WATKINS-JOHNSON COMPANY
3333 HILLVIEW AVENUE
PALO ALTO, CA 94304
(415) 493-4141

BULK RATE
U.S. POSTAGE
PAID
PERMIT NUMBER
317
SUNNYVALE
CALIFORNIA

WATKINS-JOHNSON

Manufacturing and Office Locations

United States

SALES OFFICES

CALIFORNIA
Watkins-Johnson
2525 North First Street
San Jose, 95131
Telephone: (408) 262-1411

Watkins-Johnson
440 Kings Village Road
Scotts Valley, 95066
Telephone: (408) 438-2100

Watkins-Johnson
831 South Douglas Street
Suite 131
El Segundo, 90245
Telephone: (213) 640-1980

DISTRICT OF COLUMBIA
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, MD 20878
Telephone: (301) 948-7550

GEORGIA
Watkins-Johnson
4250 Perimeter Park, South
Suite 123
Atlanta, 30341
Telephone: (404) 458-9907

MARYLAND
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, 20878
Telephone: (301) 948-7550

MASSACHUSETTS
Watkins-Johnson
5 Militia Drive
Suite 11
Lexington, 02173
Telephone: (617) 861-1580

OHIO
Watkins-Johnson
2500 National Road
Suite 200
Fairborn, 45324
Telephone: (513) 426-8303

TEXAS
Watkins-Johnson
9216 Markville Drive
Dallas, 75243
Telephone: (214) 234-5396

International

ITALY
Watkins-Johnson
S.p.A.
Piazza G. Marconi, 25
00144 Roma-EUR
Telephone: 59 45 54
Telex: 612278
Cable: WJ ROM I

UNITED KINGDOM
Watkins-Johnson
Dedworth Road
Oakley Green
Windsor, Berkshire SL4 4LH
Telephone: (07535) 69241
Telex: 847578
Cable: WJUKW-WINDSOR

GERMANY, FEDERAL REPUBLIC OF
Watkins-Johnson
Manzingerweg 7
8000 Muenchen 60
Telephone: (089) 836011
Telex: 529401
Cable: WJDBM-MUENCHEN

Watkins-Johnson
Burgstrasse 31
5300 Bonn 2
Telephone: 35 30 91
35 30 92
Telex: (886) 9522

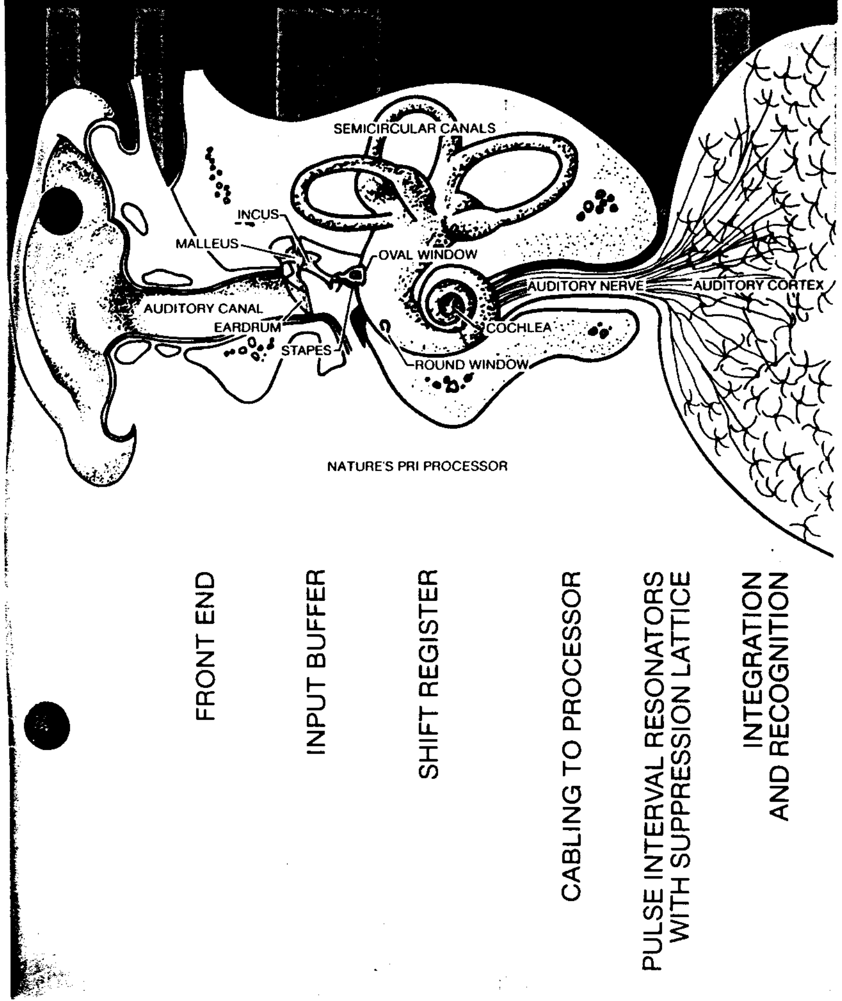
The Watkins-Johnson *Tech-notes* is a bi-monthly periodical circulated to educational institutions, engineers, managers of companies or government agencies, and technicians. Individuals may receive issues of *Tech-notes* by sending their subscription request on company letterhead, stating position and nature of business to the Editor, *Tech-notes*, Palo Alto, California. Permission to reprint articles may also be obtained by writing the Editor.

Printed in U.S.A.

VOL. 9 NO. 6 NOVEMBER/DECEMBER 1982

Tech-notes

Time-Domain Receivers For Pulsed Signals — Part 1



NATURE'S PRI PROCESSOR

The electromagnetic spectrum contains tens of thousands of signals, yet they are invisible to the human senses. To monitor the spectrum, or to utilize a particular signal, a receiver must be used. A receiver must utilize some criterion or criteria to select the desired signal, and then convert the selected signal into perceptible form.

