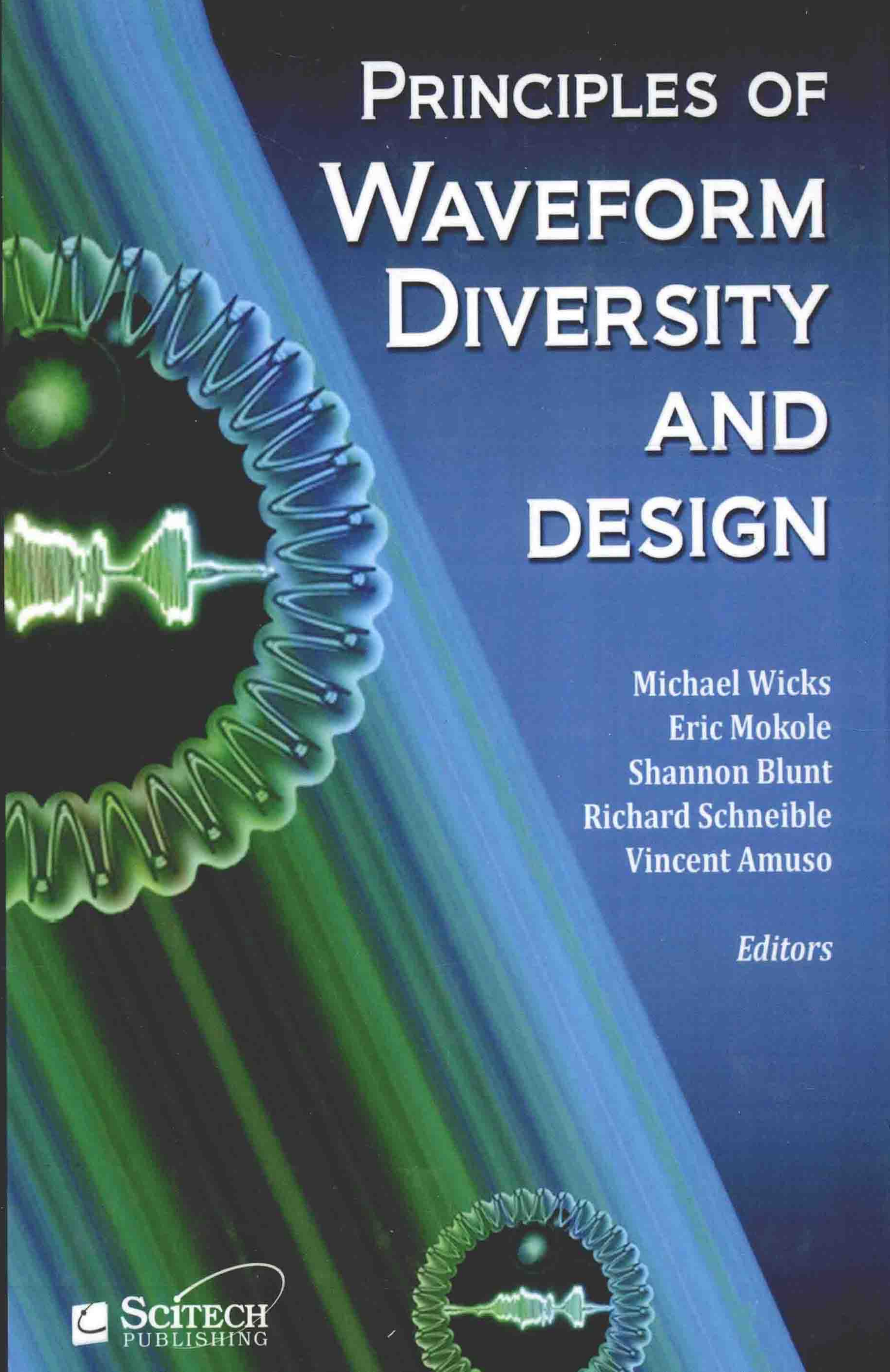

# Principles of Waveform Diversity and Design

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# Principles of Waveform Diversity and Design

# Dedication

## P. M. Woodward and the Ambiguity Function

*Lars Falk*

## 1 Introduction

Fifteen years ago a small book was brought to my attention, *Probability and Information Theory with Applications to Radar* [1]. I had recently returned to radar and wanted to learn more about signal processing. It seemed strange to be directed to a book printed in 1953, but it obviously enjoyed an excellent reputation in view of the number of references found in books and articles.

