

Track 1

- 1.1: 8:00 - 10:00 **Timing for GNSS and GNSS for Timing**
Pascale Defraigne, Royal Observatory of Belgium, Belgium
- 1.2: 10:30 -12:30 **Statistical Characterisation of Clocks for Timekeeping and Navigation Applications**
Patrizia Tavella, Istituto Nazionale di Ricerca Metrologica, Italy
- 1.3: 1:30 - 3:30 **Fabrication Methods for MEMS-Based Frequency Control Devices**
Clark T.-C. Nguyen, Berkeley, USA
- 1.4: 4:00 - 6:00 **Fundamentals of Crystal Resonators and Oscillators**
John Vig, USA

Track 2

- 2.1: 8:00 - 10:00 **Femtosecond Laser-based Optical frequency combs for frequency metrology**
Yann Le Coq, LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, France
- 2.2: 10:30 - 12:30 **Lasers for Optical Frequency Standards**
Stephen Webster, M SQUARED LASERS LTD, UK
- 2.3: 1:30 - 3:30 **Frequency & Time Transfer using Optical Fibres**
Gesine Grosche, PTB, Germany
- 2.4: 4:00 - 6:00 **Compact Atomic Clocks**
Gaetano Miletì, Université de Neuchâtel, Institut de Physique, Laboratoire Temps – Fréquence

Track 3

- 3.1 8:00 - 10:00 **Crystal Oscillator Design, Analysis, Simulation and Verification**
M. Michael. Driscoll, USA
- 3.2 10:30 - 12:30 **The Pound Drever Hall Frequency Control Loop, Theory and Application**
E. Rubiola, FEMTO-ST Institute, France
- 3.3 1:30 - 3:30 **Optical Oscillators**
Lute Maleki, OEWaves, USA
- 3.4 4:00 - 6:00 **Phase and Amplitude Noise: Theory & Measurement**
Craig Nelson, NIST, Boulder USA

1.1: 8:00 - 10.00 **Timing for GNSS and GNSS for Timing**

Pascale Defraigne, Royal Observatory of Belgium, Belgium

Course Description

Humans have always needed time for precise navigation. If he had a clock, Christopher Columbus would not have made an error of 150° on his longitude... To date, GNSS also relies on time, as these systems could never work without atomic clocks as the basis of the navigation is a reference time scale maintained by the operators and broadcast by the satellites. On the other hand, the satellite navigation systems offer a wonderful tool for time and frequency metrology, as these flying atomic clocks onboard the satellites can be used as a reference for the comparison of ground time and frequency standards. The tutorial will raise both aspects of the link between GNSS and TIME. After showing concretely the need for accurate time scales for the GNSS, the “GNSS time transfer” technique will be detailed. Code and carrier phase measurements will be presented and the procedure to get a precise and accurate clock comparison will be explained, both from the instrumental point of view and in terms of data analysis. GNSS Common View (or All in View) as well as Precise Point Positioning will be detailed in the presentation. The different error sources on the measurements will be studied and hence an ideal station setup will be presented.

Pascale Defraigne obtained her PhD in Physics at the Université Catholique de Louvain (UCL), Belgium, in 1995, for studies on the deformations of the Earth internal boundaries induced by Mantle density heterogeneities. She then applied her results on modelling of Earth rotation variations (precession, nutation, length of day variations) associated with the internal Earth structure. She is now head of the Time Laboratory at the Royal Observatory of Belgium, where she maintains the Belgian realisation of UTC, the basis of Legal Time, and her present researches are in the frame of GNSS Time and Frequency transfer, i.e. the comparison of remote atomic clocks using GNSS measurements. P. Defraigne is chair of the CCTF Working Group on GNSS Time Transfer and is also member of the IGS Working Group on 'Clock Products' (since 2003).

1.2: 10.30 -12.30 **Statistical Characterisation of Clocks for Timekeeping and Navigation Applications**

Patrizia Tavella, Istituto Nazionale di Ricerca Metrologica, Italy

Course Description

When working in timekeeping or in setting up a navigation system, we need to answer a certain number of questions on clocks and time scales for which suitable statistical and mathematical treatments are necessary.

For example we may need:

- A reference time scale against which all the clocks can be synchronized and estimated;
- an algorithm for forming a single time scale from a clock ensemble;
- the steering of a time scale or a clock with respect to another one;
- a good statistical tool to characterize clock stability, accuracy, and reliability;
- an efficient algorithm for predicting the clock behaviour,
- a rapid algorithm able to identify clock failures or anomalies

These issues are frequently raised in Timing laboratory and in Navigation system contexts; the questions are the same but the answers may be different due to the different aims, requirements, technology availabilities, environment.

