of this activity in the academy and in industry for satellite communication, nano-antenna technology, medical antenna applications, miniaturized MIMO radar, and RFIC design challenges.

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Microwave Engineering Expertise in Turkey

■ **Binboga Siddik Yarman, Osman Palamutcuogulları, Ilker Kaya, Oguzhan Kızılbey, Ahmet Aksen, Tayfun Akın, Z. Levent Ozkan, Irfan Oksar, and Tayfun Nesimoglu**

Turkey's RF and microwave engineering journey started at Istanbul Technical University (ITU) in the mid-1950s under the leadership of Prof. Adnan Ataman [1], who held a Ph.D. degree from the University of Illinois. At that time, high-frequency broadcasting stations and military radar establishments were under construction in Turkey.

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Binboga Siddik Yarman (yarman@istanbul.edu.tr) is with RFT Science and Technology Company, the Istanbul Teknopark, Istanbul University, and the Technical University of Istanbul, Turkey. Osman Palamutcuogllları (osmanp@beykent.edu.tr) is with Beykent University, Turkey. Ilker Kaya (ilker.kaya@netas.com.tr) is with Netaş Company, Istanbul, Turkey. Oguzhan Kızılbey (kizilbey@hotmail.com) is with National Research Center of Turkey, Gebze, Kocaeli. Ahmet Aksen (ahmet.aksen@isikun.edu.tr) is with Isik University, Turkey. Tayfun Akın (tayfuna@metu.edu.tr) is with the Middle East Technical University (METU), Ankara, Turkey. Z. Levent Ozkan (lozkan@ASELSAN.com.tr) and Irfan Oksar (oksar@ASELSAN.com.tr) are with ASELSAN, Ankara, Turkey. Tayfun Nesimoglu (ntayfun@metu.edu.tr) is with the METU–Northern Cyprus Campus, Kalkanlı, Guzelyurt, Turkey.

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At ITU, RF and microwave engineering education began with electromagnetic wave (EMW) propagations, antennas, and active and passive microwave components such as waveguides, filters, klystrons, magnetrons, triodes, and pentode tubes. Until the early 1980s, most microwave engineering activities were on the application layer rather than in research and technology development. With the deregulation of the government-owned Turkish Communication Company, two major companies, Teletas and Netas, were established based on the French technology of Alcatel and Canada's Nortel technology. Turkey's first X-band radio link was developed by Teletas.

Early Devlopment
Turkish military microwave systems development began in 1975, when the Turkish Electronic Industry Corporation, ASELSAN, was established by the Land Forces Foundation. The first very-high-frequency and ultrahigh-frequency communication products of ASELSAN were on the market in the early 1980s

under the leadership of Hacim Kamoy, who was chief executive officer with ASELSAN for approximately 25 years [2]. ASELSAN worked in very close collaboration with the Middle East Technical University (METU). At that time, Prof. Canan Toker, Prof. Nevzat Yildirim, Prof. Altunkan Hizal, and Prof. Yalcin Tanik were among the leading EMW, communications, and microwave scientists with METU.

ASELSAN is the leading military microwave component production and system company in Turkey. It manufactures various active and passive components and systems covering the full microwave and millimeter-wave frequency range (Figure 1). ASELSAN is listed among the top 100 military electronics companies and is the 57th largest military electronics company in the world.

The first C- and X-band radar was built by the National Research Center of Turkey (TUBITAK-MAM) in the early 1980s under the leadership of Dr. Yılmaz Tokad [3] and in collaboration with ITU. At that time, the leading names in Istanbul were Dr. Duran Leblebici, Dr. Binboga Siddik Yarman, and Dr. Osman Palamutcuogulları.

Dr. Siddik Yarman joined the ASELSAN, METU, and TUBITAK-MAM team in mid-1980s. Then, in 1986, at the request of President Turgut Ozal, he (along with his brothers and students) founded a private military electronics corporation, Savronik Electronics. Savronik has been producing uplink and downlink systems for military unmanned aerial