The slender volume was written in an unfamiliar language but surprisingly easy to read. Finally I realized that this was Bayesian theory expressed in terms of "inverse probability," the technique used by astronomers in the old days to derive orbital parameters from observational data. The formalism, which simplified the subject and expressions for the accuracy and thresholds of radar measurements, seemed to appear from nowhere. You just had to accept the basic premise that no information should be wasted during processing and interpretation of radar signals. This requirement sounds natural enough, but few authors have dared to use it as a starting point. The principle leads directly to the idea of ideal receivers and matched filters and ultimately to the ambiguity function. The final chapter of Woodward's book is devoted to waveform design, but the author only mentions in passing that the ambiguity function was introduced for the first time in this book.

Another mystery proved harder to solve. What had happened to the author? After writing the book Woodward seemed to have vanished from the radar scene, or "radar screen" as Professor Nadav Levanon put it. Like other radar experts he wondered what had happened to P.M. Woodward. This question led to a quest that lasted for several years. Now and then I would ask radar scientists what had happened to P.M. Woodward, but without success. Finally, just before giving a talk that was important to me (about crosseye jamming at the AOC conference in Zürich, 2000) I asked a fellow lecturer, Mike Corcoran, the usual question. To my surprise he announced that a Woodward building had recently been inaugurated in Malvern. This did not sound particularly promising, but I soon got a telephone number and started an e-mail conversation. Finally I met Woodward in Malvern in 2003 and could ask him about the book.

## 2 Three Fields of Excellence

The mystery was easily solved. At the peak of his fame Woodward moved from radars to computers, where he became equally famous. Such moves are unusual, but evidently typical of Woodward. Later he became equally famous in a third field, the construction of mechanical clocks. He seems to have focused on each subject for 20–30 years and achieved outstanding results in all of them.

- Radar, 1941–60
- Computers, 1955–80
- Mechanical clocks, 1975 – present

Philip Woodward was born in 1919 and arrived at the Telecommunication Research Establishment (TRE) at Swanage in 1941. He had studied mathematics for two years at Oxford and found it dull, but TRE was different: "Here was real research with a real purpose." "The cream of Britain's scientific talent had been thrown together at TRE under single-minded leadership, and most were under thirty years of age." [2]

Woodward started by doing numerical calculations on radar antennas affected by reflections from land and sea. This work led to his first paper concerning a clever method of designing radar antennas based on Fourier sampling theory [3]. After the war Woodward remained in Malvern, where he introduced the ambiguity function in 1953. He taught at Harvard in 1956 and then moved on to electronic computers. Woodward became responsible for one of the United Kingdom's first computers, TREAC, and the first solid state computer, RREAC. In the 1960s his computer software team provided the Royal Radar Establishment with the world's first implementation of the programming language ALGOL 68.

Woodward's achievements in horology are equally impressive. He has constructed the best existing mechanical clock, though he modestly assured me that such claims are difficult to verify. His book, *My Own Right Time*, [4] is as highly regarded in the field of horology as *Probability and Information Theory with Applications to Radar* in ours. Woodward contributed dozens of articles to horological periodicals over more than 30 years, including the definitive analysis of balance springs and work on the properties of pendulums. In 2006 the British Horological Institute published a hard-cover collection of 63 articles with his own notes, *Woodward on Time*.

Woodward became a Deputy Chief Scientific Officer at the Royal Signals and Radar Establishment (RSRE). In addition he became Honorary Professor in Electrical Engineering at the University of Birmingham and Visiting Professor in Cybernetics at the University of Reading. In June 2005 the Royal Academy of Engineering gave Woodward its first Lifetime Achievement Award, recognizing him as an outstanding pioneer of radar and for his work in precision mechanical horology. In 2009 he received the IEEE Dennis J. Picard Medal for Radar Technologies and Applications, "For pioneering work of fundamental importance in radar waveform design, including the Woodward Ambiguity Function, the standard tool for waveform and matched filter analysis."

## 3 Shannon and Woodward

The historical summary of Woodward's accomplishments in the last section was presented in a banquet lecture at the First International Conference on Waveform Diversity and Design in Edinburgh Scotland in 2004 [5]. The reaction of the audience showed that Woodward's ambiguity function is a central concept to everyone involved with radar waveform design.