This tutorial will present the needs of Timing and Navigation, and the different tools that are well suited to satisfy them, giving insight on the most challenging topics that are still under investigation.

Patrizia TAVELLA obtained a degree in Physics and Ph.D. in Metrology. She is now senior scientist with the Italian Metrology Institute, INRIM, Torino, Italy. Her main interests are mathematical and statistical models mostly applied to atomic time scale algorithms. She is currently involved in the development of the European Navigation System Galileo. She collaborates with the Bureau International des Poids et Mesures, where she chaired the working groups on “International Atomic Time” and “Algorithms” of the Consultative Committee of Time and Frequency.

1.3: 1:30 - 3.30 **Fabrication Methods for MEMS-Based Frequency Control Devices**
Clark T.-C. Nguyen, Berkeley, USA

Course Description

This tutorial aims to describe fabrication process flows that make possible MEMS-based frequency control devices, including oscillator reference resonators, radio frequency filters, and resonant sensors. The tutorial starts with a review of classic MEMS techniques, including surface and bulk micromachining, then proceeds to detail process flows used to achieve existing MEMS-based timing and other products. It then concludes with an overview of up-and-coming fabrication methods for next generation products, including methods for packaging and complete integration alongside transistors.

Prof. Clark T.-C. Nguyen received the B. S., M. S., and Ph.D. degrees from the University of California at Berkeley in 1989, 1991, and 1994, respectively, all in Electrical Engineering and Computer Sciences. In 1995, he joined the faculty of the University of Michigan, Ann Arbor, where he was a Professor in the Department of Electrical Engineering and Computer Science up until mid-2006. In 2006, he joined the Department of Electrical Engineering and Computer Sciences at the University of California at Berkeley, where he is presently a Professor and a Co-Director of the Berkeley Sensor & Actuator Center. His research interests focus upon micro electromechanical systems (MEMS) and include integrated micromechanical signal processors and sensors, merged circuit/micromechanical technologies, RF communication architectures, and integrated circuit design and technology. In 2001, Prof. Nguyen founded Discera, Inc., the first company aimed at commercializing communication products based upon MEMS technology, with an initial focus on the very vibrating micromechanical resonators pioneered by his research in past years. He served as Vice President and Chief Technology Officer (CTO) of Discera until mid-2002, at which point he joined the Defense Advanced Research Projects Agency (DARPA) on an IPA, where he served for three-and-a-half years as the Program Manager for 10 different MEMS-centric programs in the Microsystems Technology Office of DARPA. Prof. Nguyen is a Fellow of the IEEE and presently serves as the Vice President for Frequency Control in the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society.

1.4: 4:00 - 6:00 **Fundamentals of Crystal Resonators and Oscillators**
John Vig, USA

Course Description

The fundamentals of crystal resonators and oscillators will be reviewed. Emphasis will be on those aspects that are of greatest interest to users (as opposed to designers). The discussion will include:

- crystal resonator and oscillator basics;
- the characteristics and limitations of temperature compensated crystal oscillators (TCXOs) and oven controlled crystal oscillators (OCXOs);
- oscillator instabilities: aging; noise; and the effects on frequency stability of: temperature, acceleration, radiation, warm-up, pressure, magnetic field, and the oscillator circuitry;
- guidelines for oscillator comparison, selection and specification.

A preview of this tutorial can be found in the Tutorials section at:

<http://www.ieee-uffc.org/fc>

John Vig was born in Hungary. He emigrated to the United States in 1957, where he subsequently received the B.S. degree from the City College of New York and his Ph.D. degree from Rutgers - The State University. He spent his professional career performing and leading R&D in US government research laboratories - developing high stability quartz crystal resonators, oscillators, and sensors.

He has been awarded 55 patents and is the author of more than 100 publications, including nine book chapters. Since 2006, he has been a consultant, mainly to program managers at the US Defense Advanced Research Projects Agency (DARPA) for programs ranging from micro- and nanoresonators to chip-scale atomic clocks.

He is an IEEE Life Fellow, and is the recipient of the IEEE Cady Award and the IEEE Sawyer Award. He has been the Distinguished Lecturer of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control (UFFC) Society, and he has served as the president of this Society. He founded the IEEE Sensors Council, served as its founding president, and he served as the 2009 IEEE President and CEO.

