84th ARFTG Microwave Measurement Conference

NIST-ARFTG SHORT COURSE
on
Microwave Measurements

December 2nd - 3rd, 2014
Boulder, Colorado
St Julien Hotel

ARFTG-NIST Short Course on Microwave Measurements

Dec. 2^{nd}-3^{rd}, 2014
Boulder, Colorado

Overview:

Join us in a tutorial on practical microwave measurements for wireless communications. This short course is intended for engineers, graduate students, experienced technicians, or technical managers.

Day 1 will start in the morning session with (1) power measurement, (2) network analyser mesurements, (3) oscilloscope measurements and (4) measurement uncertainty theory and will continue in the afternoon session with (5) connectorized, (6) verification and (7) on-wafer S-parameter measurements at millimetre frequencies and (8) noise measurements.

Day 2 (morning only) will focus on (9) large-signal RF measurements with NVNAs, present practical examples of CW & pulsed-RF measurement applications (10 &11) and conclude with (12) spectrum & vector signal analysis.

Measurement uncertainty and the process of measurement verification will be covered in two dedicated lectures. Space is limited; please register early.

Scheduled Instructors:

- Tom Crowley – *NIST*
- Ken Wong – *Keysight Technologies*
- Paul Hale – *NIST*
- Nick Ridler – *NPL*
- Jon Martens – *Anritsu*
- Ron Ginley – *NIST*
- Dylan Williams – *NIST*
- Ali Boudiaf – *Infineon Technologies*
- Dominique Schreurs – *K. U. Leuven University*
- Jean Pierre Teyssier – *XLIM*
- Patrick Roblin – *The Ohio State University*
- Tom Kuntz – *Tektronix*

Contact:

Prof. P. Roblin, The Ohio State University, OH, USA (roblin.1@osu.edu)
Short Course Coordinator

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AGENDA

Tuesday, December 2nd

7:30 a.m. – 8:00 a.m.	**Registration**
8:00 a.m. – 8:10 a.m.	**Welcome and Introduction** *Patrick Roblin – The Ohio State University*
8:10 a.m. – 9:00 a.m.	**High Speed Oscilloscope Measurement Advancements** *Paul Hale – NIST*
9:00 a.m. – 9:50 a.m.	**VNA Measurements & Calibration** *Ken Wong – Keysight Technologies*
9:50 a.m. – 10:20 a.m.	**Break**
10:20 a.m. – 11:10 a.m.	**Principles of Power Measurement & Uncertainties** *Tom Crowley – NIST*
11:10 a.m. – 12:00 p.m.	**Measurement Uncertainties** *Nick Ridler – NPL*
12:00 p.m. – 1:00 p.m.	**Lunch**
1:00 p.m. – 1:50 p.m.	**Millimetre-Wave Connectorized S-Parameter Measurements** *Jon Martens – Anritsu*
1:50 p.m. – 2:40 p.m.	**Measurement Verification at MM-Wave Frequencies** *Ron Ginley – NIST*
2:40 p.m. – 3:10 p.m.	**Break**
3:10 p.m. – 4:00 p.m.	**On Wafer S-Parameters & Uncertainties** *Dylan Williams – NIST*
4:00 p.m. – 4:50 p.m.	**Microwave Noise Measurements** *Ali Boudiaf – Infineon Technologies*
4:50 p.m. – 5:00 p.m.	**'Bring your problem'** *All instructors*

Wednesday, December 3rd

8:00 a.m. – 8:50 a.m.	**Vector Large-Signal Measurements** *Gustavo Avolio – K.U.Leuven*
8:50 a.m. – 9:40 a.m.	**Application of NVNA to RF Engineering** *J-P Teyssier – XLIM*
9:40 a.m. – 10:10 a.m.	**Break**
10:10 a.m. – 11:00 a.m.	**CW and Pulsed RF Load-pull Measurements** *Patrick Roblin – The Ohio State University*
11:00 a.m. – 11:50 a.m.	**Spectrum Analysis & Vector Signal Analysis** *Tom Kunz – Tektronix*
11:50 a.m. – 12:00 p.m.	**Wrap-up**

Contact

Prof. P. Roblin, The Ohio State University, OH, USA (roblin.1@osu.edu)
Short Course Coordinator

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ABSTRACT

1. Principles of Power Measurement & Uncertainties
Thomas P. Crowley – NIST

The equipment and techniques for making power measurements at radio, microwave and millimeter wave frequencies will be described. The terminology used to describe power measurements will be defined. Power measurement devices will be discussed including primary standards and commercially available sensors. The commercial power sensors discussed include thermistor, thermoelectric, and diode sensors and their power meters. The technique for transferring effective efficiency from a standard to another device will be illustrated with an example. This example will include the appropriate mismatch correction. The same example will then be used to demonstrate how to calculate uncertainty using 1) an analytical approach based on partial derivatives or 2) a Monte-Carlo analysis. Typical uncertainty levels and sources of error will be described.

