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Tutorial Detailed Program

TRACK 1

Demetrios Matsakis (Masterclock)
Timekeeping and time transfer

After a brief introduction about what exactly we are measuring, the topics will start with noise and its statistical descriptions such as the Allan variance, and algorithms for free-running and steered timescales including Kalman filters, exponential filters, Coordinated Universal Time (UTC), and control theory. Time and frequency transfer will include the correction and reduction of data from GNSS, fiber-optics, Two-Way Satellite Time and Frequency Transfer, Network Time Protocol, Precise Time Protocol, E-Loran, and several complementary low-frequency low-accuracy transmissions. I will close with a single viewgraph extrapolating some current trends in timekeeping a decade or two forward.

For background, one might want to read Banerjee and Matsakis, “Introduction to Modern Timekeeping and Time Transfer”, available from the Amazon and Springer web pages.

Tobias Kippenberg (EPFL)
Physics and applications of microcomb technology

Jochen Kronjaeger (PTB)
Optical fiber links for time and frequency transfer

The very high stability and accuracy of state-of-the-art optical frequency standards require matching techniques for comparison and dissemination. For example, demonstrating agreement between different (possibly remote) optical frequency standards with an uncertainty below $5 \times 10{-}18$ is a key requirement towards the redefinition of the SI second. Optical fibre links have emerged as an excellent tool to meet this challenge.

In this tutorial, we will first focus on optical frequency transfer over fibre, which offers the lowest instability and best accuracy over distances up to thousands of kilometers to date. Starting from basic concepts of frequency transfer, we will investigate which factors limit the performance of fibre links, and how and to which degree some of them can be overcome. We will also look at typical implementations and discuss practical aspects, including specific challenges of long-distance fibre links.

For many applications, synchronisation or time transfer is important. We will discuss how this relies on the same concepts yet goes beyond frequency transfer. We will look at some options for implementing time transfer over fibre and the performance achievable. For comparison, I'll provide a brief outlook at what is possible with free-space links.

Anne Curtis (NPL)
Optical Clocks

The accuracy and stability of optical frequency standards make them ideal metrological tools, with numerous applications in areas requiring precise positioning, navigation, and timing. In this tutorial we will focus on laser-cooled ion- and neutral-atom-based optical frequency standards. A strong motivation in the development of such frequency standards is in fulfilling the key requirements for the international effort in the redefinition of the SI second in terms of an optical frequency. Therefore, we will investigate what it takes to evaluate and reduce systematic uncertainties in optical clocks to the 1E-18 level and below, as well as the methods by which absolute frequency measurements and optical frequency comparisons are being made around the globe. Finally, we will look into how the data from these frequency measurements are being used not only in the evaluation of clock systems, but also in other areas, such as in tests of fundamental physics.

TRACK 2

Franck Pereira dos Santos (SYRTE)
Atom interferometers

In my talk, I will present quantum sensors based on atom interferometry. I will explain the principle of their physical measurements and describe different instrument architectures. I will discuss their limits in performances, in terms of stability and accuracy, and the solutions currently explored to overcome these limits, such as based on the use of ultracold atom sources and large momentum transfer beamsplitters. I will finally review some of their present and future applications.

Patrick Berthoud (OSA)
Commercial Atomic Clocks and How They Are Employed in the Real World

Atomic clocks are devices that can measure the SI second unit with the highest precision among all fundamental units. This allows in particular to test and validate some physical laws and models. But beside this fundamental use, atomic clocks find applications in commercial and professional cases, such as telecommunication, navigation, data synchronization, time scale generation, metrology … And to meet the requirements of those applications, simple, reliable and affordable devices must be developed and regularly produced by companies.
In this tutorial, I will first detail the different steps and constrains to turn an academic breadboard into an industrial product. The focus will be given on the optically-pumped cesium beam clock that Oscilloquartz has recently commercially released. Then I will present some real use cases where this clock or others play a central role.

The presentation will last 1 h and will be followed by a 45 min Q&A during which I will answer any questions you might have on commercial atomic clocks and their practical use.

Enrico Rubiola (FEMTO-ST)
Instrumentation for the measurement of time and frequency

This lecture focuses on inside the main instruments for precision time-and-frequency measurements: (i) the general-purpose time and frequency counter, (ii) the phase noise analyzer, and (iii) the Allan variance analyzer, including the multichannel analyzers used to monitor the frequency standards of a time scale. The building blocks and the statistical tools we go through are of much wider usefulness. Applications are ubiquitous, scientific experiments, industrial products (radars, telecom, space), and consumer products (lidar in autonomous cars and in vacuum-cleaner robots), etc.
A variety of time-to-digital converters (TDC) feature picosecond resolution, ≥3 orders of magnitude better than counting the clock cycles. This is achieved with interpolators (Nutt, Vernier, or thermometer-code). Unlike the methods described below, the TDC is suitable to the measurement of single events in a broad range, with minimum a-priori knowledge. PCI and PXI cards provide ≥10 MS/s sampling rate.
The old good double-balanced mixer (DBM) is the phase-to-voltage converter which exhibits the lowest background noise (white PM and flicker PM), used in the traditional phase noise analyzers up to microwaves. It can also be used to beat RF/microwave signals down to lower frequencies, amplifying the time fluctuations. In turns, it enables higher resolution.
The direct digitization (DD) of the RF signal enables the measurement of phase and amplitude via the CORDIC algorithm. The DD is used in recent phase noise analyzers, and in Allan variance analyzers. However, it suffers from higher background noise than the DBM, and from a severe tradeoff between resolution and maximum frequency.
The tracking DDS (TDDS) is an emerging technology for the measurement of time fluctuation, which exploits a DDS phase-locked to the input signal. The control word of the DDS is the phase of the input, versus the digital clock. The TDDS is simple because the complexity is moved from the (fast) RF signal to the (slow) baseband, and it enables full control on the measurement bandwidth (the "mysterious" f_h of the Allan variance).
For repetitive events, increased resolution is achieved with different estimators of the average frequency, among which we mention the Π (flat), Λ (triangular), and Ω (linear regression) estimator. After doubling the hardware (using two separate inputs per signal under test), correlation enables the rejection if the instrument background.
A wealth of material is available on https://rubiola.org. Participants are encouraged to start from the Enrico's chart and the Companion article (on the top-left corner).

Dana Weinstein (Purdue Univ)
Strategic materials and emerging opportunities for IC-MEMS

Micro-electromechanical Systems (MEMS) offer compact, high-performance hardware solutions for sensors and actuators, communication, timing, ultrasonic imaging and stimulation, and energy harvesting. If MEMS can be embedded within ICs, whether in standard CMOS or in emerging 3D heterogeneously integrated (3DHI) platforms, trusted foundries can dramatically increase their microelectronics capabilities with little to no modification to their process flow or packaging. Moreover, embedded MEMS devices could provide chip-scale security through uniquely designed signatures.

This tutorial focuses on the penetration of MEMS devices into integrated circuits, including an overview of state of the art and digging deeper into design and demonstration of acoustically waveguided modes achieved within standard CMOS technology. Methods for mode selection and optimization, confinement, and focusing are discussed. We show both analytically and experimentally the ability to realize high-Q resonance modes in multiple IC platforms ranging from ~100 MHz to ~30 GHz. Looking forward to emerging materials in CMOS, this talk also addresses opportunities and challenges to ferroelectric transducers, typically implemented for ferroelectric random access memory (FRAM).