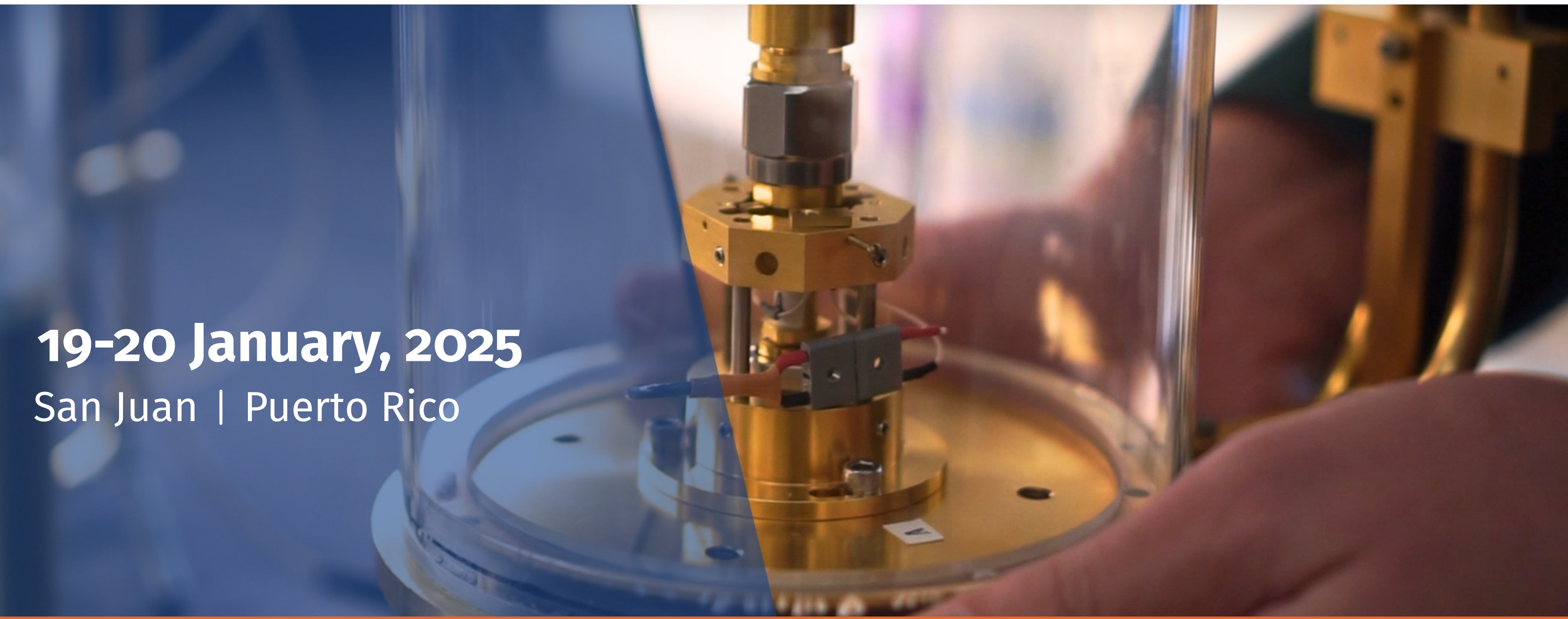


19-20 January, 2025

San Juan | Puerto Rico

SHORT COURSE PROGRAM

NIST/ARFTG Short Course on Microwave Measurements

Join us for a practical tutorial on microwave measurements tailored for wireless communications! This short course is designed for engineers, graduate students, experienced technicians, and technical managers looking to enhance their expertise in precision microwave measurements.

This year's course features sessions on:

- Measurement Fundamentals
- Fundamentals of Nonlinear Measurements
- On-Wafer Measurements and Applications

Our speakers are renowned experts in the field of microwave measurements and metrology, hailing from leading National Metrology Institutes, top universities, and prominent instrumentation vendors.

For any questions or suggestions, please contact Angela C. Stelson at the National Institute of Standards and Technology (NIST), who serves as the NIST-ARFTG Short Course Coordinator, at angela.stelson@nist.gov.

