



In this article, we describe two engineer-friendly events—the Automatic RF Techniques Group (ARFTG) Nonlinear Measurements Workshop and the Nonlinear Vector Network Analyzer (NVNA) Users’ Forum—designed to let participants learn about and discuss issues related to large-signal and nonlinear measurements. Because new methods and applications of nonlinear measurements are being developed at a rapid pace, these events were organized to provide a forum where bench-level engineers and the research community alike could learn about the latest techniques and technologies and share experiences.

Why have nonlinear and large-signal measurements become so important to the microwave community? One key driver is the large increase in the world market for wireless communications and broadband data transfer. To transfer large amounts of data, wireless systems require highly efficient handsets, transmitters, and receivers. Efficiency in terms of power consumption extends handset battery life and minimizes base station utility costs. Efficiency

in terms of spectral usage lets providers transmit more bits per Hertz in already crowded frequency bands. Efficiency in terms of design lets developers incorporate more components into a smaller footprint while accurately modeling complex system behavior. This desire for more efficient systems drives the need for improved large-signal and nonlinear measurements.

During the 1990s, technological and theoretical advances greatly simplified the direct measurement of the complex large-signal response of devices, circuits, and systems containing nonlinear elements. Tools for performing large-signal measurements include load-pull systems, vector signal analyzers, real-time analyzers, and oscilloscopes. Recent additions to this collection of tools include instruments capable of direct large-signal network analysis, such as the microwave transition analyzer (MTA) [1]–[2], and its two-port extension that includes an external phase calibration, the large-signal network analyzer (LSNA) [3], [4]. These last instruments followed the development of special calibration techniques, including calibration of

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the phase of harmonic components of a signal relative to its fundamental frequency [5]–[9].

As technology and methods have been developed to carry out nonlinear and large-signal measurements, technical papers on large-signal measurement methods have also become more prevalent in

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the literature. Many of these papers have been presented at the semiannual ARFTG Microwave Measurement Conferences in the United States. As indicated by the name, this conference is devoted entirely to the topic of microwave measurement techniques. Its relatively small size (typically about 100 attendees) and informal atmosphere facilitates discussion with like-minded engineers on many topics of interest. See [10] for more information on the ARFTG conference. Both the ARFTG Nonlinear Measurements Workshop and the NVNA Users' Forum were developed through the ARFTG conferences. The NVNA Users' Forum has continued to grow and is now held each fall at the European Microwave Week as well.

The ARFTG Nonlinear Measurements Workshop

In 2001, ARFTG introduced the half-day Nonlinear Measurements Workshop at its fall meeting. This workshop is organized each year by an expert in some

aspect of nonlinear measurement, with a different emphasis each time. This meeting often takes the form of a series of workshop talks on a common theme, but in some cases the organizer has made it a more interactive event. In some sense, the Nonlinear Measurements Workshop gives the participants a window into the way that the expert organizer approaches understanding a given topic.

Past Nonlinear Measurements Workshop topics include:

- advanced nonlinear measurement techniques
- measurement-based behavioral modeling
- pulsed measurements
- broadband measurements for wireless telecommunications
- high-speed measurements
- RF samplers.

The NVNA Users' Forum

A natural outgrowth of the Nonlinear Measurements Workshop was the NVNA Users' Forum [10], the initial meeting of which occurred in 2002. ARFTG members, including the authors of this article and Prof. Wendy Van Moer of the Vrije Universiteit Brussel (VUB) in Belgium, decided to create this forum for engineers who use or would like to learn more about vector large-signal measurements. The forum provides an opportunity to gather together and discuss issues unique to this new technology. Because ARFTG was originally formed as a vector network analyzer (VNA) users' group, this organization seemed like a natural sponsor.

The NVNA Users' Forum is "an informal discussion group devoted to sharing information and issues related to instrumentation utilized in vector large-signal network analysis of microwave circuits and systems that contain nonlinear elements" [11]. For the purposes of the Users' Forum discussion group, all of the instruments described in the introduction are lumped together under the general classification of NVNAs, even though certain instruments are not directly capable of network analysis.

To date, 12 meetings have taken place; the first was held in Washington, D.C. in the fall of 2002, where about 25 attendees discussed their research projects and their interest in nonlinear vector network analysis. The group decided that the forum was of continuing interest and agreed to meet again at the next ARFTG conference during the spring IEEE International Microwave Symposium (IMS). The Users' Forum has met regularly at the fall and spring ARFTG conference ever since. In the fall of 2004, the Users' Forum took a trip across the Atlantic, and it has been organized in conjunction with the European Microwave Week ever since. This European event is cosponsored by the European Network of Excellence Top Amplifier Research Groups in a European Team (TARGET) program [12]. Thus, the group meets regularly three times per year.



