2014 EFTS

European Frequency and Time Seminar

Lecture Abstracts

Enrico Rubiola

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Introduction to Time and Frequency

Noel Dimarcq, LNE-SYRTE, Observatoire de Paris, France

The abstract will be inserted as soon as available

Oscillator primer

Jean-Pierre Aubry, Consultant, Neuchatel, Switzerland

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 to day's 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 (Metrologiy, 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.

The Measurement of Phase 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 Sφ(f) or L(f). The amplitude noise, denoted with Sα(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.

Time Domain Representation of Oscillator Performance

David A. Howe, Time and Frequency Division, NIST, Boulder, CO, USA

This lecture will be focused on variance analysis of time-series data and why they are used for oscillators and clocks. Time series are frequency, phase, or time residual-difference values of a pair of signals from oscillators/clocks using measurement methods with data taken preferably at equal-spaced time intervals. We will delve into the basis for five noise types and their causes found in oscillators/clocks association with frequency-domain characterization using the Fourier spectrum. This will be followed by definitions and examples of the analysis process that involves time-domain statistical estimators of the following established and modern variances:

- Allan Variance and estimator ADEV
- Modified Allan Variance and MADEV

- Time Variance and TDEV
- Hadamard Variance and HDEV
- Total Variance and TOTDEV
- Thêo

We will then develop an understanding of the efficient interpretation of statistics for:

- Determining noise types, commonly done by noting slopes of the statistic over an averaging time
- Matching a statistical construct to the way the oscillator/clock is to be used
- Establishing operational criteria
- Improving statistical confidence with limited data runs

The lecture will conclude with a recent compilation of applications and measurements of different classes of oscillators and clocks.

Quartz Oscillators

Jean-Pierre Aubry, Consultant, Neuchatel, Switzerland

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 its polarization, its propagating vector, its 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.

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.

Space Projects

Noel Dimarcq, LNE-SYRTE, Observatoire de Paris, France

The abstract will be inserted as soon as available

Synchronization over Networks

Jean-Pierre Aubry, Consultant, Neuchatel, Switzerland

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, trough 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 In/Out 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 Javier Serano's lecture) are described.

White Rabbit

Javier Serrano, CERN, Neuchatel, 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.

Atomic Clock Physics

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.

Relativity for Reference Systems and Time Metrology (two lectures)

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).

Time Transfer I and II

Andreas Bauch, PTB, Braunschweig, Germany

Time and frequency comparisons represent an integral part of time and frequency metrology in general. My lecture will restrict to the use of radio-signals for that purpose. The operation of a Global Navigation Satellite System (GNSS) is one of the most obvious uses of timing signals, and at the same time, the reception of GNSS signals has been used for time transfer since the early 1980s when just the first few GPS satellites were in the sky. In my lecture I will present the current status, explain the uncertainty that can be achieved and will briefly touch one particular class of equipment that is widely used in laboratories and calibration facilities, namely the GNSS disciplined oscillator.

Part II of my lecture will deal with the less common but scientifically very important subject of Two-way Satellite Time and Frequency Transfer. This technique has also been used since the 1980s, but 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. Last but not least I should say a few words on time dissemination for the common man via long wave signals. It is old-fashioned but it serves Millions.

The material used is to a large extent based on the lecture of Pascale Defraigne of Observatoire Royale de Belgique from the EFTS 2013.

VLBI

Ulrich Schreiber, Technische Universitaet Muenchen, Forschungseinrichtung Satellitengeodäsie Geodätisches Observatorium Wettzell, Germany

According to Friedrich Robert Helmert geodesy is the science of the measurement and mapping of the figure of the Earth. With the advent of the space age it was possible to establish a global reference frame, which can relate different locations across the entire Earth with an accuracy of currently about 1 cm with respect to each other. A rapid development of highly precise and stable frequency standards took place at the same time and is an important prerequisite for the actual quality of this global terrestrial reference frame. In fact all measurement techniques in modern space geodesy are based on precise time and frequency. Growing demands for the monitoring of global change as one of several examples of the importance of a highly resolved reference frame require more than one order of magnitude improvement over the existing level of quality. This talk outlines the use of time and frequency in space geodesy and looks at some demanding future applications.

Optical Fiber Link

Anne Amy-Klein, LPL, University Paris 13, France

Long distance ultrastable 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 satbilisation.

Ultra Stable Lasers

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

The field of Laser local oscillators (LLOs) took on tremendous importance for time and frequency metrology at the turn of the twentieth century. With the development of optical frequency combs, ultra-stable signals can be converted from the optical to the RF frequency range without degradation. This has led to fast progress of fields such as optical atomic clocks and microwave photonics, which all require an ultra-stable LLO. In addition, ultra-stable optical signals can be transmitted over very long distances through optical fiber networks, paving the way for a new generation of long-distance metrological comparisons.

In this lecture, I will present the basics of ultra-stable Fabry-Perot cavities for LLO stabilization. The interferometer theoretical transmission and finesse will be calculated. The fundamental limit to the cavity frequency stability is set by the thermal noise, which constrains the choice of materials. Sensitivity to external fluctuations must also be reduced, with consequences on both the cavity design, support and housing. Several geometries will be presented, that reduce sensitivity to accelerations and/or temperature fluctuations. The most recent advances in the field will be reviewed.

Small Clocks

Christophe 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.

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.

Optical Femtosecond Comb

Anne Amy-Klein, LPL, University Paris 13, 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.

Optical Clocks

Jérôme Lodewyck, 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 10^{15}. 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.

The Leeson Effect

Enrico Rubiola, FEMTO-ST Institute, Besancon, France

Simply stated, an oscillator consists of a loop in which a resonator sets the oscillation frequency and an amplifier compensates for the resonator loss. The oscillation amplitude is set by clipping or other gain-saturation mechanism, usually in the amplifier. When phase noise is introduced in the loop, the oscillator converts it to frequency, and makes the phase fluctuation diverge in the long run. This phenomenon is referred to as the *Leeson Effect*.

After a heuristic explanation based on physical insight, we derive the theory from the elementary properties of the resonator.

There follows the analysis of the phase noise spectra of real oscillators. Our analysis gives information on the most relevant design parameters, like the quality factor Q, the power, and the flicker noise parameters.

Servo Loops

Gonzalo Cabodevilla, FEMTO-ST Institute, Besancon, France

The abstract will be inserted as soon as available