Sunday, January 19th

Morning Session

MEASUREMENT FUNDAMENTALS

SC-i

8:00-8:10

Welcome Note and Introduction

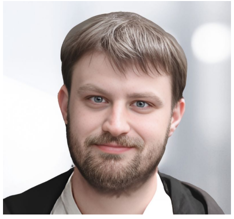
SC-1

8:10-8:55

Microwave Power and Traceability

Aaron Hagerstrom (NIST)

International trade requires standardization of measurements between countries. In principle, this standardization is achieved through the concept of metrological traceability. Roughly speaking, a traceable measurement of a physical quantity can be compared to the physical constants that define the SI units, such as the speed of light and Planck's constant, through an unbroken chain of measurements with uncertainties. In this talk, we will discuss what traceability means in practical terms, from the perspective of a person who performs measurements. In particular, we will focus on microwave power measurements at NIST. These measurements are traceable to scattering parameters and DC power. We will describe how we achieve traceability for these measurements, and how traceability can be extended to other measurements. This talk will emphasize uncertainty evaluation, as understanding measurement uncertainty is important not just for traceability, but also for measurements in general.



Aaron Hagerstrom received the B.S. degree in Physics from Colorado State University in 2010, and the Ph.D. in Physics from the University of Maryland in 2015. He joined National Institute of Standards and Technology (NIST) in 2016 as an NRC postdoctoral associate and developed techniques for microwave-frequency characterization of nonlinear materials and devices. In 2019, he was hired into a staff position at NIST to research traceable power measurements at microwave and mm-wave frequencies. He was part of the team who received the 2022 Allen V. Astin Measurement Science Award for the development of a rigorous new traceability path for microwave power and scattering parameter measurements at millimeter-wave frequencies relevant for new 5G/6G wireless communications systems.

SC-2

9:00-9:45

Updating NIST's Traceability: S-Parameters and Beyond

Angela Stelson (NIST)

Traceability of S-parameters to fundamental SI quantities (the second and the meter) is key to assessing uncertainties of microwave measurements across the telecommunications industry. S-parameters are a fundamental microwave-frequency measurand and are part of the traceability chain for numerous quantities, including antenna factors, microwave power, and phase. Here, we outline a comprehensive uncertainty budget for S-parameters in the WR-15 waveguide band with the goal of establishing traceability for these S-parameters, wave parameters, and further derived measurements. The uncertainty analysis presented here begins by evaluating uncertainties related to the imperfect physical dimensions of the calibration standards and test ports. Then, we outline experiments to evaluate instrumentation uncertainties including drift, noise and receiver nonlinearity, and assess their contributions to the total uncertainty of the measurement. Overall, this talk aims to demonstrate a workflow to incorporate the major sources of systematic and statistical uncertainties in S-Parameter measurements to the measurement of unknown devices.

Angela C. Stelson received her B.S. in physics, mathematics, and political science from the University of Oregon in Eugene, OR, USA (2012), and her Ph.D. in Materials Science and Engineering from Cornell University in Ithaca, NY, USA (2017). Her graduate work focused on the electric field-directed assembly of colloids for photonic crystals. She joined the National Institute of Standards and Technology as a National Research Council Fellow in 2017. Currently, she works in the RF Electronics group developing traceable scattering parameter calibrations and new microwave microfluidics measurement techniques for chemical and biological applications.

9:45 – 10:15

Coffee Break

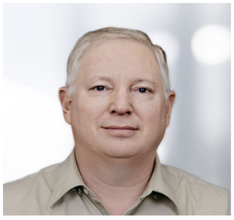
SC-3

10:15 – 11:00

Modern Network Analyzers Calibration Techniques

Rusty Myers (Keysight Technologies)

Calibration is crucial for making accurate measurements with a Vector Network Analyzer. This talk will start with basic explanation of VNA calibration to provide the background for historical 1-port and 2-port calibration methods. Next up, modern advances in calibration methods will be explained. It will wrap up with some real world measurement challenges and how these modern techniques can tackle them.



