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Strategy and innovation for clock services over optical-fibre networks

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High precision T&F needs of research infrastructures

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LIST OF ACRONYMS AND ABBREVIATIONS

ACES	Atomic Clock Ensemble in Space
DCF77	German longwave time signal and standard-frequency radio station
EMPR	European Metrology Research Programme
EMPIR	European Metrology Programme for Innovation and Research
EOSC	European Open Science Cloud
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
Galileo	Name of the European GNSS
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICRF	International Celestial Reference Frame
NEAT-FT	Accurate time/frequency comparison and dissemination through optical telecommunication networks
NMI	National Metrology Institute
NREN	National Research and Education Network
NTP	Network Time Protocol
OFTEN	Optical frequency transfer - a European network
PTP	Precision Time Protocol
RF	Radiofrequency
RI	Research Infrastructures
SI	Système International d'unités / International System of units
T&F	Time and Frequency
TWSTFT	Two Way Satellite time and Frequency Transfer
UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry

LIST OF PROJECT PARTNER ACRONYMS

AGH / AGH-UST	Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, Cracow, Poland
CESNET	CESNET, zájmové sdružení právnických osob, Prague, Czech Republic
CNRS[*]	Centre National de la Recherche Scientifique, Paris, France
INRIM	Istituto Nazionale di Ricerca Metrologica, Turin, Italy
GARR[#]	Gruppo per l'Armonizzazione delle Reti della Ricerca, Rome, Italy
Menlo	Menlo Systems GmbH, Martinsried, Germany
Muquans	Muquans, Talence, France
NPL	National Physical Laboratory, Teddington, United Kingdom
OBSPARIS[¶]	Observatoire de Paris, Paris, France
OPTOKON	OPTOKON a.s., Jihlava, Czech Republic
Piktime Systems	Piktime Systems sp z o.o., Poznan, Poland
PSNC	Instytut Chemii Bioorganicznej Polskiej Akademii Nauk – Poznańskie Centrum Superkomputerowo-Sieciowe, Poznan, Poland
PTB	Physikalsch-Technische Bundesanstalt, Braunschweig, Germany
RENATER	Groupement d’interêt Public pour le Reseau National de Telecommunications pour la Technologie, l’Enseignement et la Recherche, Paris, France
SEVENSOLS	Seven Solutions S.L., Granada, Spain
TOP-IX	Consorzio TOrino Piemonte Internet eXchange, Turin, Italy
UCL	University College London, London, United Kingdom
UP13	Université Paris 13, Villetaneuse, France
UPT AV CR (ISI)	Ustav Pristrojove Techniky AV, v.v.i., Brno, Czech Republic

[*] linked third party to OBSPARIS
[#] third party to INRIM
[¶] coordinator

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[12] http://www.eso.org/public/about-eso/faq/faq-elt/

[13] https://www.xfel.eu/

[14] http://www.fair-center.de/index.php?id=1&L=1

[15] https://home.cern/

[16] https://www.skatelescope.org/

[17] http://www.evlbi.org/

[18] https://www.jive.nl/

[19] https://www.esa.int/ESA

EXECUTIVE SUMMARY

This deliverable summarizes the major outcomes of a survey performed to identify future needs of research infrastructures (RI) in Europe for receiving or sharing precise and accurate time and/or frequency. Overall 37 institutes and organisations representative of the high performance time and frequency (T&F) needs of RIs responded to the survey. The survey revealed that applications requiring highest-performance frequency accuracy and instability seem to be more numerous than those requiring precise timing. However, the most demanding timing applications already require an instability that can only be met by dissemination through optical fibres. Among the respondents there seems to be a clear understanding and ranking of the importance of traceability to the SI, the availability of T&F signals at a remote location, the resilience of such signals and issues related to security. The *availability* of a fibre based T&F service is, on average, rated the highest by all respondents, followed by *resilience* with *security* being the least critical aspect, while *traceability* has divergent ratings. The communities that expect to benefit most from fibre based T&F service are radio-astronomy, geodesy, accelerator and spectroscopy laboratories, calibration laboratories and potentially space agencies. There is a growing awareness of the potential of fibre-based T&F services and at the same time an increasing need for better performance than currently available via classical satellite based technology.

1 INTRODUCTION

The availability of high performance time & frequency (T&F) signals is currently at the very heart of research activities in fundamental physics, such as high-resolution spectroscopy, special and general relativity, the search for temporal variations of fundamental constants and quantum optics. Additionally, it will have a strong impact on a wide range of applied sciences, such as geodesy (chronometric levelling), Very Long Baseline Interferometry (VLBI) and laser ranging. The industrial applications of high performance T&F signals are not limited to telecommunication (i.e. the supervision of the next generation of mobile networks), but will also include applications such as high speed trading, synchronisation in smart grids and the augmentation of existing techniques of the Global Navigation Satellite Systems (GNSS) such as Global Positioning System (GPS), or Galileo. In the future, high performance T&F signals derived from ultra-stable lasers or optical clocks will play a similarly important role in the development of novel applications and fundamental research as low noise RF-oscillators and primary Cs clocks have done over the last decades.

Today’s best optical clocks can reach an estimated systematic fractional frequency uncertainty at the level of a few 10^{-18} ([1], [2], [3]). Satellite-based frequency comparison techniques offer world-wide coverage, but lack the performance required for optical clock comparisons (e.g. [4]). A transportable clock has become available recently ([5], [6]), but with an accuracy of 7×10^{-17} it is still far from the full performance of its stationary counterparts. The unprecedented accuracy of modern optical clocks has spurred the development of frequency comparison techniques with an equivalent performance. An optical frequency transfer over fibre is currently the only technique capable of comparing high-performance clocks across long distances without degrading the stability and accuracy of the comparison ([7], [8]). The European Union (EU) funded projects NEAT-FT and OFTEN of the European Metrology and Research Programme (EMRP) and its successor European Metrology Programme for Innovation and Research (EMPIR), have demonstrated technologies for disseminating and comparing ultra-stable optical and radio-frequencies over fibre links. The efforts of these projects have culminated in the first international comparison of primary Cs fountains and optical clocks, which was not limited by the link between the clocks ([9], [10]).

