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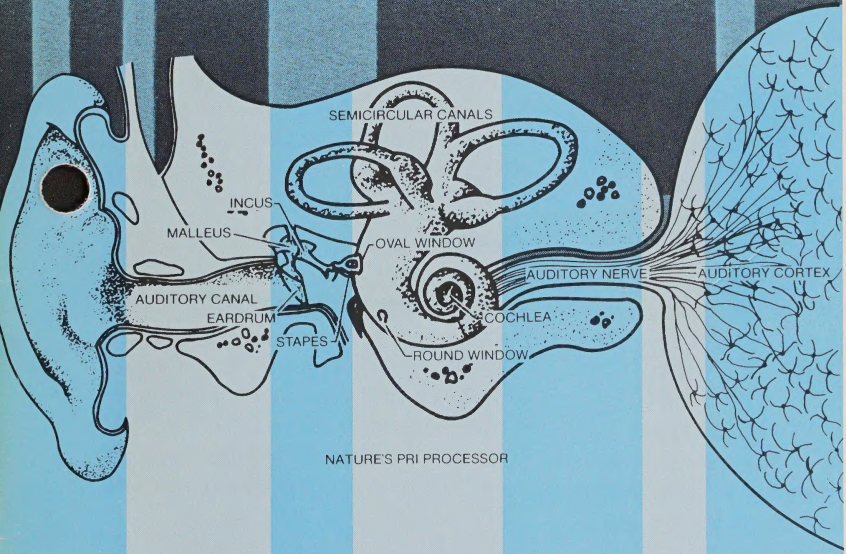
Time-Domain Receivers For Pulsed Signals — Part 2



NATURE'S PRI PROCESSOR

FRONT END

INPUT BUFFER

SHIFT REGISTER

CABLING TO PROCESSOR

PULSE INTERVAL RESONATORS WITH SUPPRESSION LATTICE

INTEGRATION AND RECOGNITION

WATKINS-JOHNSON COMPANY

Tech-notes

Part 1 of this article examined the characteristic parameters of radar signals, identified the utility and characteristics of time-domain PRI processing, and examined aural processing in the human ear. Part 2 identifies a key property of human aural processing and discusses the architecture and performance of a recently developed pulse interval processor (PIP) which incorporates this property and thereby avoids significant problems normally found in PRI processors.

Aural Processing In The Human Ear — The Extra Ingredient

The ear can be modeled as an input transducer (ear canal, eardrum and impedance-matching bone structure) and a transmission line (semicircular canal) feeding a neural array in the auditory cortex. Neurons in the auditory cortex are sensitive to inputs which are separated by a precise number of milliseconds. Neurons which are sensitive to a particular interval are co-located in given regions of the cortex. Most hardware PRI processors reflect this model, yet they generate an excessive number of spurious responses.

The ear exhibits an additional key property whose critical role has only recently been recognized. The neural areas in the auditory cortex are extensively cross-coupled in such a manner that a stimulus in one area tends to reduce excitation in other areas. Cross-coupling, tends to focus the auditory response. This characteristic is called *afferent inhibition,* and is described as follows:

> In the auditory as in the visual and somesthetic systems, afferent inhibition is topographically disposed in such a way that delivery of a stimulus that excites a certain number of cells in a neural field will suppress the activity of those that surround it, thus tending to sharpen and isolate the island of activity.[1]

The Time-Domain Receiver — The Real Thing

A block diagram of the prototype WJ-1921 Pulse Interval Processor appears in Figure 1. The architecture of the prototype WJ-1921 Pulse Interval Processor is designed to emulate the aural processing performed by the human ear. Input to the processor is taken from the video output of any receiver or tape containing pulse signal data. The input circuitry performs a threshold detection and quantizes the time of arrival of the leading edge of the pulse. These data are fed sequentially into a shift register for transmission to the processors. The results of the processing are provided on a CRT depicting signal activity versus PRI, and are also output on a pulse-by-pulse basis for optional downstream processing. The processor has the ability to tolerate very high burst rates as well as provide PRI detection over a wide range of PRIs (from 100 msec to 3 μsec).

The prototype PIP and its display unit are shown in Figure 2. The basic display is a PRI spectrum display of PRI versus activity, much as a frequency domain spectrum analyzer or panoramic receiver provides a display of frequency versus amplitude. The PIP thus functions as a channelized time-domain receiver that is wide open to all PRIs.