Rusty Myers is a Master Metrology Engineer at Keysight Technologies where he is involved in various projects related to measurement science and uncertainties of precision instruments. Most of his work is centered on Vector Network Analyzers and accessories including calibration kits, verification kits, ECal and network analyzer measurement accuracy. Rusty has extensive experience with passive microwave components and electromechanical devices ranging from RF to sub-mm. During more than a decade at Maury Microwave, Rusty was involved in simulation, design, manufacturing, and test of Maury's complete product portfolio. Over that time, he served in the role of Senior Engineer, Engineering Manager and Director of Engineering. He previously had positions in R&D and manufacturing at Agilent/HP working with a wide range of microwave products. He has a BS in Electrical Engineering with microwave specialization from the University of Illinois, Urbana. Rusty is an executive committee member for the Automatic Radio Frequency Techniques Group (ARFTG) and has been involved with various aspects for ARFTG conferences. He is an IEEE MTT-S member and has given calibration talks at his local IEEE chapter with plant tours for local students. He is an active participant in the P287 working group for coaxial connectors and previously contributed to the P1785 working group for waveguide standards above 110 GHz.

SC-4

11:00 – 11:45

Uncertainties in Microwave Measurements

Uwe Arz (PTB)

Currently, on-wafer traceability is directly linked to Multiline TRL, which is widely recognized as one of the most accurate on-wafer calibrations. In industrial applications, however, fixed-distance calibrations such as SOLT, LRM or SOLR using commercial impedance standard substrates (ISS) are usually preferred for measurements in a great variety of substrate technologies. In this talk, we will show how traceable uncertainties can be obtained for reference multiline TRL calibrations on different substrates. Next, we will demonstrate how these traceable uncertainties can be transferred to industrial calibrations as mentioned above, enabling fixed-distance lumped-element calibrations with commercial ISS, suitable for the targeted application and including uncertainties. Key is the proper characterization of lumped-element standards on the commercial ISS with custom-made, application-specific reference calibration standards.

Uwe Arz (S'97-M'02-SM'09) received the Dipl.-Ing. degree in electrical engineering and the Ph.D. degree (summa cum laude) from the University of Hannover, Hannover, Germany, in 1994 and 2001, respectively. In 2001, he served as a Post-Doctoral Research Associate with the National Institute of Standards and Technology, Boulder, CO, USA. In 2002, he joined the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, where he develops metrology for on-wafer measurements. From 2015 to 2018, he led the European EMPIR Project PlanarCal as a Coordinator. He is currently the Head of the Working Group On-Wafer Scattering Parameter Measurements at PTB. Dr. Arz is the recipient of the first ARFTG Microwave Measurement Student Fellowship Award in 1999 and of the 2003 AHMT Measurement Award presented by the Association of German University Professors for Measurement Science. He received three ARFTG Best Poster and two ARFTG Best Paper Awards, and was a co-recipient of the 2011 European Microwave Prize. He has authored and coauthored more than 100 publications in the fields of on-wafer S-parameter measurements, broadband characterization of high-speed interconnects, high-impedance probing, network analyzer calibration and dielectric material measurements. In January 2023, he was honored as an ARFTG Life Member.

12:00 - 13:00

Lunch Break

Sunday, January 19th

Afternoon Session

FUNDAMENTALS OF NONLINEAR MEASUREMENTS

SC-5

13:10 – 13:55

Everything You Can Do with Vector Nonlinear Microwave Measurements

Patrick Roblin (NIST)

The advent of nonlinear vector network analyzers (NVNA) has stimulated the introduction of new paradigms in microwave engineering for (1) the measurement, (2) the modeling and (3) the design of nonlinear microwave circuits such as microwave power amplifiers and oscillators. First the various types of NVNA architecture available, the procedure used to calibrate them and the calibration traceability will be presented. Then the various behavioral models used for the data representation will be reviewed. Circuit-based nonlinear microwave models of transistors can also be directly extracted from large-signal measurements. NVNA's can further be used to verify the nonlinear embedding device model which predicts from the desired internal PA mode of operation, the required amplitude and phase of the multi-harmonic incident waves at the transistor package reference planes. Example of design of power amplifiers (PA) such as Class F, J, Doherty and Chireix amplifiers will be presented.