2. VNA Measurements and Calibration
Ken Wong – *Keysight Technologies*

Vector Network Analyzers (VNA) is the instrument of choice to measure input, transfer, and output vector characteristics of high frequency devices, from passive one port devices to multi-port networks and systems. Modern VNAs are very versatile, flexible and potentially very accurate. This versatility and flexibility can cause misunderstandings and lead to missuses. This short course is intended to provide VNA users an overview of how VNAs work and why calibrations are necessary. Basic systematic error models, calibration methods and their assumptions will be discussed. Best practices, some verification methods also will be presented.

3. High Speed Oscilloscopes: Calibration and application to waveform metrology
Paul D. Hale –*NIST*

This lecture briefly reviews real-time and equivalent-time (sampling) oscilloscopes, how their timebases work, and some pros and cons for each type of instrument. Full waveform metrology is introduced and contrasted with traditional ways of using oscilloscopes. Measurement errors in equivalent-time oscilloscopes and methods for calibrating them are then reviewed in some detail. These errors include noise, timing jitter and drift, impedance mismatch and cable/fixture loss, and sampler response. Use of electro-optic sampling to calibrate a photodiode frequency response transfer standard is reviewed. Finally, use of the calibrated oscilloscope for measuring digital and modulated mm-wave signals is then described.

4. Measurement Uncertainties
Nick Ridler – *NPL*

This lecture will describe the general principles involved in evaluating and expressing uncertainty in measurement. The lecture will start from basics (no assumed prior knowledge) and describe the methods that are used to evaluate errors in measurement and present them as contributions to the overall uncertainty in the measurement. The process will be accompanied by examples, taken from actual microwave measurement situations, to illustrate the various methods used. Finally, the use of uncertainty for assessing test results and compliance to specifications will be described.

5. Millimetre-Wave Connectorized S-Parameter Measurements
Jon Martens – *Anritsu*

Connectorized S-parameter measurements take on some new dimensions at mm-wave frequencies in terms of changes in component modeling, repeatability characteristics and calibration choices. These behaviors will be discussed with a primary focus on 1mm and smaller coaxial connectors and on comparisons to relevant waveguide performance.

6. Measurement Verification at Millimetre-Wave Frequencies
Ron Ginley – *NIST*

Verification techniques for microwave measurements with an emphasis on vector network analyzers measurements will be covered. This will include the concept of verification, data handling including dealing with outliers and comparison of data sets. Finally, verification for terahertz measurements will be briefly covered.

7. On Wafer S-Parameters & Uncertainties
Dylan Williams – *NIST*

The principles behind making accurate on-wafer scattering parameters in the microwave, millimeter-wave, and sub-milllimeter-wave wavelengths will be discussed. Approaches for identifying errors due to inconsistencies in the calibration kits, drift, and systematic errors will be presented.

8. Microwave Noise Measurements
Ali Boudiaf – *Infineon Technologies*

This lecture focuses on microwave noise measurements. The importance of noise measurement and the measurement techniques available will be reviewed. The applications of source-pull noise measurement to device characterization and modeling will then be discussed.

9. Vector Large-Signal Measurements
Dominique Schreurs – *K.U.Leuven*

This lecture focuses on vectorial large-signal measurements. It is explained how such measurements can be achieved starting from a vector network analyzer architecture. Next, the calibration procedure and corresponding traceability are covered. Often, an additional de-embedding step is required, especially in case of on-wafer measurements. Therefore the difference between linear and non-linear de-embedding will be highlighted. Finally, some experiment design considerations related to non-linear measurements based model construction are touched upon.

10. Application of NVNA to RF Engineering
Jean Pierre Teyssier – *XLIM*

NVNAs are involved with the most advanced measurement technologies used to characterize RF active devices: time domain load-pull, X-parameters extraction, waveform engineering in I(V) and envelope domain; … all this is mostly driven by new telecommunication technologies with high power efficiency and increased bit rates which are setting very demanding requirements. This lecture proposes a tour of modern applications involving NVNA measurement technologies, starting from device-level measurement, with modeling and model verification and going to system-level, with the dynamic optimization of the load cycles and the testing of devices for wideband modulated signals.

11. Pulsed RF Load-pull Measurements
Patrick Roblin – *The Ohio State University*

This lecture focuses on pulsed vectorial large-signal measurements. The motivation for broadband pulsed-RF measurement to address memory effects such as self-heating, trapping and parasitic BJT will be reviewed. The calibration procedure for pulsed large-signal measurement will then be addressed. Applications of pulsed-RF load-pull measurements to device characterization and modeling and PA design will then be discussed.

