WATKINS-JOHNSON CO.
PALO ALTO, CALIFORNIA

BULK RATE
U.S. POSTAGE
PAID
PERMIT NUMBER
7577
SAN FRANCISCO
CALIFORNIA

WATKINS-JOHNSON **Manufacturing and Office Locations**

United States

SALES OFFICES

CALIFORNIA
Watkins-Johnson
3333 Hillview Avenue
Palo Alto 94304
Telephone: (415) 493-4141

Watkins-Johnson
440 Mt. Hermon Road
Scotts Valley 95066
Telephone: (408) 438-2100

DISTRICT OF COLUMBIA
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, Md. 20760
Telephone: (301) 948-7550

FLORIDA
Watkins-Johnson
325 Whooping Loop
Altamonte Springs 32701
Telephone: (305) 834-8840

MARYLAND
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg 20760
Telephone: (301) 948-7550

NEW JERSEY
Watkins-Johnson
90 Monmouth Street
Suite 207
Red Bank 07701
Telephone: (201) 842-2422

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 Italiana
S.p.A.
Piazza G. Marconi, 25
00144 Roma-EUR
Telephone: 59 45 54
Telex: 60117
Cable: WJROM-ROMA

GERMANY, FEDERAL REPUBLIC OF
Watkins-Johnson
8033 Planegg
Münchener Strasse 17
Telephone: (089) 859-9441
Telex: 529401
Cable: WJDBM-MUENCHEN

UNITED KINGDOM
Watkins-Johnson
Shirley Avenue
Windsor, Berkshire SL4 5JU
Telephone: Windsor 69241
Telex: 847578
Cable: WJUKW-WINDSOR

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.

Vol. 3 No. 6 November / December 1976

Signal Recognition in a Complex Radar Environment

Tech-notes

Cover Story

The microwave environment is comprised of many pulsed radar emitters, each characterized by a radio frequency, a pulse repetition interval (PRI), a pulse width, an amplitude, and other less obvious pulse characteristics. These parameters may be stable for each recurring pulse in an emitter's pulse train, or may change with each pulse emitted. A large number of signals exhibit a pattern in one or more of these parameters, making recognition of uncooperative emitters possible with the aid of a digital computer. However, the system attempting to classify these patterns receives many emitters simultaneously. The identification process is further complicated by atmospheric noise, dropout of pulses, and reflection of pulses.

In order to operate effectively in this complex environment, a computer controlled reconnaissance system must produce very few misidentifications or "false alarms." Typically, the system is designed to monitor signals known to exist in a geographical area, and to notify the operator if any unexpected emitter is present. If this system has a false alarm rate of 1%, and receives 50 emitters every second, the system will produce a false alarm every two seconds. However, since it may take the operator 10 to 20 seconds to confirm the false alarm, the system becomes almost useless. Therefore, if a computer-aided identification technique is to be viable, it must produce a very low false alarm rate.

This issue describes a computer oriented PRI analysis method for identifying radar emissions. Using PRI classification as the primary sorting parameter allows rapid identification of most emitters in an interleaved environment and at an acceptably low false alarm rate. Determining patterns in other pulse parameters, such as frequency, pulse width and amplitude augments the PRI analysis results and, thereby, further increases the system's emitter identification accuracy.

