2021 EFTS

European Frequency and Time Seminar

Abstracts

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June 28 to July 2, 2021
at the FEMTO-ST Institute / ENSMM site
Besancon, France

http://efts.eu

EUROPEAN FREQUENCY AND TIME SEMINAR

Scientific Council

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Lecture Abstracts

1 Monday

1.1 Introduction to Time and Frequency Metrology

Yann Le Coq, LNE-SYRTE, Observatoire de Paris, France

This introductory lecture will provide general and basic information on different topics related to time & frequency (T/F) measurements that will be detailed later in more specialized lectures. First, different concepts for time measurement will be described, from Earth rotation to atomic clocks. Then, the different ways to characterize the uncertainties in frequency, phase and time domains will be presented. The stability and accuracy will be defined, and the basic scheme for their measurements will be discussed, as well as the influence of the distribution technique when the user is far from the T/F standards. The wide exploitation of T/F measurement precision will be illustrated with a short presentation of various applications, from fundamental science to operational systems used in daily life.

1.2 Introduction to Oscillators

Enrico Rubiola, FEMTO-ST Institute, Besancon, France

As a matter of fact, most systems rely on a time or frequency reference, and the *stability*, rather than accuracy, is the most desired feature. The variety of oscillators is impressive for the spread of frequency, accuracy, stability, noise, physical size, electrical power, and suitability to more or less hostile environment. However, they are governed by simple principles. We describe the oscillator loop, and how a steady oscillation is achieved at the desired frequency. We introduce the noise of the internal components, and we show the noise mechanism known as the Leeson effect. We derive the noise equations, and we show the behavior of some oscillators.

1.3 Phase Noise

Enrico Rubiola, FEMTO-ST Institute, Besancon, France

This lecture focuses on the measurement of the random phase fluctuations of oscillators and their internal components. The preferred measure is the power spectral density of the random phase $\varphi(t)$, and denoted with $S_\varphi(f)$, or equivalently $\mathcal{L}(f)$. The amplitude noise, denoted with $S_\alpha(f)$ is also important in some cases, chiefly in optics. We review the basic concepts and mechanisms. There follows the architecture of the commercial instruments suitable to the measurement of components and oscillators, and the cross-spectrum method, used in virtually all of such instruments. The cross spectrum may go with unpleasant, embarrassing surprises.

1.4 Variance Measurements

Francois Vernotte, Besancon Observatory, France

After having defined the useful quantities in the time and frequency field, in the time domain as well as in the frequency domain, we will introduce the main time stability estimator: the Allan variance. It will be described as a statistical tool as well as a spectral analysis tool. We will then introduce other variances defined in the same way as the Allan variance and describe their properties. Finally, we will give practical examples of use of the variance analysis.

1.5 Servo Loops

Frederick Du Burck, LPL, Villetaneuse, France

The point of the presentation is to highlight interactions between frequency control and automatic control and to give some perspectives of applications of well-known controllers in the field of time and frequency control.

The basics of servo systems (model, trade off stability-accuracy-speed) are presented and examples are chosen in the field of laser frequency stabilization. Limitations dues to the components of the loop (sensors, detection systems, actuators, delay ...) are then considered.

1.6 Quartz Oscillators

Bernd Neubig, Axtal, Germany

The abstract is not available at the time of printing

2 Tuesday

2.1 Information Technology and Security – Online lecture

Kristof Teichel, PTB, Braunschweigh, Germany

The abstract is not available at the time of printing

2.2 Relativity for Reference Systems and Time Metrology

Gerard Petit, BIPM, Int'l organization (Paris, France)

The lecture includes three parts:

1. A very quick reminder of some basic features of the relativity theory, notably the notions of proper and coordinate time and the conventions for simultaneity and synchronization, ending with the post-Newtonian formalism used to express the metric tensor and coordinates for the Solar system barycentric and for the geocentric systems.
2. A presentation of the current definitions and realizations of space-time reference systems for the Solar system and for the Earth, respectively the International Celestial Reference Frame and the International Terrestrial Reference Frame. The time coordinates of these systems are defined and the transformation between the time coordinates are given with practical formulas.
3. Application of the formalism in the geocentric system to solve practical problems encountered when using or comparing clocks in the vicinity of the Earth: the transformation between proper time and coordinate time for clocks on the Earth and in GNSS satellites (with the well-known "gravitational redshift"); the computation of the coordinate time of propagation of an electromagnetic signal in the vicinity of the Earth (needed e.g. for laser ranging or for GNSS signals).