Although an optical fibre frequency transfer is capable of reaching a stability and an accuracy in the 10^{-19} to 10^{-20} range ([7], [8]), the fibre-based frequency transfer capabilities in Europe have not yet advanced towards the development of a sustainable, universal tool for T&F metrology for Europe. In order to create a T&F infrastructure benefitting European science and society, the main issues hampering this development need to be addressed. Firstly, there is neither a reliable data base describing the T&F transfer techniques currently being used or evaluated by RIs nor is there a clear understanding of the current and future needs of such RIs for precise and accurate T&F transfers. Secondly, the capability and the benefits of fibre based T&F services are largely unknown to the user community and thirdly, the capacity for the integration of T&F transfer in existing networks provided e.g. by National Research and Education Networks (NRENs) has been explored only in very few countries.

This deliverable focuses on the needs of RIs for high precision T&F transfer, whereby high precision refers to performances superior to those provided by standard Precision Time Protocol (PTP), e.g currently served by H-masers, Rb clocks or GNSS. The report is based on data collected through a survey of RIs, which previously had been identified as relevant.

2 THE SURVEY

2.1 Definition and identification of RIs

Relevant RIs in the context of this deliverable are institutes and organizations which have timing needs in excess of standard PTP, H-masers or GNSS based services. They include National Metrology Institutes (NMIs), university based research groups in the field of quantum optics and high precision spectroscopy, research organizations (e.g. academies of science, the Max-Planck Society and the Fraunhofer Gesellschaft) and certain pertinent consortia interested in sharing T&F transfer technology (e.g. the ACES consortium, the Geodetic Observatory Wettzell and the International Association of Geodesy). Additionally, big infrastructures according to the European Strategy Forum on Research Infrastructures (ESFRI) were considered as relevant. In particular, RIs from the physical sciences and engineering [11], such as the European Extremely Large Telescope [12], the European X-Ray Free-Electron Laser [13], the Facility for Antiproton and Ion Research [14], the European Organization for Nuclear Research [15], the Square Kilometre Array [16], the European VLBI Network [17], the Joint Institute for VLBI ERIC [18], and the European Space Agency [19] were contacted.

In total, 52 RIs deemed as representative of the institutes and organizations having high precision timing needs were identified and contacted for the survey by means of an electronic questionnaire. Among these 52 RIs are 17 labs that contribute to Coordinated Universal Time (UTC). They are referred to as UTC(k) labs, whereas the remaining 35 RIs are classified as non-UTC(k) labs. Previously established contacts to the relevant RIs were exploited to ensure an adequate response to the survey. Overall 37 RIs (11 UTC(k) labs and 26 non-UTC(k) labs) responded to the survey, which is sufficient to obtain a general overview of the T&F needs of RIs. The RIs that participated in the survey are located throughout Europe, with responses coming from a wide range of different countries (Figure 1). There is a relatively large participation in France and the Czech Republic. The NRENs in these countries are very active in the field T&F distribution potentially leading to a greater awareness of the topic.

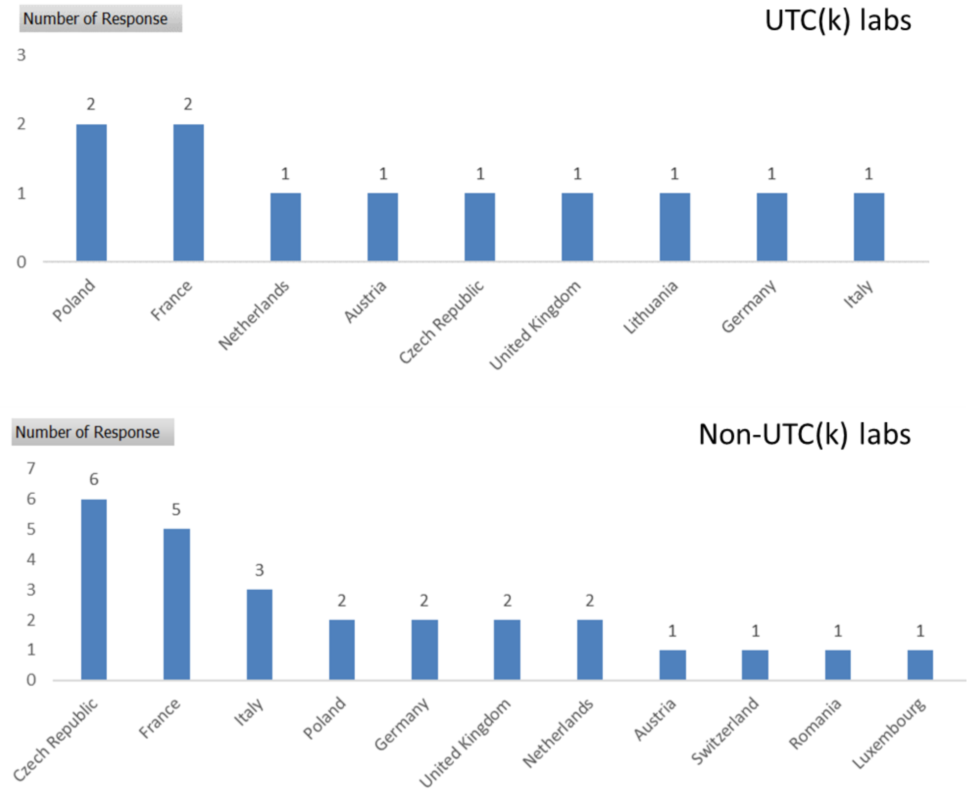

Figure 1. Responses received from UTC(k) labs (top) and non-UTC(k) labs (bottom) according to country.