Figure 1. NVNA Users' Forum organizer Dominique Schreurs gives an overview of the forum's agenda at a meeting during European Microwave Week.

A typical meeting, such as the ones shown in Figures 1, 2, and 3, includes moderated discussions on topics suggested by the participants, brief research updates reporting on the latest work from participating labs, demonstrations (often new software), and announcements of events relevant to large-signal and nonlinear measurement practitioners. We also normally include a presentation and discussion of the Ph.D. work of a student whose research might benefit from discussion with engineers involved in the complicated technical area of nonlinear network analysis. Notes from the meetings are summarized and presented on the ARFTG Web site [11].

As the objective of the Users' Forum is to exchange experiences and share knowledge, interactive discussions are an important part of the meeting. Some of the topics already covered in the meeting include:

- "Are current large-signal measurement hardware set-ups adequate to support the needs of behavioral modeling techniques?"
- "Software: What do users want their large-signal measurement control software to do?"
- "Phase calibrations—How necessary are they?"
- "What is the status of research on measurement-based behavioral modeling? Is it still academic, or are these techniques being used on a large scale? What is missing to further deploy these techniques?"
- "Tips and tricks for distortion measurements."
- "Uncertainties in measurement-based models—Is it possible?"
- "Frequency- and time-domain models: How do you choose which one to use?"
- "TARGET NVNA round robin results."
- "What is the importance of modeling memory effects?"
- "Figures of merit for behavioral modeling comparison."
- "Verification of LSNA measurements."
- "Signal measurement and network analysis: When to use which?"



Figure 2. Informal presentations and discussions are part of every NVNA Users' Forum.

- "Classes of 'nonlinear' behavior: Definition of 'weakly nonlinear'; Is there a definition beyond the link with Volterra series analysis?"
- "Are periodic, discrete-tone signals sufficient to emulate digital signals in device-, circuit-, and system-level applications?"

Efficiency in terms of design lets developers incorporate more components into a smaller footprint while accurately modeling complex system behavior.

As mentioned above, some of the latest research in nonlinear and large-signal measurement is first introduced during the research update portion of the meeting. Some past topics that were discussed at the meeting and have turned into published works include:

- load- and source-pull measurements using an NVNA [13]
- differential measurements for nonlinear circuits [14], [15]
- repeatability and stability of commercial harmonic phase standards [16], [17]
- extraction of conversion matrices for nonlinear devices based on vector large-signal measurements [18]
- state-space modeling of slow-memory effects based on multisine vector measurements [19]
- using an NVNA to measure the impedance of a vector signal source in its large-signal operating condition [20]
- improvements in measurement-based behavioral modeling [21], [22]

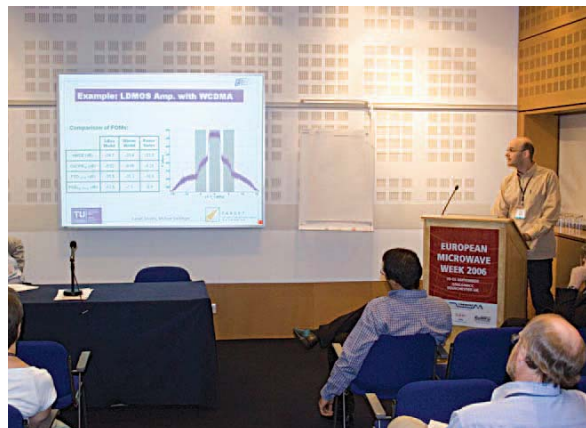


Figure 3. A participant in the NVNA Users' Forum discusses spectral regrowth.

- using oscilloscopes for microwave measurements [23], [24].

The desire for more efficient systems drives the need for improved large-signal and nonlinear measurements.

Conclusions

This article has presented an overview of the ARFTG Nonlinear Measurements Workshop and the NVNA Users' Forum. An important aspect of both of these regular events is their interactivity. Whether you are experienced in large-signal measurements or just starting out, these events are ideal as they encourage participation and interaction. The organizers (and authors) hope that if you are interested in finding out more about large-signal and nonlinear measurements, you will attend a future meeting of the Nonlinear Measurements Workshop or the NVNA Users' Forum.

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References

[1] C.J. Wei, Y.E. Lan, J.C.M. Hwang, W.J. Ho, and J.A. Higgins, "Waveform-based modeling and characterization of microwave power heterojunction bipolar transistors," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 12, pp. 2899–2903, Dec. 1995.

[2] M. Demmler, P.J. Tasker, and M. Schlechtweg, "A vector corrected high power on-wafer measurement system with a frequency range for the higher harmonics up to 40 GHz," in *Proc. 24th European Microwave Conf.*, pp. 1367–1372, 1994.