12. Spectrum Analysis and Vector Signal Analysis
Thomas Kuntz – *Tektronix, Inc.*

The swept spectrum analyzer was originally developed in the days of analog radios as a way to see the behavior of RF signals both inside their intended RF channel assignments and their behavior as potential interferers to users of other channel assignments. As RF transmissions become increasingly digital, the modulation becomes more complex and channel assignments include time domain and code domain as well as frequency domain elements. This has led to vector signal analyzer (VSA) and real time signal analyzer (RSA) architectures. The relentless quest for data transmission speed has led to ultra wideband techniques and engendered the need for signal analyzers that can process multi GHz of bandwidth simultaneously. The presentation covers the key architectural elements for each type of analyzer as well as relevant applications and specifications.

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Lecturer Bios:

Thomas P. Crowley received the S.B. degree in physics from MIT and the Ph.D. degree in plasma physics from Princeton U. From 1986 to 2000, he was a faculty member in the Electrical, Computer, and Systems Engineering Dept. at Rensselaer Polytechnic Institute with a research focus on particle beam diagnostics of fusion plasmas. Since 2000, he has been a physicist at NIST and is responsible for the U.S.' primary power standards from 50 MHz to 95 GHz.

Ken Wong received his BSEE from Cal Poly, SLO in 1972 and has been with HP/Agilent/Keysight since graduation. He also did some graduate level work at UC Berkeley under the HP Honor Coop program. His experience at HP/Agilent/Keysight includes product design, manufacturing process development, and test process development of microwave hybrid microcircuits and instruments. Currently, he is the principal engineer responsible for the development, modeling, and measurement of microwave reference standards and Vector Network Analyzer calibration methods. Ken Wong has published and presented many papers on VNA calibration and standards. He had been granted over a dozen patents on connector design and VNA calibration. He has held numerous leadership positions in the Automatic Radio Frequency Techniques Group (ARFTG) since 1994, including a term as president, vice-president, treasurer and now the membership chair. He was elected a senior member of the IEEE in 2003. He is an active participant in many IEEE standards work groups related to connector standards and high frequency instrumentation performance verification guides. . He is a member of MTT-S and IM-S transaction and magazine technical paper review committees.

Paul D. Hale received a Ph.D. in Applied Physics from the Colorado School of Mines, Golden, CO, in 1989. Since then, he has been with the Optoelectronics Division of the National Institute of Standards and Technology (NIST), Boulder, CO where he conducts research on broadband optoelectronic device and signal metrology. Current technical work focuses on extending both time- and frequency-domain optoelectronic measurements to beyond 110 GHz, implementing a novel covariance-based uncertainty analysis that can be used for both time- and frequency-domain quantities, and disseminating NIST traceability through high-speed electronic and optoelectronic measurement services. He has been Leader of the High-Speed Measurements Project in the Sources and Detectors Group since 1996.

Nick Ridler is from the United Kingdom (UK). He received the BSc degree from the University of London in 1981. He has since spent 30+ years working in both industrial and government research establishments. Nick is currently a Principal Research Scientist at the National Physical Laboratory (NPL) – this being the UK's National Measurement Institute. Nick is currently involved in research into measurements at millimeter and submillimeter wavelengths. He is also involved in high-speed measurements on Printed Circuit Boards (PCBs).

Jon Martens received his Ph.D. in electrical engineering from the University of Wisconsin in 1990. Since 1995, he has been with Anritsu working on measurement system architectures, measurement and calibration algorithmic development, and microwave/mm-wave circuit design.

Ronald A. Ginley spends as much of his time as possible ski patrolling at the Loveland Ski Area. When he is not there he is either taking loud voice classes or at his present place of employment - The National Institute of Standards and Technology (NIST). He has worked at NIST for the past 30 years in the areas of microwave network analysis and microwave power measurements. He is presently the Group Leader of the RF Electronics Group of NIST. This includes the management of the microwave measurement services; fundamental research in the areas of power, thermal noise and scattering-parameters; nanoscale device metrology, high speed electronics, THz network analysis, remote sensing for climate change monitoring, and electromagnetic properties of materials.

Dylan F. Williams (M’80-SM’90-F'02) received a Ph.D. in Electrical Engineering from the University of California, Berkeley in 1986. He joined the Electromagnetic Fields Division of the National Institute of Standards and Technology in 1989 where he develops electrical waveform and microwave metrology. He has published over 80 technical papers and is a Fellow of the IEEE. He is the recipient of the Department of Commerce Bronze and Silver Medals, the Astin Measurement Science Award, two Electrical Engineering Laboratory's Outstanding Paper Awards, three Automatic RF Techniques Group (ARFTG) Best Paper Awards, the ARFTG Automated Measurements Technology Award, the IEEE Morris E. Leeds Award and the 2013 IEEE Joseph F. Keithley Award. Dylan also served as Editor of the IEEE Transactions on Microwave Theory and Techniques from 2006 to 2010 and is currently the Executive Editor of the IEEE Transactions on Terahertz Science and Technology.

