be used to locate grid faults, using a time of propagation principle. Standards for disturbance monitoring indicate a threshold of 2ms, but fault location may require clock accuracies as high as 1μs. IEC 61850, a standard for electrical substation automation, also specifies microsecond precision. ([7])

At the transmission level, operators already use phasor measurement units (PMU's) to compare measured amplitude/phase with theoretical values, again to microsecond accuracy. Micro PMU's with GNSS timestamping [Von Meier et al., 2014] are now available. Future developments in GNSS and CSAC technology may therefore offer enhanced possibilities for monitoring smart grids. Reduction of the unit cost of PMU's would make it economic to install them at more points, to get a more complete picture at the local distribution level.

Finally, one may conjecture that precise time distributed on a smart electrical grid might be offered as a service to customers, separate from its use for the grid itself.

3.5.2 EU policies

Parliament/Council Regulation (EU) No. 347/2013 on guidelines for trans-European energy infrastructure

Commission delegated Regulation (EU) No. 1391/2013 amending above

Parliament/Council Directive 2009/28/EC on the promotion of the use of energy from renewable sources

EU policy, as stated in Regulation 347/2013, is to upgrade Europe's energy networks by interconnecting them at the continental level, in particular to integrate renewable energy sources.

([7]) The idea of writing PTP into IEC 61850 is being discussed.

3.6 Geodetic Height Measurement

3.6.1 Background

Very precise time is fundamental for geodesy. Global geodetic reference frames, consisting of geodetic satellites and ground station networks such as the International Terrestrial Reference Frame (ITRF), will benefit in several ways from greater clock precision and accuracy which will allow new ways of inter-technique combination and calibration in geodetic fundamental stations.

Atomic clocks can be so precise that they are significantly affected by the relativistic gravitational redshift over height differences of centimetres. As mentioned above, this has to be taken into account when defining standard time. Conversely, very precise measurement of time by optical clocks can be used to measure height with respect to a gravitational equipotential. A stability of 10^{-18} corresponds to 1cm in height. Only one clock in the world currently achieves this precision, although several can achieve slightly lower precisions, corresponding to 10cm.

The observation of the relativistic gravitational redshift in networks of ultraprecise clocks would therefore allow the building of fundamental height networks based on atomic standards, and the achieving of consistent, well-defined continental or worldwide height systems. These could replace the inconsistent patchwork of national height systems, based on laborious theodolite measurement, which we have today. A global network of clocks operating at the 10^{-18} level would not only provide a more accurate time standard but would also form the basis for a unified long-term stable geodetic height reference frame [Ludlow et al., 2015]. Applications benefiting could include those in civil engineering, such as tunnelling, and in basic science, such as Very Long Baseline Interferometry (VLBI). One example project is SFB 1128 GeoQ "Relativistic Geodesy and Gravimetry with Quantum Sensors" funded by the Deutsche Forschungsgemeinschaft.

International cooperation in geodesy is organized by several scientific NGO's, under the umbrella of the International Union of Geodesy and Geophysics (IUGG). The national laboratories of EU member states play a very strong role in this cooperation. The International Earth Rotation and Reference System (IERS) service is responsible for the International Terrestrial Reference System (ITRS). It was established by the IUGG, with the International Astronomical Union. Three ITRS Combination Centres, in Paris, Munich and Pasadena, are responsible for the computation of ITRS realizations. After a validation procedure, one realization is defined to be the official ITRF solution.

ITRS is a set of points with their 3-dimensional Cartesian coordinates, realized by estimates of the coordinates and velocities of a set of stations observed by VLBI, GPS, LLR (lunar laser ranging), SLR (satellite laser ranging) and DORIS (Détermination d'Orbite et Radiopositionnement Intégré par Satellite/ Doppler Orbitography and Radiopositioning Integrated by Satellite).

An IUGG European geodetic reference also exists: the European Terrestrial Reference System 89 – ETRS89. ETRS is maintained by the EUREF, the Reference Frame Sub-Commission for Europe of the International Association of Geodesy, which is an IUGG body. Having a European reference is not in conflict with having an international reference: movement of tectonic plates makes it necessary.

