86th ARFTG Microwave Measurement Conference

NIST-ARFTG SHORT COURSE
on
Microwave Measurements

December 1st – 2nd, 2015

Atlanta, Georgia

ARFTG-NIST Short Course on Microwave Measurements

Dec. 1sd-2nd, 2015
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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 measurements, (2) network analyser measurements, (3) oscilloscope measurements, and (4) noise measurements theory and will continue in the afternoon session with (5) connectorized and (6) on-wafer S-parameter measurements, (7) VNA calibration techniques and (8) verification at millimetre-wave frequencies.

Day 2 (morning only) will focus on (9) large-signal RF measurements with NVNAs, present practical examples of advanced 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.

Scheduled Instructors:

- Andy Brush – *Tegam*
- Ken Wong – *Keysight Technologies*
- Paul Hale – *NIST*
- Gary Simpson – *Maury Microwave*
- Jon Martens – *Anritsu*
- Andrej Rumiantsev – *MPI Corporation*
- J. Apolinar Reynoso-Hernández – *CICESE*
- Ron Ginley – *NIST*
- Dominique Schreurs – *K. U. Leuven University*
- Jean Pierre Teyssier – *XLIM - Keysight Technologies* ***(not confirmed)***
- Patrick Roblin – *The Ohio State University*
- Marcus da Silva – *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 1st

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.	**Principles of Power Measurement** *Andy Brush – Tegam*
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.	**High Speed Oscilloscopes: What the manual doesn't tell you** *Paul Hale – NIST*
11:10 a.m. – 12:00 p.m.	**Microwave Noise Measurements** Gary Simpson – *Maury Microwave*
12:00 p.m. – 1:00 p.m.	**Lunch**
1:00 p.m. – 1:50 p.m.	**Connectorized Millimeter-Wave S-Parameter Measurements** *Jon Martens – Anritsu*
1:50 p.m. – 2:40 p.m.	**On Wafer S-Parameters & Uncertainties** *Andrej Rumiantsev – MPI Corporation*
2:40 p.m. – 3:10 p.m.	**Break**
3:10 p.m. – 4:00 p.m.	**VNA Calibration Techniques: Theory and Applications** *Apolinar Reynoso-Hernández – CICESE*
4:00 p.m. – 4:50 p.m.	**Measurement Verification at MM-Wave Frequencies** *Ron Ginley – NIST*
4:50 p.m. – 5:00 p.m.	**'Bring your problem'** *All instructors*

Wednesday, December 2nd

8:00 a.m. – 8:50 a.m.	**Vector Large-Signal Measurements** *Dominique Schreurs – K.U.Leuven*
8:50 a.m. – 9:40 a.m.	**NVNA Measurements: from Legacy to Wideband Spectrum Analysis** *J-P Teyssier – XLIM*
9:40 a.m. – 10:10 a.m.	**Break**
10:10 a.m. – 11:00 a.m.	**Real-Time 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** *Marcus da Silva – 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)
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ABSTRACT

1. RF Power Measurement & Uncertainties
Andy Brush – *Tegam*

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: What the manual doesn't tell you
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. Microwave Noise Measurements
Gary Simpson – *Maury Microwave*

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.

5. Connectorized Millimeter-Wave 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. On Wafer S-Parameters & Uncertainties
Andrej Rumiantsev – *MPI Corporation*

Wafer-level S-parameter measurement at mm-wave and sub-mm wave frequencies plays a crucial role in the model development and IC design verification and debug of advanced semiconductor technologies. Accurate calibration of the entire wafer-level measurement system to the RF probe tip end or to the intrinsic device terminals is a critical success factor for extracting trustable device model parameters and characterizing true performance of a RF IC. This presentation will start with the basics of S-parameter measurement and calibration techniques at wafer-level. Special attention will be paid to how to choose the right calibration method for specific measurement application needs. Definition of the calibration reference plane and the measurement reference impedance of a calibrated system will be reviewed as well. Finally, the potential sources of calibration residual errors will be analyzed. Practical examples will be given on how to minimize the impact of such errors on the measurement accuracy of a calibrated probe system.

7. VNA Calibration Techniques: Theory and Applications
J. Apolinar Reynoso-Hernández – *CICESE*

At microwave frequencies, the use of a calibrated vector network analyzer (VNA) is mandatory to characterize, in magnitude and phase, the linear behavior of a device under test (DUT). To represent the no-ideal behavior of the VNA, 8-terms and 12-terms error models are the most commonly used. To remove these errors different calibrations techniques have been proposed in the literature to date, each based on measuring a determined set of standards instead of the DUT. Some of the most commonly used methods to calibrate the VNA are: SOLT (Short-Open-Load-Thru), TRL/LRL (Thru-Reflect-Line/ Line-Reflect-Line), TRM/LRM (Thru-reflect-Match/ Line-reflect-Match) and LRRM (Line-reflect-Reflect-Match). In this short course an overview of the theory of these calibration techniques along with some applications (e.g. transistor characterization, load-pull,etc) will be presented.

8. 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.