He and his wife (of 49 years) live in Colts Neck, NJ, USA. Their main hobby is ballroom dancing.

2.1: 8:00 - 10:00 **Femtosecond Laser-based Optical frequency combs for frequency metrology**
Yann Lecoq, LNE-SYRTE, Observatoire de Paris, CNRS, UPMC, France

Course Description

In this tutorial, I will cover the basics of optical frequency combs, in the context of frequency metrology. I'll introduce the physics, concepts and technical implementations related to femtosecond lasers for metrology, concentrating on the work-horses of metrology laboratories (Ti:Sapphire and Er-doped fiber lasers). I will show how these lasers are used routinely to measure and compare optical frequency standards in research laboratories.

I will further describe the concepts and technology that are used nowadays for realizing efficient servo-locking of optical frequency combs, as well as give an overview of the "transfer oscillator technique" which is a servo-loop free alternative to phase-locking techniques. I will also comment on the various counters technology (pi-counter, lambda counters, dead-time,...) and a few statistical tools for frequency metrology (Allan variance, modified-Allan variance, time variance). Some words will be said about the current limitations of the optical frequency combs technology (narrow-linewidth regime, residual noise, amplitude-phase conversion in photodetection,...) and the research which is being led worldwide to overcome them.

I will finish by describing briefly some open perspectives of the domain, including "new" application of frequency combs beyond the usual measurement of optical frequency standard, like low noise microwave generation, whispering gallery modes frequency combs, direct frequency comb spectroscopy, gas traces detection, combs for astronomy,...

Yann Le Coq graduated from an Engineering school specialized in optics (Institut d'Optique Graduate School) in France in 1998. He studied as a PhD student at Institut d'Optique under supervision of Alain Aspect and Philippe Bouyer. He obtained his doctorate in 2002 with a dissertation on "Bose-Einstein condensate and atom lasers" and kept working on this subject at Institut d'Optique until 2004. He was a post-doc at the National Institute of Standards and Technology (NIST) in Boulder, CO (USA) from 2004 to 2006, where he worked in the group led by Leo Hollberg on a cold neutral Calcium optical frequency standard and its interaction with optical frequency combs.

Since 2007, he has been working at LNE-SYRTE in Paris, in the optical frequency group, where he is in charge of the optical frequency comb activities. His research has focused mainly on the ultra-high performance requirement of the measurements of optical frequency standards based on neutral mercury and Strontium atoms, as well as low phase-noise microwave generation with optical frequency combs and ultra-high stability lasers.

2.2: 10:30 - 12.30 **Lasers for Optical Frequency Standards**

Stephen Webster, M SQUARED LASERS LTD, UK

Course Description

Over the past 50 years, atomic clocks have been based on microwave frequencies and primary standards have demonstrated uncertainties at the level of a few parts in 10^{16} . Optical clocks are a new generation of atomic clock, in which the frequency of light is the signal used for timing. They are based on “forbidden” atomic transitions for which light is absorbed over a very narrow range of frequencies. Depending on the particular atomic species and transition used, the ratio of the frequency to the frequency width (Q-factor) ranges from 10^{14} - 10^{23} , thus, these transitions constitute very precise frequency references. They are also insensitive to external electromagnetic fields and can be highly reproducible and it is anticipated that optical clocks will reach uncertainties of a part in 10^{18} . Further, given that the frequency of light is $\sim 100,000$ times higher than that of microwaves, the same level of precision as a microwave atomic clock may be reached in a much shorter time. As optical clocks come of age and prove the stability and reproducibility predicted of them, the prospect will open up for a redefinition of the second in terms of an optical frequency.

The atomic absorber in an optical clock takes one of two forms: it is either a single ion confined in an electro-dynamic trap (Paul trap), or an ensemble of neutral atoms held in an electric dipole force trap (optical lattice). The atomic absorbers are laser cooled so that they are nearly at rest and, to first order, do not experience a Doppler shift on interaction with the light used to probe the atomic transition. To make use of the high-Q of the atomic transition, the probe light must also have a very narrow frequency width and this is achieved by stabilizing a laser to a secondary reference, a high-finesse Fabry-Pérot etalon. A mode-locked femtosecond-pulsed laser (femtosecond comb) converts the very rapid oscillations of the light from some 100's of THz down to a radio frequency so that output of the optical clock can be counted by commercial electronics and compared to the SI second and the outputs of other optical clocks.