ISO also contributes to cooperation in geodesy; its technical committee ISO/TC 211 is responsible for standards on Geographic information/Geomatics. The standard ISO 19111:2007 "Geographic information -- Spatial referencing by coordinates" defines the conceptual schema for the description of spatial referencing by coordinates. It describes the minimum data required to define one-, two- and three-dimensional spatial coordinate reference systems with an extension to merged spatial-temporal reference systems. It also describes the information required to change coordinates from one coordinate reference system to another and includes definitions for terms such as geoid, height, gravity-related height and mean sea level.

3.6.2 Legal terrestrial reference

ETRS89 is a part of the INSPIRE Data theme Coordinate reference systems, defined in Annex I of Parliament/Council Directive 2007/2/EC of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). The use of ETRS89, where it exists, is legally binding for EU member states under Annex II para 1.2 of Commission Regulation (EU) No 1089/2010, the implementing regulation for INSPIRE:

"For the three-dimensional and two-dimensional coordinate reference systems and the horizontal component of compound coordinate reference systems used for making spatial data sets available, the datum shall be the datum of the European Terrestrial Reference System 1989 (ETRS89) in areas within its geographical scope, or the datum of the International Terrestrial Reference System (ITRS) or other geodetic coordinate reference systems compliant with ITRS in areas that are outside the geographical scope of ETRS89. Compliant with the ITRS means that the system definition is based on the definition of the ITRS and there is a well-documented relationship between both systems, according to EN ISO 19111"

A majority of member states have implemented official national geodetic references based on ETRS89 [Bruyninx et al.,2014]

The legal definition of geodetic height in Europe is already well-harmonized by INSPIRE, so an improved European geodetic height reference, based on measurements of gravitational redshift, could be introduced without the need to create an entirely new framework. It would be possible for the EU to move ahead with such a system before a global initiative took place, and as a step towards one.

INSPIRE Homepage http://inspire.ec.europa.eu/index.cfm/pageid/761

Two other bodies of European law have been identified which make reference to altitude: vehicles emissions and aviation safety.

Commission Regulation (EU) 2016/646 as regards emissions from light passenger and commercial vehicles (Euro 6) requires the altitude at which vehicles are tested to be recorded because it affects their emissions performance.

Even if it seems unlikely that improvements in height precision of the order of cm would affect measurements conducted under Euro 6, any change to the legal definition of height would need to be assimilated into the legislation.

Commission Implementing Regulation (EU) No 923/2012 of 26 September 2012 laying down the common rules of the air and operational provisions regarding services and procedures in air navigation sets the Standardized European Rules of the Air (SERA). It is an implementing regulation of Parliament/Council Regulation (EC) No 216/2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency (EASA). SERA makes numerous references to altitude, which is defined as being with respect to mean sea level.

EASA's Certification Specifications for European Technical Standard Order provides some rules for certification of both radio and pressure-activated altimeters, but they do not at present require calibration to geodetic height.

EASA is considering amending its basic regulation to include rules for unmanned aerial vehicles (drones), for which purpose rules for flight paths might need to be defined at a finer scale than is necessary for manned aircraft.

Any change to the legal definition of height would need to be assimilated into aviation safety legislation.

Extension of SERA to UAV's may make a more precise definition of altitude necessary.

The impact of any change, even a small one, should be carefully analysed and examined for unintended consequences, because altitude is so fundamental a concept for aviation.

3.7 Basic Research

3.7.1 Background

In this section are listed some of the applications of ultraprecise time in basic research. It is intentionally brief, since details of the research are outside the scope of this report. Nevertheless, to the extent that much of this work is publicly funded by European agencies and institutions, it is linked to EU policy.