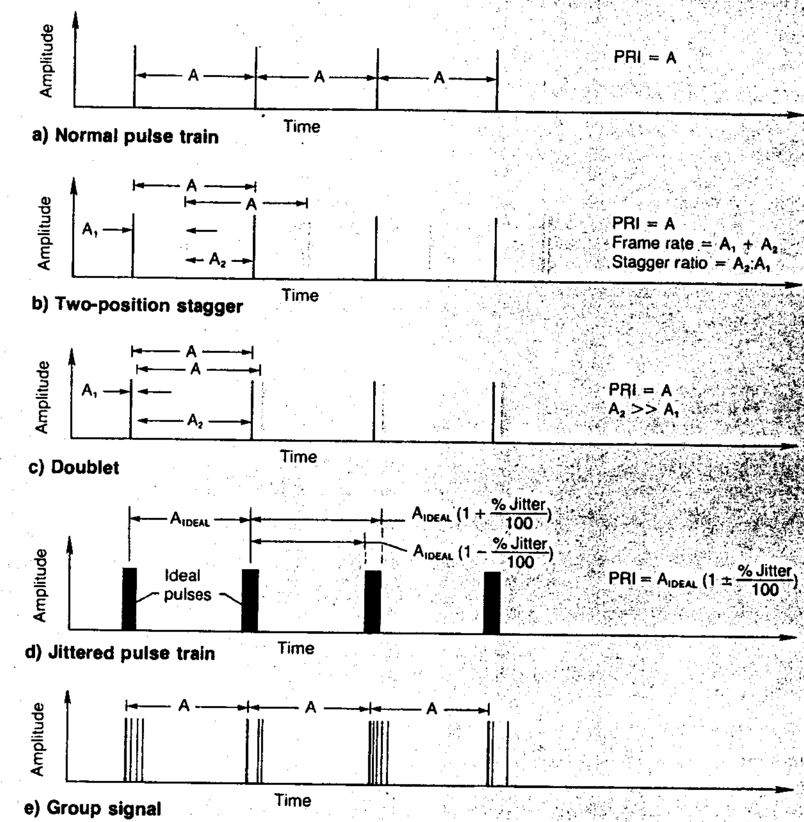


Figure 1. Characterizing pulsed emitters by their PRI patterns makes signal recognition possible. Examples of several ideal PRI patterns are shown above. In actual radar pulse trains, the amplitude of the pulses may vary and the pulse width may range from 0.1 to 20 microseconds.

Pulsed Signal Characterization

Although there will always be a few signals defying standard characterization, most pulsed emitters can be classified by their PRI patterns. Examples of a few simplified patterns are shown in Figure 1. The simplest of these is the "normal" signal shown in Figure 1a. Characteristic of this emission is a pulse train exhibiting a single valued time interval between all adjacent pulses, or a constant PRI.

A more complex emission is the "stagger" signal consisting of a number of different PRI's within the pulse train. For the two-position stagger shown in Figure 1b, the common PRI of the stagger or "frame rate" is the addition of the A_1 and A_2 time intervals. The time by which each component pulse train is offset from another is termed the "stagger ratio," A_2:A_1. Two-position staggers can be extended to more complex n-position staggers, characterized by the frame rate, $\sum_{i=1}^{n} A_i$, and the stagger ratio, $A_n:A_{n-1}:\ldots:A_2:A_1$.

The doublet signal, Figure 1c, is similar to the two-position stagger except that the A_2 time interval is much larger than A_1. As in the case of n-position staggers being an extension of the two-position stagger signal, triplet and n-let signals are extensions of the doublet having three to n-different time intervals between pulses, respectively.

A radar emission's pulse rate stability depends on the timing circuitry used to generate the signal. Instability in the observed signal is referred to as PRI jitter, illustrated in Figure 1d. The jitter present is measured by the percent deviation from the ideal pulse data interval. It causes the actual PRI to fall within the range of $A_{IDEAL}(1 \pm \frac{\%\ jitter}{100})$. Emitters not requiring a stable PRI can exhibit a jitter as high as 15%, while others may exhibit no measurable jitter.

An example of an information-carrying signal also present in the radar environment is a group signal shown in Figure 1e. Unlike normal or staggered signals, a number of pulses occur within 40–50 microseconds after the leading pulse. To the receiving system, these pulse trains can appear as doublets, triplets, n-lets or periodic pulse bursts, depending on the emitter's mode of operation at the observation time.

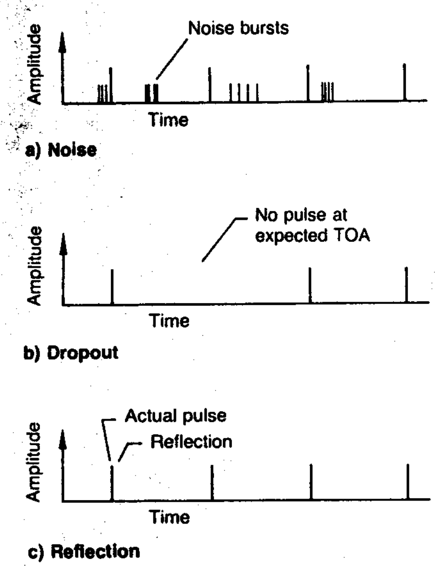


Figure 2. Typical pulse distortion found in the radar environment.