This tutorial will give an overview of the essential elements of an optical clock: the atomic reference, the ultra-stable laser and the femtosecond comb. It will describe how each of these elements is realized in practice and the experimental challenges involved in operating such an apparatus. In particular, a review will be made of the laser sources required for operation of an optical frequency standard, the techniques employed in their stabilisation and the characterization of their noise.

Stephen Webster joined M Squared lasers as their Scientific Products Specialist in September 2012. The company specialises in the research, development and manufacture of solid-state lasers and photonic instruments for a wide range of industrial and scientific applications; his role is to engage with scientific customers and develop new products to meet scientific needs.

Previous to his work at M Squared, Stephen was a senior research scientist at the National Physical Laboratory in the UK for over a decade, where he worked on optical frequency standards, ultra-stable lasers and vibration-insensitive cavities. Highlights of his work there were publications on a force-insensitive optical cavity, the lowest reported acceleration sensitivity for an optical cavity, subhertz laser linewidth, observation of the thermal-noise limit for a cavity and frequency measurements of the electric quadrupole and octupole transitions in $^{171}\text{Yb}^+$ ion with a fractional uncertainty of 10^{-15} . In 2008, he received the Young Scientist of the Year Award at the European Frequency & Time Forum.

Stephen was awarded a D.Phil from the University of Oxford in 2000 for work on Bose-Einstein Condensation of atomic gases.

Outside of work, Stephen is a keen musician and enjoys hiking and cycling. He is married with two children, aged 4 and 10 months.

2.3: 1:30 - 3.30 **Frequency & Time Transfer using Optical Fibres**
Gesine Grosche, PTB, Germany

Course Description

Ever more accurate clocks and frequency references are being developed in dedicated laboratories around the world, reaching astonishingly low instability and high accuracy, currently near 1 part in 10^{17} . Yet, making the ultra-stable output of these powerful instruments available beyond the walls of the metrology laboratory, to enable physics experiments, remains a challenge.

In the wake of the optical telecommunication revolution, transfer techniques that make use of optical fibre have greatly developed: within one decade, improvements of more than three orders of magnitude in precision have been achieved. Frequency transfer accuracy at the level of 1 part in 10^{19} , and, for 1 km-scale links, synchronisation at the level of femtoseconds has been reported. Fibre based transfer of frequency and time has been achieved over distances exceeding 500 km, enabling international comparisons and joint experiments.

In this tutorial I will illustrate the advantages and challenges of using optical fibre as a transmission medium for precision metrology. This will cover basic concepts, techniques and limitations, focussing on optical telecommunication fibre (1.5 μm), which is both cheap and optimised for low loss, making it suitable for long-distance transfer. The tutorial will give an overview and comparison of different frequency and time transfer techniques, including methods based on radio-frequency modulation, on using the optical carrier phase, and on the transmission of fs-pulses generated by mode-locked lasers.

Gesine Grosche is head of the research group for optical frequency dissemination at the German Metrology Institute, PTB, in Braunschweig, Germany. She received her B.A. degree in Physics from Cambridge University, UK (Trinity College, 1993) and her PhD in Semiconductor Physics from University of London (Imperial College, 1997). After initially joining PTB to invent optical methods for measuring fluid flow velocities from an airplane, she moved on to coordinate a European project providing reference wavelengths for optical telecommunications, and, from 2003, to establish and develop frequency comb metrology based on mode-locked fiber lasers at PTB. From 2001, she has pursued the vision of ultra-stable frequency dissemination using telecommunication fibre, pioneering and refining techniques for remote metrology, which includes remote frequency measurements and frequency synthesis. Her group currently concentrates on long-distance phase-stable fibre links to connect metrology institutes across Europe.

2.4: 4:00 - 6:00 **Compact Atomic Clocks**
Gaetano Mileti, Université de Neuchâtel, Institut de Physique,
Laboratoire Temps – Fréquence

Course Description

Atomic frequency standards play an essential role as the backbone of the international navigation and timing infrastructure. For over 50 years, practical applications have been served by three basic technologies: cesium beam frequency standards, rubidium clocks, and hydrogen masers. The technology choice for a particular application is determined by a trade-off between the required performance and practical considerations of Size, Weight, and Power consumption (SWAP). In the past decade, extensive research has been devoted to the development of atomic clocks with extraordinarily low SWAP, enabling emerging applications in communications and navigation systems with a need for increased mobility and bandwidth in portable battery-powered hand-held devices. So-called "Chip-Scale Atomic Clocks" (CSACs) are now commercially available while on-going research worldwide continues.