The PIP incorporates two processors, performing separate, but complementary functions. The first processor, the Matched Interval Processor, performs near-real-time, wide-open PRI detection on every pulse present at the input. The second processor, the Pulse Anticipation Processor, operates as a pulse gate to isolate individual pulse trains at the cursor PRI from the surrounding environment. When used together, the Matched Interval Processor provides a total picture of which PRIs are present

(1) Medical Physiology, Thirteenth Edition, Edited by Vernon B. Mountcastle, C.V. Mosby Co., St. Louis, 1974, Volume 1 Page 422.

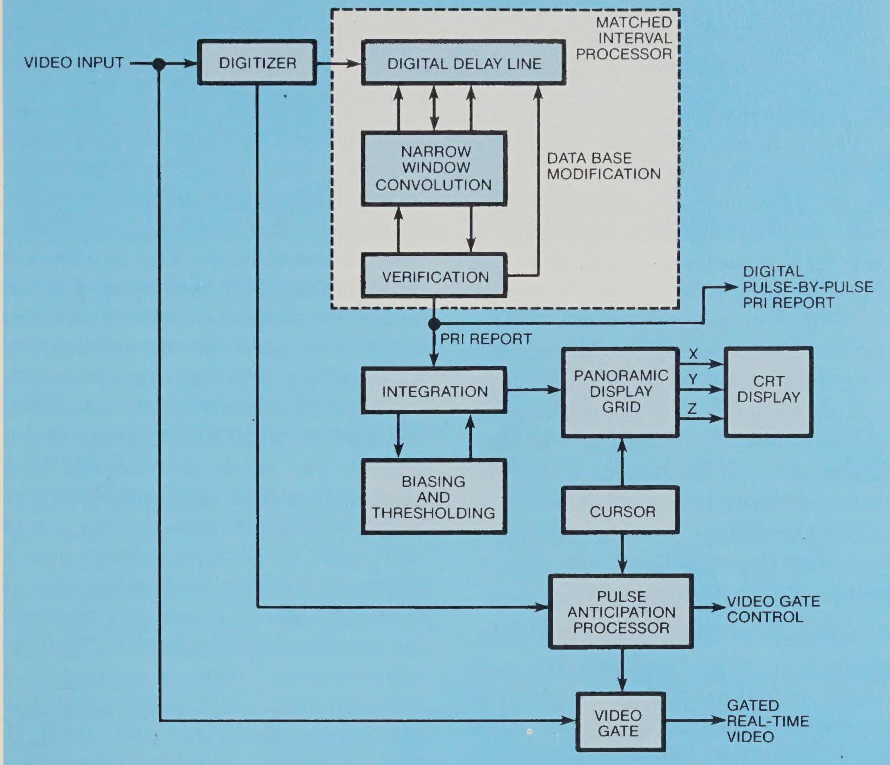


Figure 1. PIP functional block diagram.

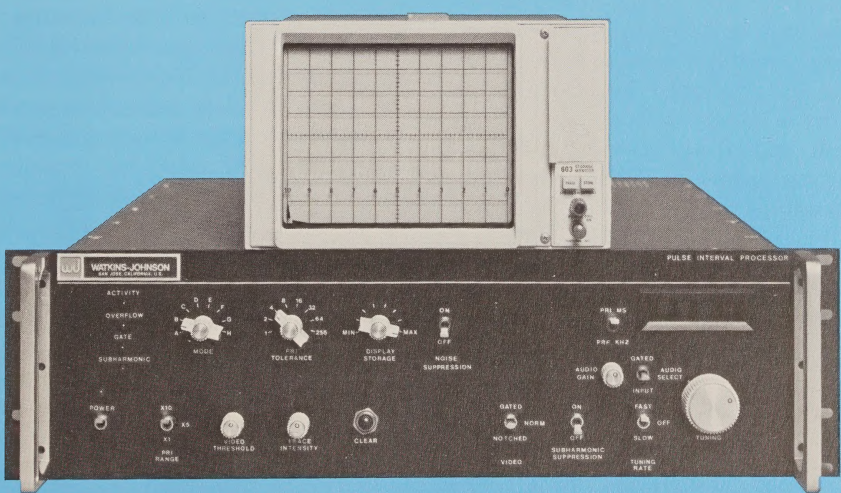


Figure 2. WJ-1921 Pulse Interval Processor.

in the environment, while the Pulse Anticipation Processor permits the operator to gate through any signal of interest for further analysis.