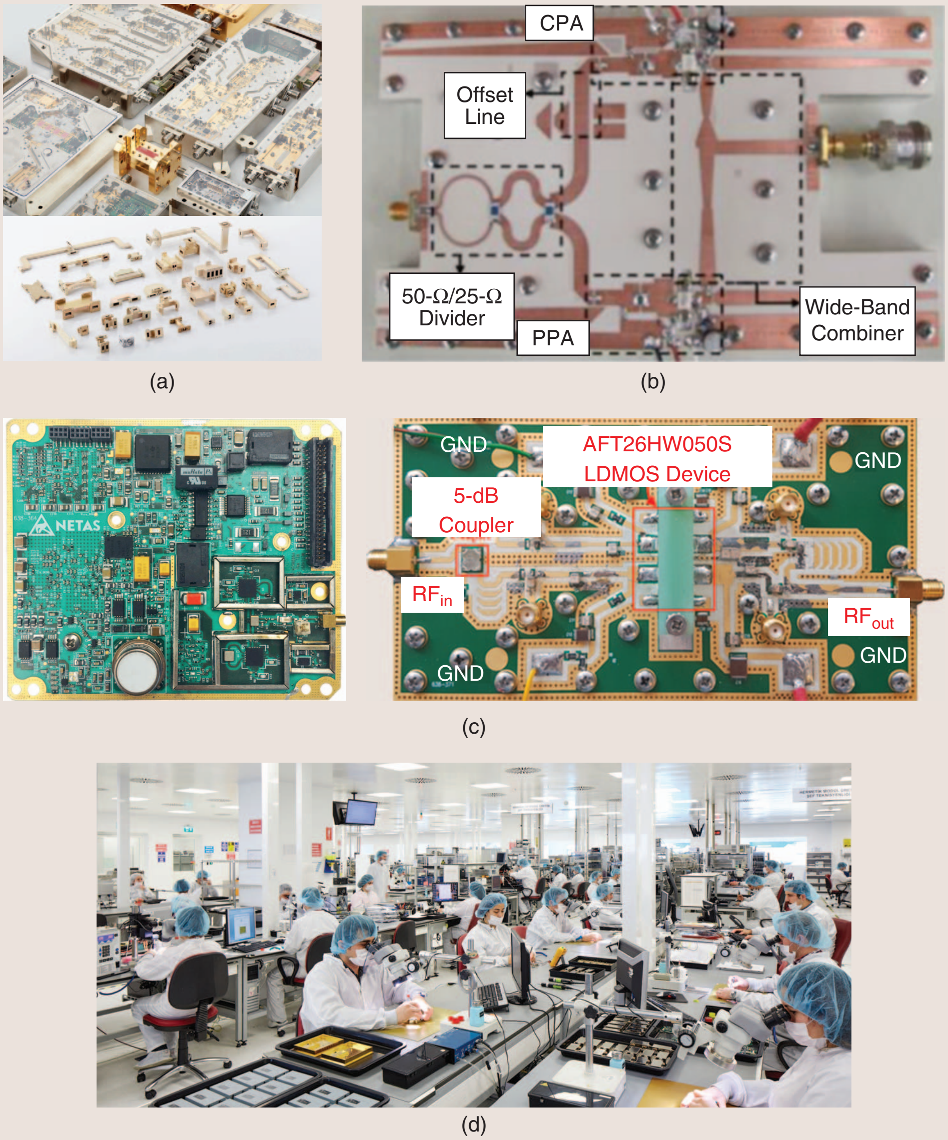

Figure 1. *(a) Examples of the broad range of microwave products manufactured by ASELSAN. (b) A 25-W wide-band Doherty power amplifier (PA) with gallium nitride high-electron-mobility transistors CGH40010 and CGH40025 (manufactured by ASELSAN based on the Ph.D. degree work of Dr. Necip Şahan). (c) A GPS L1 and GLONASS L1 (G1) receiver card (left) with a 40-W asymmetrical Doherty PA AFT26HW050S laterally diffused metal-oxide-semiconductor (LDMOS) device manufactured by NETAS (right). (d) A view of the ASELSAN microwave production facilities. CPA: chirped-pulse amplifier; PPA: peaking PA; GND: ground.*

vehicles in the C-, X-, and Ku-bands. Recently, Dr. Siddik Yarman initiated a research and technology development company, RFT Science and Technology, within the Teknopark–Istanbul, which is Turkey's first research and technology development zone [4], [5].

Educational Activities

With advances in wireless and cellular communication systems, education and research activities in microwave engineering are scattered across various universities and startup companies. Major microwave circuit design and technology development efforts are concentrated in Istanbul and Ankara.

