Terahertz Pioneer: Robert W. Wilson

The Foundations of THz Radio Science

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THE son of the manager of a Texas mud logging service (which analyzed the cuttings from the bore hole of an oil well as it is being drilled) who held a Master's degree in chemistry from Rice University, a gifted "Mr. Fixit", and a graduate of Rice himself, Robert Woodrow Wilson[1] has more than lived up to the namesake that is his cognomen. It was an exciting time in radio science. In 1957, young Mr. Wilson left Texas for southern California to attend graduate school in physics at the California Institute of Technology. He settled in at the Athenaeum, then graduate housing and a favored temporary residence of Albert Einstein. At Rice, he had some experience with low temperature physics, but this group at Caltech was already quite full, as was the group that focused on the then very popular field of nuclear physics. Wilson was looking for a path less trodden, and visiting British astronomer and librarian, David W. Dewhirst (Dewhirst Classification System—Cambridge University, UK), suggested that Wilson talk with Caltech Professor John Bolton, director of the new Owens Valley Radio Observatory facility (OVRO), 5 hours north of Pasadena by car. Professor Bolton had just finished overseeing the completion of two 90-foot radio telescope dishes that would serve as one of the first large radio frequency interferometers in the U.S. The possibility of lots of hands on electronics work and the association with radio (Wilson had earned extra money in high school repairing tube based radios and TV sets), made this an ideal match, and Professor Bolton found himself with another eager student. The choice was fortuitous as Sputnik had launched in the fall of 1957 and overnight, the esoteric field of radio astronomy was transformed into a profession with extremely practical applications. *This pairing of basic science and practical technological application was to follow Dr. Wilson for his entire career*.

Wilson began work with Bolton's group at Caltech, which included now noted astronomers Barry Clark and Ken Kellermann (National Radio Astronomy Observatory), Al Moffet and Richard B. Read (Caltech), and research fellow Venkatraman Radhakrishnan (Director of the Raman Research Institute, Bangalore, India). However, he went back to Houston in the summer of 1958 to work for a short time at a petrochemical company and to marry his hometown girlfriend Elizabeth Sawin, who returned to Pasadena with him the following fall. On his first drive up to OVRO with Al Moffet over Thanksgiving week 1958, Wilson was shown the telescope drive systems and quickly came to the conclusion that the controls needed some serious redesign. To his surprise and gratification, when he spoke with Bolton about the problems he saw, he was told to go ahead and make the needed fixes. It was clear from the tone, and the way he spoke about these days working alongside his graduate student colleagues that this was a very special time and place. Wilson spoke fondly about working with Bolton, who did everything he asked his students to do, from digging trenches to wiring up power supplies.

Robert W. Wilson

At OVRO, Wilson got a lot of practical electronics and antennas experience in addition to observation time. He worked on a helium cooled 21 cm (1420 MHz) low noise maser receiver from Bell Labs, tube-based local oscillator sources, high quality liquid nitrogen loads, stable power supplies, and even the implementation of a receiver polarization rotator which used an old automotive starter gear drive. For his Ph.D. thesis, he did a Milky Way survey at 960 MHz using the interferometer [1], [2] and later published a catalog of galactic radio sources [3]. As a

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[1]**Robert Woodrow Wilson** lives with his wife of 53 years, Dr. of Psychiatry Elizabeth Sawin Wilson, in Holmdel, New Jersey, USA. Since 1994 he has been commuting back and forth by train, plane and automobile, between Crawford Hill and his second home in Cambridge, Massachusetts, where he works at the Harvard-Smithsonian Center for Astrophysics. At 76, he still takes on projects that occasionally bring him to remote and physically challenging locations, and he still enjoys tinkering with equipment and with programming as much as he enjoys learning and speaking about physics. Professor Wilson graciously consented to give us some of his very sought after personal time to conduct this interview at his office in Cambridge on December 6, 2011.

hallmark of Wilson's personality, he never was really satisfied with the technique he used for both observing and calibrating the emission from the Milky Way's disk he had measured during his galactic survey, and he looked forward to a chance to perhaps revisit some of these measurements later in his career.