[3] J. Verspecht, P. Debie, A. Barel, and L. Martens, "Accurate on wafer measurement of phase and amplitude of the spectral components of incident and scattered voltage waves at the signal ports of a nonlinear microwave device," in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1029–1032, June 1995.

[4] Product note on MT4463A large-signal network analyzer. Maury Microwave Corp. Web page [Online]. Available: <http://www.maurymw.com>

[5] G. Kompa and F. van Raay, "Error-corrected large-signal waveform measurement system combining network analyzer and sampling oscilloscope capabilities," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 4, pp. 358–365, Apr. 1990.

[6] K. Rush, S. Draving, and J. Kerley, "Characterizing high-speed oscilloscopes," *IEEE Spectr.*, pp. 38–39, Sept. 1990.

[7] A. Ferraro and U. Pisani, "An improved calibration technique for on-wafer large-signal transistor characterization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 2, pp. 360–364, Apr. 1993.

[8] J. Verspecht and K. Rush, "Individual characterization of broadband sampling oscilloscopes with a nose-to-nose calibration procedure," *IEEE Trans. Instrum. Meas.*, vol. 43, pp. 347–354, Apr. 1994.

[9] T. Van den Broeck and J. Verspecht, "Calibrated vectorial nonlinear-network analyzers," in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1069–1072, June 1994.

[10] D. Schreurs, K.A. Remley, and W. Van Moer, "NVNA users' forums: Mission and overview," in *Proc. European Microwave Conf. (EuMW)*, Amsterdam, The Netherlands, 11–15 Oct. 2004, pp. 427–430.

[11] Automatic RF Techniques Group Web page [Online]. Available: http://www.arftg.org/about_lsna.html

[12] C. Devlin, T. Brazil, and G. Magerl, "TARGET network: Microwave power amplifiers," *IEEE Microwave Mag.*, vol. 7, no. 2, pp. 34–48, Apr. 2006.

[13] M. Vanden Bossche, "Curiosities on accurate large-signal measurements in combination with passive tuners," in *62nd ARFTG Conf. Dig.*, Boulder, CO, pp. 171–180, Dec. 4–5, 2003.

[14] Y. Rolain, W. Van Moer, J. Schoukens, and R. Pintelon, "Measuring nonlinear differential RF amplifiers using one single-ended source," in *62nd ARFTG Conf. Dig.*, Boulder, CO, pp. 17–23, December 4–5, 2003.

[15] J. Broomall, K. Garg, and T. Clupper, "A coaxial to differential adapter," in *62nd ARFTG Conf. Dig.*, Boulder, CO, pp. 9–16, Dec. 4–5, 2003.

[16] J. Jargon, D. DeGroot, and D. Vecchia, "Repeatability study of commercial harmonic phase standards measured by a nonlinear vector network analyzer," in *62nd ARFTG Conf. Dig.*, Boulder, CO, pp. 243–258, Dec. 4–5, 2003.

[17] G. Pailloncy and M.V. Bossche, "Gaining advanced insight in the phase stability of comb generators using a large-signal network analyzer," to be published in *2007 IEEE MTT-S Int. Microwave Symp. Dig.*

[18] A. Cidronali, K.C. Gupta, J.A. Jargon, K.A. Remley, D.C. DeGroot, and G. Manes, "Extraction of conversion matrices for P-HEMTs based on vectorial large-signal measurements," in *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 777–780, June 2003.

[19] D. Schreurs, K.A. Remley, M. Myslinski, and R. Vandersmissen, "State-space modeling of slow-memory effects based on multisine vector measurements," in *62nd ARFTG Conf. Dig.*, Boulder, CO, pp. 81–88, Dec. 4–5, 2003.

[20] J. Verspecht, D.F. Williams, D. Schreurs, K.A. Remley, and M.D. McKinley, "Linearization of large-signal scattering functions," *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 4, pp. 1369–1376, May 2005.

[21] F. Verbeyst and M. Vanden Bossche, "Measurement-based behavioral model under mismatched conditions: A new and easy approach for an accurate model," in *Proc. 2005 European Microwave Conf. (EuMC)*, Paris, France, 4–6 Oct. 2005, pp. 605–608.

[22] F. Verbeyst and M. Vanden Bossche, "Speed up power amplifier design by fast source-pull, real-time load-pull and accurate measurement-based behavioural models," *Microwave J.*, pp. 24–30, Nov. 2005.

[23] D.F. Williams, T.S. Clement, P.D. Hale, and A. Dienstfrey, "Terminology for high-speed sampling-oscilloscope calibration," in *68th ARFTG Conf. Dig.*, Dec. 2006, pp. 9–14.

[24] D.F. Williams, P.D. Hale, and K.A. Remley, "The sampling oscilloscope as a microwave instrument," *IEEE Microwave Mag.*, vol. 8, no. 4, pp. 59–68, Aug. 2007. 