
Robert Price

ROBERT PRICE

1929–2008

Elected in 1985

"For pioneering achievements in applying statistical communication theory to radio communication, radar astronomy, and magnetic recording."

BY THOMAS KAILATH

ROBERT PRICE, a communications scientist, died December 3, 2008, at the age of 79 in Lexington, Massachusetts, where he had resided for more than 50 years.

Bob was born on July 7, 1929, in Ft. Washington, north of Philadelphia, and studied at the William Penn charter school, one of the oldest private schools in Philadelphia. Following his AB degree in physics in 1950 from Princeton, and a short stint at Philco Labs in Philadelphia, he joined the MIT Lincoln Laboratory and simultaneously enrolled at MIT, where Robert Fano suggested the topic that would lead to his ScD dissertation, "Statistical Theory Applied to Communication Through Multipath Disturbances" (MIT RLE Technical Report 266, September 1953).

Bob's thesis contains a number of channel capacity calculations and some results on optimal receivers. The latter material is further developed in Price (1956), where in the (later extensively studied by others) problem of the detection of Gaussian signals in additive white Gaussian noise, Bob made a very important observation. The main computation requires the evaluation of a double integral of a quadratic function of the received signal, with a weighting function obtained as the solution of an integral equation. The required computations will be fairly complicated in any physical problem but it is a characteristic of Bob's work that he sought to find a physical interpretation of the mathematical formulas.

It was well known that the detection of a deterministic signal in additive white Gaussian noise involved cross correlation between the received waveform and the deterministic signal. This would not work when the signal is random, but studying his formulas, Bob noticed that the computation could be regarded as a cross correlation between the received waveform and a least mean squares estimate of the random Gaussian signal. In actual applications even such an estimate would be difficult to compute, but he pointed out that it would be possible to use intelligent approximations to obtain a useful estimate. This now celebrated "estimator correlator" principle has been found to be of value in many problems, but it found relatively quickly an application in the development of the famous "Rake" multipath-embracing receiver, done together with his close friend and colleague Paul Green (Price and Green 1958).

For years, Price and Green had worked together at Lincoln Laboratory on different aspects of a noise modulation and correlation (NOMAC) system. Following ideas put forward in information theory by Claude Shannon, Jerome Wiesner, director of the Research Laboratory of Electronics (who later became science advisor to President Kennedy and then president of MIT), proposed building a system that transmitted wideband (pseudo)random signals detected by the use of correlation between the received signal and the transmitted (pseudo)random signal. NOMAC was put into service by the Army Signal Corps under the name F9C. One of the systems was deployed in Germany at the time of the Berlin blockade. But in the field, it was soon found that NOMAC's performance was seriously affected by the presence of multipath propagation (signals arriving at the receiver after multiple reflections via a randomly varying fading channel). How to mitigate this deterioration was the topic suggested by Fano for Price's doctoral research.

The Rake receiver consists of several "fingers" with different delays, which look like a rake, hence the name. It took advantage of the multiple signals to enhance the signal strength, combining the signals from the different fingers with the right weights to undo the multipath effects. The Rake receiver concept, first used for ionospheric communications, has been applied in a variety of areas such as underwater communications, analysis of seismic signals, and, as described below, planetary radar astronomy. Most significantly, the success of modern mobile phones relies heavily on the rake concept, with almost every cell phone implementing a Rake receiver.

As the rake paper by Price and Green (1958) got more attention, questions were raised about the very large bandwidth of the transmitted signals: A bandwidth of 10 kHz was used to support a single 60-word-per-minute teletype channel! But the reason could not be revealed at the time, because the main purpose of the system was its antijamming function.

NOMAC and Rake were examples of what came to be called spread-spectrum (SS) systems. Two papers by Robert Scholtz (1982, 1983) gave a comprehensive history of early spread-spectrum communications, supplemented by a fascinating paper by Price (1982), "Further Notes and Anecdotes on Spread-Spectrum Origins."

This is a good point at which to mention some notable characteristics of Bob's work. He took great pleasure and pride in diligently seeking out and acknowledging all, even potential, prior references, and paid close attention to motivation and clarity of exposition. The just-cited paper is a wonderful example.