This two-part article discusses methods of using the Pulse Repetition Interval (PRI) to select and characterize radar signals. A novel configuration has been developed which avoids the problems normally found in PRI processors. A time-domain receiver employing the PRI principle has been developed and evaluated, and is described in Part 2 of this article. This time-domain receiver can select a desired signal, even when multiple radars are present at the same frequency, and even when frequency modulation techniques such as chirp, frequency agility, spread spectrum, and ultra-narrow pulses are employed. As a result, this processor greatly enhances the utility of PRI for radar signal sorting.

What Is A Time-Domain Receiver?

What criterion should be used for selecting and characterizing radar signals? Radar signals can be characterized by a number of parameters, including carrier frequency, pulse spacing, pulse width, pulse amplitude, and direction of arrival. Traditional receivers almost invariably select the desired signal on the basis of frequency. However, this is not effective when frequency modulation techniques are employed, when wide receiver bandwidths are necessary for signal processing, or when multiple radars exist at the same frequency. Some alternate means of signal selection is required.

Another key radar parameter is the pulse spacing, called the pulse repetition interval, or PRI. In fact, the whole notion of radar operation depends on the interval between the transmitted pulse and the reflected pulse. Since most radar signals are effectively characterized by their PRI, PRI is a useful criterion for admitting or receiving a desired radar signal. Since the authority for signal selection is the time interval between pulses rather than the sinusoidal frequency of the carrier waveform, a receiver that uses this method is called a *time-domain receiver* to distinguish it from the normal *frequency-domain receiver.*

More About The Time Domain

What do we mean by frequency domain and time domain? Electrical waveforms can be characterized either in terms of their sinusoidal frequency components or in terms of their behavior as a function of time. The two domains are equivalent and are related mathematically by the Fourier transform. Certain situations are easily and naturally described in the frequency domain, but are more complex to describe in the time domain, while the reverse is true for other types of signals. The frequency domain is a world inhabited by sinusoids, integrals, derivatives, Fourier spectra, tuned circuits, inductors, capacitors and analog circuitry. The time domain is a world inhabited by pulses, pulse reflections, correlations, time delays, time intervals, counters, clocks, and digital logic. A pendulum or a spring are easily described in the frequency domain, while the ticking of a clock, the firing of a nerve cell, or the pulsing of a radar are best described in the time domain.

While they sound equivalent, there is a fundamental difference between sinusoidal waveforms (frequency domain) and pulses (time domain). Frequency-domain processing is characterized by tuned circuits, where the energy is constant and always present, oscillating between voltage and current (or between electrical and magnetic fields). In time-domain processing of pulses, the energy is located only in the pulse. There is *no signal present between pulses.* This is a critical distinction, with the result that pulse trains at different PRI are not truly independent, and there is no true time-domain equivalent to the tuned circuit. Consequently, previous techniques for receiving a radar signal based upon its PRI have been more complex and less effective than techniques for using frequency as the sorting parameter.

Radar Sorting Parameters

Conventional radar signals, as illustrated in Figure 1, are primarily distinguished by five parameters: carrier frequency, PRI, pulse shape (sometimes simplified as pulse width), angle-of-arrival, and amplitude scan pattern. These five parameters are independent, and thus form an independent set for the purpose of admitting or receiving a particular emitter.

A receiver might use any of these five parameters to select signals. Intelligence and tactical microwave receivers almost invariably use frequency as the primary sorting parameter, but frequency is not always the most effective sorting parameter. In fact, for spread spectrum, frequency-agile, and chirp transmissions, frequency is not a very effective sorting parameter at all. The dominance of frequency sorting arises from the elegant characteristics of the Fourier transforms, the straight forward implementation of the resonant LC circuit, and the resulting potency of the superheterodyne or channelized receiver configuration. Moreover, frequency has for so long been the primary receiver sorting parameter that it is conceptually difficult to think in terms of receivers based on alternate parameters.

A simplified example of sorting may be given as follows: Imagine a small classroom where the teacher calls on people by name. It is a formal classroom, so the teacher might call on "Mr. Smith" or "Mr. Adams," and Mr. Smith or Mr. Adams would then stand and be recognized. However, if the class got larger, several people might stand up when Mr. Smith was called, or it might be harder to hear the teacher and the wrong person might stand. This would result in confusion and frustration. A breakthrough might occur when the teacher called out "John Smith" or "Bill Adams," and only the person actually addressed stood up. Simple as

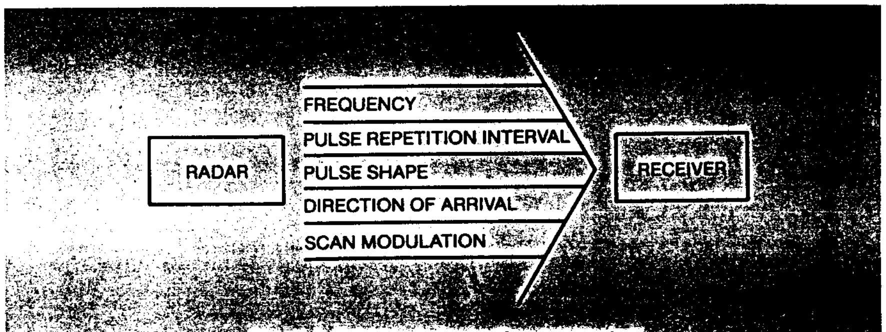


Figure 1. Primary radar sorting parameters.

that seems, it represents a new dimension for selecting people. On the other hand, the teacher might call on "Short Mr. Smith" or "Tall Bill." There are many parameters for selection, and some are more effective than others.

How effective are each of the primary radar parameters as a means of selecting a particular signal? The domain and effectiveness of the radar parameters are summarized in Figure 2. Each has its strengths and weaknesses when used as a sorting parameter.