There are several reasons for the success of Woodward's book [1]. The language is clear and accessible to foreigners, as he mentioned in an e-mail: "One thing that very much pleased me was a letter I had from the translator for the French edition. I no longer have the letter, but he said he had found my style of English easier to translate than that of any other English author with which he had had to contend." The book looks like a series of lectures, but was actually written in bed. Pleasure is a good starting point, but trouble came later. The preface contains the innocuous phrase: "I have to thank the Chief Scientist, Ministry of Supply, for permission to publish this book." In fact, permission was only reluctantly granted. The unwillingness may have been motivated, because Soviet authorities immediately translated the book into Russian in 1955.

Woodward wrote his book while radar signal processing was still in its infancy. Yet he managed to deduce almost all modern methods of data processing by applying the general principles suggested by Shannon in his papers on information theory [6,7].

I got a clue to Woodward's gifts as a scientist when he explained that components in a mechanical clock do not have to be complicated if you design them correctly. Woodward has constructed many tools and the ambiguity function is one of them. One of his scientific heroes is Claude Shannon. They have many talents in common; in particular they have an ability to combine advanced mathematics with engineering that was unusual at the time.

The war moved many scientists into radar and electronic communication. Yet Shannon managed almost single-handedly to transform the subject. I asked Woodward whether he remembered when he first read Shannon's paper. Yes, he said, in those days there were few journals around and he read the article in the TRE library. He was surprised to see all his questions answered at one stroke and reacted in characteristic fashion: "I could have done that!"

Many people must have felt the same. Wiener and Tuller published similar results concerning the maximum amount of information contained in a signal of known bandwidth and signal-to-noise ratio (SNR). Shannon kindly introduced references to their papers in the book version of his papers [6.7], but this was small consolation. Woodward told me that Tuller described this twist of fate when he visited Malvern several years later. Next day Tuller departed for the USA, but the plane crashed and he was killed, oddly enough near Shannon in Ireland.

Wiener and Tuller made significant contributions, but Shannon completely changed our views on information theory. Woodward recognized this, as shown by the title of his book, which emphasises probability and information theory rather than radar.

At the beginning of our correspondence Woodward noticed that he now had two admirers, a Swedish radar specialist and an English teacher, who thought that his book was the best possible introduction to probability theory for students. This is a reasonable view. The first chapter addresses probability theory without fear of mathematics. The second chapter describes signals and noise and the third explains information theory. After that the reader is ready to study radar theory.

Many radar pioneers thought that radar signals should be described as deterministic functions with added noise. In particular, Gabor wrote influential papers about the amount of information contained in wave fields. He invented holography in the process and got a Nobel Prize for his method of storing and retrieving phase information. Gabor supported Woodward in many ways, but he was apparently too anxious about counting degrees of freedom in terms of time and bandwidth to consider noise and signal amplitudes in the proper way.

The problem is subtle, as shown by the sampling theorem. Most textbooks derive this theorem by considering analytical functions that vanish outside some frequency band or time interval. This method is effective until you consider that in practice most signals are zero both outside a frequency band and a time interval. There are no analytical functions with this property and new methods are required.

Shannon solved the problem by introducing the idea of the probability of a signal defined within an ensemble. The idea of assigning probabilities to signals proved fruitful, but many people thought it was impossible to apply such methods to radar. A transmitted radar signal does not contain information and can not be coded like a message. The received signal contains information about the targets, but coding can only be applied to transmitted signals. Many people thought that this was the end of the argument.

I may inadvertently have shocked Woodward by reminding him of some of the disputes that took place at the first symposium devoted to communication theory and which are duly recorded in the proceedings [8]. Many people failed to understand Shannon's theory. Others thought that radar signals were fleeting dots on a screen and did not allow much processing. This situation has changed completely; nowadays no one would dream of throwing away data stored in digital memories before all available information has been extracted.

I suggested to Woodward that this was the reason why he abandoned radar. Perhaps he wanted to construct the required tools by developing computers? "There is an atom of truth in that", he replied in 2003. In September 2008 I gave a talk in Malvern and was delighted to see Philip Woodward in the front row. He had been thinking about my question and wanted to add to his answer.

Woodward told me that at the time he was involved with experiments with a radar system designed to detect submarine snorkels and other objects hidden by sea waves. The idea was to filter in range and Doppler as suggested by Woodward's theory. Data was stored in a Williams tube, a cathode ray tube that can hold about 1000 bits. The experiment failed for unknown reasons and Woodward decided that processing techniques were not yet mature enough to apply his methods. Computers were already available but computer memories were not fast enough before solid state memories appeared in the 1970s.

