Radar Warning Receiver (RWR) Time-Coincident Pulse Data Extraction and Processing

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Abstract—This paper will present an approach for implementing an airborne radar warning receiver (RWR) pulse data extraction (PDE) and processing technique capable of handling multiple time-coincident radio-frequency (RF) pulse input threat emitter signals received in a dense threat radar signal environment. The pulse data extraction technique is specifically developed to accommodate the RF to video response of current commercial-off-the-shelf (COTS) or militarized COTS (MOTS) extended-range detector logarithmic video amplifiers (ERDLVAs), including extracting signal information in the presence of device noise. The approach uses a combination of time-domain filtering, adjustable thresholds, and edge detection techniques combined with a four-quadrant data comparison to extract individual pulse data from overlapped multi-source and uncorrelated noisy pulse inputs, and the processed data output can be used as part of the presented PDE algorithm and also may provide pre-processing for currently used pulse deinterleaving and sorting methods. The developed technique has the potential to provide system response that is optimized for various threat environments via pre-deployment programming or continuous-time dynamic variations in the PDE.

Keywords - RWR, radar warning receiver, pulse processing, signal processing, electronic countermeasures, ECM

I. INTRODUCTION

With expected increasing range and accuracy of modern radar-guided ground-to-air and air-to-air weapons systems, there is a need for combat aircraft RWRs to receive, detect, and identify threat radar signals at greater distances via increased receiver sensitivity. However, increased receiver sensitivity can also result in an overload of RF sensor receive/detection circuits in dense threat environments where a significant increase in time-coincident or pulse-on-pulse (POP) signals may be present. In addition to fundamental operational challenges, there is a demand for Department of Defense (DoD) RWR systems to utilize COTS or MOTS circuit and system components to provide acceptable performance while minimizing hardware cost and development time. In RWR systems, a typical RF to video conversion interface circuit is the extended-range detector logarithmic video amplifier (ERDLVA).

This work presents an approach for accurately interpreting incoming time-coincident pulse signal data for highly sensitive RWR systems in dense threat emitter environments. The concepts described use some well-known real-time signal processing techniques optimized for specific ERDLVA noise and waveform performance characteristics along with simultaneous RWR multi-quadrant data processing. This combination of techniques facilitates identification of threat emitter locations in a non-ideal noisy environment. The approach enables accurate interpretation of time-coincident RF threat signals as a standalone monopulse detection method, and can also be used to complement current deinterleaving and processing methods.

Section II of the paper will discuss the motivation behind this work. Section III will present a block diagram of a typical four quadrant RWR system and include description of the key components included in RF to video conversion circuits. Components of the system where specific performance characteristics contribute to the pulse data extraction processing methods will be identified and explained. Section IV of the paper will show an example of detected, partially coincident RF input pulses that might be received and detected by a single quadrant of an RWR subsystem using a COTS ERDLVA device. Section V will provide a description of the PDE algorithm and an outline of specific components of the algorithm including noise floor & minimum detectable level threshold setting, signal multi-sampling variation, moving average filter window point sizing, and d/dt or derivative threshold settings. Section VI presents simulated results for a low-probability coincident threat emitter signal group to demonstrate the effectiveness of the processing techniques for a difficult to distinguish time-coincident RF signal group. A comparison will also be presented to show the differences in raw video data vs. PDE-processed video signals for the algorithm output. The data extraction technique will be presented operating on synthesized pulse data that includes Gaussian random noise used to replicate non-ideal RWR system
RF/video performance characteristics. Finally, the paper will provide a summary along with prospective future effort that can be undertaken to continue development and refinement of the coincident pulse extraction technique.

II. MOTIVATION

The deployment of RWR processor algorithms specifically tailored to function efficiently with current COTS/MOTS ERDLVA devices provides the opportunity for DoD system designers and maintainers to leverage off of current industry innovation and competition in ERDLVA development in their effort to support or update legacy RWR systems at a lower cost and with a larger source of hardware suppliers. By using COTS ERDLVAs and/or common RF to video logarithmic conversion techniques, costs associated with development and acquisition of customized hardware can be shifted to the software/firmware development area. Moving development to the area of software/firmware facilitates overall reduced system costs along with flexibility in implementing operational modifications through system reprogramming as opposed to hardware redevelopment.

A significant amount of investigation and research exists in the area of pulse deinterleaving methods for sorting and identifying multiple non-coincident pulse signals in RWR systems [1]-[4]. These algorithms are tailored to accommodate narrow, interleaved, mostly non-coincident pulses. In an RWR system with lower sensitivity, the probability of time-coincident signals is expected to be lower due to shorter detectable range and smaller effective sensing area. With minimal signal coincidence and narrow pulse-width signals, existing deinterleaving algorithms can provide acceptable functionality with minimal or no video pre-processing. However, in an extended range system with more sensitive receivers in an environment of modern wide pulse and high duty cycle signals (e.g. pulse Doppler) an increase in time-coincident signals is expected. Overlapping pulses detected in this environment may create ambiguous ‘wildcards’ that must be discarded without signal pre-conditioning.