Mapping the Earth's gravitational field from space
Atom interferometric sensors (e.g. accelerometers) have been proposed for future space missions to monitor gravity and mass variations. Two examples of recent missions with these objectives are ESA's GOCE (Gravity field and steady-state Ocean Circulation Explorer) mission, 2009-2013, and the ongoing NASA-DLR GRACE (Gravity Recover and Climate Experiment) mission.
http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE
http://www.nasa.gov/mission_pages/Grace/index.html

Tests of general relativity and gravitational wave detection
An example was the SAGAS proposal, submitted to ESA in 2007 (Search for Anomalous Gravitation using Atomic Sensors), which aims at flying an optical clock, a cold atom accelerometer and an optical link on a Solar System escape trajectory during the period 2020 to 2030. https://arxiv.org/abs/0711.0304

The ESA ACES mission (Atomic Clock Ensemble in Space) to operate a cold-atom microwave clock on the international space station will provide an improved measurement of the gravitational red-shift, a search for anisotropies of the speed of light, and a search for space-time variations of fundamental physical constants (see below). A follow-on mission, SOC (Space Optical Clock) is also planned, with a Sr lattice optical clock, intended to improve performance by at least a factor of 10 [Bongs et al., 2015].

Fundamental constants
The principle of atomic clocks is that the frequencies depend on fundamental physical constants, which are considered to be invariant. Conversely, comparison between different types of atomic clock can be used to search for any very slow change, in particular in the fine structure constant and the electron proton mass ratio [Ludlow et al., 2015].

Studies of the solar system
For example, the aims of SAGAS include improved measurement of the mass and mass distribution of the Jupiter system and the exploration of the Kuiper belt.

Radio astronomy
The technique of very long baseline interferometry (VLBI) employs separate atomic clocks on each antenna to measure the phase differences between signals received from the same object at different antennas, allowing interferometry without a physical connection. A large amount of information about the technique and its capabilities, and coordination of European activities in the field may be found at the website of the European VLBI network. http://www.evlbi.org.

Precise timing in particle accelerators and free electron lasers
Future accelerators and light Sources, such as X-ray free-electron lasers require femtosecond, and potentially attosecond, timing accuracy between electron beams and optical lasers for improved performance and to study the spatiotemporal dynamics of ultrafast processes on atomic and molecular scales. [Kärtner et al., 2010].

4 Conclusions

Policy areas where precise time is important vary between the highly regulated, with specific EU regulations and directives, to those where effective voluntary harmonization exists through international scientific non-governmental organizations and standards bodies. Coordination of standard clocks between NMI's is well-developed but no EU-wide, harmonized legal definition of time exists, nor is there an EU-wide system of traceability of precise time.

An application of particular importance is timestamping financial transactions, but the current regulatory regime does not yet adequately meet the needs of modern high speed trading or take advantage of what is already technically feasible.

The continuing evolution of atomic clocks has led to important technological shifts which carry policy implications. Optical clocks are now starting to outperform microwave clocks and fibre optic networks are under development for coordination between NMIs. Together, these offer new possibilities for applications of ultraprecise time, including but not limited to basic research.

A more precise geodetic framework may be established on the basis of gravitational redshift, affecting policies which make use of this.

Fibre distribution of precise time may lead to it becoming available as a commoditized or free service, not subject to the limitations of GNSS and terrestrial radio sources. At the same time, atomic clocks of lower precision are becoming smaller and cheaper, which also offers new possibilities for cost reductions in applications in telecommunication networks and smart grids and may help to mitigate risks brought about by technology change e.g. in power grids; or risks from malfeasance e.g. GNSS jamming and spoofing.

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ESMA Regulatory Technical Standard 25 (RTS25)

IEC 61850 for electrical substation automation

Network Time Protocol (NTP) a standard for synchronisation of computer networks, set by the Internet Engineering Task Force, an open community

1588-2008 - IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems

ITU-T G.705 Characteristics of plesiochronous digital hierarchy (PDH) equipment functional blocks

ITU G.811 : Timing characteristics of primary reference clocks

ITU G.812 : Timing requirements of slave clocks suitable for use as node clocks in synchronization networks

ITU G.813 : Timing characteristics of SDH equipment slave clocks (SEC)