Distortion Effect on Signal Identification

The degree of difficulty in determining the type of signal incident to a signal identification system depends on the emitter complexity, environment density, and environment created distortion. Several pulse train distortions severely affect the signal identification system's ability to accurately characterize an emitter. Noise pulses generated either by the environment, or the signal identification system itself, result in random pulse data interspersed with an emission as shown in Figure 2a. Often, noise occurs in bursts which can lead to misidentification of a normal signal as a more complex signal. Noise pulses also can be mistakenly combined with other random signals to form pseudo-periodic pulse trains.

Dropout distortion caused by the antenna scan pattern of the receiver, or emitter, or an obstruction is shown in Figure 2b. Signal misidentification results if the identification system prematurely considers the pulse train to have ceased. Reflection distortion resulting from an emission's reflection from an obstruction is shown in Figure 2c. Although the reflection pulse amplitude is usually less than the actual emission, it follows the emission pulse after only a short delay and is often sporadic, thus leading to possible misidentification.

The combined effect of these distortions is to cause two types of errors; 1) failure to identify an emitter in the data sample or, 2) identification of an emitter that is not in the data sample. The first type of error is usually caused by an inadequate data sample; however, the second type of error is caused by faulty analysis and results in a high false alarm rate. Performance degradation caused by false alarms usually does not show up in laboratory tests, since pulse generators or emitter simulators do not create the noise, dropouts or reflections in the quantity or variety that occur in the real environment. A system that successfully completes laboratory testing and appears to be able to discern pulse trains generated by a simulator may cause a large number of false alarms during an actual mission. As a guideline, any signal identification methodology using a digital computer must be extensively tested in the environment for which it was designed.

Processor Approach to Signal Identification

Achieving very fast and accurate environment characterization demands the reconnaissance or tactical receiving systems be computer equipped. A typical signal identification system common to both narrowband and wideband receivers is shown in Figure 3. The tuner system, consisting of antennas, tuner, demodulator and frequency measurement hardware, translates microwave emissions to lower frequency video information. It also supplies frequency measurement information and digital measurement of an emission's frequency, time of arrival (TOA), angle of arrival (AOA), pulse width and amplitude. The computer system uses these parameters for signal characterization.

Simplistic Analysis Method May Lead to Misidentification

Using a simplified approach to emitter characterization can lead to a reasonably adequate identification for the number of signals incident to the system. However, oversimplified software analysis can also lead to a large number of misidentified characterizations or false alarms. An example of misidentification due to oversimplified analysis is an emitter with a stagger ratio which approaches unity (i.e., $A_2 \approx A_1$, Figure 1b). A simplistic analysis of this emitter would identify the data sample as a normal signal with a small percentage of jitter. A more exhaustive software analysis would determine that a consistent alternative pulse pattern does in fact exist, and the pattern is very stable.

A second misidentification due to simplistic analysis is two pulse trains with "identical" PRI's, normally indicating the pulse trains are staggered signal components. Further analysis is needed before assuming that pulse trains with identical PRI's are stagger components, since there may either be two identical emitters received simultaneously, or a single reflected normal signal.

Implementing PRI Analysis

Complex emitters, environmental distortion and even random radar transmitter emissions make it impossible for one type of analysis to associate all data samples to a given signal. The number of allowable misidentifications and, therefore, the complexity of the analysis method, defines the sophistication of the recognition processing. One of the best identification methods determines the PRI of signals in a data sample. Because of PRI data complexity, the method chosen to analyze this parameter must account for all anomalies. Many methods may seem adequate to analyze PRI, but, once implemented, may be found to be quite error prone.

