2019 EFTS

European Frequency and Time Seminar

Abstracts

Enrico Rubiola

July 1–5, 2019
at the FEMTO-ST Institute / ENSMM site
Besancon, France

http://efts.eu

Scientific Council

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2019 EFTS Week Schedule

Time	Mon, July 1	Tue, July 2	Wed, July 3	Thu, July 4	Fri, July 5
8:15	7:30–8:30 Registration	Coffee	Coffee	Coffee	Coffee
8:30 – 9:20	8:30 Welcome and Introduction to TF Y. Le Coq	IT & security K.Teichel, PTB (D)	Cold Atoms C.Lacroute, FEMTO	Small Clocks Ch.Affolderbach,	8:30–11:30 Lab 5 Atoms Resonators / GPS-RX / Rinex
9:20 – 10:10	Oscillators Primer J.P. Aubry (F/CH)	Relativity G.Petit, BIPM (Int'l)	Navig / GNSS P.Defraigne, ROB (B)	The New SI T. Quinn	
10:10 – 10:40	Coffee & cookies	Coffee & cookies	Coffee & cookies	Coffee & cookies	
10:40 – 11:30	Phase Noise E.Rubiola, FEMTO	Intro Atomic Clocks G.Mileti, LTF (CH)	FS Combs G. Santarelli, IO (F)	Optical Clocks J.Lodewyck, SYRTE (F)	
11:30 – 12:20	Variances F.Vernotte, FEMTO	Time Scales G.Petit, BIPM (Int'l)	Satellite Synch P.Defraigne, ROB (B)	Nuclear Clocks E. Peik PTB (D)	11:30 Quick coffee 11:45-12:30 Historical Perspective F.Vernotte, OB (F)
12:20 – 13:50	Lunch	Lunch	Lunch	Lunch	12:30—12:45 Closing 12:45–14:15 Lunch
13:50 – 14:40	Controls G.Cabodevila, FEMTO	Atomic Clock Phys G.Mileti, LTF (CH)	Sync over Fibers G. Santarelli, IO (F)	White Rabbit M.Lipinski CERN (Int'l)	14:15–16:00 Visit at FEMTO-ST
14:40 – 15:30	Quartz Oscillators J.P. Aubry (F/CH)	Stabilized Lasers C.Lacroute, FEMTO	Coffee 15:10–17:10 Lab 3 GPS, PRN, RINEX	Coffee 15:00–18:00 Lab 4 Atoms Resonators/PRN/GPS	
15:30 – 16:00	Coffee	Coffee			
16:00 – 18:00	Lab 1 PM/AM noise, Data Analysis	Lab 1 PM/AM noise, Data Analysis	17:10 Go downtown		You are free
18:00 – 19	Visit at the Observatory	Backup for the Observatory visit. Depends on weather for the Astronomy session	Visit at the Museum of Time, and Drink	Go downtown	
19 – 20				Social Dinner downtown	
20 – 21:30	Dinner on your own	Dinner on your own	Dinner on your own		
21:20 – 24	Backup for the Astronomy session, depending on weather	Astronomy	Last chance for the Astronomy session, depending on weather		

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Logistics & events
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Welcome & Closing

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By color

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E. Rubiola

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E. Rubiola

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G. Mileti

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F. Vernotte

Laboratories
Y. Gruson & E. Rubiola

Last update
May 3, 2019

Lecture Abstracts

1 Monday, July 1

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 Oscillator Primer

Jean-Pierre Aubry, AubryConseil, Vannes, France

In this lecture we will provide the basics on resonators and oscillators. We first recall the harmonic oscillators and provide some basics on time to frequency (from frequency to time). A review of main definition of frequency or time signals characteristics (accuracy, stability, time and phase noise) related to the intrinsic resonator performances is introduced.

Various oscillating technologies used in nowadays systems or clock are introduced, ranging from the quartz diapason, solid state oscillators (MEMS SI), miniature atomic clocks, dielectric resonators, industrial Atomic standards, cold dielectric, cold atoms and up to optical clocks on scientific side. Dedicated oscillators technologies related to main applications (Metrology, Space, military, Industrial, consumer…) are reviewed.

Trends and evolution of application and needs are given, showing developments in cost and size reduction for mass market, in environmental immunity, and in the continuous frequency increase demand, or the permanent quest for better frequency stability are given.

1.3 The Measurement of Phase and Amplitude Noise

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.

This lecture focuses on the stability of such reference, described in terms of random phase fluctuations. The spectral measure of such fluctuations is referred to as phase noise, and denoted with $S\phi(f)$ or $L(f)$. The amplitude noise, denoted with $S\alpha(f)$ is also important in some cases, chiefly in optics.

We review the basic concepts, the elementary noise mechanisms, origin of noise in components, the measurement methods for components and oscillators, and the cross-spectrum method.

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

Gonzalo Cabodevilla, FEMTO-ST Institute, Besancon, France

The point of the presentation is to highlight some 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. Analog servo loops are well known in the community of time & frequency, but recently the extensive use of digital controls allow a glimpse at the jungle of different types of digital controllers. After some tips and tricks concerning the analog control like the limitations of the well-known PID, an overview of the digital methods will be shown with their domains of applications, their pros and cons. From the digital PID to the Dead-Bit controller passing through the RST controllers, the main methods will be shown. We will give attention to the state space approach and related tools, like the LQ regulator, the Luenberger observer and the Kalman filter.