## 4 The Ambiguity Function

Woodward was particularly influenced by Shannon's paper on communication in noise [7]. He emphasised to me the significance of Shannon's interpretation of how ambiguities are formed. Similar thoughts can be found in chapter 5 of his book, where the time delay $\tau$ of a single target is analysed. "Shannon (1949) gives an interesting interpretation of the intelligence threshold in communication systems, showing that disconnected ambiguity is liable to occur whenever a signal of low dimensionality is encoded as a signal of higher dimensionality. The simple radar message we have been considering is one-dimensional, namely $\tau$. The signal representing $\tau$, on the other hand, is a waveform of many dimensions." [1]

Shannon showed how a complicated message can be coded to reduce disturbances. The success of radar during the war was due to its simplicity. There are very few ambiguities in a low pulse-repetition-frequency (PRF) radar in view of the one-to-one correspondence between range and time delay. However, signals with large time-bandwidth products are necessary to improve power management and this inevitably leads to ambiguities. Woodward noticed that in this case the correspondence between time delays and target range will be many to one and investigated the consequences using Shannon's theory. Shannon and Woodward were both mathematicians with a strong interest in applications. They developed their theories from experience, unlike most scientists who use established techniques to solve accessible problems.

Shannon's approach led to unexpected concepts like signal entropy and coding. Woodward defined the equally important idea of an ideal receiver, a component that preserves information. It is interesting to notice that Shannon and Woodward knew probability theory but avoided Bayesian terminology, perhaps because statisticians were already waging war on "subjective" methods. Woodward stated his views clearly in the preface [1]: "The present approach was suggested to me by Shannon's work on communication theory and is based on inverse probability; it is my opinion that of all statistical methods, this one comes closest to expressing intuitive notions in the precise language of mathematics." Woodward explained this further in an e-mail: "My own knowledge of probability theory had been gained exclusively from Jeffreys, long before Shannon's work was published. In his book, Jeffreys spends some time defending the "subjective" point of view, and it was only from that defence that I learned of the opposition from statisticians. I knew about insurance companies and life tables, of course, but I regarded statistics as a different subject from probability theory, and still do. To my way of thinking, statistics is concerned with finding the parameters of populations, rather than describing states of mind, whilst probability is concerned with making predictions from hypotheses, no matter how the latter may have been arrived at. It seemed wrong that statisticians should trespass into the domain of probability and inflict their narrow-minded rules on us all. After all, a mathematician can make his own axioms."

Shannon solved the coding problem by applying knowledge about the statistics of transmitted messages but avoided words like "prior knowledge". Woodward did not even mention Harold Jeffreys in his book, though Jeffreys' book on *The Theory of Probability* is given as a reference in his brilliant paper on radar design [9]. Prior knowledge is obviously useful when one is decoding messages or interpreting radar signals, as Woodward emphasised in chapter 6 of his book: "First, however, a definite assumption has to be made about the prior distribution because ambiguity is a phenomenon which very definitely depends on the extent of prior knowledge." [1]

Woodward introduced Shannon's ideas in a manner that is easily understandable to radar engineers. The ideal receiver is defined as a component that preserves information by processing signals in a reversible manner: "Reconstructibility or reversibility, to use the technical term, is the keystone of the subject." [1]

Woodward and Davies [10,11] used inverse probability to obtain the limits of accuracy of an ideal (correlation) receiver. Their results agreed with those already derived by Marcum in classified papers, but in this case the principle is the important thing. Woodward noticed that phase information omitted in radar measurements contains accurate information about range. This information is in