Ali Boudiaf received a Ph.D. in Electrical Engineering from the University of Paris XI, Orsay, France in 1993. He is currently with Maury Microwave as Application Engineering Manager. He worked at Focus Microwaves, Agilent Technologies and ATN-Microwave where he led the enhancement of the noise parameter measurement systems and the load-pull measurement systems. From 1994 to 1998, he was an Assistant Professor at the University of Marne-la-Vallee, France. His research works focused on semiconductor device modeling and microwave monolithic circuit design. He is the author of several technical papers and holds 3 patents.

Dominique Schreurs received the M.Sc. and Ph.D. degrees in electronic engineering from the Katholieke Universiteit (KU) Leuven, Belgium. She was a post-doc fellow of FWO-Flanders, and has been Visiting Scientist with Agilent Technologies (USA), Eidgenössische Technische Hochschule Zürich (Switzerland), and the National Institute of Standards and Technology (USA). She is now Full Professor at KU Leuven. Her main research interests concern the (non)linear characterization and modeling of microwave devices and circuits, as well as (non)linear circuit design for telecommunications and biomedical applications. Prof. D. Schreurs is serving on the Executive Committee of the ARFTG organization, presently as Chair of the Technical Committee. She was General Chair of the Spring ARFTG Conferences in 2007 and 2012. In 2002, she was one of the initiators and is now still co-organizer of the successful NVNA Users’ Forum. She is also IEEE Fellow and serves on the IEEE MTT-S AdCom. She has been Chair of the IEEE MTT-S Technical Committee on Microwave Measurements (MTT-11), and now she is chair of the IEEE MTT-S Education Committee. She was also co-chair of the European Microwave Conference in 2008 and then initiated the IEEE Women in Microwaves event at the European Microwave Week.

Jean Pierre Teyssier was born in 1963 in Brive, France. Since 1990, he works as a professor and research director at the IRCOM / XLIM laboratory of the University of Limoges, France, in the group of Prof. Raymond Quere. He has presented his PhD thesis in 1994, the subject was about pulsed I(V) and pulsed S-Parameters for nonlinear characterization of microwave active devices, and his research director thesis in 2007. Up to now, he is involved in the design of measurement systems and instrumentation for microwave nonlinear investigations, with an emphasis on time domain pulsed large signal characterization of transistors (pulsed NVNA harmonic load-pull).Since many years, Jean-Pierre Teyssier and his students are frequent contributors of ARFTG sessions, he has been in fall 2006 the organizer of the ARFTG workshop about RF samplers. He is a member of ARFTG ExCom since Fall 2007, in charge of Workshops.Starting in 2007, he was a co-founder of the company VTD (Verspecht Teyssier DeGroote) that builds and sells its own NVNA solution. The VTD company has been acquired in 2011 by Agilent Technologies. Subsequently, he has spent the academic year 2012-2013 in Agilent/Keysight facilities at Santa Rosa, CA.

Patrick Roblin was born in Paris, France, in September 1958. He received the Maitrise de Physics degree from the Louis Pasteur University, Strasbourg, France, in 1980, and the M.S. and D.Sc. degrees in electrical engineering from Washington University, St. Louis, MO, in 1982 and 1984, respectively. In 1984, he joined the Department of Electrical Engineering, at The Ohio State University (OSU), Columbus, OH, as an Assistant Professor and is currently a Professor. His present research interests include the measurement, modeling, design and linearization of non-linear RF devices and circuits such as oscillators, mixers, and power-amplifiers. He authored and co-authored two textbooks published by Cambridge University Press. He is the founder of the Non-Linear RF research lab at OSU. He has developed at OSU two educational RF/microwave laboratories and associated curriculum for training both undergraduate and graduate students.

Thomas Kuntz is a Senior Engineer with Tektronix in Beaverton, Oregon. He received a BSEE from the University of North Dakota in 1985 and MSEE from the University of Iowa in 1995. His early career was spent at Rockwell Collins in Cedar Rapids, Iowa, developing communications and GPS systems for commercial and military avionics platforms. Thomas has been with Tektronix since 1996, where he has developed spectrum and signal analysis and measurement algorithms and software for bench and handheld products, including ATSC broadcast signal analyzers, handheld cellular basestation analyzers, and laboratory spectrum/signal analyzers. His recent work has included creating OFDM signal analysis suites for the RSA analyzer products. He has received 10 US Patents in the area of test and measurement.