ITU G.8261/Y.1361: Timing and synchronization aspects in packet networks

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Parliament/Council Regulation (EU) No. 347/2013 on guidelines for trans-European energy infrastructure

Commission delegated Regulation (EU) No. 1391/2013 amending the above

Parliament/Council Directive 2009/28/EC on the promotion of the use of energy from renewable sources

Council Directive 2007/2/EC establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)

Commission Regulation (EU) No 1089/2010 implementing the above, as regards interoperability of spatial data sets and services

Commission Regulation (EU) 2016/646 as regards emissions from light passenger and commercial vehicles (Euro 6)

Commission Implementing Regulation (EU) No 923/2012 laying down the common rules of the air and operational provisions regarding services and procedures in air navigation sets the Standardized European Rules of the Air (SERA)

Council Regulation (EC) No 216/2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency (EASA)

List of abbreviations and definitions

ACES Atomic Clock Ensemble in Space

BIPM Bureau International des Poids et Mesures

CSAC Chip-scale atomic clock

CSEM formerly Centre Suisse d'Electronique et de Microtechnique, acronym is now name

DORIS Détermination d'Orbite et Radiopositionnement Intégré par Satellite/
Doppler Orbitography and Radiopositioning Integrated by Satellite

EAL Échelle Atomique Libre

EASA European Aviation Safety Agency

EMRP European Metrology Research Programme

ENTSO-E European Network of Transmission System Operators for Electricity

ESA European Space Agency

ETRS 89 European Terrestrial Reference System

ETSI European Telecommunications Standards Institute

EUREF Reference Frame Sub-Commission for Europe (of the International Association of Geodesy)

EURAMET European Association of National Metrology Institutes

FET Future and Emerging Technology

GNSS Global navigational satellite system

GOCE Gravity field and steady-state Ocean Circulation Explorer

GPS Global Positioning System

GPSDO GPS disciplined oscillator

GRACE Gravity Recover and Climate Experiment

INRiM Istituto nazionale per la ricerca metrological (NMI of Italy)

INSPIRE Infrastructure for Spatial Information in the European Community

IP Internet Protocol

ISO International Standards Organisation

ITAR International Trade in Arms Regulation

ITRF International Terrestrial Reference Frame

ITRS International Terrestrial Reference System

ITU International telecommunications union

IUGG International Union of Geodesy and Geophysics

JRC Joint Research Centre of European Commission

LIFT Link Italiano per la Frequenza e il Tempo

LLR lunar laser ranging

LNE Laboratoire national de mésures et d’essais (NMI of France)

NIST National Institute of Standards and Technology (NMI of USA)

NMI national metrology institute

NPL National Physical Laboratory (NMI of UK)

NTP Network Timing Protocol

PDH plesiochronous digital hierarchy

PMR personal Mobile Radio

PMU Phase Measurement Unit

PRC Primary reference clock (of a telecommunications network)

PSTN Public switched telephone network

PTB Physikalisch-Technische Bundesanstalt (NMI of Germany)

PTP Precision Timing Protocol

SAGAS Search for Anomalous Gravitation using Atomic Sensors

SDH synchronous digital hierarchy

SERA Standardized European Rules of the Air

SI Système international d'unités

SLR satellite laser ranging

SOC Space optical clock

SONET Synchronous optical networking

SyncE Synchronized Ethernet

SYRTE/OP Système de Références Temps-Espace/Observatoire de Paris (of LNE)

TDMA Time division multiple access

UTC Universal Coordinated Time/Temp universel coordonée

VLBI Very long baseline interferometry

List of tables

Annexes

Annex 1. Organizations participating in the Workshop of 12th May 2016

CSEM

CSEM is a private, non-profit Swiss research and technology organization with longstanding links with the watch industry. Its research interests include miniaturized atomic clocks.
https://www.csem.ch/Watchmaking

Istituto Nazionale per la Ricerca Metrologica (INRiM)

INRiM is an Italian NMI. Its Time and Frequency Laboratory realizes and makes available to users the UTC(IT) time scale, the standard time for Italy.
http://rime.inrim.it/labtf/