The Matched Interval Processor incorporates a high-speed-state machine that scans the incoming data and performs high-speed detection of short-term periodicities in the incoming pulse data. In this sense, it is similar to the array of interval-sensitive neurons found in the auditory cortex. When periodicities are found, the data bank is iteratively modified in a proprietary manner to accentuate the resonances and minimize the sensitivity to false alarms and PRI harmonics. This data bank modification is analogous to the afferent inhibition function that is performed by the lattice interconnection of neurons in the auditory cortex.

A variety of lattice-suppression algorithms were implemented and evaluated in the prototype. Selection of the proper algorithm was found to be extremely critical. The data base interaction in the suppression mode is complex and interactive, and most algorithms were ineffective or suffered from "seizures," and either destroyed the data base or failed to function at all. The algorithm which has been selected has demonstrated its effectiveness under a variety of operational conditions, and clearly provides a marked improvement in PRI processing capability.

The enhanced pulse-by-pulse reports from the Matched Interval Processor are integrated in a digital memory and displayed visually on a CRT as a panoramic display of PRI versus activity. This provides an immediate visual display of active PRIs in the environment, and is analogous to the areas of increased activity that are identified by the brain when it "hears" different tones. In addition, a digital PRI report is provided on a pulse-by-pulse basis as an output for further processing. Pulses in the data which do not correspond to any PRI train are denoted by a residue flag.

The Pulse Anticipation Processor executes an algorithm very similar to that of the Matched Interval Processor. However, the algorithm is used in a very different way. The processor's basic function is to predict pulse occurrences for pulse trains to which it is tuned. The result is an anticipatory time gate which is used to gate through (or to reject) pulses at a particular PRI. The gate is tuned via a cursor on the display. The cursor is overlayed on a signal of interest and automatically locks itself to any pulse train or trains with a PRI equal to the value to which it is tuned. Synchronization is achieved after four pulses. Once synchronized, the gate is a highly selective PRI filter which passes pulses of interest and rejects others. After every pulse, the gate automatically recenters itself. It can also tolerate pulse dropouts without losing synchronization.

Both the Pulse Anticipation Processor and the Matched Interval Processor provide a variable PRI tolerance in detecting pulse-train activity. This variable tolerance allows the receiver to be used to detect pulse trains with considerably different amounts of PRI jitter. The PRI tolerance associated with the Pulse Anticipation Processor is intentionally different from that associated with the Matched Interval Processor. The Matched Interval Processor is attempting to detect every pulse train present in the environment. As a result, the tolerance is desired to be as wide as possible without seriously degrading the false alarm rate. On the other hand, the Pulse Anticipation Processor is attempting to isolate one pulse train from the surrounding environment. In this case, as narrow a toler-

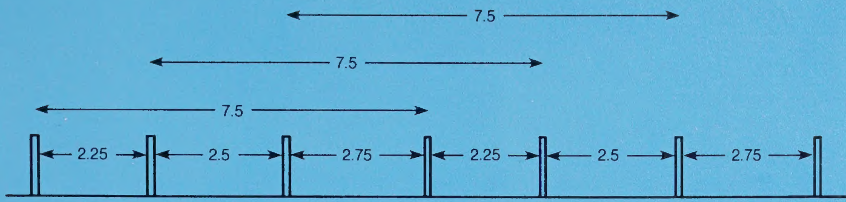


Figure 3. Three-position stagger (msec).

ance as possible is desired to select the train of interest and reject all others. A wider tolerance will result in the admittance of more spurious pulses, which randomly line up with the time window of interest, consequently degrading the signal selectivity.

What of staggered pulse trains? Pulse trains which exhibit multiple PRIs are detected by their frame rate. For example, Figure 3 depicts a three-position staggered signal. By examining the time relationships, it can be seen that the first, fourth and seventh pulses are separated by a common PRI. The same can be said of the second, fifth and eighth and the third, sixth and ninth pulses. This common PRI is defined as the frame rate. In fact, a three-position stagger looks just like three interleaved signals with a PRI equal to the frame rate, and this is what is detected by the PIP. To identify the stagger intervals, the PIP also incorporates a special stagger algorithm. The user (or computer) can overlay a cursor on the frame rate of the signal, and then shift to the stagger mode. If the signal is indeed a stagger, the display will then show each separate stagger interval instead of showing the overall frame rate (see Figure 4).