Education in microwave theory and techniques is offered mainly through undergraduate and graduate level programs within the electrical and electronics engineering departments of various universities. In more than 100 universities, undergraduate-level microwave engineering-related courses are offered, and more than 60 graduate schools conduct advanced-level courses, such as computational electromagnetics, antennas and propagation, microwave circuit design, radio communications, RF integrated circuits (RFICs), monolithic microwave ICs (MMICs), nano-electronics, and nanophotonics.

METU is one of the preeminent universities leading microwave teaching and research activities in Turkey. At METU, a broad range of teaching and research-oriented laboratories are available for microwave and millimeter-wave circuits and antennas, including anechoic environments. The Ayaslı Research Center, under the umbrella of METU, hosts research activities in microelectronics, communications, microwaves, and antenna and radar applications in RFIC, MMIC, complementary–metal-oxide-semiconductor (CMOS), bipolar-junction-transistor CMOS, silicon-on-insulator, gallium-arsenide, and gallium-nitride (GaN) technologies. The computational electromagnetics group in electronics engineering departments at the university has made substantial research contributions in developing accurate implementations for electromagnetic simulations on nanowire transmission lines, nano-optical couplers, subwavelength imaging, energy harvesting, photonic crystals, printed antennas, and metamaterials.

Bilkent University is another major center of microwave studies. The Nanotechnology Research Center (NANOTAM) of Bilkent University focuses particularly on metamaterials, nanoelectronics, nanophotonics, GaN, and terahertz technology.

ITU has a solid laboratory infrastructure in the microwave field. The ITU RF laboratory contains equipment for testing and implementation up to 50 GHz and is heavily engaged with student research projects on active and passive microwave circuits and antenna designs. The ITU Duran Leblebici very-large-scale integration lab is one of the most advanced measurement laboratories in Turkey. The lab focuses on wired and wireless communication systems, high-speed and high-resolution data converters, and mixed-signal electronic systems. The design of broadband matching networks and work on microwave amplifiers are concentrated under the leadership of Dr. Siddik Yarman, Dr. Palamutcuogullari, and Dr. Ahmet Aksen at the RFT Science and Technology Company, Netas Corporation [6], TUBITAK-MAM [7], ITU, and Isik University.

Most of this work employs real-frequency techniques (RFTs) initiated by H.J. Carlin and Dr. Siddik Yarman [8]–[10]. Recent research results have been presented in several books and papers published in this area [11]–[17].

The microwave group of Istanbul University is working in the areas of applied microwave electronics with a prime focus on broadband matching, multiband microwave filters, equalizers, and broadband microwave amplifiers. The group has reported pioneering work in numerical modeling and real-frequency semi-analytic broadbanding techniques for microwave and millimeter-wave circuits.

The Sabancı University MicroElectronics Research group is working on IC design up to 240 GHz for high-frequency, analog, and mixed-signal applications (RFIC, millimeter-wave IC, fifth-generation, terahertz imaging, and radiometry), infrared imaging systems, energy harvesting, biosensors, and microelectromechanical systems (MEMS). For advanced fabrication requirements, Sabancı University's Nanotechnology Research and Application Center has tools for very-high-frequency measurements from cryogenic temperatures (–196 °C) up to +200 °C.

In addition to these institutions, remarkable contributions in microwave theory and techniques have been reported by researchers from many other universities and institutions. In the following sections, we outline major research and technology work completed at various institutions of Turkey.

Broadband Microwave Circuit Designs Employing RFTs (Istanbul University, TUI, Isik University, RFT Science and Technology Company, and Netas)

RFTs are regarded as the optimum methods in the design of broadband matching networks and microwave amplifiers [8]–[18]. RFTs work directly on the measured immittance or scattering parameter data obtained from the devices to be matched, and it automatically generates the optimum circuit topology and element values for the matching. There is no need to select a circuit topology for the matching networks to be designed; such typologies are the outcome of the RFT method.