2.3 Introduction to Atomic Clocks

Gaetano Mileti, LTF, Neuchatel, Switzerland

This lecture will introduce the chapter on atomic clocks and will be divided in two parts. In the first part, we will describe the basic principles of atomic frequency standards and present their general functional principles as well as their main building blocks. In the second part, we will give specific examples of atomic clocks of various types: commercial, laboratory, primary, etc. We will conclude the lecture by presenting the main current trends of the field.

2.4 Atomic Time Scales

Gerard Petit, BIPM, Int'l organization (Paris, France)

The lecture presents the main features of atomic timescales, particularly those under the responsibility of the BIPM (TAI, UTC, UTCr and TT(BIPM)) which all provide realizations of Terrestrial Time TT, a coordinate time of the geocentric system.

International Atomic Time TAI, from which UTC is derived, is generated on a monthly basis while UTCr is a rapid realization of UTC which has been provided weekly since 2013. The ensemble of atomic clocks, the time transfer techniques and the algorithms for TAI are presented along with the achieved performance in stability and in accuracy. TAI accuracy is provided by primary frequency standards (Cs fountains, based on the Cs transition defining the second) and secondary frequency standards (presently mostly one Rb fountain) regularly operated in a number of contributing time laboratories. Frequency standards also form the basis for TT(BIPM), the ultimate reference time coordinate produced by the BIPM. Finally, some information is given on upcoming and future developments of time transfer techniques and atomic clocks and on their potential impact on atomic timescales, with some emphasis on ultra-accurate optical clocks that may provide a future re-definition of the second.

2.5 Introduction to the Physics of Atomic Clocks

Gaetano Mileti, LTF, Neuchatel, Switzerland

The lecture concerns the main basic physical phenomena occurring in an atomic clock. First, we will recall the principles of nuclear magnetic resonance and show how the classical Bloch equations may be generalized to describe any resonant interaction of an electromagnetic field with an atom or an ensemble of atoms. Using the developed formalism, we will then present selected topics relevant for atomic clocks: the Ramsey scheme, the Dick effect, the AC Stark shift, the laser radiative forces, etc. Finally, we will discuss some examples of applications of atomic clocks, which will illustrate the various areas of research in this active field.

2.6 Stabilized Lasers

Clement Lacroute, CNRS, FEMTO-ST Institute, Besancon, France

Lasers can be found in most modern experimental physics laboratories. The fast spreading of coherent optical sources has deeply revolutionized the fields of atomic and molecular spectroscopy as well as time and frequency metrology. Among other things, lasers can be used for laser-cooling of ions, atoms or molecules, optical pumping, detection of atomic fluorescence or absorption, etc. For all these applications, the laser frequency needs to be stabilized to some level, with the most stringent specifications being required when a laser is used as the local oscillator in an optical atomic clock.

In this lecture, I will first present the basics of Light Amplification by Stimulated Emission of Radiation, before presenting a few frequency stabilization techniques, with a focus on saturated absorption by an atomic vapor and on ultra-stable Fabry-Perot cavities.

3 Wednesday

3.1 Cold Atoms

Clement Lacroute, CNRS, FEMTO-ST Institute, Besancon, France

Proposed theoretically in the 1970s and pioneered experimentally in the 1980s, optical trapping and cooling of neutral atoms had an immediate impact on time and frequency metrology. The use of cold atoms enables both increased interaction times and better control of the atomic state through optical pumping. The atomic fountain clock is the most remarkable example of cold atoms clocks, and has been the best atomic standard for almost twenty years. Today's optical standards also rely on laser cooling. Other techniques such as isotropic cooling or magnetic trapping have also been used successfully.