Specifications for the WJ-1921 Pulse Interval Processor are shown in Figure 5. The PIP functions in the PRI or time domain to provide the following:

1. A refreshed panoramic display of all pulse trains in the environment.
2. A gate, or gates, to select individual train(s) on the basis of PRI.
3. A pulse-by-pulse output for a computer, where each pulse is tagged with its associated PRI. In this mode, it functions as a hardware PRI preprocessor for use with computerized signal identification systems.

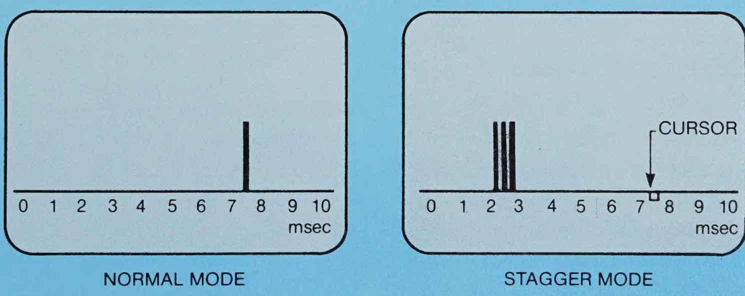


Figure 4. PIP display — normal and stagger modes.

Input waveform	Log video or threshold video	Analog	0 to 5V
Outputs	PRI versus activity display (with cursor)	X, Y Z	±2.5V, 100Ω 0 to 3V, 100Ω
	PRF versus activity display (with cursor)	X, Y Z	±2.5V, 100Ω 0 to 3V, 100Ω
	Threshold video	TTL	
	Time gate	TTL	
	Gated video	Analog	0 to 5V
	Data	PRI Data strobe Residue flag	16 bits 1 bit 1 bit
	Audio	Analog	0 to 3V, 600Ω

PRI range	3 microseconds to 100 milliseconds (prototype is 3 μsec to 10 msec)
PRI resolution	62.5 nsec (prototype is 1 and 10 μsec)
Jitter tolerance	1 microsecond to 63 microseconds
Pulse density	Single signal exceeds 333 kpps Multiple signal 50 kpps minimum for most environments
Subharmonics	Not susceptible to subharmonic responses
Probability of intercept	100% for qualifying pulse trains
Display	TEK 608
Size	7 inches high by 19 inches wide by 19 inches deep, rack mountable
Weight	40 pounds
Power	110/220 Vac, 48 to 420 Hz, 120 watts
Options	Expanded sector display High accuracy PRF interpolation Multiple time gates Pulse width measurement Pulse parameter memory Matrix display (generated from IF or digital signal inputs)

Figure 5. PIP performance specification.

How Well Does It Work?

Researchers who study the human ear become extremely frustrated when they face the problem of deterministically specifying its performance. One can conceive of experiments to determine the ear's frequency range and sensitivity, and work has been done with two-tone ear response. Beyond that, the measurements of performance are extremely subjective. The same is true of PRI domain processing. It is impossible to specify all of the PRI phases, dropouts, overlaps, and complex patterns which will be encountered in a real environment at any given moment. Statements such as "Capable of deinterleaving 15 signals" are simplistic and misleading.

For this reason, the prototype processor has been operationally evaluated over the past year in some of the most complex radar environments in the world. Tests were conducted on airborne platforms as well as ground-based locations in the U.S., Europe, and the Middle East. These tests confirmed that a wide-open, time-domain receiver could be built and used operationally. The receiver characterized PRIs very effectively, even in dense signal environments, and exhibited a very low false-alarm rate despite numerous environmental anomalies. Tests were also conducted in analysis facilities using actual field tapes. Again, results were very positive. In several cases, the tests resulted in the detection of new signals which were later verified by traditional techniques. The effectiveness of the PIP has been demonstrated even with interleaved pulse trains and with environmental anomalies such as pulse dropouts and signal walkthrough. The results can be generally summarized as follows:

1. The Pulse Interval Processor didn't overload, even in the densest environments.
2. It always provided an effective and useful display.
3. It often revealed new signals which the operators at the site had not previously detected.
4. The format of the display was easily interpreted by the operators, since it is so similar to the conventional frequency-spectrum display.
5. It detected emitters such as a radar "hiding" among several fishing-boat radars, a jittered wartime mode of a Navy radar, and some previously undetected short-duration radar signals on an analysis tape.
6. A higher resolution mode is required to separate radars of the same type, and this is being incorporated into the final version as an expanded display option.
7. A higher accuracy mode is required to fingerprint radar PRIs, and this is being incorporated into the final version as an interpolate mode.
8. Operators were generally impressed by the PIP's immediate and unambiguous responses.