Even though the total number of responses is larger than anticipated, the large spread in applications does not allow for a thorough statistical analysis or quantitative statements. In this report, we present a qualitative overview of the results and attempt to identify trends in the high precision T&F needs of RIs.

2.2 The Questionnaire

The questionnaire of the survey can be divided into four sections:

- general information on the RI (Section 2.2.1)
- status-quo of the T&F systems employed (Section 2.2.2)
- T&F reference performance requirements (Section 2.2.3)
- future needs of high precision T&F signals (Section 2.2.4)

The information was collected through a combination of prescribed answers and text boxes allowing the respondent to provide additional information where appropriate. The responses were split into UTC(k) labs and non-UTC(k) labs for the first two sections.

2.2.1 General information

In the first section of the questionnaire, the participant was asked to provide general information on their research group and the RI, such as the approximate number of employees at the RI, major activities of the group and role within the RI, and research fields of particular interest to the organization. The interviewed person could either mark the prescribed fields such as metrology, astronomy, geodesy, and geo sciences, particle physics, etc. (Figure 2) or specify another research field. In case several people of the same RI responded to the survey the information about the RI was merged into a unique dataset for this RI. However, for each RI multiple fields of interest could be named.

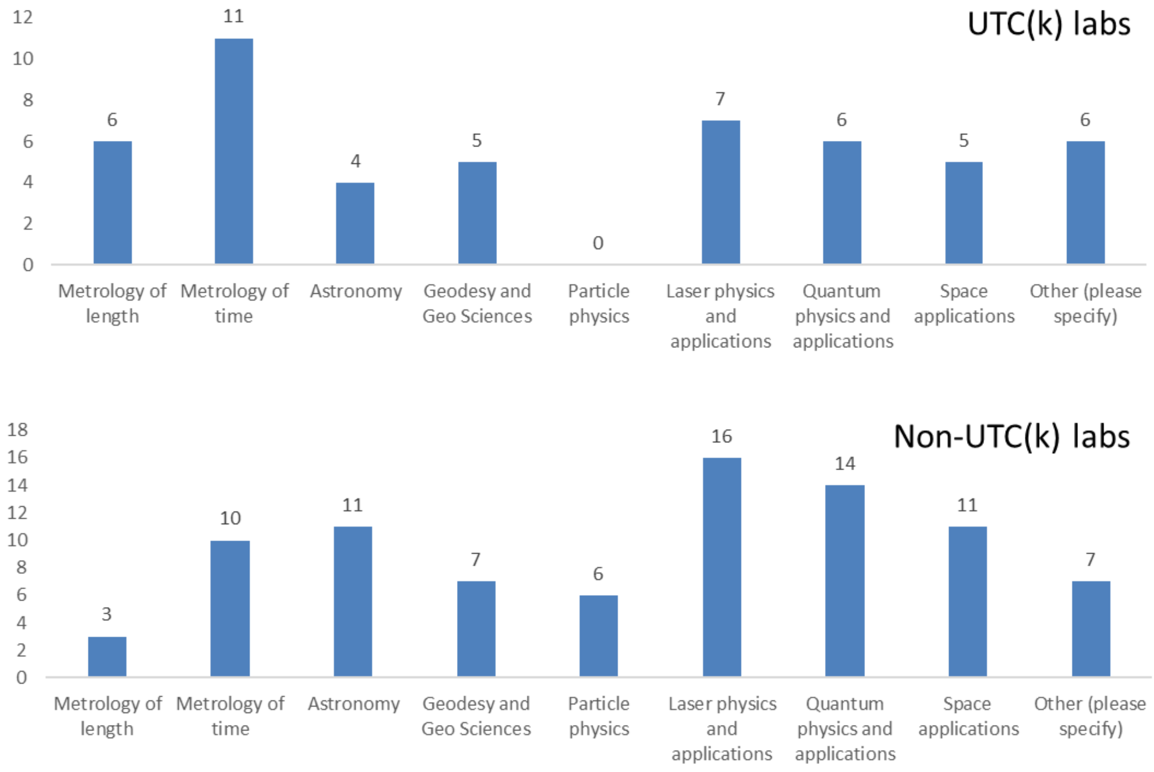

Figure 2. Fields of interest specified by UTC(k) labs (top) and non-UTC(k) labs (bottom).

The RIs interviewed are involved in a wide range of applications requiring high precision T&F transfer as shown in Figure 2. UTC(k) labs are not only involved in time metrology, but have interests in a wide range of applications. The overlap in research activities between the

UTC(k) labs and non-UTC(k) labs could potentially be indicative of the already established collaborations between the different types of labs.

2.2.2 Current T&F systems

Next, information about the status quo of the T&F systems employed to disseminate reference signals within the RI was collected. This included the following questions:

- What frequency standards does your organisation operate now?
- Does your organisation receive time from external signals?
- Does your organisation operate an internal time dissemination network?