In [13], a typical RFT lumped-element power amplifier (PA) constructed using load-pull measured data of a Mitsubishi LDMOS RD007 was presented. The design spanned the frequency range of 330–530 MHz, with approximately 20 W of output power and 50% power-added efficiency (PAE). In [14], a broadband (0–10-GHz) small-signal amplifier constructed with commensurate transmission lines was presented. The amplifier gain is about 10 dB over a 10-GHz bandwidth. RFT designs can also be accomplished using mixed elements, i.e., transmission lines and lumped elements [19]. In [20], a broadband (8–10-GHz) 50-W PA was presented

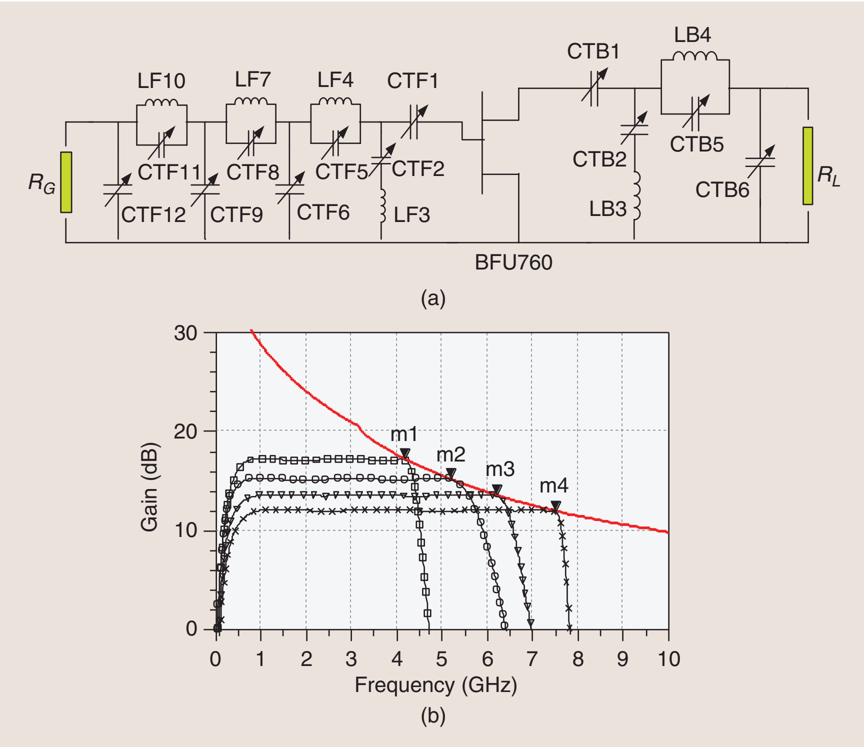

Figure 2. *(a) A designed flat-gain tunable amplifier and (b) its gain response. Red line: maximum stable gain of BFU760 (transistor part number); black line: gain performance of the tunable amplifier; m1 = 17.212 dB, m2 = 15.188 dB, m3 = 13.585 dB, and m4 = 12.006 dB [28].*

with mixed elements, wherein a Cree CGH V1JD0D50 GaN device was employed; the achieved PAE is about 50%. These results were automatically obtained using the network synthesis robot of the RFT Science and Technology Company of Teknopark Istanbul [4].

Today, NETAS is one of the major communication companies of Turkey. In recent years, the company has been concentrating on RF front-end designs, switching, transmission, and navigation systems. The company's research and development groups have produced work on state-of-the-art high-frequency power combiners, Doherty PAs, and global navigation satellite system receivers using RFT [21]–[23].

Microwave System Design (METU, METU–Northern Cyprus Campus, Bilkent University, and ASELSAN)

METU offers an excellent microwave education, research, and measurement infrastructure that covers the full microwave and millimeter-wave range and even goes beyond optical frequencies. The METU microwave engineering team works in close cooperation with Turkey's military industries.

One of METU's major software products is the RF filter and multiplexer design package FILPRO, created by Prof. Nevzat Yıldırım [24]. METU is also the site of Turkey's first MEMS foundry, under the leadership of Prof. Tayfun Akın (who is also founder of the Nanokon and MikroBiyo-Sistemler Elektronik corporations [25], [26]). These companies produce RF-MEMS and RF-bio sensor chips for various communication and medical applications.

Bilkent University is well known for having the first nanotechnology research center, under the leadership of Prof. Ekmel Ozbay [27]. NANOTAM produces various MMICs for military ground and airborne systems, such as ground radars and satellite transponders. In collaboration with ASELSAN, NANOTAM has begun producing high-power GaN devices for electronic warfare and radar applications.

The realization of a software-defined radio has been a particular objective of the military industry and academia in Turkey. Broadband frequency-tunable PAs and matching networks [28], [29] (see Figure 2) were designed at METU–Northern Cyprus Campus's RF and Telecommunication Laboratory (established by Dr. Tayfun Nesimoglu [30]) using RFT [8]–[18].