Frequency, the most common parameter, is undoubtably effective. Most radars operate at a single frequency, individual frequencies are mutually orthogonal, and convenient circuit elements exist from which effective frequency filters can be constructed. Nevertheless, frequency does have its limitations. Modern radars often employ frequency diversity techniques, either to achieve processing gain or for intentional deception purposes. Also, the modern environment is so crowded that multiple signals may exist within a given bandwidth, and the problem is made worse by the wide bandwidths required in modern receivers to pass the narrow pulse widths now being employed. Frequency sorting will undoubtably continue to predominate, and it should. The premise of this article is that effective sorting in today's environment demands that methods be developed to sort other parameters which are as effective and straightforward as the present technology for frequency sorting.

What of the other parameters? Angle-of-arrival (AOA) offers a unique advantage, since it is the only one which cannot be deceived through emitter parameter modulation. Unfortunately, most methods for determining angle-of-arrival through a single channel, such as rotary or switched techniques, degrade to uselessness when multiple emitters are present. Multichannel techniques are very effective for sorting, and, in addition, provide information on emitter bearing, but their implementation is expensive and complex. Also, while AOA is excellent for sorting, it does not assist in identifying the emitter type, so some other parameter must still be used for identification purposes.

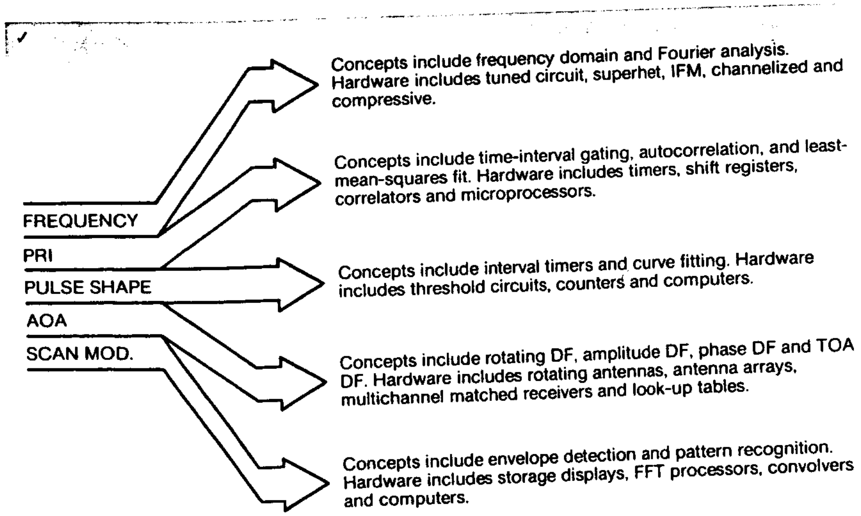


Figure 2. Radar parameter recognition techniques.

Pulse width is of limited utility for emitter identification, since reflections act to severely distort the apparent pulse width. Pulse shape offers considerably more promise, and some sophisticated and effective mathematical techniques have been developed to characterize high-order pulse shape coefficients. Despite these breakthroughs, present designs are quite elaborate and still appear to exhibit limited throughput rates and significant false alarm rates due to the complexity of the processing and the wide variety of environmental distortion of radar pulse shapes.

Scan pattern is uniquely linked to the geometry and scan mode of the transmitting antenna, and consequently provides critical information regarding the radar's operating mode. Its critical limitation as a sorting parameter is that a scan pattern cannot be taken on a particular emitter until that emitter has already been sorted out from the other emitters that are present. Consequently, scan pattern is an excellent identification parameter, but is not effective for initial selection. The utility of a scan pattern measurement is also limited by the relatively long length of time needed to monitor a complete emitter scan to derive a measurement. Also, note that the ability to make a scan pattern measurement presupposes a method to compensate for the scan pattern of the receiving antenna and a sufficient signal-to-noise ratio to achieve side-lobe penetration.

PRI offers some excellent properties for purposes of signal sorting. For one, it is always available without the need for special antennas or receivers. The video output from any narrowband or broadband receiver can be used. Most radars exhibit a stable PRI, and PRI data can be extracted on the basis of a relatively short intercept. Since the very principle upon which radar is based is one of time-interval range measurement, it would seem that PRI characterization would be extremely useful and effective. Unfortunately, it has not been quite that straightforward. Unlike different frequency sinusoids, different PRI signals are not quite independent. The PRI domain is not as well-behaved as the frequency domain. There is no time-domain analogy to the tuned circuit, superposition, or Fourier analysis. PRI analysis has generally involved recirculating shift registers which exhibit a variety of anomalies, or has required extensive software processing. Does a more effective technique exist for PRI processing? To answer this question, we must look more closely at the PRI domain and the associated processing requirement.

Characteristics Of The PRI Domain

Our intuitive notion of selecting a signal by "tuning" a resonant circuit represents a frequency-domain concept. To investigate the concept of PRI tuning, it is useful to begin by looking for mappings between frequency-domain resonance and time-domain resonance.

Consider some basic characteristics of the frequency domain. Each frequency is independent of other frequencies. If two signals at the same frequency are added, the result is a single signal which is the vector sum of the two signals — the same frequency with altered amplitude and phase. These are concepts with which we are comfortable. Does the PRI domain exhibit analogous characteristics? Let's examine some frequency-domain situations and compare them with the corresponding time-domain situations.