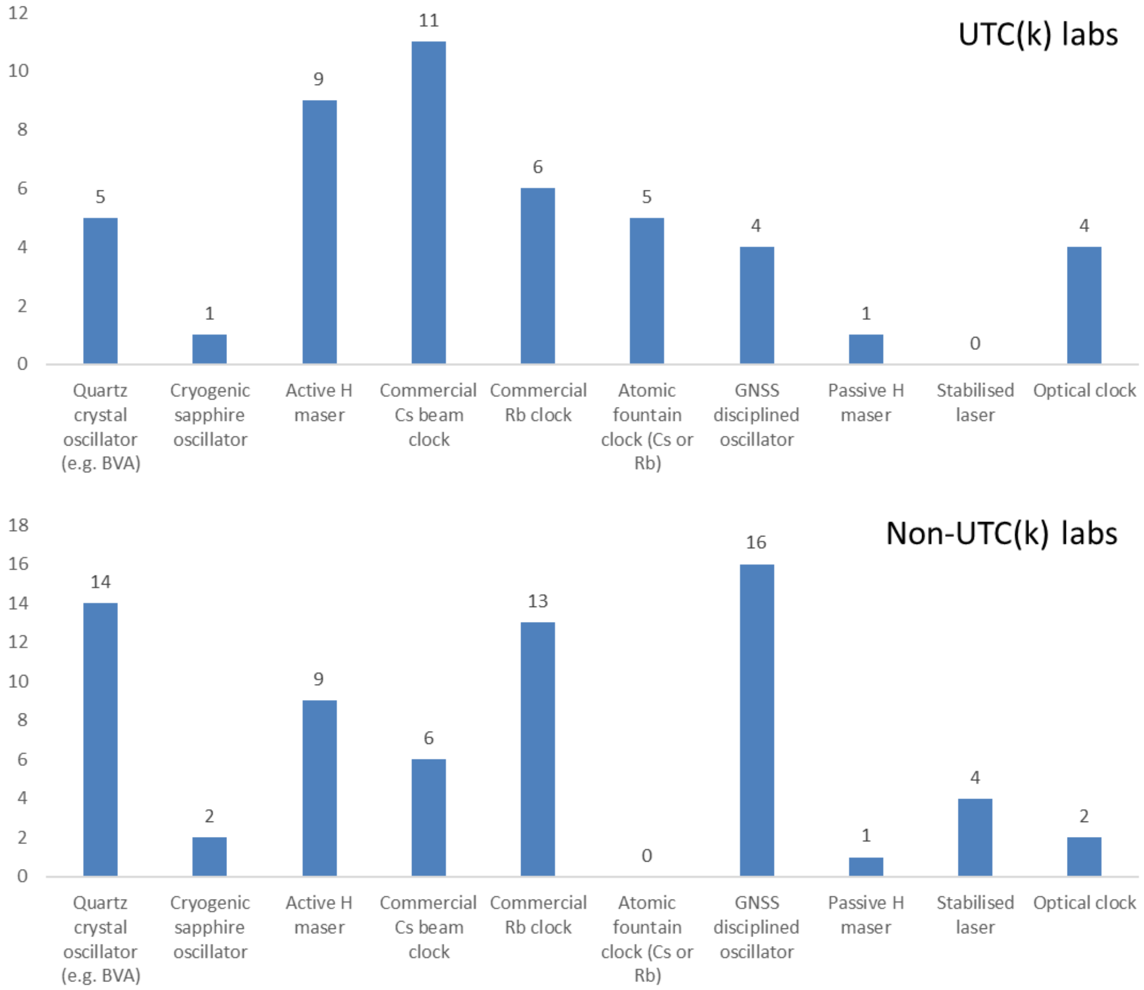

Figure 3. Frequency standards and clocks operated at the surveyed UTC(k) labs (above) and non-UTC(k) labs (below).

As can be seen from Figure 3, the majority (< 85%) of the in-house frequency standards operated at the surveyed RIs are based on RF sources such as H-Masers, commercial Cs- or Rb-clocks or GNSS disciplined oscillators. Atomic fountain clocks are operated exclusively at UTC(k) labs. Among the surveyed RIs, only 6 (4 UTC(k) labs and 2 non-UTC(k) labs) currently operate optical clocks as a frequency standard. As optical clocks are a novel technology and are still in development, it is not surprising that they are not yet widely available. The prevalence of optical clocks is higher among UTC(k) labs compared to non- UTC(k) labs reflecting the continuing effort made by UTC(k) labs to improve standards and the particularly high significance of high precision T&F standards for metrology.

In UTC(k) labs more than 50% of the frequency standards are based on atomic transitions (RF or optical) and thus are considered as absolute frequency standards. Only a few such absolute frequency standards (< 12%) are in use within non-UTC(k) labs. Here satellite and radio techniques (such as GNSS, TWSTFT, DCF77) or internet based protocols are used to achieve absolute accuracy via an external reference (see Figure 4). A smaller number already receives reference frequencies over fibre (other than Network Time Protocol (NTP)). According to the survey, the majority of RIs does not depend on a single frequency standard, but on combinations of active, passive and GNSS referenced devices.