III. TYPICAL RWR SYSTEM

A block diagram of one RWR system quadrant channel is shown in Fig. 1. One ERDLVA signal path is shown (DLVA) to simplify. A four quadrant RWR system would consist of four copies of this subsystem, with each antenna positioned at 90° azimuth spacing on the host platform.

A description of the RWR channel functional blocks is provided below:

- **Input RF Filter or Multiplexer**: Provides filtering and frequency division to accommodate reduction of total signals processed by each ERDLVA of a multi-ERDLVA system.
- **RF Amp**: RF gain optimized for utilized detector device.
- **Detector**: Detector circuits will generally linearly add coincident RF input pulses (within device/circuit dynamic range) which results in compound multi-level video pulse signals and the requirement for the PDE technique.
- **Special video processing**: Included in custom non-COTS circuitry. Fixed specialized hardware processing techniques fundamentally limit reconfigurability of the RWR system due to custom hardware that may cost more and be more difficult to manufacture and support.
- **Log Video Amp**: Logarithmic video amplification and drive circuitry compatible with cabling and input signals of the processor subsystem.
- **Sig Processor, Interface**: Provides input terminations to accept log video signals from RF/video section.
- **Sig Processor, analog-to-digital converter (ADC)**: Provides sampling of time-coincident video pulses prior to pulse data extraction being performed.
- **Sig Processor, µP**: Microprocessor executes pulse processing algorithms including PDE techniques for digitized video from ADC.

IV. TIME-COINCIDENT VIDEO SIGNALS

An example of additive detected video output for time-coincident RF input pulses that might be received in a single quadrant of an RWR subsystem and processed by a COTS ERDLVA is shown in Fig. 2. The figure shows two ideal, noise-free pulses and the resultant additive signal (re-scaled for clarity). Also, the flat additive response levels are based on assumption that carrier frequencies of Signal 1 and Signal 2 are sufficiently spaced to allow ERDLVA video filtering circuits to remove any mixing products resulting from the non-linear response of the ERDLVA detector diode.

![Figure 1. One quadrant of an RWR system.](image-url)
As seen in the figure, ‘Signal 1’ (Sig1) and ‘Signal 2’ (Sig2) video voltage levels do not add linearly. However, RF power adds linearly at the detector and the video output voltage is determined by the sum of the coincident RF energy signals. The detected video voltages for Sig1, Sig2, or ‘Signal 1+2’ (Sig12) are given by:

$$v_{\text{dB}} = \left( \log_{10}(\text{Sig1} + \text{Sig2})_{\text{dBm}} \right) \times v + v_{\text{min}} \quad (1)$$

where $v_{\text{dB}}$ is the log slope or linear video voltage output transfer function of the ERDLVA as a function of RF input power in dBm and $v_{\text{min}}$ is the lowest output voltage that also corresponds to ERDLVA sensitivity, $P_{\text{Sens}}$. The additive RF input power of the coincident areas, or overlap, of the two RF pulses is given by:

$$\text{(Sig12)}_{\text{dBm}} = 10 \log \left[ 1000 \times \text{(Sig1 + Sig2)}_{\text{watts}} \right] \quad (2)$$

The example signals and calculations shown in Fig. 2 assume $v_{\text{dB}} = 0.10$ volts and ERDLVA sensitivity, $P_{\text{Sens}}$, is equal to -50dBm with a corresponding minimum video voltage, $v_{\text{min}}$, of 1.5 volts. To obtain accurate voltage for a later-arriving and coincident pulse, the calculated power of the preceding pulse(s) will be used for ‘normalization’, with video voltage of the second arriving pulse given by:

$$\text{(Sig2)}_{\text{watts}} = \left( 10 \log \left[ 1000 \times \text{(Sig12 - Sig1)}_{\text{watts}} \right] - P_{\text{Sens}} \right) \times v_{\text{dB}} + v_{\text{min}} \quad (2)$$

V. PULSE DATA EXTRACTION

The PDE algorithm includes continuous-time signal conditioning, pulse edge detection, and decision algorithm for valid pulse edge identification. The PDE obtains magnitude and timing information from noisy coincident detected video pulse voltages in each system quadrant by setting a baseline lowest acceptable voltage, averaging to reduce signal noise, extracting pulse edge information, then identifying magnitude and time for valid pulse edges. A flowchart showing one RWR quadrant with PDE and decision algorithms is illustrated in Fig. 3.