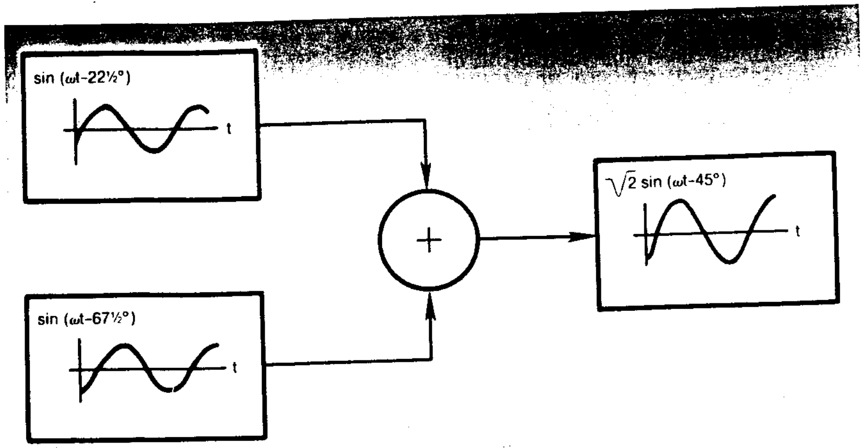


Figure 3A. Two sinusoids at same frequency sum to a single sinusoid at same frequency.

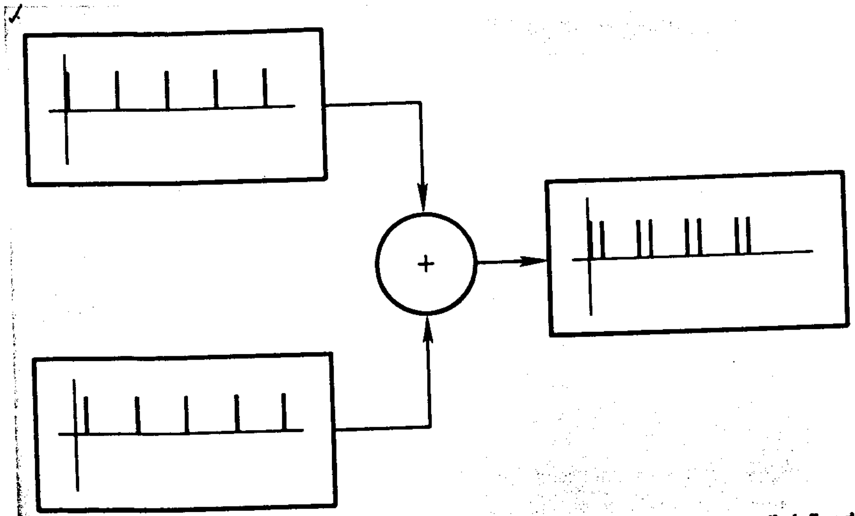


Figure 3B. Two pulse trains at same PRI sum to combined pulse train without well-defined PRI.

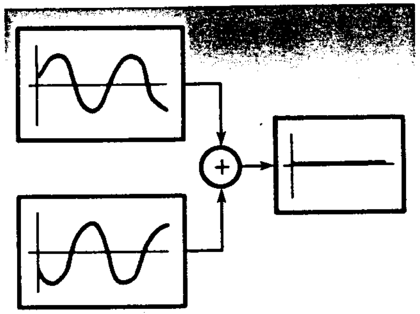


Figure 3C. Two sinusoids at same frequency with 180° phase shift cancel out.

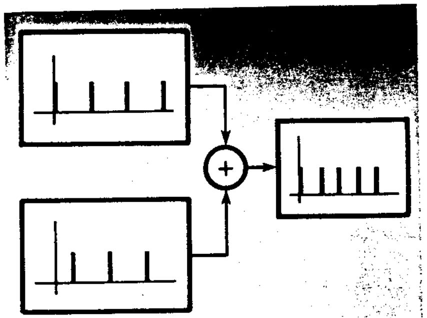


Figure 3D. Two pulse trains at same PRI with 180° phase shift produce a single pulse train with half the PRI.

Figure 3A demonstrates that two sinusoids at the same frequency, with different phase, results in a single sinusoid at that frequency. On the other hand, two pulse trains at the same PRI, with different phase, will sum into a combined pulse train, as shown in Figure 3B. So, signal phase appears to have different effects. Can we conclude this by simply defining pulse trains with different phases to be independent? Unfortunately, the interaction with phase is not independent of (or distinct from) the PRI. Consider two pulse trains that are exactly 180 degrees out of phase. Two sinuoids with this characteristic would cancel out, as shown in Figure 3C, whereas the two pulse trains add together without interfering with each other, and produce *a single pulse train at half the PRI,* as shown in Figure 3D. This is quite a staggering result. No amount of phase shifting and adding of a given frequency can produce a new frequency, yet by repeatedly shifting a pulse train by 1/n, and adding the resulting trains, a pulse train at 1/n of the original PRI is produced — certainly an unsettling behavior. In fact, what is the distinction between one pulse train with 3 msec PRI versus two pulse trains 180° out of phase with 6 msec PRI, or, for that matter, versus ten pulse trains at 30 msec PRI that are 36° shifted in phase from the other? This is diagrammed in Figure 3E. And what of two signals 179° out of phase — do we

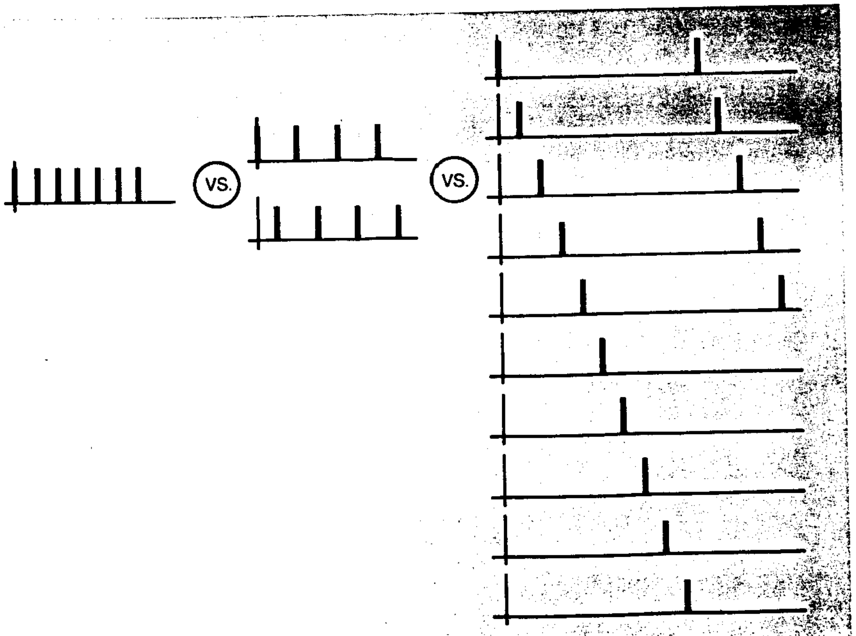


Figure 3E. Possible components of a pulse train — What is the distinction?