Although after his Ph.D., Wilson stayed on at Caltech for a short post-doc, he had already been recruited by, and had his eyes set on Bell Laboratories. Radhakrishnan had returned from making the 21 cm maser there with wonderful stories about the environment and the people. Wilson was convinced by one of Bell Labs only radio astronomers at the time, Arno Penzias, whom he had met earlier at an American Astronomical Society meeting, to join him, Penzias, at the Bell Labs Crawford Hill facility in central New Jersey. The 20-foot Horn-Reflector at Crawford Hill offered the unique ability to make absolute sky temperature measurements (and perhaps fix up his thesis). Bell labs management were interested in radio astronomers both for their technical skills (almost all were very hands-on engineering types) and for their knowledge of radio physics, which was becoming a very important field as the U.S. vigorously began pursuing the possibility of satellite communications systems. The list of notable scientists at Bell at that time is so long it would fill up the remainder of this article.[2] John Pierce (Pierce gun), Kumar Patel (CO_2 laser), William Merlin Sharpless (Sharpless wafer mounts), Sergei A. Schelkunoff (Electromagnetic Fields and Waves), Dennis Ritchie (UNIX inventor), Willard Boyle (CCD's, 2009 Nobel Laureate in Physics), were just a few of the names that would have attracted a young radio scientist hoping to make a career in this burgeoning field.

In 1963, with wife and young son in tow, Wilson made the journey across the US to set up his home for the next 48 years in Holmdel, New Jersey. The radio astronomy team at Bell fell under the direction of Roy Tillotson, who was interested more in the practical aspects of radio science, than in observational astronomy. However these were the days when quality basic research was encouraged at Bell Laboratories, and Wilson and Penzias were allowed to pursue their observational astronomy experiments, but they were expected to work half time on a more practical understanding of basic atmospheric propagation and antenna performance issues, with an eye towards eventual satellite communications systems.

When Wilson arrived, the 20-foot Horn had a traveling wave maser amplifier at 4 GHz and was being used to monitor a beacon on the Telstar satellite. David C. Hogg (radio propagation), who was well established at Crawford Hill, had started working on making an accurate gain measurement of the 20 foot horn-reflector antenna, at that frequency. He was also performing propagation experiments to locate optical and infrared atmospheric transmission windows. Hogg and Wilson completed the precise gain calibration measurements on the horn antenna in 1964 [4] and Penzias and Wilson were working on using that knowledge to make very accurate absolute flux measurements on Cassiopeia A and other cosmic radio sources [5]. These measurements were expected to be useful for calibrating Earth station antennas as well as to radio astronomers.

[2]http://www.aip.org/history/acap/institutions/inst.jsp?bell.

The work at Owens Valley had taught Wilson about extremely careful calibration and loss tracing in radio systems, and the very low back lobes of the 20-foot horn made it good enough to perform precise measurements of the sky background temperature. With a very thorough understanding of all the losses in the 20-foot horn antenna, and the very accurate liquid helium cooled reference noise load which Penzias had made, the persistent excess thermal noise contribution that was always present on sky background measurements of radio sources were a major puzzle. Wilson and Penzias began searching for, and ruling out all of the explanations they could think of. They eventually heard about the work on radiation from the Big Bang by Robert Dicke's (Dicke switch) group at nearby Princeton University, including Jim Peebles (cosmologist) and David Wilkinson (Precise Cosmic Microwave Background observations, NASA's Wilkinson Microwave Anisotropy Probe satellite—WMAP), which provided an explanation. Although skeptical about the concept of a universe that was continually expanding, collapsing, and re-exploding (having had Steady State Cosmologist, Fred Hoyle, as a professor at Caltech), Wilson and Penzias agreed to publish their article on extraneous noise measurements in conjunction with a lead-in letter on the potential theoretical explanation by the Princeton group, in the *Astrophysical Journal* in 1965 [6], [7]. This paper, and subsequent cosmic background measurements [8]–[10], led to the 1978 Nobel Prize in Physics for Wilson and Penzias.