Specific PDE algorithm components are utilized to condition and extract data from coincident signals as described below:

- Baseline noise floor & minimum detectable level threshold setting: Level determined by combination of lowest ERDLVA video voltage out and overall expected device noise floor. Could be dynamically modified to account for detected errors for the long range, i.e. low video voltage, signals.

- Signal multi-sampling: Sampling a time window of repetitive signals ‘n’ times will provide a $1/\sqrt{n}$ improvement in noise superimposed on the detected pulsed RF signals included in that window. Only useful if monitoring a consistent pattern of distant fixed signals that may exhibit periodicity in overlapping pulses. Not used for random signals where monopulse interpretation of aperiodic coincident signals is required.

- Moving average filter window sizing and offset: A simple, effective filter for time-domain processing of pulsed signals, the moving average filter reduces random noise while retaining a sharp step response [5]. This response is optimal for the PDE approach of extracting pulse edges in near real-time to extract time and magnitude information. Offset or delayed level reading, taking max of several data points, is used to ensure voltage read is sufficiently ‘inside’ the pulse and not rise-time averaged.
• Derivative (d/dt) threshold settings: d/dt threshold selects the voltage delta from consecutive data samples to separate actual pulse edges from random noise spikes. This level is adjusted by weighing expected ERDLVA minimum voltage, RF/video log transfer curve, and expected video signal noise levels.

• Voltage/power calculations and decision algorithm: Magnitudes of processed waveforms are compared to determine threat headings. Rising edges used to determine pulse start and determine if subsequent pulses need to be ‘normalized’ due to pre-existing pulse and using data from all four system quadrants. Note that a required element of the PDE is simultaneous comparison of input from all quadrants to extract two valid quadrant voltages (i.e. associated with one threat).

VI. PDE Algorithm Example

A multiple pulse signal threat environment is simulated to demonstrate operation and effectiveness of the PDE algorithm. Fig. 4 shows relative power levels for the simulation (unitless) of the four signals for a randomly selected 100us time sample while Fig. 5 shows relative azimuth threat positions. The example uses a low-probability scenario consisting of four uncorrelated coincident signals with various pulse widths and PRIs, with a 15us interval highlighted where close and coincident monopulse information is difficult to extract. Table I provides signal IDs, absolute power incident to aircraft (if emitter positioned at antenna boresight), pulse width, and PRI.

TABLE I. Threat Signal Magnitudes and Pulse Timing

<table>
<thead>
<tr>
<th>Signal ID</th>
<th>Incident Power (dBm)</th>
<th>Simulated Heading (degrees)</th>
<th>Pulse width (us)</th>
<th>PRI (us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-48</td>
<td>298</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>-48</td>
<td>118</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>-49</td>
<td>335</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>-46</td>
<td>347</td>
<td>3</td>
<td>75</td>
</tr>
</tbody>
</table>

Fig. 4 qualitatively illustrates the high level of probability for varying levels of time-coincidence for the four presented signals, with the time from 0-15us exhibiting the greatest percentage of overlap in this example. A quantitative probability of signal overlap can be computed using ‘window functions’ in a similar fashion that probability of intercept (POI) might be calculated for uncorrelated scanning antennas or sweeping receivers. Closed-form solutions for various parameters including probability of intercept for any two signals in a given time and mean period between signal coincidence can be found in [6] but will not be presented in detail in this work as the focus will be on the extraction of information from the multi-signal coincidence condition expected to exist.

The simulation uses 40mV RMS random noise on the video signals, nominal for typical COTS ERDLVAs and logarithmic amplifiers at example power levels. The ERDLVA model has a video output minimum voltage of +0.6 volts with an RF/video log transfer curve of 70mV/dB. A simulation sample rate of 25nS is used, corresponding to a 40MHz RWR system ADC. Ideal Gaussian antenna response with 80° beamwidths are used to replicate response of typical RWR system cavity-backed spiral antennas. The PDE algorithm variables in this example are set to:

- Baseline threshold = 0.55V
- Multi-sampling, ‘n’ = 1 (monopulse detection)
- Moving pts avg/offset = 2/5
- d/dt threshold = 0.14V

PDE-processed detected waveforms are shown in Fig. 6 and a graphical representation of the corresponding four-quadrant PDE-processed video output signals for the example is provided in Fig. 7. The data in Fig. 7 consists of pulse edge information extracted from examination of the processed video signals with start and stop information for the extracted pulses notated below the figure.