Bob was also extremely generous in his interactions with others, as I and many others gratefully acknowledge. His long-time colleague at Lincoln Laboratory, Paul R. Drouilhet, wrote in the IEEE obituary for Bob: "In addition to pursuing his own research, Dr. Price always assisted those who worked around him, and was the source of many ideas helpful to his colleagues." As one testimonial among many, I quote from a letter written to me by Robert Scholtz of the University of Southern California, concerning his papers (Scholtz 1982, 1983):

> Price was recruited to help me…, and that is when I experienced Bob's bulldog tenacity first hand. He thoroughly researched all leads to SS history, especially through the patent office records which I believe were available in Boston Public Library at the time, and interviewed many engineers on the East Coast who worked on SS. He got the librarian at Sperry Research to cull through archives for anything related to it. Every week or two I would get a very thick envelope of selected pages from documents related to SS with Bob's annotations written all over them or notes stapled to them. These typically were followed by phone calls, often on weekends, starting in the late afternoon and usually ending 4–6 hours later! Somewhere I remember him indicating that he had run up enormous phone bills at Sperry on this research project (thousands of dollars). I vividly remember one night (after one of these calls) waking bolt upright after a dream in which Bob was running me down with a steamroller!

Because of this extensive help, Scholtz invited Bob to be a coauthor, but characteristically, Bob declined.

However, there is one historical nugget that Bob had dug up in the course of those discussions, which he told Scholtz he wanted to reserve for his own supplement (Price 1982). Following a lead from his sister, Bob tracked down a 1942 patent by Hedy K. Markey and composer George Antheil for a secrecy system employing frequency hopping. Of Hedy, Bob wrote, "growing up in Austria, the only child of a prominent Vienna banker had shown, at age 16, a flair for innovation by letting herself be filmed in total nudity when starting in the Czech-produced classic, 'Ecstasy' (the 5th of her many motion pictures)." In 1938, Hedy left behind her husband and secured a seven-year contract from Metro-Goldwyn-Mayer, under the stage name Hedy Lamarr. When Bob discovered that she was now living in New York he arranged an interview, for which he had to be first screened by a lawyer. Bob was very happy with the meeting and secured an autographed photograph of Hedy Lamarr (figure 2 in Price 1982). There are many other nuggets in Bob's fascinating paper—it is a wonderful read.

Bob's contributions to both the technology and the history of secure communications became widely known and highly respected. He was invited to the opening of the Cabinet War Rooms in London for his research into the secret wartime telephone conversations between Roosevelt and Churchill. Another historical nugget is a long two-part interview with Claude Shannon, the founder of information theory.[1] Price had a special connection with Shannon, because when Shannon went out of town, Bob and a couple of his friends had rented Shannon's home on the lake in Winchester, MA.

With the success of Rake under their belts, Price and Green began to look around for new challenges. One arose quite fortuitously. On completion of his doctoral research, Price had applied for and received a Fulbright Fellowship to spend a year at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Radio Physics division in Sydney. Here he was part of a team that found the strength of the 327-MHz spectral resonance of deuterium in our galaxy to be anomalously weak—a result of some cosmological significance. Fifteen years later this experience led to an interesting lunchtime conversation between Price and Green about a book on radio astronomy by Pawsey and Bracewell of the CSIRO (*Radio Astronomy*, Oxford Clarendon Press, 1955). The book noted that radar astronomy might be able to get better results in studying planets than was possible via existing optical techniques.

Successful radar bounces off the moon had actually been achieved in 1946 by groups in New Jersey and Hungary. But going beyond the moon would require much more powerful transmitters and more sensitive receivers. A powerful radar had recently been built by Lincoln Laboratory at the MIT Haystack Observatory atop Millstone Hill in nearby Westford, and Price and Green wondered if it could be used to bounce signals off the planet Venus! Rough "paper napkin" calculations cast doubt on these hopes, but it was allayed when Robert Kingston joined the discussions. He had just built a

[1] Available at www.ieeeghn.org/wiki/index.php/OralHistory:Claude_E._Shannon.

relatively new, quite sensitive solid state microwave receiver called a maser (microwave amplification by stimulated emission of radiation).

In February 1958 Price and Green collected almost 59 hours of radar reflections from Venus. As anticipated, none of the echoes was above the receiver noise level and so the data had to be averaged over multiple runs in order to improve the signal-to-noise ratio. For this, the data were digitized onto magnetic tape and fed into a solid state digital computer at Lincoln Laboratory. Price then closeted himself for several months in a basement office, in effect doing pioneering work in what later came to be called digital signal processing. (I remember Price excitedly communicating that in the digital domain he could easily get excellent approximations to the physically unrealizable "boxcar" analog filter.) In March 1959 Lincoln Laboratory announced that it had bounced radar waves off Venus (Price et al. 1959), and a year or so later the Jodrell Bank Observatory in England announced that it had confirmed the results. Attempts by a group led by the famous Soviet radio scientist V.A. Kotelnikov gave further confirmation.