After the article appeared, Wilson and Penzias were contacted by cosmologist George Gamow (Alpher-Bethe-Gamow theory), then at University of Colorado, Boulder and heard about the calculations by Johns Hopkins physicists Ralph Alpher and Robert Herman, that set an upper limit of 5K on the remnant isotropic thermal signature from the Big Bang. The work that preceded the cosmic background discovery is well documented in several nice articles by Wilson himself [11], [12], as well as in a recent video interview from the 60th meeting of the Nobel Laureates in Lindau, Germany in June 2010 [13].

Following these very ground breaking astronomical observations from 1964 through 1966, Wilson and Penzias were true to their organization's mantra about working on practical radio science problems. Optical and near IR transmission along long horizontal paths had been shown to be hopeless in bad weather by Hogg, so they set up one of Patel's CO_2 lasers at the main Holmdel building and a telescope with a thermopile detector on Crawford Hill to check out atmospheric transmission at 10 microns [14].

In the mid-1960's, there was talk about the very high bandwidth communications links required for the new picture phone technology that had been recently demonstrated to a wide public audience at the 1964 New York City World's Fair. Coast-to-coast and continent-to-continent telecom links were envisioned using two-inch diameter circular metal waveguides propagating the ultra low loss TE_{01} mode. The Communications Satellite Corporation (COMSAT) had just been created in 1962 as a public corporation with a board of directors appointed by President John F. Kennedy, ruling AT&T out of the international satellite communications market. The need to increase bandwidth and move up in frequency was pushing Bell labs researchers to start working at shorter wavelengths.

Wilson turned his attention to the problem of transmitting millimeter-wave radiation through the atmosphere, and with Dave Hogg, designed and built a Sun/sky brightness temperature radiometer for all-weather attenuation measurements [15]. Again this practical sidestep away from radio astronomy observations, and insisted on by Roy Tillotson, proved to be fortuitous. It pushed Wilson and Penzias into the world of high frequency receivers, this time based on new photolithographed GaAs Schottky barrier diodes being realized for the first time by Crawford Hill researcher Charles Burrus [16], a former student of pioneering millimeter-wave spectroscopist Walter Gordy at Duke University. These "packaged" devices (they were mounted in field replaceable Sharpless wafer mounts [17]) were far more robust than existing point contact crystal rectifier diodes, and allowed much more stable continuous operation of low noise receivers in the 90–140 GHz frequency range.

At this time Gerry Wrixon (now at University College, Cork, Ireland) came over from Berkeley to help with the microwave radio astronomy. Keith Jefferts, a noted quantum physicist with an engineering streak, in the physics group at Murray Hill, also joined the Penzias and Wilson team. By 1968 higher frequency radio telescopes had sprung up in several places [18], and the National radio Astronomy Observatory (NRAO) had just completed a 36 foot dish on Kitt Peak in Tucson, Arizona with a surface finish and accuracy that could work well above 200 GHz.

NRAO was having some trouble getting sensitive receivers up and running, so Penzias suggested that they take a Burrus Schottky receiver, which could operate up to 140 GHz, over to Kitt Peak. Their first effort in 1968 was to measure quasars at about 90 GHz with Ken Kellerman (former graduate student with Wilson at OVRO and now at NRAO) and also look for fluctuations in the cosmic background emission at these higher frequencies [19]. The quasar observations were not very successful because the telescope was not quite ready for serious observations. However, Penzias had been a student of Charles Townes then at Columbia University, New York (1964 Nobel Prize in Physics, inventor of the maser and author of Microwave Spectroscopy with Arthur Schawlow), and was attuned to the value of microwave spectroscopy as a tool for probing molecular structure. There had also been both observational [20]–[23] and theoretical work [24] in the millimeter wave range on the presence of various lightweight molecules in specific regions of outer space. Colleagues Patrick Thaddeus (then at Columbia University and the NASA Goddard Institute for Space Studies in NYC, now at Harvard-Smithsonian Center for Astrophysics) and Philip Solomon (then at Princeton University, later at State University of New York at Stony Brook) along with Townes, suggested several poignant molecular signatures that would likely exist in the interstellar medium. The idea of spectral line observations was intriguing, and so the Bell team talked with Sandy Weinreb, then director of the NRAO Electronics division in Charlottesville, Virginia, who agreed to supply expertise and critical parts of the receiver electronics to make spectroscopy possible with the 36-foot antenna. The team applied for observing time and made the observing trip to Kitt Peak in the spring of 1970.