In this lecture I will emphasize the theoretical basis of laser cooling and illustrate its use in the case of microwave clocks. I will first explain how the optical force can induce Doppler cooling or optical dipole potentials (eg., optical lattices or optical tweezers). I will then focus on the most widely spread experimental tool: the Magneto-Optical Trap. Several examples of microwave clocks based on cold atoms will finally be illustrated, with a focus on the atomic fountain clock.

3.2 & 3.3 GNSS and Satellite Time Transfer

Andreas Bauch, PTB, Braunschweigh, Germany

The function of a Global Navigation Satellite System (GNSS) is based on propagation time measurements with highest accuracies between the clocks in the space segment and the clock at the user side. I will give an overview of the elements of a GNSS, including some details on the kind of signals transmitted from the space vehicles. The matter of signal processing in the receiver and of data content in the navigation message is subject of LAB 3, 4, 5. So will concentrate on the introduction of the concepts. It will become obvious that GNSS signals can be considered as sources of time-of-day and the time unit. I will thus briefly touch one particular class of equipment that is widely used in laboratories and calibration facilities, namely the GNSS disciplined oscillator.

Time Transfer

The reception of GNSS signals has been used for time comparison since the early 1980s when just the first few GPS satellites were in the sky. In my lecture I will present the current status, and explain the uncertainty that can be achieved. Two-way Satellite Time and Frequency Transfer is the second global time comparison technique in use, also since the 1980s. Recently new kinds of signals and signal processing were demonstrated, giving evidence that this technique keeps (at least partially) pace with the advances in the performance of frequency standards. I will briefly discuss the use of TWSTFT between ground and the International Space Station in the frame of the ACES project and in proposed future space-born time-dissemination services.

Time and frequency comparisons represent an integral part of time and frequency metrology in general. The two lectures deal with the use of radio-signals for that purpose and are therefore complementary to the presentations on Synch in Networks and Sync over fibers.

3.4 Femtosecond Combs for Frequency Metrology – Online lecture

Jochen Kronjaeger, NPL, Teddington, United Kingdom

Femtosecond lasers have revolutionized the field of accurate frequency measurement by giving the possibility to directly compare two frequencies in a wide spectral range from radiofrequencies to optical frequencies. Femtosecond lasers exhibit a comb structure in the frequency domain, and the frequency of these modes can be controlled very efficiently, resulting in a frequency "ruler." Such an optical frequency comb is now used routinely in many labs and enables the comparison of various atomic frequency standards. Moreover, it opens the way to a wide range of applications, including ultraviolet and infrared spectroscopy, frequency synthesis, test of the variation of the fundamental constants, or attosecond pulse generation.

3.5 Optical Fiber Links for Frequency & Time Transfer Online lecture

Jochen Kronjaeger, NPL, Teddington, United Kingdom

Long distance ultra-stable frequency transfer is an issue for time and frequency metrology. For over 10 years, optical fiber links have brought the potential to transfer frequency with very high accuracy and stability thanks to an active compensation of the phase noise induced by the propagation in the fiber. First optical links used an amplitude modulated optical carrier around 1.55 µm to transfer radio-frequency or microwave signals. A significant gain has been achieved using the very high frequency (~200 THz) of the optical carrier to transfer an ultra-accurate and stable optical frequency reference over long distances. Since a few years, several experiments of optical frequency transfer were reported over dedicated fiber or Internet fiber over a few hundreds of km. Current developments are concerning the extension of the fiber network to a continental scale, time transfer and applications to remote clocks comparison or laser stabilization.

4 Thursday

4.1 Small Clocks – Online lecture

Christoph Affolderbach, LTF, Neuchatel, Switzerland

This lecture will give an overview over the physics and development of miniature and chip-scale atomic clocks. After a motivation and application examples for these clocks, we will discuss the main clock schemes of relevance for their realization. A number of different approaches for the realization of the main clock components will be presented, in particular for miniaturized alkali vapour cells. Finally, examples of miniature atomic clock realizations and selected new trends towards miniature atomic clocks will be discussed.