System Applications

A wide-open, real-time PRI receiver offers a considerable number of system applications. These include intelligence collection, tactical threat recognition, off-line signal analysis, and range test monitoring. In many situations, the narrow bandwidth gate complements the wide bandwidth processor very effectively.

In both manual and automated intelligence collection, the wide-open PRI receiver is a very effective tool for determining how many emitters are present at the receiver input and for quickly identifying those emitters. In addition, it provides a relatively good resolution PRI measurement and, with the expanded trace or interpolate options, can also provide an extremely accurate PRI measurement. In manual applications, or under computer direction, a wide-open PRI receiver incorporating appropriate gate circuitry can be used to determine whether or not the signal is a staggered pulse train. The gate can be used to isolate a particular emitter for recording, direction finding or scan pattern measurements.

When a PRI receiver is fed from a wideband receiver, such as a channelized or IFM unit, a very useful two-dimensional matrix display can be generated. In this application, the wideband receiver tags each pulse with the associated RF frequency, while the PIP then tags each pulse with its associated PRI. These two parameters can be displayed on an X-Y display, or input to a computer for processing. Conventional emitters would appear as a dot on the matrix display, where the location of the dot identifies both the emitter frequency and its PRI. A frequency-agile emitter appears as a line or a series of dots, while multiple PRIs at the same frequency appear as separate dots (see Figure 6). A low false-alarm rate is extremely important in automatic signal processing. Since matrix processing correlates pulse trains by both PRI and frequency, the false-alarm rate is now the product of the frequency false-alarm rate and the PRI false-alarm rate, which is much smaller than either rate taken separately. A matrix-processing system has been operated effectively, using an IFM front end, in areas of extremely high signal density. IFM units alone generate a prohibitively high false-alarm rate in that environment, but the combination of frequency and PRI sorting operated with almost no false alarms. This configuration is employed in the WJ-1920 system. A block diagram of the WJ-1920 is shown in Figure 7.

A PRI receiver is useful as a preprocessor in automated systems. The obvious advantage is that it relieves the central processor of the requirement for deinterleaving and PRI recognition, thus increasing system capacity and throughput. The PIP offers another advantage when used as a preprocessor. Since it operates directly on a pulse-by-pulse basis, incoming pulses can be tagged with both frequency and PRI as they flow through the system. With this information, priority emitters can immediately be identified by the central processor. In the case of an intelligence mission, this identification would automatically trigger the recording of pulse data or performing of a higher level analysis. In the case of a tactical mission, the immediate identification would enable pulse-by-pulse

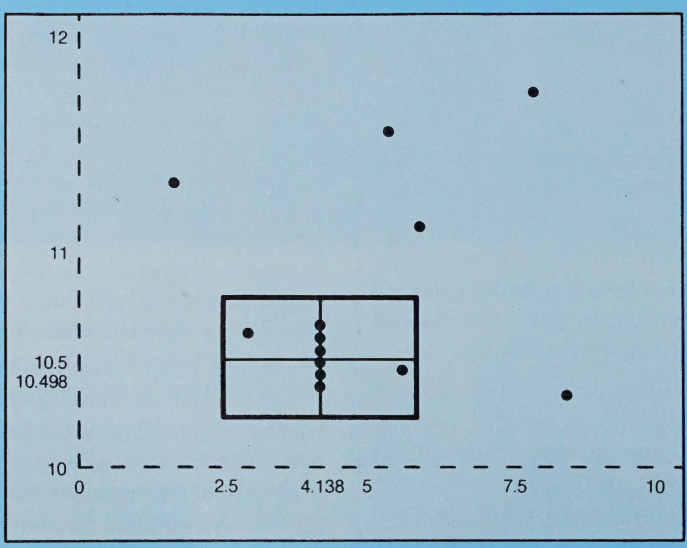


Figure 6. Matrix display with cursor.

generation of an appropriate ECM response.

The PIP can also be useful in analysis facilities. Many times, signal recording can be successfully performed on a narrowband receiver without any contamination from other emitters. However, in wideband recording or in dense signal environments, recording without contamination is often not possible. The resulting spurious pulses cause off-line analysis to be very complicated. It is highly probable that a pulse train could be mixed in with the other recorded pulses and missed entirely. The PIP solves this problem.