For example, one method uses the minima of the discrete autocorrelation function as an estimate of the signal's PRI. This function is defined as the sum of the differences in the TOA of all pulses in the actual pulse train and the TOA of the nearest pulse in another train formed by delaying the actual pulse train. The time delay giving the smallest sum of the differences is an estimate of the actual pulse train's PRI, and is an excellent discriminant if there is only *one* signal in the data sample. For the two pulse

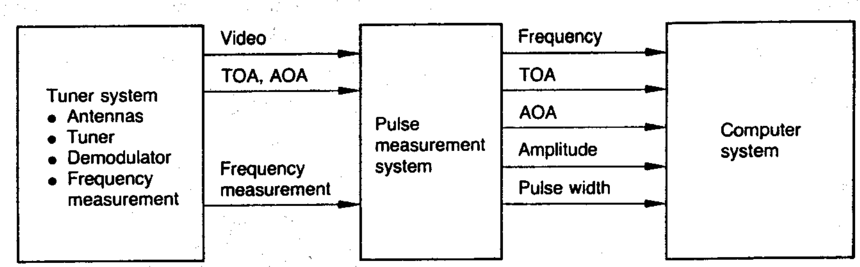


Figure 3. A typical signal identification system common to both narrowband and wideband receivers.

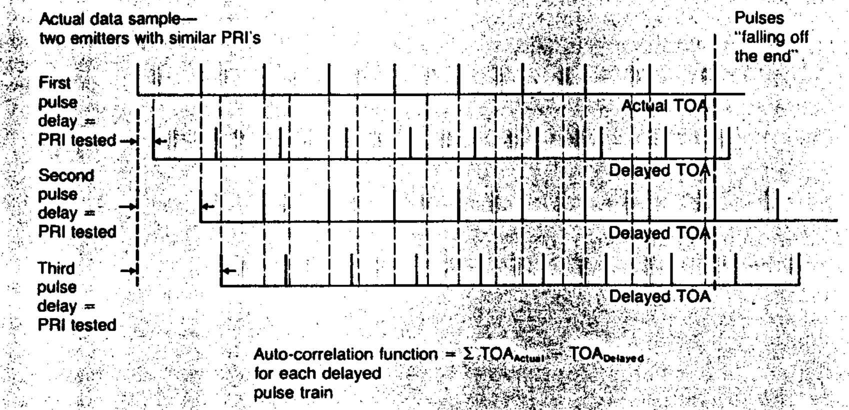


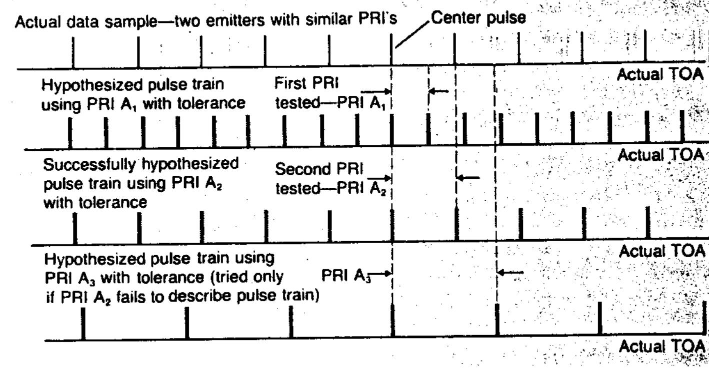
Figure 4. The auto-correlation approach to estimate an emitter's PRI performs successive time delays on the actual data sample in order to find the smallest sum of the differences between the actual TOA and delayed TOA.

trains shown in Figure 4, the auto-correlation method does not estimate both PRI's. The first and third time delays do not define a PRI since there is no well defined minima for the auto-correlation function. The second time delay describes the pulse train represented by the black pulses, but does not describe the pulse train indicated by the white pulses. Furthermore, any time delay greater than the third still does not describe a pulse train represented by the white pulses.

If there is more than one signal in the data sample, or the PRI is jittered, the correlation minima are not very pronounced. Also, there is a large number of possible time delay values that must be evaluated, with no particular reason to prefer one delay over another. Finally, since the data sample is finite, as the delay grows larger, more pulses in the delayed train "fall off the end" of the actual train and cannot be used in the correlation process. This loss in pulses establishes a bias in the data against large PRI values that can never be overcome. Thus, a method initially appearing promising fails in the presence of many signals, a short delay, excessive jitter, or noise.

A PRI analysis method developed by the Watkins-Johnson Company achieves very fast, low false alarm rate signal identification using a small number of pulses. The analysis method uses a computer algorithm which conditionally reiterates the analysis process, depending on the outcome of previous iterations. The algorithm is implemented in three basic steps.