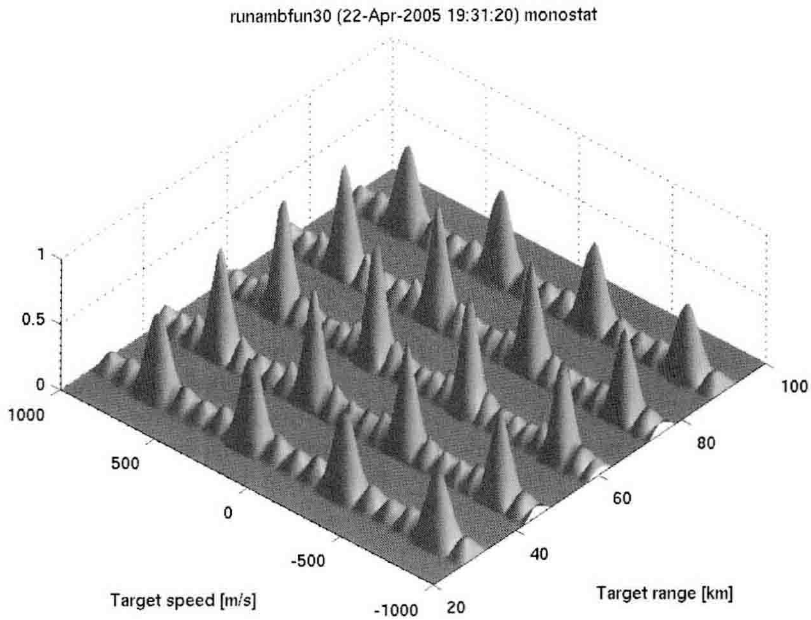


**FIGURE 1** The ambiguity function calculated for a pulse train of seven rectangular pulses (courtesy of Svante Björklund, FOI).

fact used in some modern GPS applications, illustrating the fact that a good theory will often predict new phenomena. This observation is equally true of the last chapter, where the ambiguity function is introduced. Woodward pointed out that a matched filter (correlation receiver) will preserve all information contained in the received signal. To see what happens if the targets are moving, you have to correlate the emitted pulse with a copy shifted in range and Doppler. This leads to the definition of the ambiguity function,

$$\chi(\nu, \tau) = \int u(t)u^*(t+\tau)\exp(-2\pi i \nu t)\, dt.$$

The important point is that the previous analysis can only be improved by adding new information. A typical example is Space-Time Adaptive Processing (STAP), where geometrical information about the possible location of clutter and point jammers is used to suppress interference and locate weak targets.

The ambiguity function has become an indispensable tool for radar signal analysis. Modern computers can present the function in great detail (Figure 1). It is instructive to compare such figures with the contour plots used in Woodward's book [1].

The conclusion of Woodward's book offers a fine example of the British art of understatement. Two cases were offered in 1953. Watson and Crick announced the spiral structure of DNA with a carefully formulated final sentence: "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." Woodward formulated an equally subtle conclusion in his book: "The reader may feel some disappointment, not unshared by the writer, that the basic question of what to transmit remains substantially unanswered." The lack of a unique answer can of course be interpreted more optimistically as a freedom to design waveforms without restricting oneself to the requirements imposed by range and Doppler shifts.

Woodward still preferred the pessimistic note when he summarized the possibilities of removing radar ambiguities in a "futility theorem" published in a 1967 report on radar ambiguity analysis [12]: "Like slums, ambiguity has a way of appearing on one place as fast as it is made to disappear in

**FIGURE 2** P. M. Woodward in his garden in Malvern (Photo: Lars Falk, 2003).

another. That it must be conserved is completely accepted, but the thought remains that ambiguity might be segregated in some unwanted part of the *tf*-plane where it will cease to be a practical embarrassment." This statement recalls Carson's famous assertion about radio reception: "Noise, like the poor, will always be with us." The point is that Shannon had refuted Carson's view in an unexpected way by introducing digital coding. Similarly, Woodward has taught us to look for new possibilities when designing radar waveforms. It is only necessary to take into account the restrictions imposed by nature by expressing them in terms of the ambiguity function.

## 5 Woodward's Theorem

A note on naming is indicated here. It is sometimes claimed that Wigner derived the ambiguity function in 1932 within the field of quantum mechanics and that Ville made a similar contribution to signal theory in 1948. This view is anachronistic, because neither Wigner nor Ville was thinking of radar. In fact, Woodward included Ville's paper among the nine references in his book. The question is what Ville did with his function. Different physical concepts can have the same mathematical form. Stigler stated a law of eponomy: "No scientific law is named after its original discoverer." This statement applies to Stigler's Law, but Woodward's ambiguity function is correctly labeled as long as it used for radar waveform design. It provides a unique description of radar ambiguity while Ville's function is one of infinitely many functions used to perform time-frequency analysis. The functions look similar but they describe different properties. If the function is used to describe radar, it should be called Woodward's ambiguity function.

The problem of naming leads to strange situations. A search for Woodward will locate Woodward's theorem, an elementary approximation for the power spectrum of a frequency modulated (FM) signal derived by Woodward in 1952 [13]:

$$S(f)\,df \approx {}^1\!/_2 A^2 p(f - f_0)\,df.$$

This approximation works well unless the modulation is spike-like [14]. The point is that the approximation is based on probability theory, a subject of particular interest to Woodward. The probability distribution, $p(f - f_0)$, describes how often a particular frequency is visited by the signal, but it is hardly obvious whether this probability should be regarded as subjective or objective.

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