call the result two signals, or a single signal at twice the PRI with a one degree "jitter" (or uncertainty) in pulse arrival time? This gets even more complex when we consider stagger (pulse trains with a repetitive PRI pattern). What is the difference between a 3:4:5 stagger and three pulse trains with PRI equal to the frame rate of the stagger and with 90° and 210° relative phase shifts (as diagrammed in Figure 3F)?

It is evident that there is some sort of basic distinction between the frequency domain and the PRI domain. This distinction arises because the energy in a sinusoid is constant, oscillating between voltage and current (E-field) and H-field), whereas the energy in a pulse train is discontinuous, existing only during the pulse duration. There is no energy present between pulses — the PRI information is coded as the duration of the *non-signal interval*. The PRI information is coded "in the gap."

Filter Elements In The PRI Domain

The fundamental effectiveness of receiver technology arises because there exist easily realizable circuit elements — inductors and capacitors — whose behavior in the frequency domain is frequency-selective. A simple LC network will resonate at, or "permit to enter," only frequencies which are in a very narrow range about the tuned frequency of the network. This is illustrated in Figure 4A. All frequencies outside this narrow band are rejected, including harmonics and subharmonics. Is there a circuit element that exhibits these characteristics in the PRI domain? That is, is there a circuit element or network as diagrammed in Figure 4B that will pass only a narrow range of PRI's and reject all others? As will be shown, there is not. This discontinuous nature of the PRI domain leads to significant anomalies in the behavior of PRI filter elements.

Consider first the most obvious approach to a PRI filter element: a multivibrator or clock element to generate a tunable time interval against which to sort or select incoming pulses. A given pulse train would then be admitted only if the pulse arrival times coincided with the firing of the multivibrator, as illustrated in Figure 5A. However, note that another pulse train at the same PRI, but different phase, would not be admitted by such a circuit, as shown in Figure 5B. Also, the multivibrator exhibits zero bandwidth; that is, however closely it was tuned to the incoming PRI, it would gradually drift out of synchronization (see Figure 5C).

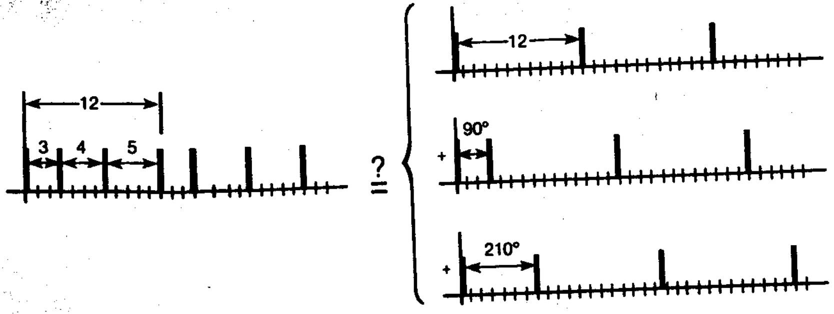


Figure 3F. Is it a 3:4:5 stagger or the sum of three separate pulse trains?

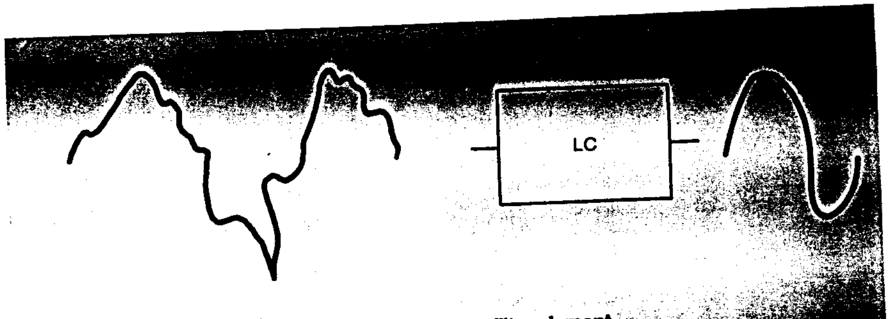


Figure 4A. Frequency filter element.

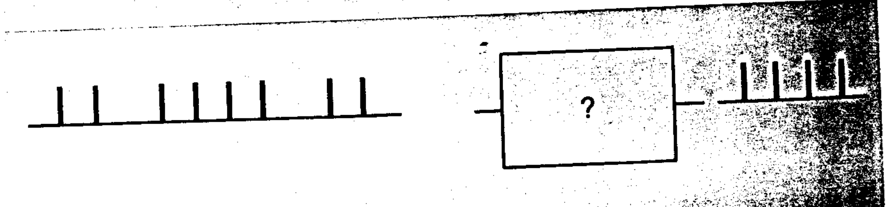


Figure 4B. PRI filter element.