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, power-amplifiers and MIMO systems. In 2016 he served from three years as DML for IEEE-MTT. He is currently serving as vice-president of ARFTG and as co-chair of the MTT Technical Committee TC3 on Microwave Measurements.

SC-6

14:00 – 14:45

Load-Pull Measurement Techniques: Architecture, Accuracy, and Applications

Mauro Marchetti (Maury Microwave)

This presentation focuses on load-pull measurement systems and applications. We will discuss the architecture and the design aspects of state-of-the-art load-pull measurement systems. We will discuss how to evaluate and verify measurement accuracy and describe a procedure for evaluating traceable uncertainty of power measurements as a function of the load impedance. We will present several application examples, ranging from high speed load-pull for technology evaluations and power amplifier design to modulated testing for 5G applications.

Mauro Marchetti received the B.S. and the M.Sc. degree in electrical engineering from the University of Naples "Federico II," Italy, and the Ph.D. degree from Delft University of Technology, The Netherlands. In 2006 he joined the Electronics Research Laboratory, Delft University of Technology as a Ph.D. researcher. In 2010 he co-founded and was appointed CEO of Anteverta-mw B.V, a company providing pioneering solutions in the fields of load pull device characterization and high-performance power amplifier design. In 2015 Anteverta-mw B.V. was acquired by Maury Microwave Corporation. Since 2022 he is Vice President of Engineering at Maury Microwave Corporation.

14:45 – 15:30

Coffee Break

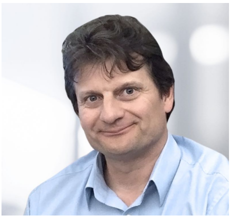
SC-7

15:30 – 16:10

Measuring Modulation Distortion of Active Devices Using a Vector Network Analyzer

Jan Verspecht (Keysight Technologies)

A new method is described to characterize signal distortion of active devices like amplifiers, mixers and frequency converters under modulated operating conditions. The method is called "Vector Component Analysis" and typically uses a vector signal generator and a vector network analyzer. Vector component analysis is based on the decomposition of the output signal into one part that is linearly correlated with the input signal, and another part that is the nonlinear distortion. The decomposition is based on calculating the statistical cross-correlation between the measured spectra of the input signal and the output signal. The input signals are repetitive and can be designed to match the statistical and spectral characteristics of any given modulation format. The method has unprecedented dynamic range and accuracy and provides derived quantities like error-vector-magnitude (EVM), noise-power-ratio (NPR), equalized channel capacity, adjacent-channel-power-ratio (ACPR), equalization filter response and best linear approximation filter response.



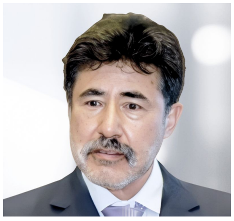
Jan Verspecht received a Ph.D. degree in Applied Sciences from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1995. From 1990 until 2002 he was a Research Engineer with HP and Agilent. In 2003 he started working as an independent consultant. In 2008 he co-founded the startup VTD. In 2012 VTD was acquired by Agilent Technologies, now Keysight Technologies, where he works as an Intrapreneur. He is a pioneer of and key contributor to Nonlinear Vector Network Analyzer (NVNA) technology, he invented X-parameters and Modulation Distortion Analysis. He holds 20 patents, and he authored and co-authored the book entitled "X-parameters", over 40 conference papers and 12 refereed journal papers. His research interests include the large-signal characterization and behavioral modeling of RF and microwave components. In 2007 Dr. Verspecht was elevated to the grade of IEEE Fellow by the IEEE Board of Directors.