This tutorial will introduce the motivation and applications for CSAC, the development and technology of existing CSACs, and an overview of active R&D addressing next-generation CSAC

Prof. Gaetano Mileti received his engineering degree in Physics from the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, in 1990 and the Ph.D. degree in Physics from the Neuchâtel University, Switzerland, in 1995. From 1991 to 1995 and from 1997 to 2006, he was a research scientist at the Observatoire Cantonal de Neuchâtel. From 1995 to 1997, he visited the National Institute of Standards and Technology (NIST) in Boulder (USA) as guest scientist. In 2007, he co-founded the Laboratoire Temps-Fréquence (LTF) at the University of Neuchâtel, where he presently serves as deputy director.

His research interests include frequency standards, atomic spectroscopy, and stabilized lasers. From 1991 to 1995 he participated to the development of the Rubidium atomic clocks now deployed for the European Satellite Navigation System GALILEO. Since 2001, he has conducted several research projects on vapour-cell atomic clocks for ground and space applications. In 2003, he launched the first Swiss projects on chip-scale atomic clocks, in collaboration with the Neuchâtel Institute of Micro-technology. Gaetano Mileti teaches and organises lectures on atomic clocks since several years.

3.1 8:00 - 10:00 **Crystal Oscillator Design, Analysis, Simulation and Verification**
M. Michael. Driscoll, USA

Course Description

This tutorial will cover both basic and advanced concepts involved in the design, analysis, simulation, and test of crystal oscillator circuits. It will cover methods for designing both traditional and novel crystal oscillator circuits, tests and software simulations that enable determination, for example, of the sustaining stage contribution to output signal phase noise and resonator loading, AM to PM conversion, methods for reducing output signal phase noise and vibration sensitivity, and a review of the current state-of-the-art.

The aim of this tutorial is to familiarize attendees with both crystal oscillator traditional and new concepts that will aid the user, specifier, and designer of crystal oscillator circuitry with useful and up to date information.

Mike Driscoll joined the Westinghouse Defense Centre (now part of Northrop Grumman Electronic Systems) in Baltimore in 1965 after graduating from the University of Massachusetts in Amherst. Since 1968, he has worked primarily on the design and development of low noise signal generation hardware for use in high performance radar systems and other special applications. He was a Senior Consulting Engineer at Northrop Grumman until retiring in February, 2008. He was a Contract Engineer, consulting at Northrop Grumman until November, 2012. His responsibilities included the design and development of high stability oscillators as well as characterization and reduction of phase noise in RF signal processing components and circuits. He is a past Secretary, Treasurer, and President of the Baltimore, Washington, and Northern Virginia chapter of the UFFC. He has been a member of the IEEE Frequency Control Symposium Technical Program Committee since 1987. He is an Associate Editor and Associate Editor-in-Chief of the IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control (UFFC) and was the Conference Chair for the 2005, 2006, and 2012 IEEE International Frequency Control Symposia (IFCS). In 1991, he was elected as an IEEE Fellow, cited for "*Contributions to the development of low-noise acoustic resonator-stabilized oscillators*". In 1997, he was the recipient of the IEEE UFFC Society CADY award, cited for "*Contributions to Low Noise Signal Generator Design*". In 2006, he was a recipient of the Northrop Grumman Lifetime Achievement Award. He is the UFFC Society's Distinguished Lecturer for 2012-2013. He has published and presented over 60 papers in IEEE Journals and at IEEE Conferences. He has presented several IEEE Tutorials and Northrop Grumman Instructional Courses and holds 16 U.S. Patents dealing with the subject of Low Noise Signal Generation.

3.2 10:30 - 12:30 **The Pound Drever Hall Frequency Control Loop, Theory and Application**
E. Rubiola, FEMTO-ST Institute, France

Course Description

The PDH frequency control loop is a milestone in radio engineering and in spectroscopy, and it is a smart and powerful tool available to numerous branches of experimental science.

First published by Robert Pound (Radiation Laboratory golden team) in 1946, the 'Pound control' was ported to optics by John Hall (Nobel prize in 2005) and R. Drever.