The complete story is described in great detail in an NRAO 50th anniversary article by Wilson [25], but suffice it to say that Wilson, Jefferts and Weinreb returned to Kitt Peak toting a 90–140 GHz Burrus heterodyne receiver with a phase locked klystron local oscillator system, filter bank and a real-time oscilloscope spectral display system with a data recording on magnetic tape put together by Weinreb.

After a series of very difficult days trying to make everything work properly at the telescope, on March 9th, Wilson and Jefferts (Weinreb had to return to Charlottesville the day before, and Penzias was not to arrive until the next day) turned the telescope to the Orion Nebula, which was high up in the sky at the time. Within a few seconds Wilson saw the center channels on their oscilloscope screen (at a frequency around 115.27 GHz) rise when the telescope was pointed at the source. This was already known from laboratory measurements to be the signature of the ground state rotational transition ($\mathrm{J} = 1$ to 0) of carbon monoxide.

There was no way to store the data at the telescope except to record it onto magnetic tape for later retrieval back in Tucson, so this first observation was seen on the oscilloscope and then disappeared as soon as the "save" button was pressed. Nevertheless Wilson and Jefferts realized the value of the observation [26] and while the Orion Nebula remained up they explored the extent of the CO radiation and carefully checked their frequency calculations and tuning. After Orion set, they took a well-earned rest while they waited for the sky to rotate through less interesting regions, and for the galactic plane to rise again. Weinreb called the next morning and was amazed that the system had worked and that CO had been discovered in outer space. Penzias arrived the next day and the trio continued their measurements of CO and also recorded seeing CN for the first time.

Although this was not the first measurement of a molecular signature in interstellar space, CO turned out to be an essential tracer for cool molecular hydrogen regions (H_2) that were not visible by other means, and became the most favored molecule for identifying and tracing the giant molecular clouds that make up the spiral arms of the Milky Way, represent a large quantity of dark mass in the galaxy, and are a pointer to new star forming regions.

After the discovery of CO, Penzias, Jefferts and Wilson began a long sequence of observational studies, many in collaboration with Thaddeus and Solomon and their students, to detect and catalog molecular line signatures throughout the millimeter-wave spectral range. Some of the many molecules identified were ^{13}CO, $C^{18}O$, SiO, CS, CH_3CN, OCS and H_2S [28]. These measurements were helped by the fact that the Burrus mixer was one of the only ones operating in this frequency range, and the 36 foot telescope was an ideal platform for these observations. Lew Snyder and Dave Buhl [29] from NRAO, found HCO^+, in the observing run following Wilson, Jefferts and Penzias' CO discovery and found HNC and HNCO during the same period.

In 1974, Bell Laboratories was convinced that they should have their own millimeter-wave telescope at Crawford Hill, and Wilson was put in charge of the project. As with all their work at Bell, the radio astronomy group was told that the research would have to play a dual role—*basic science and practical application*. The telescope therefore was also configured for satellite applications, and as such had a separate receiver box for the 20–30 GHz band along with state-of-the-art 100–240 GHz channels.

Since millimeter-wave seeing depends strongly on weather conditions, when the weather was clear and dry (winter) the telescope was used for radio astronomy. When the weather was cloudy or wet (spring and summer) the telescope was turned to satellite work. A new crew of engineers joined the team that included Martin Schneider (Schottky diode receivers), Richard Linke (receivers), Paul Henry (phase lock systems and spectrum expander), and a number of graduate students including Tony Stark (high frequency receivers) and post-docs.