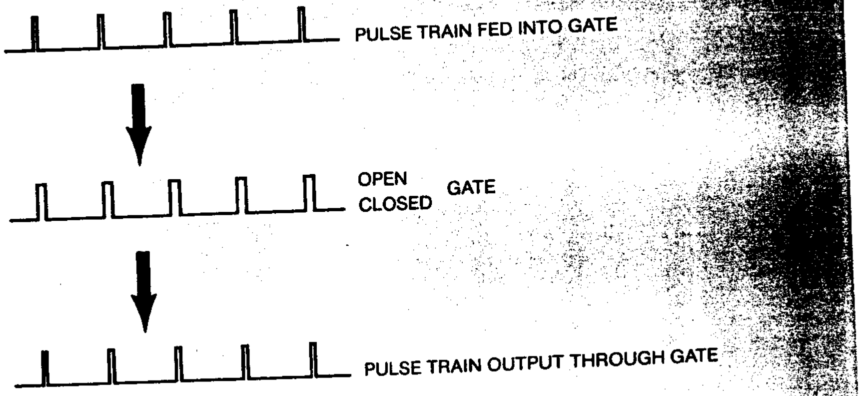


Figure 5A. Pulse train in synchronism with gate.

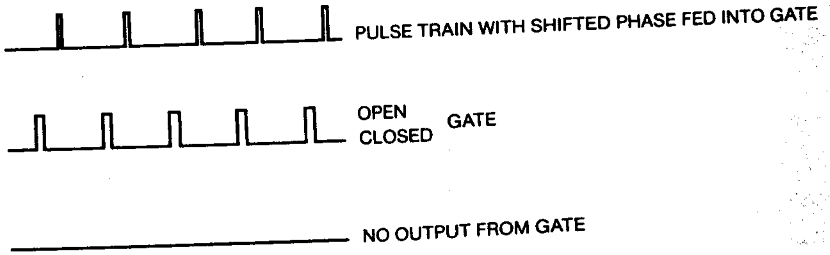


Figure 5B. Pulse train at PRI of gate with shifted phase.

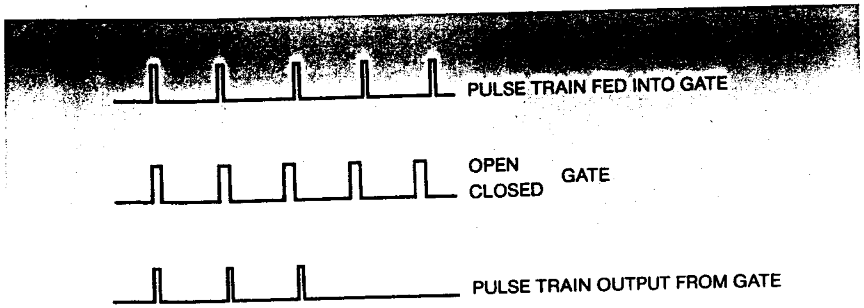


Figure 5C. Pulse train with PRI slightly greater than PRI of gate.

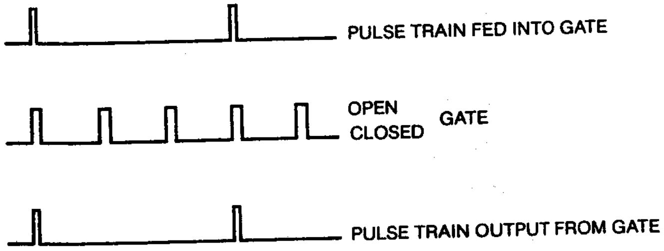


Figure 5D. Pulse train at 3 times the gate PRI.

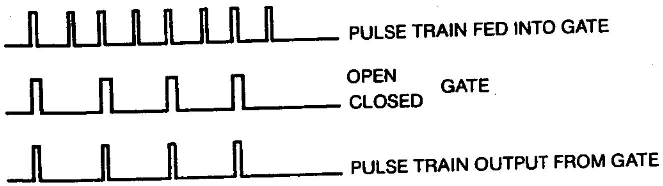


Figure 5E. Pulse train at one-half the gate PRI.

The multivibrator also has no tolerance for PRI jitter, which might be described as broadening of the PRI spectral line. Jitter tolerance could be produced by generating an admittance gate with a selected width. Obtaining bandwidth is more difficult. We could propose to synchronize the multivibrator to the incoming pulse train, but what if several pulse trains are present at the same PRI, or if two pulse trains drift through each other and the synchronization circuitry slips from one to the other, or if a pulse from another PRI captures the synchronization circuitry? And, what if a pulse train occurs at 1/n, the PRI of the multivibrator (see Figure 5D), will it get through? Should it get through? What of a pulse train at n times the PRI, where every nth pulse might get through (see Figure 5E)?

The phase problem inherent in a fixed-time gate can be solved by utilizing a rotating shift register. In this configuration, a pulse train that hits at the same location on subsequent rotations of the shift register will be passed through, and all other trains will be rejected. The shift register is then the "tuned circuit," and the rotation period defines the "resonant" PRI (Figure 6A). This principle is used in many pulse sorters, but there are still some critical problems. First, the system will pass all subharmonics of the "resonant" PRI, as shown in Figure 6B, since the nth subharmonic is indistinguishable from n evenly shifted pulse trains at the basic PRI. Some existing sorters use circuitry to recognize the second, third and fourth subharmonics, but what of the 27th subharmonic, or the 53rd subharmonic? Remember that radar PRI's range from below 100 Hz to above 100 kHz, a range of over 1000:1. Second, circuitry must still be incorporated to implement a "slip rate" or PRI tolerance, otherwise the signal will temporarily disappear when it drifts

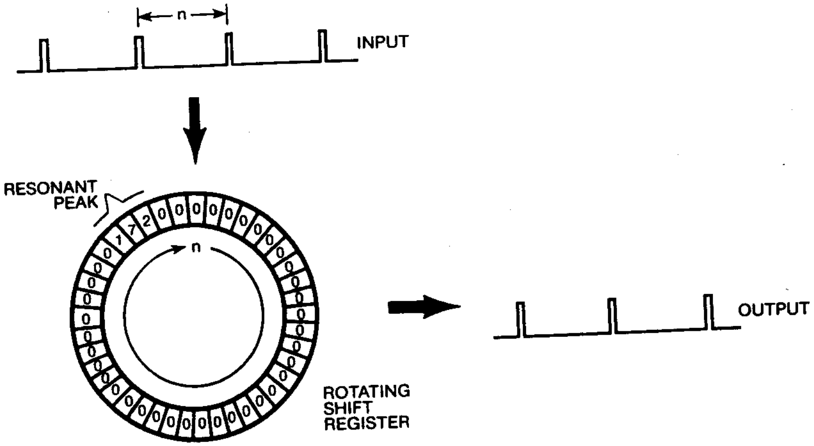


Figure 6A. Rotating shift register, fundamental resonance.