1.6 Quartz Oscillators

Jean-Pierre Aubry, AubryConseil, Vannes, France

In this lecture we will describe quartz resonators and oscillators. We first describe the basic operation of a resonator construction, a travelling acoustic wave (defined by polarization, propagating vector, velocity, …), by material / crystallographic properties and resonant condition provided by the specific device geometry. The most popular one, the low frequency 32 kHz diapason resonator, is briefly described. More detailed analysis of contoured resonator is given, to introduce the quest for high stability resonators (energy trapping for high Q optimization, process for ageing improvement). Various specific technologies (high frequency mesa, zero stress mounting, material sweeping, …) are described. Optimization of the compromise "size / performance" resonator, through energy trapping optimization, involving sophisticated geometry and mathematically solved via perturbation methods, is also described.

Various oscillators technologies (XO, TCXO, VCXO, OCXO, MXO, etc.) are described in term of performances (size, power, performance) and applications.

In the final part, we will describe shortly the competition between the low-end quartz oscillators and to date MEMS Si technology, providing lower size and cost and better performance than regular fundamental mode quartz, and competition from MEMS atomic clock arriving on the high end timing accuracy.

2 Tuesday, July 2

2.1 Timing in Networks, Networks for Timing

Kristof Teichel, PTB, Braunschweigh, Germany

[This was J.-P. Aubry]

In the first part of this lecture, the trends in timing requirement within today's networks are reviewed. The evolution of telecommunication network demand is described, from the frequency requirement of the original analog system, though the frequency accuracy requirement in the PDH/SDH infrastructure, up to the actual requirement of timing accuracy in IP based network, asking for microsecond level accuracy. Many other networks exhibit similar time requirement. Banking system requirement (High Frequency Trading asking for sub-microsecond) and energy distribution (smart metering and Smart Grid asking sub-microsecond over low voltage distribution to perform input/output energy flow integration management within the overall network), are described.

Security requirements are also described, identifying the criticity of operation based on the availability of synchronous time reference all over networks. Security concern on GNNS-only based solution are pointed out, paving the way to time dissemination over fiber networks.

In the second part of the lecture, we will focus on the network capability in time transfer, over industrial networks. Various technologies are described, point to point or point to multipoint, using cable or optical fibers. Protocol operating over fiber (amplitude modulation) or embedded in telecom layer, such as time stamp in SDH layer or in IP layer are reviewed. Technologies such as IRIG, NTP, PTP v2 (IEEE 1588), PTP-White Rabbit (detailed in another lecture) are described.

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, July 3

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 & 3.4 GNSS and Satellite Time Transfer

Pascale Defraigne, Royal Observatory of Belgium

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.

3.3 Femtosecond Combs for Frequency Metrology

Giorgio Santarelli, Institut d'Optique, Bordeaux, France

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 fundamental constants variations, or attosecond pulse generation.

3.5 Optical Fiber Links for Frequency and Time Transfer

Giorgio Santarelli, Institut d’Optique, Bordeaux, France

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, June 29

4.1 Small Clocks

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 The New SI

Terry Quinn, former director of the BIPM (retired)

This is the story of the kilogram. It begins on 19th March 1721, when five great savants of France drew up a plan to establish units of the metre and the kilogram to be taken from nature, and ends on 16 November 2018 when the 26th General Conference on Weights and Measures adopted the new definition of the kilogram, which finally brought to fruition the grand idea of 1791.

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 this 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.

4.3 Towards a Nuclear Clock

Ekkehard Peik, PTB, Braunschweigh, Germany

Under most circumstances, the energy scales of nuclear and electronic excitations in atoms are separated by 4-6 orders of magnitude. There is one notable exception: The low-energy nuclear isomer of Th-229 at an excitation energy of about 8 eV. The prospect of driving this transition between the ground state and the isomer coherently with a tunable VUV laser has stimulated numerous innovative proposals. The selection of a suitable electronic state for the nuclear excitation makes the nuclear transition frequency insensitive against field-induced systematic frequency shifts to a degree that is not obtainable in electronic transitions. A nuclear clock [1] based on laser-cooled and trapped thorium ions will benefit from this advantage. Complementary, the obtainable isolation of the nucleus in a wide-bandgap dielectric creates the opportunity to interrogate many Th-229 nuclei as dopants in a solid, in a laser-driven Mössbauer spectroscopy. While a precise value for the Th-229 nuclear transition energy and an experimental demonstration of resonant optical excitation are still missing, experiments with Th-229 recoil ions from the alpha decay of U-233 have recently provided information on fundamental nuclear properties of the isomer.

References:

[1] E. Peik, M. Okhapkin, *Nuclear clocks based on resonant excitation of gamma-transitions*, C. R. Phys. **16**, 516 (2015); also at: arXiv:1502.07322

4.4 White Rabbit

Maciej Lipinski, CERN, Geneva, Switzerland

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.

5.1 Historical Perspective

Francois Vernotte, Besancon Observatory, 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