Leibniz Universität Hannover

The Excellence Cluster "Centre for Quantum Engineering and Space-Time Research (QUEST)" unites the expertise of several institutes of the Leibniz Universität Hannover and other research and technology organisations in the neighbourhood, involved in research fields concerning ultraprecise time measurement.
https://www.uni-hannover.de/en/forschung/exzellenz/quest/

Menlo Systems

Menlo Systems is a small company employing about 100 people which works on short pulse lasers and optical frequency combs. It collaborates with several of the other participants, and with the Max Planck Institutes, from which it was spun-off.
http://www.menlosystems.com/

National Physical Laboratory (NPL)

NPL is the UK NMI which realizes UTC (NPL). It also provides the commercial service NPLTime® to the London financial centre for the timestamping of transactions.
http://www.npl.co.uk/science-technology/time-frequency/

Observatoire de Paris (LNE-SYRTE)

The Laboratoire national de mésures et d'essais (LNE) is the French NMI. Its department "Système de Références Temps-Espace" at the Observatoire de Paris (LNE-SYRTE/OP) is in charge of the realization of the references in the field of time and frequency, including UTC(OP).
http://lne-syrte.obspm.fr/

Physikalisch-Technische Bundesanstalt (PTB)

PTB is the German NMI which realizes UTC (PTB) . It currently possesses the world's most accurate primary time standard. https://www.ptb.de/cms/en/research-development/subject-areas-in-metrology/time-and-frequency.html

Ricerca Sistema Energetico (RSE)

RSE is an Italian state-owned company which carries out applied research especially for the electricity network, including communication systems for the smart grid.

http://www.rse-web.it/home.page

SP Technical Research Institute of Sweden

SP Sveriges Tekniska Forskningsinstitut is a Swedish NMI which realizes UTC(SP) . It is active, on a limited scale, in all areas of metrology. It has a long term goal of establishing an optical clock in Sweden. Relevant projects include transfer frequency over internet , not in dedicated fibre, and frequency combs for spectroscopy.

https://www.sp.se/en/units/measurement/time_frequency/Sidor/default.aspx

University of Birmingham

U. Birmingham leads the sensors hub of the UK national quantum programme.

http://quantumsensors.org/

http://www.birmingham.ac.uk/research/activity/physics/quantum/index.aspx

Collaborations

INRiM, PTB, Leibniz U. Hannover, Menlo Systems, NPL, SYRTE are members of the FP7 funded initial training network ACT (Future Atomic Clock Technology)

http://www2.hhu.de/itn-fact/doku.php

These organisations, and CSEM, are members of the FP7 project SOC2 "Towards neutral atom space optical clocks"

http://www.exphy.uni-duesseldorf.de/optical_clock/soc2/index.php

Annex 2. Terrestrial radio distribution

Table 3. EU precise time radio signals listed by BIPM

Call sign	Frequency (kHz)	Transmitter Location	NMI
DCF77	77	Mainflingen, Germany	PTB
EBC	15 006 4 998	San Fernando, Spain	ROA
MIKES	25 000	Espoo, Finland	MIKES
MSF	60	Anthorn, UK	NPL
TDF	162	Allouis, France	LNE-SYRTE

The DCF77 transmitter is approximately 25km south-east of Frankfurt am Main. Its control signal is generated in situ with the aid of a control device designed by PTB and monitored from Braunschweig. The antenna and transmitter is operated by Media Broadcast GmbH. https://www.ptb.de/cms/en/ptb/fachabteilungen/abt4/fb-44/ag-442/dissemination-of-legal-time/dcf77/localizacion-del-transmisor.html

The MSF transmitter is approximately 20km west of Carlisle, in Cumbria in north-west England. It replaces the old transmitter at Rugby which was turned off in 2007. The broadcast signal is monitored against the national time standard at the NPL site in Teddington. MSF is operated by Babcock International Group PLC, under contract to NPL.

http://www.npl.co.uk/science-technology/time-frequency/products-and-services/time/msf-radio-time-signal

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