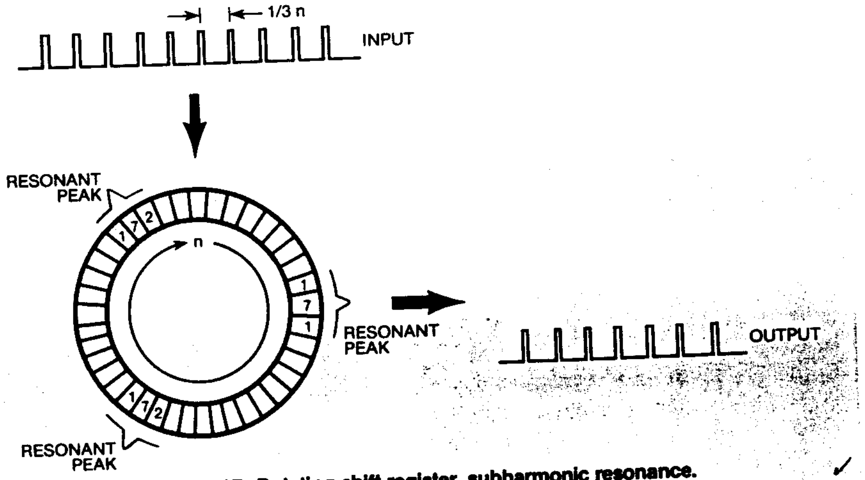


Figure 6B. Rotating shift register, subharmonic resonance.

into the adjacent cell of the shift register until several pulses are detected at that new location. This can be done, but it complicates the circuitry. Third, there is still the problem that multiple emitters at the same PRI will all be passed by the shift register, and some means is still required to identify the component signals.

On top of that, another problem arises if the PRI receiver is to be used for general surveillance. The concept of a tunable PRI filter is analagous to a superheterodyne receiver: it must scan across the band to provide overall surveillance. However, operation at the PRI of typical radar signals is much slower. If we are trying to scan from 0.01 to 10 msec in 1000 steps, we must dwell at each PRI for at least 3 pulse intervals to establish the presence of a pulse train at the PRI. The total scan time is then,

$$\sum_{n=1}^{1000} 3n\,(.01),$$

or 15 seconds. This is totally unacceptable — a threat can sweep across the receiver and be gone long before the PRI scan has reached the PRI value of the threat. The scan-on-scan problem makes things even worse, leaving an expected time-to-intercept of many minutes. What is necessary is an analog to a wide-open receiver, which would require multiple-shift registers, or perhaps some other technique altogether.

What about digitizing the PRI and applying an analysis technique such as Fourier analysis? Unfortunately, a pulsed waveform is not well represented as a sum of sinusoids. A Fourier representation can indeed be calculated, but many high-order harmonics are involved, and there is not a good correspondence between the PRI and Fourier coefficients. Specialized series, such as the Walsh-Rademacher series, have been developed to represent two-level waveforms, but they are normalized about the repetition interval of the waveform being represented (called the sequency), which is the very thing that we wish to find in the first place.

The most effective method to date has been a powerful but brute-force approach: digitize the time-of-arrival (TOA) of each pulse and feed it into a digital computer for processing. Algorithms have then been developed to identify the pulse trains in the data. This is generally done by taking a sample of between 8 and 512 pulses. The interval between pulse 1 and pulse 2 is calculated, and the computer extrapolates this forward and looks for matches; then the interval between pulse one and pulse three is calculated and extrapolated, then pulse one and pulse four, etc., followed by the pulse two and three interval, pulse two and pulse four, etc. Possible pulse trains are then evaluated according to how many pulses they account for in the data, how many dropouts occur in the suspected pulse train etc., and a decision algorithm is used to establish which pulse trains are actually present in the input data sample. The exact PRI is usually derived by using a least-mean-squares fit to the data for each separate pulse train. Effective deinterleaving requires that a large number of pulses must be sampled, because the ratio between the PRI of two pulse trains can easily be on the order of 100:1. (See *Tech-notes*, Vol. 3, No. 6, November/December 1976. "Signal Recognition in a Complex Radar Environment.")

Software processing has evolved over the last 10 or 15 years, and has become an effective technique. This is a tribute to what modern high-speed processors can do. However, a large number of comparisons are required, the output isn't calculated until long after the pulses have passed, and the computer processing is often a severe bottleneck in modern wide-open threat detection systems. Is there something better?

If At First You Don't Succeed

It appears from the previous discussion that there is no "natural" algorithm or circuit element or mathematical domain for PRI processing. Where might we look to discover a model in which PRI processing is intrinsically straightforward?

There *is* one PRI processor which already exists that is extremely effective, even in situations which require deinterleaving of multiple signals, and even in situations where the input data is extremely contaminated with signal dropouts and noise pulses. It operates with very little effort, is compact, has low power consumption, operates "wide open" over its PRI range, and can detect weak signals even in the presence of strong ones. That processor is the human ear, as diagrammed in Figure 7. Perhaps we can learn about a more "natural" and effective method of PRI processing by examining and modeling auditory processing in the human ear. By "ear," we are referring to the human auditory processing system, including associated parts of the nervous system and brain.