16:15 – 17:00

Time-Domaine Low Frequency Active Harmonic Load-pull As a Tool for verifying the theory of PA Modes of Operation

Apolinar Reynoso-Hernández (CICESE)

The theory of all the classes of power amplifiers has been developed based on the transistor's behavior at the intrinsic current source plane. Therefore, measurements of the transistor's behavior at that plane are intended to be the best way for experimentally studying it. Considering the advantages offered by three-harmonic time-domain Low Frequency (LF) active load-pull systems over their high frequency (HF) counterparts, they can be useful for investigating the resistive-reactive (R-R) continuous modes based on class-B. In this short course, the use of a three-harmonic time-domain (LF) active load-pull system, which is implemented using a Low-Frequency nonlinear vector network analyzer, is utilized for measuring the current and voltage waveforms at the intrinsic current source plane of SiC-MESFET, GaAs-MESFETs and GaN-HEMT packaged transistor operated as a R-R class-J, and Class-F modes. From the current and voltage waveforms, the device's drain efficiency and output power (loading the transistor with fundamental and harmonic impedances corresponding to the design space of R-R class-J, and class-F modes) are calculated and compared with those predicted by the theory. The goal of this short course is to demonstrate that the R-R Class-J and R-R class-F modes can be experimentally studied by using three-harmonic time-domain Low Frequency (LF) active load-pull systems.



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 developing the LZZ calibration technique and the generalized theory of the TRM calibration technique. He has contributed more 15 publications at the ARFTG and has leaded CICESE's, Microwave group to obtain the best interactive forum paper award five times. Since 2013 he has served as TPC of ARFTG and ARFTG-MTT Workshop organizer.

17:00

End of the First Day Short Course Session

Monday, January 20th

Morning Session

ON-WAFER MEASUREMENTS AND APPLICATIONS

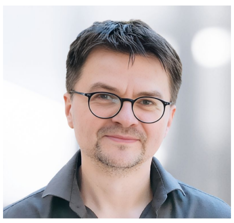
SC-9

8:00 – 8:45

Fundamentals of Successful Wafer-Level Calibration at mm-Wave Frequencies

Andrej Rumiantsev (MPI Corporation)

The accuracy of the wafer-level calibration procedure can be hindered by several effects, such as unoptimized boundary conditions of calibration standards, unwanted modes propagating in the substrate, the parasitic coupling of calibration standards and RF probe with neighbor elements, specifics of the calibration algorithm used, the impact of the temperature, system operator and the laboratory environment, and others. In this discussion, we will review concepts and essential differences in widely used RF calibration methods and their sensitivity to various parasitic effects. We will also address aspects related to the instrumentation and system accessories. Finally, we will review and discuss several examples of improving the confidence of measured data at the mm-wave frequency range.



Andrej Rumiantsev received Diploma-Engineer degree (with highest honors) in Telecommunication systems from the Belarusian State University (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. He joined SUSS MicroTec Test Systems (from 2010 Cascade Microtech) in 2001, where he held various engineering product management and marketing positions. He significantly contributed to developing the RF wafer probes, wafer-level calibration standards, calibration software, and probe systems. Dr. Rumiantsev is currently with MPI Corporation, holding the 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. Dr. Rumiantsev is a member of the IEEE MTT-3 Microwave Measurements Committee, the chair of IEEE MTT-S P2822 Working Group "Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De-Embedding and Measurements" and the ExCom member of the Automatic RF Techniques Group (ARFTG). He holds multiple patents in wafer-level RF calibration and measurement techniques. His doctoral thesis was awarded as "Best Dissertation of 2014 at Brandenburg University of Technologies.

SC-10

8:45 – 9:30

Fundamentals and Challenges of On-wafer Measurements above 100 GHz

James Hwang (Cornell University)

Hexagonal semiconductors such as 4H SiC have important high-frequency, high-power, and high-temperature applications. These applications require accurate knowledge of their permittivity as functions of orientation, frequency, temperature, and humidity. However, due to challenges for suitable test setups and precision high-frequency measurements, little reliable data exists for these semiconductors especially at millimeter-wave frequencies. Further, the limited data often exist nonphysical dispersions due to measurement artifacts. Using innovative measurement techniques, we will show that the dielectric constant is constant, and the loss tangent is linear for 4H SiC from 55 to 330 GHz. In fact, the loss tangent, less than 10^{-4}, is significantly lower than that of sapphire, our previous low-loss standard.