The unit can also be very effective in monitoring the performance of equipment in range tests. This could be useful in analyzing the performance of deceptive jammers as well as the susceptibility of weapon systems to deceptive jammers. In addition, it provides the ability to validate the test through the evaluation of the background environment.

Where Do We Go From Here?

The successful PIP prototype is being redesigned as a production model which will incorporate finer PRI quantization (62.5 nsec rather than 1 and 10 μsec), broadened PRI range (3 μsec to 100 msec), an optional expanded sector trace, an optional interpolate function for increased accuracy (limited only by the reference crystal used), a more flexible control interface, an IEEE-488 bus interface, capability for multiple PRI gates, and other features which were suggested by users during the operational evaluation of the initial prototype. The production model will be available as a standard unit, suitable for stand-alone use or as a part of a more comprehensive system.

The prototype has already been tested successfully in a two-dimensional

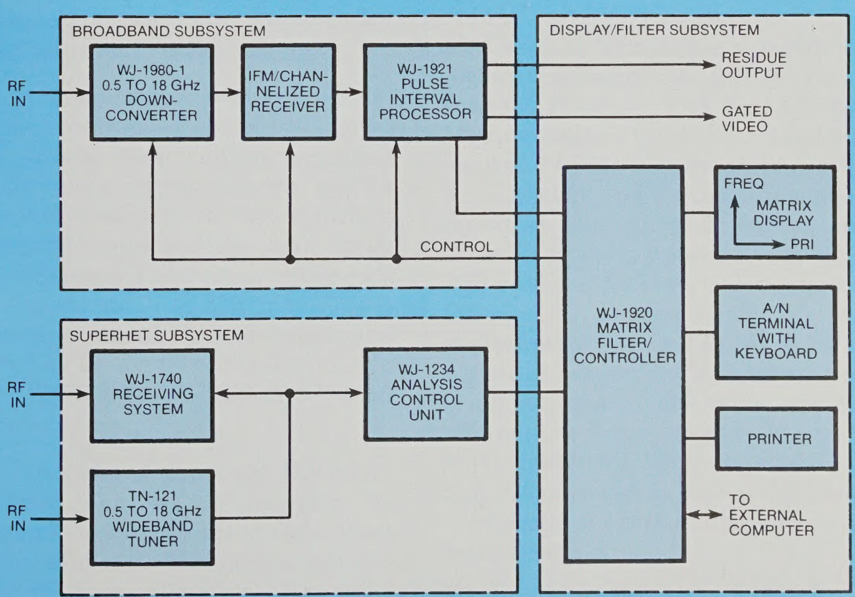
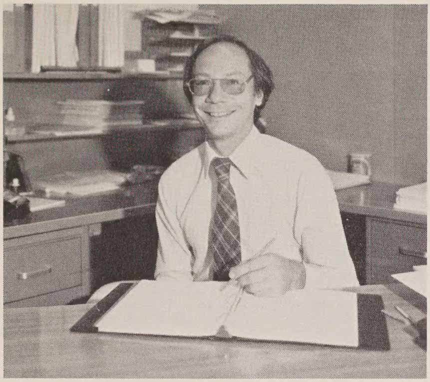


Figure 7. WJ-1920 system block diagram.

frequency/PRI matrix system as part of the WJ-1920 system, and second-generation processing software for automatic signal processing and identification is being developed. In a PRI/frequency matrix application, the input to the PIP is the stream of digital pulse data blocks from the receiver front end, where time of arrival (TOA) is one of the parameters. The output of the PIP is the same stream of data blocks, except that TOA has been replaced by PRI, using the processing technique of afferent inhibition, based on human auditory processing. The PIP is therefore very efficient as a PRI preprocessor, relieving the central processor of the need to perform constant PRI analysis.

Finally, it is worth noting that the brain uses similar neural processing concepts to implement auditory direction finding. Initial efforts suggest that a DF scheme based on the Pulse Interval Processor may be extremely effective. Work in this area has begun.

Authors:



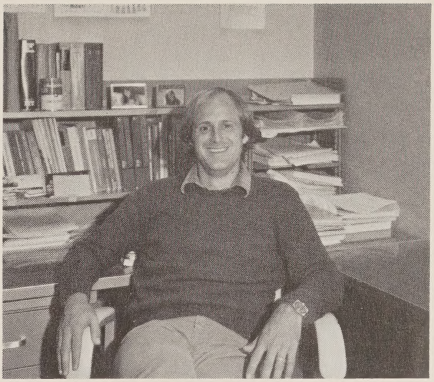
Joel E. Schindall

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.

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