Aural Processing In The Human Ear

The PRI of most radars falls within the audible frequency range. Consequently, an operator can "hear" the PRI by using headphones or a loudspeaker to listen to the detected video waveform. Except for a difference in tonal quality, the ear "hears" a pulsed waveform just about the same as it hears a sinusoidal waveform. The skilled intelligence operator can often identify a particular radar by the way it sounds, and he has little difficulty in deinterleaving two or three simultaneous radar signals. His ear operates as a wide-open receiver, providing unity probability-of-intercept for new signals. If two signals are present at the same PRI, the operator will hear the fundamental repetition frequency, except when the phase difference is approximately between 179° and 181° (which corresponds to the minimum pitch difference which the

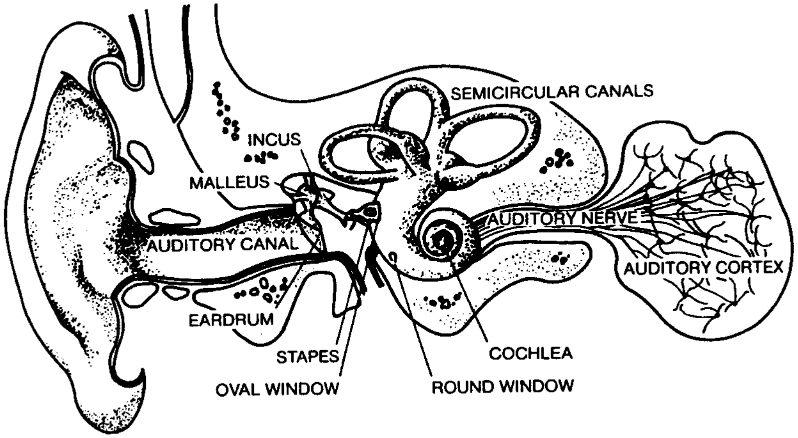


Figure 7. Nature's own PRI processor.

ear can discern), at which the harmonic frequency will be heard. How does the ear do all this?

Early models of the ear characterized it as a transducer (ear canal, eardrum, and impedance-matching bone structure) and a transmission line (semicircular canal). Sound waves were transmitted to the semicircular canal which was then thought to set up standing waves. Neurons in the canal would decode the location of pressure peaks, and the distance between peaks would define the pitch or PRI of the incoming signal. A good mathematical analogy to this operation is the autocorrelation function. This type of processing has been developed and implemented for PRI identification, but the results have generally been disappointing. The processing is complex, many minor peaks are developed in the autocorrelation pattern as the result of random beats between separate pulse trains, and the processing accentuates rather than avoids the harmonic problem.

Later research has revealed that the damping in the spiral canal is far too high to support the standing wave model. The canal simply functions to map pressure peaks into zones of neural activity. The primary PRI decoding is performed by neurons in the auditory cortex. Neurons in this area are sensitive to inputs which are separated by a precise number of milliseconds. Neurons which are sensitive to a particular interval are collocated in a given region of the cortex. The result is a mapping between PRI components in the aural input and areas of the auditory cortex which exhibit increased neural activity. This array of tuned mono-interval PRI detectors is suggestive of a channelized receiver. In addition, the fact that there are many neurons for each PRI allows some to synchronize to a given interval in one pulse train, while others trigger from the same interval in other pulse trains (in the event that several trains at the same PRI are present). The brain then reacts to areas of increased activity by "hearing" a tone at the corresponding pitch. The brain also associates the patterns which correspond to harmonic activity so that a low-level harmonic is heard as a change in tonal quality rather than as a separate tone.

This model suggests that the organization of a PRI processor might incorporate multiple interval detectors followed by an integration function and a pattern-detection processor. Such a processor has been implemented, but the results are not significantly different from correlation techniques. There is still an excessive number of spurious responses. So far, the model or architecture does not represent a breakthrough.

The ear exhibits an additional key property whose importance has only recently been recognized. Part 2 of this article describes this property and discusses the architecture and performance of a recently developed pulse interval processor (PIP) incorporating this property, thereby avoiding the problems normally found in PRI processors.

Authors:

Joel E. Schindall

Dr. Schindall is a Staff Scientist in the Watkins-Johnson Company Recon Division. He is presently developing an innovative PRI Spectrum Analyzer which will introduce a new capability in signal processing. He is also evaluating a promising monopulse DF system with considerable market potential.

Dr. Schindall has played a key role in the evolution and growth of the Recon Division as an MTS, Department Manager and Division Manager.

Dr. Schindall also played a strong role in identifying and capturing the market for standardized digitally controlled microwave receiving systems, and for expansion of this technology to include computer control and automatic signal identification. Previous developments by Dr. Schindall at Watkins-Johnson Company, include the invention and design of the digital controllers used in the QRC-259(T), WJ-1240 and WJ-940 receivers.

Dr. Schindall received B.S.E.E., M.S.E.E., and Ph.D. degrees from the Massachusetts Institute of Technology and taught at the Massachusetts Institute of Technology and Stanford University. He is also a member of the IEEE, Eta Kappa Nu, and Tau Beta Pi.

Malcolm J. Caraballo

Mr. Caraballo is a Member of the Technical Staff, Recon Division, and is attached to the Receiver Department of the Recon Division. Since coming to Watkins-Johnson Company, he has been involved primarily in the design and development of digital hardware and firmware for various reconnaissance receiver and analysis systems, and is responsible for the management of various programs.

Mr. Caraballo's present responsibilities include the design of the WJ-1921 Pulse Interval Processor and the WJ-1920 Multiparameter Distributed Processing System. The WJ-1921 is an innovative time-domain receiver utilizing pulse repetition interval as its sorting criterion. It provides wide-open, real-time PRI detection for every pulse entering the receiver. Design efforts include algorithm development as well as hardware architecture. The WJ-1920 System is an automated collection system utilizing the Pulse Interval Processor as a preprocessor. He is responsible for the system design as well as the hardware design for various components of the system.

Mr. Caraballo holds an M.B.A. from the University of Santa Clara and a B.S.E.E. from the University of California, Berkeley.