First, the data sample from the pulse measurement system is analyzed to determine the possible pulse trains which might characterize an emission. Next, the possible pulse trains are tested by a least mean squares (LMS) fit to verify whether or not pulse trains exist, and defines the PRI more precisely. If other pulses in the data sample are found to satisfy the



Hypothesized pulse train tested	Ratio of the number of hypothesized pulses matching actual pulses to the number of hypothesized pulses
• PRI A_1	3/18
• PRI A_2	11/11
• PRI A_3 (tried only if PRI A_2 fails to describe a pulse train)	3/7

Figure 5. Hypothesized pulse trains generated by the pulse selection algorithm. PRI's are established by using the time between the chosen starting pulse and successive pulses following it in the actual data sample. A successful PRI is defined when the actual data sample accounts for most all pulses in the hypothesized pulse train.

more precise PRI, the LMS is repeated. Finally, pulse trains with similar PRI's are combined to determine whether or not a stagger signal can be produced. The outcome verifies that the signal resulting from similar PRI combinations is either an n-let, n-position stagger, or more than one normal signal with similar PRI values.

Determining Possible Pulse Trains Within Data Sample

The simplest way to determine the existence of a pulse train in a data sample is to measure the time interval between all adjacent pulse pairs. The time interval for one pulse pair can next be compared with other adjacent pulse pairs to verify the PRI's are the same and a pulse train can be defined. This method of pulse train recognition works only if the data sample contains no more than one normal pulse train. PRI's obtained by measuring the time interval between adjacent pulse pairs will not account for pulse trains needed to define emitters in a complex data sample, since complex pulse trains often consist of more than one pulse within a frame, and interleaved pulse trains may be present.

To estimate all possible pulse trains within a data sample, a pulse selection algorithm is used. A starting pulse located in the center of the data sample is hypothesized as a member of a periodic pulse train. The starting pulse is then paired one by one with the pulses following it, as shown by PRI A_1, PRI A_2 and PRI A_3 in Figure 5. Every time a pulse pair is chosen, the PRI of the pair (referenced from the starting pulse) is used to generate a hypothesized pulse train. The algorithm continues to use the same starting pulse until a pulse train is found, or the test PRI increases to a value greater than any possible emitter PRI in the environment.

Each pulse in the hypothesized pulse train is then compared to the actual data sample. If a pulse in the data sample matches one in the hypothesized pulse train within a given tolerance, a successful comparison is recorded. The tolerance is incorporated to account for jitter. If no pulse in the actual data sample exits at this TOA, a failure is recorded. A score is maintained which reflects the number of pulses accounted for by the hypothesized train. As shown in Figure 5, the actual data sample will account for only a few of the pulses hypothesized by the pulse train developed from PRI A_1, and the starting pulse. On the other hand, the actual data sample accounts for most all pulses hypothesized by the pulse train developed from PRI A_2 and the starting pulse.

The process continues by selection of the next starting pulse using a binary selection method. After the center or median pulse (i.e., 50 percentile) has been exhausted, the algorithm then successively selects the pulse representing the 75th percentile, 25th percentile, 87.5 percentile, etc., of the data sample for the next starting pulse. However, if the next selected starting pulse is already included in a successful pulse train definition, it is disregarded. This selection method is continued until all the data sample pulses have been used as a starting pulse, or used in a pulse train definition.

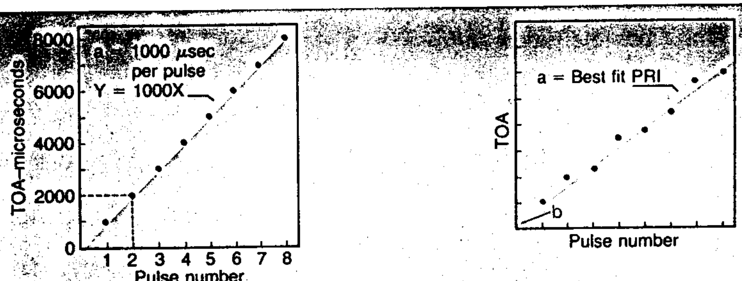
Least Mean Squares Fit

Once a pulse train is established, an LMS fit algorithm is used to define a more precise PRI for the selected pulses. This redefined PRI value may cause pulses selected to define the hypothesized pulse train to change. The LMS fit is a statistical method of deriving the slope (a) and ordinate intersection (b) of a straight line which best fits a given set of X, Y coordinates. The expression for this straight line is the equation:

$$Y = aX + b.$$

To apply the LMS fit to precise PRI identification, a coordinate system is constructed, using the pulse train's sequential pulse number as the abscissa and the pulse TOA as the ordinate. Figure 6a shows an example of points plotted for an ideal emitter with a stable PRI (i.e., no jitter). Arbitrarily choosing the first pulse received as pulse number one, the second as pulse number two, etc.; the points, if joined together, would produce a perfectly straight line. The slope (a) of the line, or the change in Y for change in X, is equal to the PRI of the emitter.

In the complex microwave environment, however, pulse trains have a jitter component, and a number of similar pulse trains may be interleaved in the data sample, causing clustered



a) Straight line formed by eight pulses of a non-jittered pulse train with a PRI equal to 1,000 microseconds

b) A more complex jittered data sample and the LMS fit

Figure 6. Example of points plotted for a) an ideal emitter with a stable PRI and, b) the plotted points of a real pulse train resulting from the PRI and tolerance defined by the pulse selection algorithm (Figure 5). The LMS fit algorithm calculates the slope of the line representing the PRI that best fits the data from the pulse selection algorithm.

TOA points. Once the existence of a pulse train has been hypothesized, the LMS fit defines a statistically accurate PRI, thus defining precisely which of these clustered pulses in the data sample belong to the hypothesized pulse train. The LMS fit is performed on the hypothesized pulse train's pulse number and actual pulse TOA using the pulse number as the X-axis coordinate and the TOA as the Y-axis coordinate. As shown in Figure 6b, the slope (a) derived by this fit is the PRI that best fits the data.

Using the PRI calculated from the LMS fit, another set of data points are again determined from the original data sample by the method shown in Figure 5. This new set of data points may be exactly the same as the old set, in which case no further evaluation is needed. However, if the new set is not the same, the LMS fit is performed again with the new set. This process is iterated until no change in the set occurs.

Test for Staggers

The stagger test determines whether pulse trains with identical PRI's are part of a stagger emission or unique signals. Even if the data sample contains two pulse trains with identical PRI's, the pulse trains may not be components of a stagger. First, several identical emitters can operate simultaneously in close proximity. Second, a single reflected normal signal can appear like a stagger, since the pulse train generated by emitter reflection would have the same PRI as the emitter.

To ensure the identified PRI is truly that of a single emitter, the stagger test first calculates the mean "stagger interval" between the component pulse trains. This calculation is given by the expression μ_{B-A} for the hypothesized stagger as shown in Figure 7. Next, the pulse-by-pulse variance for the component pulse trains is calculated by the expression σ^2_{B-A}, also given in Figure 7.

In an actual stagger, the variance is very small since the pulses are generated by a timing mechanism in a single emitter. However, if the component pulse trains have actually been generated by separate identical emitters, the variance is large, since the timing mechanisms will be subject to different instantaneous environmental conditions and are not always synchronized. If the variance is too large, component pulse trains are identified as being generated by separate emitters and are not combined to form a staggered signal.

$$\mu_{B-A} = \frac{\sum_{i=1}^{n} B_i - A_i}{\text{Number of pulse pairs}}$$

$$\sigma^2_{B-A} = \frac{\sum_{i=1}^{n} [(B_i - A_i) - \mu_{B-A}]^2}{\text{Number of pulse pairs}}$$

Figure 7. Calculation of the pulse-by-pulse variance for the stagger interval of two pulse trains with "identical" PRI's.

Future Implication of Signal Identification

This issue has concentrated on a computer algorithm technique which uses PRI as the primary sorting parameter for fast signal identification. PRI analysis alone cannot totally account for all the different emissions in the environment. It must be integrated with other signal identification methods to truly be viable in the ever-increasing, complex microwave environment. Other statistical and heuristic approaches might incorporate scan modulation data, precise pulse frequency, pulse width, or frequency deviation as sorting parameters.