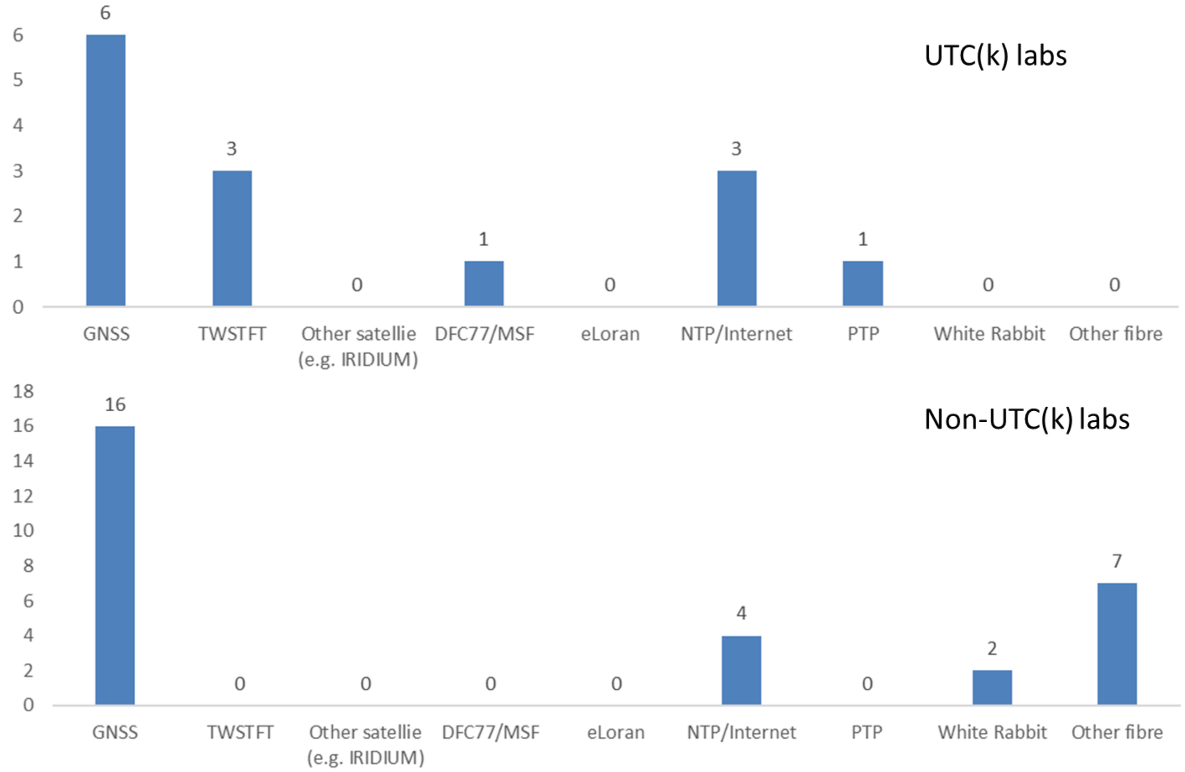

Figure 4. Source of the external T&F reference signals for UTC(k) labs (above) and non-UTC(k) labs (below).

More than 50% of the organizations do not only operate frequency standards at a single location, but also distribute the T&F signals to several other locations (typically on the order of 10). While for short distances (i.e. distances up to about 100 m, which corresponds to typical intra-building distances) the T&F signals are mainly distributed via electrical (coaxial) cables. Already at the campus level (several 100 m), distribution by optical fiber becomes the preferred method. For distances larger than 1 km optical fiber prevails.

2.2.3 Performance requirements of the T&F reference

The next section of questions addressed the performance requirements of the T&F reference signals employed by the organisation's major technical or research activities. The questionnaire made a distinction between time and frequency references. For each of these two types of references, the required performance with respect to the short-term ($\tau \approx 1$ s) instability, the long-term ($\tau \approx 1$ d) instability, and the accuracy was asked. The respondents were also asked to rate the importance of these performance criteria on a scale of 1 (critical) to 5 (irrelevant). The questionnaire also inquired about the importance of the traceability of reference signals to the SI, the security, the resilience and availability of reference signals for the RI. These criteria were rated on a scale of 1 (critical) to 5 (irrelevant), however no distinction between time and frequency references was made. Note that the data presented here is no longer separated into UTC(k) labs and non-UTC(k) labs.

According to the survey (Figure 5), frequency instability is the key performance that matters. Here a short-term instability (1 s integration time) at the level of 10^{-12} to 10^{-15} is required by most research activities, with no answers provided requiring a short-term instability lower than 10^{-15}. The long-term instability (1 d integration time) better than 10^{-14} is required by about 75% of the research activities. Among those requiring an instability better than 10^{-15} (≈ 27%) are again those who are involved in optical clock developments and other high-end applications. The performance requirements on the frequency accuracy are not equally distributed but appear to be bi-modal, with two peaks indicating a high demand for a frequency accuracy at both the 10^{-12} level and the 10^{-16} level. While the 10^{-12} level can be reached by conventional methods, the 10^{-16} level can only be reached either by in-house primary fountain clocks or by frequency dissemination via optical fibre.

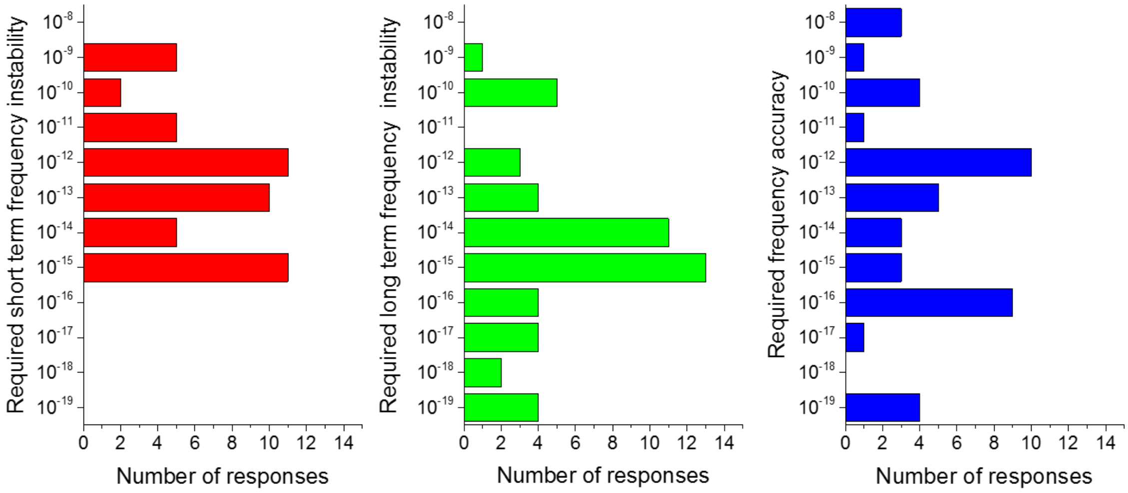

Figure 5. Fractional frequency instability (short term (red, left), long term (green, middle)) and accuracy (blue, right) required by the surveyed RIs.