Nevertheless, Price and Green decided to repeat the experiment in 1961, taking advantage of power improvements at the Millstone radar. Unfortunately, very careful analysis failed to confirm the earlier results—a stunning disappointment. A little later, the first unambiguous direct detection of echoes from Venus was announced by a team at the Jet Propulsion Laboratory (JPL) in Pasadena, California, using a much more powerful transmitter at its Deep Space Instrumentation Facility.[2] Despite his obvious regrets, Price later took comfort from the fact that the template matching methodology he had introduced enabled astronomers, many years later, to make a new confirmation of Einstein's theory of general relativity. He was also proud that he had made the first synthesis of optimum radar-radiometric signal processing techniques,

[2] Much more on all this can be found in an official NASA history (Butrica 1996), chapter 2 of which records comments by Price and Green on how the error had arisen and provides interesting background on the JPL experiment.

employing the theoretically best mix of pre- and postrectification filtering, which is significant for other sensors and in communications applications (Price and Green 1960, Price 1968).

Bob published several other important papers before he left Lincoln Laboratory in 1965. An article in 1958 showed that the cross correlation of a random process with its nonlinearly distorted version is, for many processes, proportional to its autocorrelation, thus expanding on the Bussgang (1952) theorem, which proved it for Gaussian noise. The consequence is that computation of an autocorrelation function becomes much easier, because instead of full multiplication, multiplying by just +1 or −1 was sufficient. In 1998 Bob's paper was recognized with an IEEE Information Theory Society Golden Jubilee Award for an outstanding result in the area of stochastic processes. A related efficient analytical tool, dubbed "Price's back door," appears in a book by Nelson Blachman (1982, p. 89).

Bob was always fascinated with special functions (friends referred to him as Bessel Bob) and took particular pleasure in evaluating difficult integrals arising in his work and that of his friends. In addition to the example at the end of his 1956 paper, a particularly notable example is his closed-form solution to a long-standing statistical problem in the analysis of variance (Price 1964). And as a private consultant, around 1988, Bob developed a novel statistical treatment of interference and jamming based on a new series of hypergeometric functions having superior numerical convergence properties.

He left Lincoln Laboratory in 1965 to become a research scientist and manager at the newly established Sperry Research Center in Sudbury, MA, from 1965 to 1983. He applied modern communications methods to digital recording, inventing digital equalization filtering techniques, which led to the quadrupling of data storage density (Price et al. 1978), and scotching "clever ideas" contradicting theoretical limits. This work led to several important patents.

In 1983, when the Sperry Center closed (and became Unisys), Bob was invited to become chief scientist at M/A-COM Government Systems in Lexington, where he worked for five years before leaving to become a research scientist at the

Raytheon Research Division (1988–1993). There he focused on variations and improvements on existing fast Fourier transform (FFT) algorithms (see, e.g., Proakis and Manolakis 1992, pp. 729–730). Notably, he used FFTs to create new nonlinear FM chirp waveforms for radar pulse compression; versions of this waveform have been adopted for international air traffic control. After 1993 he remained active as an independent consultant and testified in a number of patent cases.

Dr. Price received many honors. He received the Edwin Howard Armstrong Achievement Award of the IEEE Communications Society in 1981, and was elected to the NAE in 1985. He was a member of Phi Beta Kappa and Sigma XI; a Fulbright Fellow, CSIRO Radio Physics Division (1953–1954); member, Commission C (Signals and Systems), US National Committee, International Union of Radio Science (URSI; 1959); and fellow, IEEE (1962), "for contributions to communication system theory and its use in radar contact with Venus." He served on the advisory committee of the Department of Electrical Engineering and Computer Science at Princeton University (1971–1977).

His later hobbies included collecting exotic foreign currency and banknotes, such as German marks and Japanese currency used in occupied Malaya. He also did projects such as building a burglar alarm system for his home and a Heathkit color TV receiver, but his wife, the former Jennifer Martin (whom he had met on a ship returning from Australia in 1954), says that his main hobby was his work.

Bob and Jennifer were married in England in 1958 and celebrated their 50th anniversary on April 19, 2008. He is also survived by three sons—Stephen L. Price of Huntington Station, New York, Colin L. Price of North Andover, MA, and Edmund H. Price of Wayland, MA—and four grandchildren.

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