4.2 Roadmap towards the redefinition of the SI second

Noel Dimarcq, Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, Nice, France – Member of CIPM[1] and President of CCTF[2]

The current definition of the SI[3] unit of time, the second, has been adopted in 1967. It relies on the fixed numerical value of the unperturbed ground-state hyperfine transition frequency

[1] CIPM: International Committee for Weights and Measures

[2] CCTF: Consultative Committee for Time and Frequency

[3] SI: Système International d'Unités - International System of Units (https://www.bipm.org/en/publications/si-brochure)

of the caesium-133 atom, in the microwave domain. The accuracy of primary frequency standards realizing this definition (first Cs beam clocks, then cold atom fountains) has been impressively improved over decades, to reach today a relative frequency accuracy at 10^{-16} level. This accuracy is far better than those of the other SI primary units which are now all - except the mol - connected to the unit of time since the significant and historical revision of the SI in 2018, with new definitions relying on a set of fundamental constants whose values have been fixed.
Nevertheless, Cs clocks are now surpassed by optical clocks by more than two orders of magnitude. That is why the CCTF is defining and updating the roadmap towards the redefinition of the SI second with the aim to take full advantage of the outstanding potential of optical clocks with a new definition.
After a brief presentation of historical aspects related to past and current definitions of the SI second, the main issues and options for a new definition and its realization will be addressed, including the important topic of the dissemination of the unit towards users. The steps of the process for the change of the definition will be described, with a schedule depending of the fulfilment of criteria which will be presented.
There are various ways to disseminate realizations of the SI definition towards users. Among them, the dissemination via the international reference time scale UTC allows a global synchronization capability on a worldwide basis, with an uncertainty floor at the nanosecond level. The talk will address some current issues on UTC that are also studied by CCTF, such as the hot topic on “leap seconds” and the continuity of UTC.

4.3 Optical Clocks

Jérôme Lodewick, LNE-SYRTE, Observatoire de Paris, France

In optical clocks, an ultra-stable laser is locked on a narrow atomic resonance in the optical domain of the electromagnetic spectrum (hundreds of THz), yielding a large resonance quality factor of 1015. Thanks to the high quality factor, optical clocks are now the best frequency references, both in terms of frequency stability and in terms of control of systematic effects. I will present the basic principles of optical clocks, including notions about motional effects and trapping techniques, and give a comparative overview of the current performances of the two main families of optical clocks, namely ion optical clocks and optical lattice clocks, as well as the perspectives they offer.

4.4 Digital Electronics for Time and Frequency

Claudio E. Calosso, INRiM, Torino, Italy

The abstract is not available at the time of printing

4.5 White Rabbit – Online lecture

Anders Wallin, VTT, Espoo, Finland

White Rabbit (WR) is a networking technology which extends Ethernet and the Precision Time Protocol (IEEE 1588) and enables the development of distributed real-time controls and data acquisition systems whose nodes require precise synchronization. The specification calls for synchronization accuracy better than 1 ns over typical lengths of a few tens of km. The WR project deals with the development of the basic building blocks of the system, including a full Ethernet- compliant switch with WR extensions and a PTP core users can instantiate in the Field Programmable Gate Arrays (FPGAs) of their nodes. All software

and hardware in the project is developed under a free/open source paradigm, and most technical discussion happens in a public mailing list.
This talk will describe the technologies used in WR, some performance measurements and currently available open WR-compliant products with commercial support. It will then describe some current and foreseen applications of WR, concluding with an outlook of future plans for development and standardization under IEEE 1588.

5 Friday

5.1 Historical Perspective

Francois Vernotte, FEMTO-ST Institute, Besancon, France

For long time mankind has sought to measure time. It initially counted the days and invented the calendar, clashing with the difficult determination of the duration of the year. Then it sought to measure shorter durations with mechanical clocks: hours, minutes, seconds. The great discoveries of modern times have prompted watch makers to carry out prowess to be able to "keep time" on board vessels to determine longitude. Nowadays, although we no longer deal with seconds but with nanoseconds, this issue has not changed: thanks to advances in atomic clocks, GPS allows us to know very precisely our position.

Laboratory sessions

The EFTS includes 12 H lab sessions on the following topics

- AM and PM noise of oscillators and components
- Two-sample variances (AVAR, MVAR, PVAR), and their estimation
- GPS. Measurement of pseudo-random noise, Software-Defined-Radio approach, Hands on OEM receivers.
- Atomic clocks
- Quartz resonators