![Figure 4. Signal relative power and timing used for example.](image1)

![Figure 5. Signal position and relative range used for example.](image2)
Sample algorithm name ID formats can be interpreted from the names: ‘P1W_start’ is start of the first pulse which is located to the west of the platform, i.e. with the two maximum detected voltages at the 225º and 315º quadrant receivers. Part of the PDE decision process is to determine when a positive edge is processed as an individual input pulse or as a summation of separate, coincident pulses. This is achieved by ‘holding’ the voltage/power signal in a particular quadrant at an initial ‘start’ signal until a corresponding ‘stop’ is identified. For the signals in Fig. 6 this is illustrated by ‘P1E_start’ edge identification in the 45º quadrant followed by ‘P1N_start’ edge. Since the ‘P1E_stop’ edge has not yet been detected, equations (1) thru (3) (or applicable derivations) would be used to calculate the power for ‘P1N_start’ based on the absolute voltage/power and the previously observed ‘P1E_start’ voltage/power. The ‘stop’ edges are not used to extract magnitude data, they merely ‘clear’ any stored voltage/power values from associated quadrants. However, the stop edges are also used to provide end of pulse info and pulse width, up to the limitations of the ERDLVA RF/logarithmic amplifiers in the system.

Also significant to note, since direction finding relies on a comparison of the relative power and detected voltages in two adjacent quadrants with the two strongest detected signals at that particular time, using just the initial edge magnitude is sufficient to extract accurate data for pulse shapes that may not be perfectly flat or symmetrical, as any non-symmetry will be seen to relatively track in both detecting quadrants.

Table II shows simulation results for signal detection accuracy. With PDE parameter settings for this simulation and several runs with random noise variation, relative video voltage errors of less than 10% were observed as compared to a noise-free, ideal signal. Voltage variations in the simulated system translate to maximum azimuth direction error ranges below 8.0° compared to an ideal signal, comparing well with theoretical errors expected for similar noise figures and other system parameters fixed [7].

The importance of pre-processing is illustrated in the 45º quadrant waveform data. Fig. 8 shows the 45º waveform while Fig. 9 shows associated magnitude data outputs, with comparison of processed vs. unprocessed signals. The excessive false pulse detection signals in Fig. 9(a) illustrate the increase in noise-induced errors without waveform processing. When processing is applied (and all quadrants simultaneously compared), useful signal information from the noisy waveform can be extracted as shown in Fig. 9(b).

### Table II. Threat Signal Magnitudes and Pulse Timing

<table>
<thead>
<tr>
<th>Signal</th>
<th>Algorithm ID</th>
<th>Incident Power (dBm)</th>
<th>Start delay (us)</th>
<th>Pulse width (us)</th>
<th>Simulated Heading (degrees)</th>
<th>Error range (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P1W</td>
<td>-48</td>
<td>2</td>
<td>1.5</td>
<td>298</td>
<td>-0.4 to 7.5</td>
</tr>
<tr>
<td>2</td>
<td>P1E</td>
<td>-48</td>
<td>4</td>
<td>8</td>
<td>118</td>
<td>0.5 to 7.1</td>
</tr>
<tr>
<td>3</td>
<td>P1N</td>
<td>-49</td>
<td>5</td>
<td>1</td>
<td>335</td>
<td>-1.6 to 6.3</td>
</tr>
<tr>
<td>4</td>
<td>P2N</td>
<td>-46</td>
<td>7</td>
<td>3</td>
<td>347</td>
<td>1.6 to 6.3</td>
</tr>
</tbody>
</table>
VII. SUMMARY AND PROSPECTIVE FUTURE EFFORT

The development and simulation of an RWR pulse data extraction technique for time-coincident threat signals has been presented. The technique uses a unique combination of well-known time-domain processing techniques with simultaneous RWR multi-quadrant processing to enable interpretation of time-coincident RF threat signals. The approach was shown through simulations to provide an accurate method of separating time-coincident detected RF signals with video outputs typical of commonly available COTS ERDLVAs.

In this paper the presentation is limited to specific, static cases to allow for ‘discrete’ explanation of the concepts. It is understood that in different threat environments with highly dynamic threat/platform relative spatial positioning an infinite number of signal combinations can be encountered. This necessitates a more exhaustive examination of the presented research to refine and optimize the concepts for specific operational environments and tailor the approach for complementary operation with other existing, proven algorithms. An expansion of the probability of coincidence for multiple signals of various pulse widths and PRIs to understand the effectiveness of the PDE algorithm for various threat environments is also warranted. Other continuation or future research expansion is expected to include addition of a PDE code module that would dynamically optimize PDE variables for general and specific threat environments as well as hardware development concepts for novel RWR subsystem feedback and inter-communication. To refine results accuracy for practical systems more real-world variables should be introduced including non-ideal antenna response (inherent and for specific mounting configurations) and system noise variation as a function of operating temperatures.

REFERENCES