PDH control is nowadays the standard method to lock a microwave oscillator or a laser oscillator to an external frequency reference 'CAVITY', like a dielectric resonator or a Fabry-Perot cavity. The unique feature of the PDH scheme, which makes it superior to all competitors, is that the path length from the locked oscillator to the reference resonator cancels, so therefore do the loop fluctuations. Furthermore, locking relies on a null measurement of the frequency error.

Most used in general microwave and optics, this technique is the only one which can be used at 10^{-15} to 10^{-16} frequency stability levels (Femto-ST ULISS oscillator, and photonic oscillators). Applications span a wide range including: metrology, optics, spectroscopy, gravitation, space/military electronics, etc.

This course will cover the key theoretical and experimental details and present the latest state of the art results.

Enrico Rubiola is full professor at the Université de Franche Comté and a scientist at the Department of Time and Frequency of the CNRS FEMTO-ST Institute, Besançon, France. Formerly, he was a full professor at the Université Henri Poincaré, Nancy, France, a guest scientist at the NASA JPL, a professor at the Università di Parma, Italy, and an assistant professor at the Politecnico di Torino, Italy.

He graduated in electronic engineering at the Politecnico di Torino in 1983, a Ph.D. in Metrology from the Italian Minister of University and Research, Roma (1989), and a Sc.D. degree from the Université de Franche Comté in 1999.

Prof. Rubiola has worked on various topics of electronics and metrology, navigation systems, time/frequency comparisons, and frequency standards. His main fields of interest are precision electronics from dc to microwaves and phase noise metrology, which include frequency synthesis, high spectral purity oscillators, photonic systems, sophisticated instrumentation, and noise. He has developed innovative instruments for AM/PM noise measurement with ultimate sensitivity, and on a variety of signal-processing methods. Currently, he is the PI of Oscillator IMP, a platform under development, dedicated to the measurement of AM/PM noise and short-term frequency stability.

A wealth of articles, reports and conference presentations are available on the Enrico Rubiola's home page <http://rubiola.org>.

3.3 1:30 - 3:30 **Optical Oscillators**
Lute Maleki, OEWaves, USA

Course Description

Advanced microwave and mm-wave oscillators based on optoelectronics and photonics technology have emerged as new and improved alternatives to conventional devices. This new generation of oscillators can generate highly spectrally pure signals, in packages that are robust to environmental perturbations. In this tutorial a discussion of fundamental basis of photonic oscillators will be followed by details of current and emerging techniques in the field. We will begin with Leeson's equation and show how optical resonators and waveguides naturally allow realization of higher quality factor elements that significantly improve the ability to generate spectrally pure signals. This is particularly important at microwave and higher frequencies, where electronic components exhibit high loss.

We will also discuss some of the underlying physics, including linear and nonlinear optical processes that enable optical oscillators.

Lute Maleki is the Founder, President, and CEO of OEwaves, a company that has pioneered development and realization of photonics technologies. He is an inventor of the opto-electronic oscillator (OEO) and numerous other patents related to generation of electronic reference signals with photonics means. Before joining OEwaves, Lute Maleki was the supervisor of Quantum Sciences and Technologies group at JPL.

3.4 4:00 - 6:00 **Phase and Amplitude Noise: Theory & Measurement**
Craig Nelson, NIST, Boulder USA

Course Description

Noise is everywhere. Its ubiquitous nature interferes with or masks desired signals and fundamentally limits all electronic measurements. Noise in the presence of a carrier is experienced as amplitude and phase modulation noise. Modulation noise will be covered from its theory, to its origins and consequences. The effects of signal manipulation such as amplification, frequency translation and multiplication on spectral purity are examined. Practical techniques for measuring AM and PM noise, from the simple to complex will be discussed. Calibration of measurements and common problems and pitfalls will also be covered.

Craig Nelson is an electrical engineer at the Time and Frequency Division of the National Institute of Standards and Technology. He received his BSEE from the University of Colorado in Boulder in 1990. After co-founding SpectraDynamics, a supplier of low phase noise components, he joined the staff at the NIST. He has worked on the synthesis and control electronics, as well as software for both the NIST-7 and F1 primary frequency standards. He is presently involved in research and development of ultra-stable synthesizers, low phase noise electronics, and phase noise metrology. Current areas of research include optical oscillators, pulsed phase noise measurements and phase noise metrology in the MHz to THz range. He has published over 70 papers and teaches classes, tutorials, and workshops at NIST, the IEEE Frequency Control Symposium, and several sponsoring agencies on the practical aspects of high-resolution phase noise metrology.