Thanks to Wilson's direction, the telescope was successfully completed and began operations in 1977 [30]. Astronomical work continued all the way through 1994, and the telescope contributed to a substantial portion of the millimeter-wave observations that defined this early generation of radio scientists. Over these years Wilson worked with many of this first generation of radio astronomers which included William Langer (JPL), John Bally (University of Colorado), Harvey Liszt (NRAO), Peter Wannier (JPL), Pierre Encrenaz (Paris Observatory), Charles Beichman (JPL), Paul Goldsmith (UMass/Cornell/JPL), Peg Frerking (JPL) and many many more. Wilson's most cited paper is from the Crawford Hill observatory [31] as are five others of his top ten cited works [32]–[36]. The science was aided by the fact that Arno Penzias had worked his way up in the Bell Labs management chain and had taken the place of Roy Tillotson, thus assuring the continuous work of the radio astronomy group at Crawford Hill. This was certainly helped by the 1978 awarding of the Nobel Prize to Penzias and Wilson for their 1964–1966 observations of the Cosmic Microwave background.

As the 1990's approached, the Crawford Hill telescope was no longer state-of-the-art, and Wilson began to get involved in other projects. Tony Stark had hooked up with a group at University of Chicago who were interested in much higher frequency (THz) observations and were planning a telescope for the very high and dry landscape at the South Pole. They were also flying on the Kuiper Airborne Observatory, a NASA high altitude C141 aircraft that could climb above atmospheric water vapor for sustained THz observations using a built--]in 3 foot diameter infrared telescope. Wilson shifted some of his emphasis to these THz systems, and by 1994, Stark and colleagues managed to complete their South Pole telescope with a working frequency range around 500 GHz

However, by this time, Bell was no longer supportive of the submillimeter-wave development, and Stark had moved to Harvard-Smithsonian where work was beginning on the new SMA (Submillimeter Array), an ambitious program to place an 8-element THz (200–700 GHz) interferometer made up of 6 meter diameter movable dishes, at the Mauna Kea Observatory in Hawaii. Colleague and friend, Patrick Thaddeus and a large number of the radio astronomy group from Columbia University and the Goddard Institute for Space Studies in NYC, were also at Harvard-Smithsonian by this time, and it was becoming clear to Wilson that radio astronomy at Crawford Hill was no longer a priority, or even a luxury, that could be sustained at Bell. For a short time he diverted his observational work to take on some challenging, but very practical engineering tasks on large optical and RF networks for Bell, ultimately prototyping an automated pricing and inventory update system for supermarket shelf products [37]. He proudly showed me the compact LCD display and RF communications unit that was the centerpiece of the system, which was successfully deployed at this time. However Wilson also realized that even this commercial product diversion, and his scientific notoriety, did not guarantee his continued ability to do basic research. He began looking for an opportunity to apply his creative engineering talents at a location that did not require an out-and-out permanent relocation. Fortunately, noted physicist, professor and then Director of the Harvard-Smithsonian Center for Astrophysics (CfA), Irwin Shapiro, and Wilson's earlier colleagues at Harvard were calling out. Wilson decided to leave Crawford Hill, and join the staff at CfA. As his wife was now a practicing psychiatrist near his home in central New Jersey, he chose the commuters life, arranged to spend alternate weeks in Boston and Holmdel, and began by making use of all, and any means of transport that could cycle him efficiently from locations 250 miles apart. Luckily a quite frequent train link—unusual in the US—exists between Washington DC, and Boston, MA, and Wilson has been able to use this more humane method of commuting for more than 15 years.

At CfA, Wilson concentrated on the tasks that had drawn him into the field of radio astronomy from the beginning—mechanical and electronic control, system engineering and computer coding, while he continued with his observational and theoretical work in radio astronomy [38]–[41]. He ventured down to the South Pole once and has made several trips to Mauna Kea, but he says that these days there is no need to trek to wild and remote places to perform radio observations. He noted that the SMA on Mauna Kea can be controlled from a room down the hallway at the CfA in Boston.

It seemed appropriate that our discussions concluded with some reminiscences of the days when radio science was a field frequented by applied physicists and engineers. Telescope observations were both a test of endurance and a labor that required the skills and attention to detail of a practical engineer, as well as the curiosity and the drive of a theoretical physicist. Fortunately, Dr. Wilson epitomizes and embraces this combination of talents, and has applied them throughout his long and very successful career as a true *Pioneer of Radio Science*.

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