To improve the linearity of PAs, broadband analog PA linearization techniques were proposed and implemented [31], [32], as shown in Figure 3. These techniques improve the dynamic range and linearity of receivers and achieve enhanced interference rejection [33]. Tunable metamaterial resonators and sensors were designed and manufactured in the gigahertz regime that may facilitate the design of other tunable microwave circuits [34], [35]. Defected ground structures were used to improve the performance of $\lambda/4$ impedance transformers, and broadband hybrid couplers have been constructed [36]. Fractal antenna topologies have been investigated, and broadband fractal patch antennas have been designed for microwave energy scavenging [37].

ASELSAN is a 40-year-old company serving both military and commercial customers and is one of the few companies in the world involved in the design, production, and delivery of next-generation software-defined networking radios (which are being developed to satisfy the tactical and strategic radio communication requirements in land, airborne, and naval platforms). The company has a variety of microwave products, such as filters using lumped-elements (up to 6 GHz), microstrip lines (6–40 GHz), suspended striplines (2–20 GHz), cavities (6–20 GHz), and waveguides (33–50 GHz). Switched multiplexers that provide eight equally spaced channels covering the 2–18-GHz band have been developed. Frequency multipliers have been manufactured that provide frequency conversion up to 40 GHz, and high-power amplifiers have been manufactured for various applications. These include an X-band 40-W solid-state PA, a K-band gallium aresenide (GaAs) with 32-dB gain, a Ku-band 30 W, and a GaAs 45 W.