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. NVNA Measurements: from Legacy to Wideband Spectrum Analysis
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 legacy NVNA applications for time domain waveforms and pulsed characterizations. Then, we will describe a new kind of NVNA application: stimulus/responses spectrum analysis of active devices in a calibrated network environment. We will close this talk with a discussion about unequally-spaces multi-tones test signals for active devices with memory effects.

11. Real-Time and 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
Marcus da Silva – *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 1:

Andy Brush graduated from RPI 1983 with B.S. Electric Power Engineering, Case Western Reserve in 1992 M.S.M.E. He worked at NASA Lewis Research Center and Keithley Instruments prior to joining Tegam, Inc., in 2005. At TEGAM, he led engineering teams developing RF power meters, thermistor and other DC substitution power standards operating from 6 kHz to 75 GHz, flow calorimeters, and primary standards for attenuation. He has taught microwave power sensor calibration course at MSC and NCSLi more than 10 times. He has been the CEO of TEGAM since 2005.

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. He is also IEEE Fellow.

Gary Simpson received his Bachelor degree from DeVry Institute of Technology in 1972, and his Masters degree from Arizona State University in 1978. He has been involved with microwave measurements since 1973, starting with device characterization through manual load pull on microwave power transistors at his first job at Motorola. He has been with Maury Microwave since 1982, where he began developing components and fixtures for microwave measurements, including network analyzer calibration standards and techniques. Gary is a pioneer in device characterization systems; in 1987 he developed one of the earliest automated slide-screw tuners for advanced load pull measurements. Since then, he has been responsible for much of the on-going development of device characterization techniques, methodologies and systems. He is currently Chief Technical Officer at Maury Microwave Corp.

Lecturer Bios 2:

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.

Andrej Rumiantsev was born in Minsk, Belarus in 1972. He received the Diploma-Engineer degree (with highest honors) in Telecommunication systems from the Belarusian State University of Informatics and Radio Electronics (BSUIR), Minsk, Belarus, and the Dr.-Ing. Degree (with summa cum laude) in Electrical Engineering from Brandenburg University of Technology (BTU) Cottbus, Germany, in 1994 and 2014, respectively. From 2001 to 2013, he held various engineering and engineering management positions at SUSS MicroTec Test Systems (from January 2010 Cascade Microtech) . He significantly contributed to the development of the SUSS' RF wafer probe, the |Z| Probe, wafer-level calibration standards, calibration software and probe systems. At Cascade Microtech, he held the position of Product Marketing Manager of Device Characterization for Modeling and Process Development. In March 2013, he joined Ulrich L. Rohde Chair for RF and Microwave Techniques at Brandenburg University of Technologies (BTU), Cottbus, Germany. He is currently with MPI Corporation, holding a position of Director of RF Technologies of the Advanced Semiconductor Test Division. His research interests include RF calibration and wafer-level measurement techniques for advanced semiconductor devices. He is a member of the IEEE MTT-S, ARFTG from 2004 as well as the IEEE MTT-11 Microwave Measurements Committee. He serves as the Chair of the Modeling and Simulation Sub-Committee and ExCom member of IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BCTM). He is an active publishing author and reviewer at various MTT-S conferences and journals. He holds several patents in the area of wafer-level RF calibration and measurements techniques. He received the ARFTG-71th Best Interactive Forum Paper Award. His doctoral thesis was awarded as "Best Dissertation of 2014 at Brandenburg University of Technologies".

Prof. J. **Apolinar Reynoso-Hernández** (AM'92-M'2003) received his Electronics and Telecommunications Engineering degree, M. Sc. degree in Solid State Physics and Ph. D. degree in Electronics, from ESIME-IPN, Mexico, CINVESTAV-IPN, Mexico and Université Paul Sabatier-LAAS du CNRS, Toulouse, France, in 1980, 1985 and 1989 respectively. His doctoral thesis was on Low Frequency noise in MESFET and HEMTs. Since 1990 he has been a researcher at the Electronics and Telecommunications Department of CICESE in Ensenada, B. C., Mexico. His areas of specialized research interest include, high frequency on-wafer measurements, high frequency device modeling, linear and non-linear device modeling. Among the most outstanding contributions of Prof. Reynoso-Hernández and his research group to the theory of VNA calibration techniques are the development of the LZZ calibration technique and the generalized theory of the TRM calibration technique. He has contributed 15 publications at the ARFTG and has leaded CICESE's Microwave group to obtain the best interactive forum paper award five times.

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.

Lecturer Bios 3:

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 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.

Marcus da Silva, currently a Fellow and Engineering Director at Tektronix, has over 34 years of experience in the test and measurement and telecommunications fields. Before Tektronix, Marcus was Vice President of Engineering and Chief Technical Officer at Vivato, a startup company that developed long-distance WiFi communications using a combination of phased array antennas, packet switching and WLAN technology. Prior to Vivato, Marcus was R&D director at Agilent and Hewlett-Packard, where he held various engineering, management, manufacturing and marketing positions over a 23-year period. In his various roles, Marcus made notable contributions in frequency synthesis, test methodologies, device modeling, microwave component design and metrology. Marcus holds B.S. and M.S. degrees in Electrical Engineering from the University of Missouri-Rolla. He spent his childhood among Gauchos in southern Brazil and has lived in the United States since Junior High School.