In addition to integrating a software approach to signal identification, it is also necessary that both the software and hardware be designed to solve the system's recognition of emissions. No system can solve every aspect of signal identification and still perform in the fast response time required. The PRI analysis technique described has been integrated with other identification methods to provide fast, accurate signal characterization. This integrated system has been extensively field tested and shown capable of characterizing today's microwave environment.

Authors:

J. William Campbell

Mr. Campbell joined the Watkins-Johnson Company in 1972 and is currently a Staff Scientist in W-J's Recon Division responsible for the development of computer-controlled receiver architecture. Previously, he led the development of using microprocessors in receiver design. This concept produced a multi-operator control system for a larger number of independently scanning receivers. Mr. Campbell also developed the state-of-the-art computer algorithms used to analyze signal characterization such as complex PRI and scan modulation, and a unique method of automatic direction finding which employs computer-controlled antenna switching and a cross-correlation algorithm. Mr. Campbell received his BSEE and MSEE degrees from Stanford University in 1972.

Stephen Saperstein

Mr. Saperstein came to the Watkins-Johnson Company in 1972 and is currently Head, Computer Applications Section in W-J's Recon Division. His section is responsible for the programming of computers and digital processors to control scanning receivers and analyze data acquired from microwave systems. He was the software development engineer for phase one of the AN/WLR-14 (Sea Scout) System, and was responsible for the computer programming effort of subsequent Sea Scout Systems. Mr. Saperstein was also instrumental in the development of the WJ-1205 Video Digitizer, and is currently involved in a large scale signal identification project for the Air Force. Steve earned his BA degree from Rutgers University in 1965, and is a member of the Association for Computing Machinery and the Association of Old Crows.

Correction to *Tech-notes*, Titled "Gain of Directional Antennas"

We would like our readers of the July/August 1976 issue of *Tech-notes* to make note of corrections to Table 2 in that issue. The changes to be made are contained in the revised Table 2 below. The changes involve one approximation for Beamwidth (from aperture), and three approximations for Directive Gain (from aperture). These changes will eliminate possible discrepancies in the calculation of Beamwidth and Directive Gain.

Table 2. Computations of directive gain and beamwidth for representative aperture-type antennas.

Aperture-Type	Beamwidth (From Aperture)	Directive gain (From Aperture)	Directive gain (From Beamwidth)	Antenna Efficiency (Aperture Illumination Efficiency)
Uniformly illuminated circular aperture-hypothetical parabola ← a → 18 dB side-lobe level	$\theta = \frac{73\lambda}{a}$ $\theta = \theta_1 = \theta_2$	$g_d = \frac{10\,a^2}{\lambda^2}$	$g_d = \frac{52{,}525}{\theta^2}$ $\theta = \theta_1 = \theta_2$	100%
Uniformly illuminated rectangular aperture or linear array a, b 13 dB side-lobe level	$\theta_1 = \frac{51\lambda}{a}$ $\theta_2 = \frac{51\lambda}{b}$	$g_d = \frac{16\,a\,b}{\lambda^2}$	$g_d = \frac{41{,}253}{\theta_1\theta_2}$	100%
Rectangular horn a) Polarization plane: E-plane a_E 13 dB side-lobe level b) Orthogonal polarization plane: H-plane ← a_H → 26 dB side-lobe level	$\theta_1 = \frac{56\lambda}{a_E}$ $\theta_2 = \frac{67\lambda}{a_H}$	$g_d = \frac{8\,a_E\,a_H}{\lambda^2}$	$g_d = \frac{31{,}000}{\theta_1\theta_2}$	60%
Nonuniformly illuminated circular aperture (10 dB taper)–normal parabola ← a → 26 dB side-lobe level	$\theta = \frac{72\lambda}{a}$ $\theta = \theta_1 = \theta_2$	$g_d = \frac{5\,a^2}{\lambda^2}$	$g_d = \frac{27{,}000}{\theta^2}$ $\theta = \theta_1 = \theta_2$	50%
	$a >> \lambda$	$G_d = 10 \log_{10} g_d$ dB	$G_d = 10 \log_{10} g_d$ dB	