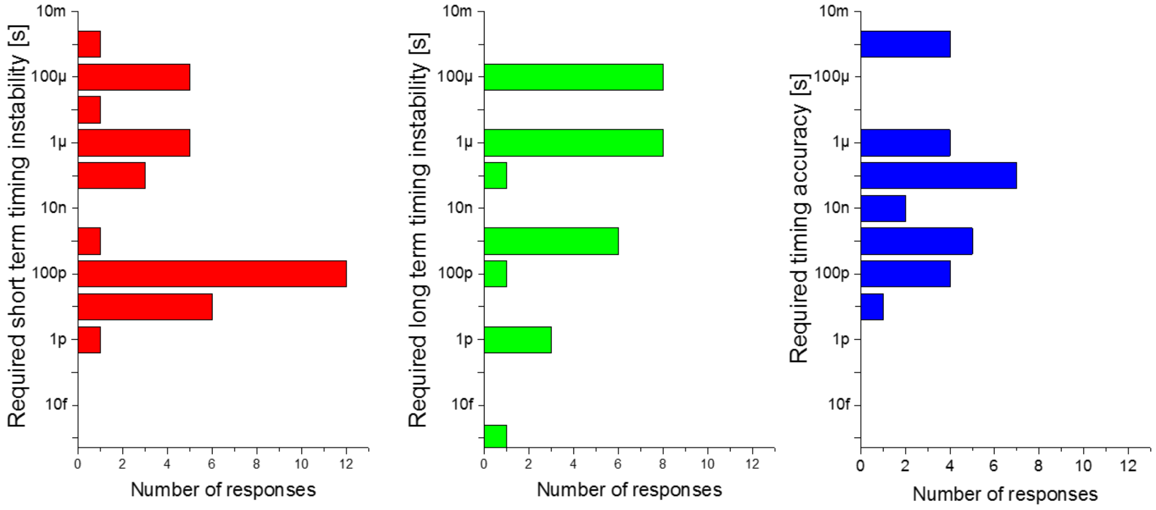

Figure 6. Timing instability (short term (red, left), long term (green, middle)) and accuracy (blue, right) required by the surveyed RIs.

For timing references the requirements are more complex (Figure 6). The required short term instability can be grouped in three groups: one group demanding stability and accuracy up to 10 µs, the next group up to 10 ns, and the largest group requiring a performance significantly better than 1 ns or even 100 ps. Again, the performance level of the latter case can only be met by a distribution system based on optical fibre.

Considering the way the RIs were chosen, in particular through the inclusion of UTC(k) labs, we suppose that the general findings are due to the fact that the T&F systems in place and the applications considered here strongly depend on each other. In other words: either the T&F systems already in place foster the development of the certain research activities of the RI (see Figure 2) or vice versa. Any application or experiment that requires a higher or better performance than readily available, would first have to focus its effort on the generation of a higher or better performance T&F signal. This assumption is further confirmed by the answers given when asking for the level of satisfaction with the current implementation of the T&F systems at the RI in view of the requirements (see Figure 7). In fact, about 80% of the respondents indicated that the current implementations of T&F reference systems operated by the RI are at least adequate matching or even exceeding the requirements. Among the approximately 13% of respondents rating their in-house implementation and performance as inadequate, are those that deal with the development of optical clocks, gravimeters or high-resolution laser spectroscopy.

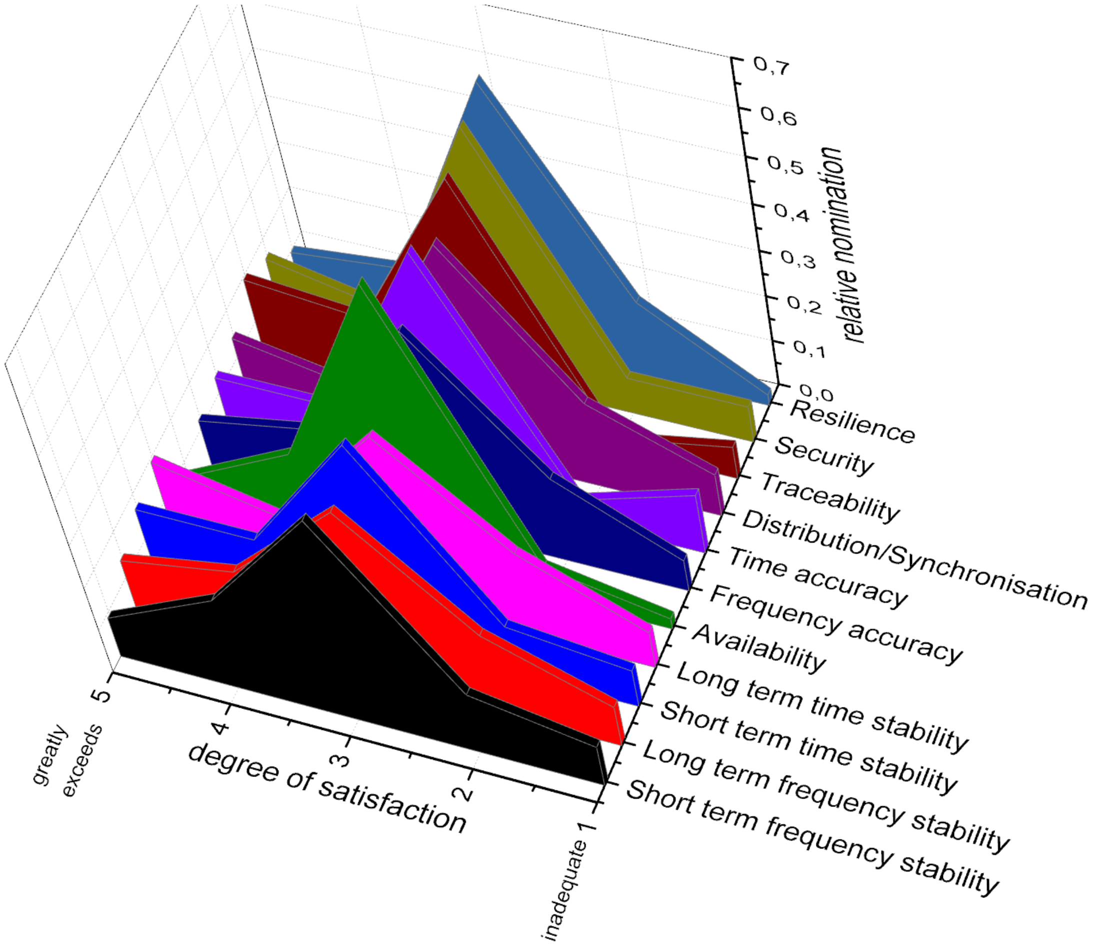

Figure 7. Degree of satisfaction with the currently implemented T&F systems.