James Hwang graduated from the Department of Materials Science and Engineering, Cornell University with a PhD degree. After years of industrial experience at IBM, Bell Labs, GE, and GAIN, he spent most of his academic career at Lehigh University. He cofounded GAIN and QED; the latter became the public company IQE. He used to be a Program Officer at the U.S. Air Force Office of Scientific Research for GHz-THz Electronics. He had been a visiting professor at Cornell University in the US, Marche Polytechnic University in Italy, Nanyang Technological University in Singapore, National Chiao Tung University in Taiwan, and Shanghai Jiao Tong University in China. He is an IEEE Life Fellow and a Distinguished Microwave Lecturer. He is also a Track Editor for the IEEE Transactions on Microwave Theory and Techniques. He has published approximately 400 refereed technical papers and been granted eight U.S. patents. He has researched electronic, optical, and micro-electromechanical devices and circuits. His current research interest includes scanning microwave microscopy, two-dimensional atomic-layered materials and devices, and electromagnetic sensors for individual biological cells.

9:30 – 10:15

Coffee Break

SC-11

10:15 – 11:00

Fundamentals of On-Wafer Power

Christian Long (NIST)

Talk 11 Abstract (tbd)

Christian J. Long is the project leader for the Radio-Frequency Power and Impedance project at the National Institute of Standards and Technology (NIST). Dr. Long received the B.S. and Ph.D. degrees in physics from the University of Maryland at College Park, College Park, MD, USA, in 2004 and 2011, respectively. His doctoral research focused on development of both near-field scanning probe microscopy techniques and new methods to analyze data from combinatorial materials experiments. From 2012 to 2015 he was a postdoctoral research fellow with NIST, Gaithersburg, USA, where he focused on techniques for characterizing nanoscale materials. In 2016, he joined the staff at NIST, Boulder, USA, to work on development of standards for radio-frequency, microwave, and mm-wave calibrations.

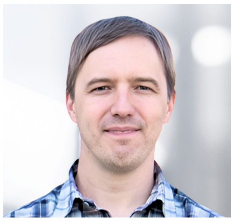
SC-12

11:00 – 11:45

Fundamentals of On-Wafer Cryogenic RF Measurements

Nathan Flowers-Jacobs (NIST)

Cryogenic microwave calibrations are becoming more important with rising interest and investment in superconducting quantum computing. Some calibration approaches closely follow room temperature methods. I will discuss the use of cryogenic probe stations with on-chip standards and the use of cryogenically compatible RF switches and coaxial standards to implement SOLR (Short Open Load Reciprocal) calibrations at relevant superconducting qubit frequencies below 10 GHz. Among other challenges, the cryogenic environment forces the use of long coaxial cables leading to a remote measurement. An additional challenge in the context of superconducting qubits is the low power and thermalization requirements which often results in over 30 dB of attenuation on the RF bias lines and makes using RF probes difficult. I will also discuss other approaches that leverage the cryogenic environment as part of the calibration. We have demonstrated a method that uses different temperature-dependent impedance states of an on-chip superconducting coplanar waveguide as calculable calibration standards. Superconducting qubits can also be used as in situ standards with nonlinear properties calculable from independent measurements. Using this approach, a qubit coupled to a transmission line can become an on-chip, wideband, calibrated power sensor. Finally, I will mention how we are extending audio frequency quantum-based voltage sources into the microwave regime.



Nathan Edward Flowers-Jacobs was born in Urbana, IL, USA, on June 15, 1979. He received the B.S. degree in physics from the California Institute of Technology, Pasadena, CA, USA, in 2001, and the Ph.D. degree in physics from the University of Colorado Boulder, Boulder, CO, USA, in 2010, for his work on a quantum-limited detector of nanomechanical motion based on electron tunneling across an atomic point contact. He was with Massachusetts Institute of Technology Lincoln Laboratory, modeling radar cross sections for two years, before joining the Graduate School at JILA and the University of Colorado Boulder. From 2010 to 2014, he was a Postdoctoral Associate with Yale University, New Haven, CT, USA, working on nanomechanical displacement measurements at the quantum limit using optical cavities. In 2014, he joined the Quantum Voltage Project, National Institute of Standards and Technology, Boulder, CO, USA, where he has been working on development, characterization, and applications of the Josephson arbitrary waveform synthesizer, which is an ac Josephson voltage standard based on pulse-biased arrays of Josephson junctions.

12:00

End of the NIST/ARFTG Short Course