Also among the company's product lines are high-power MMIC amplifiers,

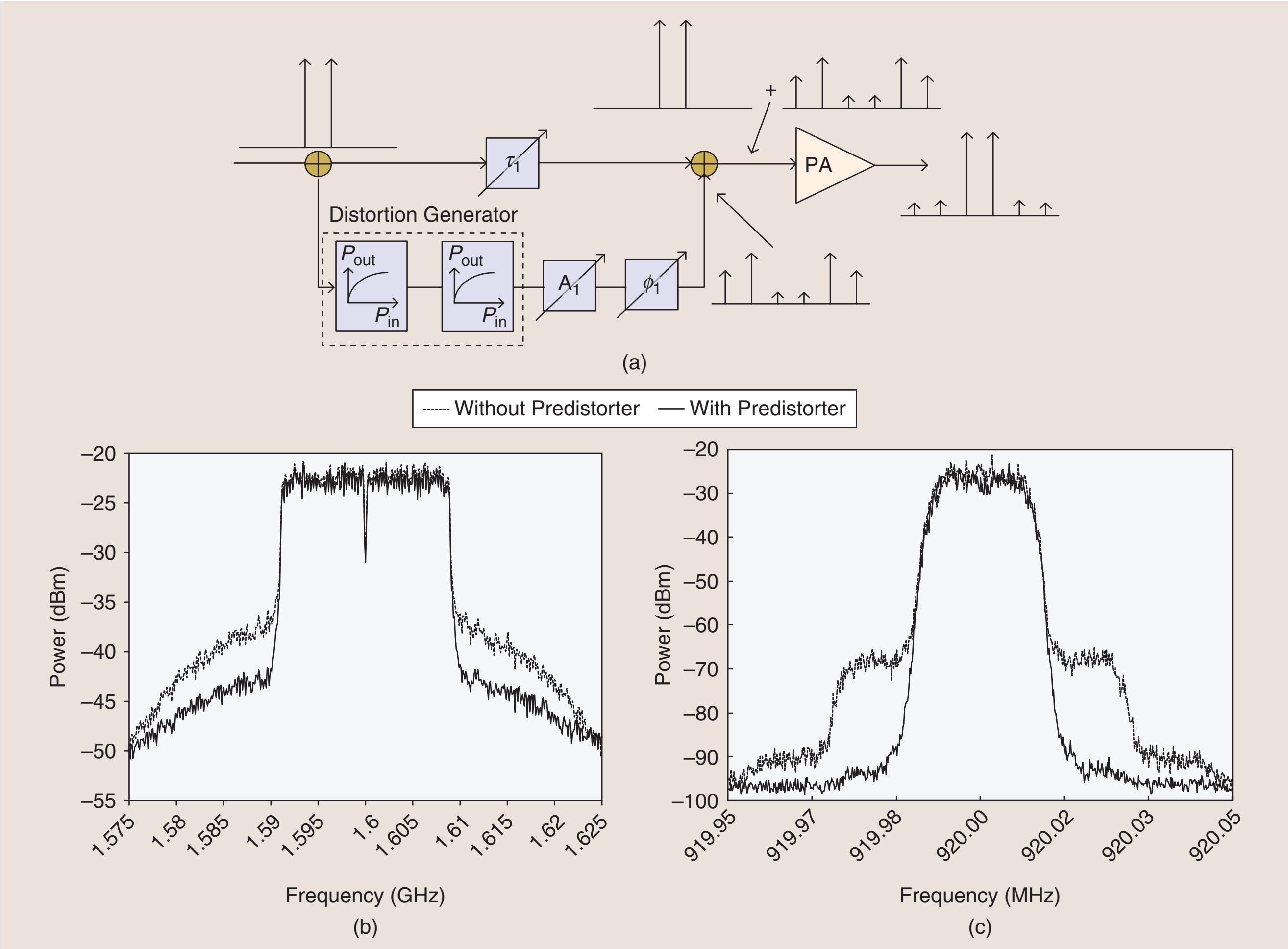

Figure 3. *(a) A block diagram of the realized predistorter using a two-stage distortion generator to suppress fundamental signals while generating intermodulation distortion. The amplifier's output spectrum with and without predistortion tested using (b) a 802.11-a/g wireless local area network signal with 20 MHz bandwidth at 1.6 GHz and (c) a terrestrial trunked radio modulated signal with 25-kHz bandwidth at 920 MHz.*

such as 6–18-GHz, 4.5-W, 750-MHz Doherty PAs; 10-W, 8–12-GHz 16-W PAs; and 32–39.5-GHz, 2.5-W output PAs. For phased-array antenna systems, MMIC GaAs phase shifters have been developed, operating over the frequency range of 2–18 GHz. ASELSAN also manufactures multipurpose electronic support measure/electronic intelligence/electronic countermeasure systems for a variety of applications.

Conclusion

Turkey is an emerging high-tech market with promising microwave engineering expertise due to a growing population of young engineers. Microwave engineering is developing not only at the circuit level but also at the component level, with recently established microwave semiconductor device manufacturing and research facilities.

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Ham Radio at IMS2018 *(continued from page 75)*

electronics, and it is often used in the classroom, from elementary schools to major universities, to provide hands-on experience in science and engineering.

IMS2018 will be hosting a ham radio social event in Philadelphia, Pennsylvania, celebrating a return to the location of the very first in the series 15 years ago. All radio amateurs and other interested IMS attendees are cordially invited. Be prepared to swap stories and have a face-to-face chat with other fellow hams. Members of the Mt. Airy VHF Club (aka the Packrats) will present a display of equipment and their contest activities. The club, founded in 1957, is dedicated to serving the very-high-frequency (VHF)/ultrahigh-frequency (UHF)/microwave amateur radio community, as well as enhancing the state of the art for 50-MHz and higher weak-signal operation. The social will also include a demonstration by Temple University students of mesh networking using modified wireless routers.

The keynote speaker will be Joe Taylor (call sign "K1JT"). Dr. Taylor obtained his first amateur radio license as a teenager, which led him to the field of radio astronomy. His amateur radio feats have included mounting an April 2010 "expedition" to use the Arecibo (Puerto Rico) radio telescope to conduct moonbounce with other amateurs around the world using voice, Morse code, and digital communications. His talk will be about WSJT-X (or Weak-Signal Communication by K1JT), a computer program suite he created that offers specific digital protocols optimized for Earth–Moon–Earth communication (moonbounce), meteor scatter, and ionospheric scatter at VHF and UHF, as well as for low-, moderate-, and high-frequency propagation. The program can decode fraction-of-a-second signals reflected from ionized meteor trails as well as steady signals fewer than 10-dB below the audible threshold.

Professionally, Dr. Taylor was the James S. McDonnell Distinguished University Professor in Physics at Princeton University, New Jersey, having also served for six years as the dean of faculty. He retired in 2006. Dr. Taylor was awarded the 1993 Nobel Prize in Physics for the discovery of a new type of pulsar, opening possibilities for the study of gravitation. In addition to the Nobel Prize, Dr. Taylor won the Wolf Prize in Physics (1992) and was awarded a MacArthur fellowship in 1981.

We hope to see you in Philly for a memorable ham radio event. For now, "73 and DX" (that's "greetings and long-distance contacts" in ham jargon).