The importance of instability and accuracy were rated independently for frequency and timing aspects (see Figure 8 and Figure 9). While frequency aspects are rated as of very high importance, there is no clear picture for timing instability and accuracy. Over a fourth of the respondents consider timing aspects to be irrelevant to their applications; but an almost equal number of respondents rate performance level of timing as critical. Among the latter are the majority of UTC(k) labs, labs disseminating T&F signals for synchronisation of, for example, accelerators, and astronomical infrastructures.

The number of applications putting an emphasis on the performance of a frequency reference outnumber those depending on time references. This distribution is mirrored by the responses given when asked for the specific performance requirements of the reference signal (see Figure 5 and Figure 6). A higher number of people provided performance requirements for a frequency reference than for a time reference.

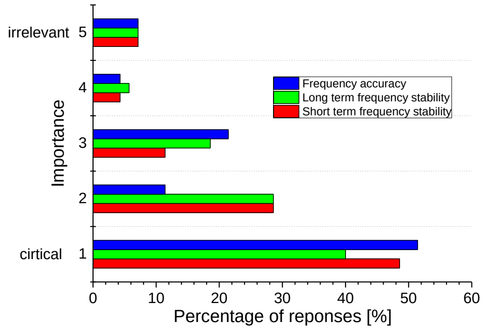

Figure 8. Importance of frequency accuracy (blue) and instability in the long term (green) and in the short term (red).

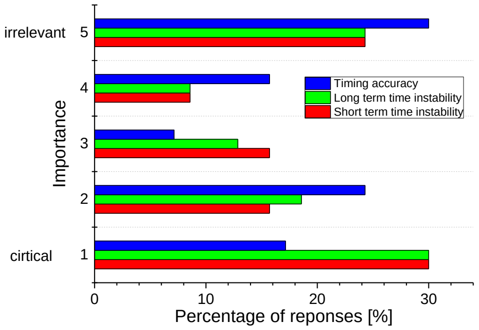

Figure 9. Importance of timing accuracy (blue) and instability in the long term (green) and in the short term (red).

In addition to instability and accuracy, the consortium collected information on achieving traceability to the SI, security, resilience and availability including a rating of their respective importance. Traceability is achieved by own Universal Time Coordinated (UTC) (15 responses), GNSS (13 responses) or calibrated references (3 responses). Four RIs (8 responses) already achieve traceability via optical fibre. The latter set of RIs have an established collaboration with an NMI and are actively involved in the development of an optical fibre infrastructure for T&F dissemination. A surprisingly large number of empty responses were received, i.e. the question was not answered by 20 of the respondents. We assume that traceability is not a concern for the involved applications, because relative measures suffice and traceability to the SI is not (yet) imperative. For the majority of the respondents, security issues are mainly solved through restricted access or redundancy. Overall, security tends to be less of a concern. Resilience, on the other hand, is considered to be significantly more critical. This is confirmed by the fact that almost 50% of respondents indicated that local backup solutions are already in place. The importance of availability of reference signals is on average rated very high, higher than the other criteria listed above. Our understanding is that this reflects the need to have a guaranteed and readily available access to T&F reference signals and that a reasonable amount of occasional down times can be managed. Hence, resilience providing a 24/7 performance with minimum down time is desired, but not rated as critical. In summary:

- Traceability is considered *critical* by UTC(k) labs, whereas non-UTC(k) labs in almost equal numbers rate it as either *critical* or *irrelevant* for a given application.
- Security is the least important (lowest critical rating and highest irrelevant rating). It does not seem to be a concern for most of the applications.
- Resilience is desired, but not rated as critical.
- Availability is of highest importance, with no answer considering it as irrelevant.

An attempt to find correlations or relations between different criteria was made, however, no distinct conclusions could be drawn.

2.2.4 T&F future perspectives

The final section of the questionnaire was dedicated to identifying future applications and needs for improved T&F performances. The participants were asked how and whether a remotely delivered T&F reference could help improve existing applications and/or could trigger new possibilities for the participant. Several predefined categories were provided (see Figure 10). The majority of the labs (both UTC(k) labs and non-UTC(k) labs) replied that calibration or dissemination services would benefit from such a reference and that synchronization issues between sites could be improved or resolved. However, a significantly higher percentage of non-UTC(k) labs compared to UTC(k) labs consider the replacement of in-house standards by a remotely delivered T&F reference as a benefit.

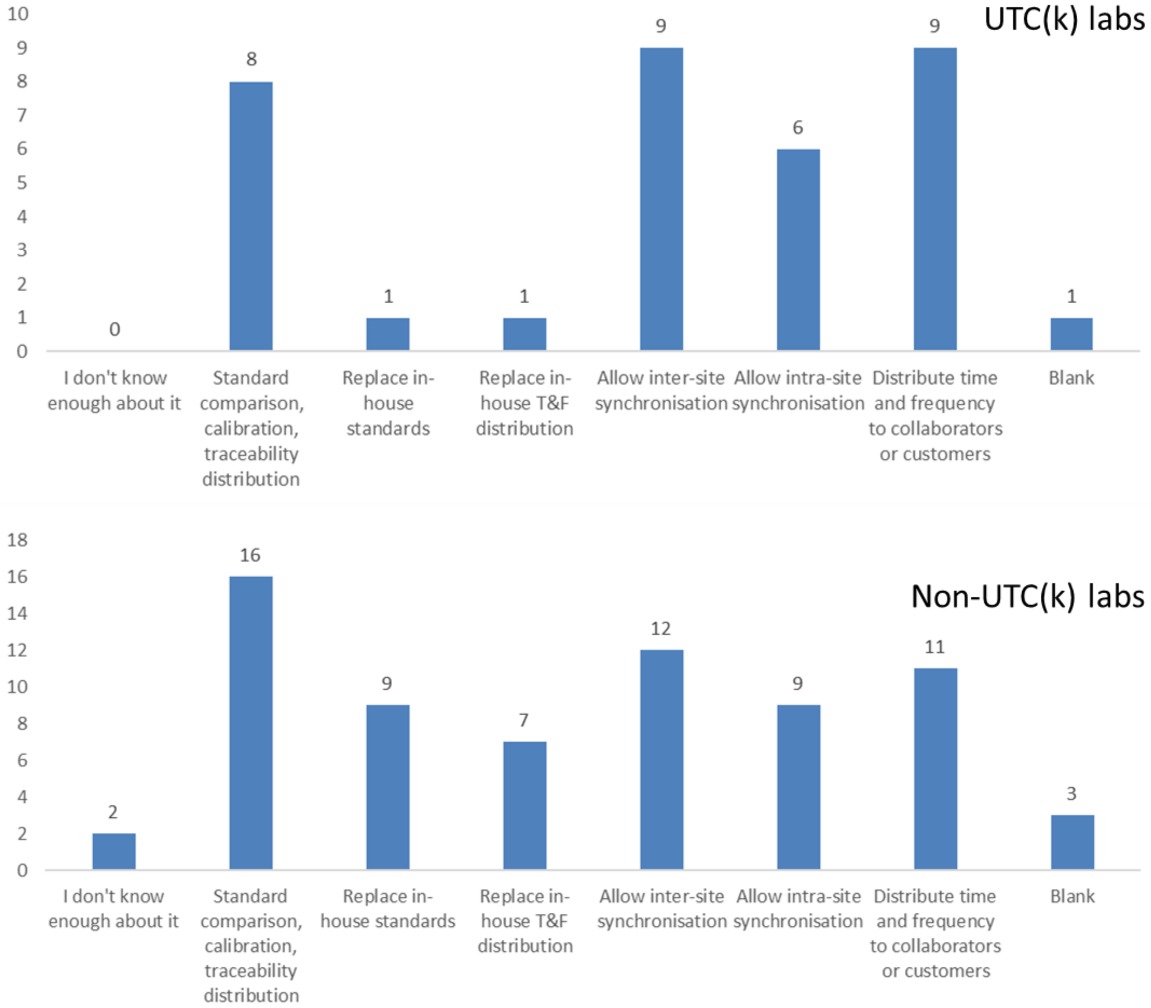

Figure 10. Responses to the question: How could high performance T&F delivered over optical fibre open new possibilities that your organisation would be interested in?

In addition to the predefined questions, the participants could add text in free form. The answers given by UTC(k) labs concerning future benefits of fibre-delivered high-performance T&F ranged from better traceability, improved performance, availability or latency, high-performance comparison of time scales via remote verification of clock performance, fibre-delivered time dissemination services including UTC generation and inter-comparisons to a better assessment of metrological characteristics of other time transfer methods. In radio-astronomy and geodesy the benefits are expected to arise from improved phase and time stabilities/accuracies in the clock/phase distribution system of telescopes. A better accuracy than is provided by the International Celestial Reference Frame (ICRF) is anticipated from a fibre-based T&F distribution. Additionally, it would eliminate the need for clock-searching observations of remote telescopes due to common clocks scenarios. Overall, the extension of geodetic measurement techniques is expected. For universities, spectroscopy and laser labs, or quantum technological applications, the major benefits are expected to be gained from a better long-term stability of narrow line width lasers, a more accurate calibration or synchronization of devices and laser sources or even quantum operations, a direct characterization of local frequency reference prototypes with remote standards. Finally, it is generally agreed on that fundamental physics experiments and novel clock concepts would strongly benefit from a remote access to the best European clocks.

3 SUMMARY

3.1 Key findings of the survey

In general, the survey has revealed that applications requiring highest-performance frequency accuracy and instability seem to be more numerous than those requiring precise timing. As of today, receiving *time* at remote places is still based on satellite techniques, with a few exceptions such as time & frequency links operated in Poland, Germany or the Czech Republic. However, the most demanding timing applications already require an instability that can only be met by dissemination through optical fibres.

Among the respondents there seems to be a clear understanding and ranking of the importance of traceability to the SI, the availability of T&F signals at a remote location, the resilience of such signals and issues related to security. The *availability* of a fibre based T&F service is, on average, rated the highest by all respondents, followed by *resilience* with *security* being the least critical aspect. *Traceability* has divergent ratings; it tends to either be considered as critical or as irrelevant. Among those that consider it to be critical are the UTC(k) labs. A large fraction of non-UTC(k) labs, on the other hand, do not regard *traceability* as particularly problematic.

There is a strong link between T&F systems in place and the applications considered in the survey. On the one hand, a readily available high-performance T&F system encourages the development of new applications otherwise not realisable. On the other hand, novel applications or cutting-edge experiments that demand better performance T&F systems, encourage their development and dissemination. The CLONETS consortium members are active at the interface between T&F and research, and the results of the survey are globally consistent with the consortium's understanding of the relevance of high precision T&F reference signals for RIs. The communities that expect to benefit most from a fibre based T&F service are radio-astronomy, geodesy, accelerator and spectroscopy laboratories, calibration laboratories and potentially space agencies. There is a growing awareness of the potential of a fibre-based T&F service and at the same time an increasing need for better performance than currently available via classical satellite based technology.

3.2 Conclusion

The survey was intended to identify the current and future needs of RIs for precise and accurate T&F transfer. We have received an adequate number of responses to consider the outcome of the survey as a representative spectrum of the high precision T&F needs of European RIs. Together with the outcome of the survey performed in Work Package 3 addressing the needs of European industry, we will be able to shape a future time and frequency service that covers the needs of science, industry and society.