IMPROVED PULSE REPETITION INTERVAL (PRI) DEINTERLEAVING FOR ELECTRONIC SUPPORT MEASURE (ESM) RECEIVER

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***Abstract*- In an electronic warfare (EW) battlefield environment, it is highly necessary for a fighter aircraft to intercept and identify the several interleaved radar signals that it receives from the surrounding emitters, so as to prepare itself for countermeasures. The main function of the Electronic Support Measure (ESM) receiver is to receive, measure, deinterleave pulses and then identify alternative threat emitters. Deinterleaving of radar signals is based on time of arrival (TOA) analysis and the use of the sequential difference (SDIF) histogram method for determining the pulse repetition interval (PRI), which is an important pulse parameter. Once the pulse repetition intervals are determined, check for the existence of staggered PRI (level-2) is carried out, implemented in MATLAB.**

***Keywords*- pulse deinterleaving, pulse repetition interval, stagger PRI, sequential difference histogram, time of arrival.**

I. INTRODUCTION

Electronic warfare (EW) refers to the military use of the electromagnetic spectrum and electronics to attack an enemy or impede attacks from an enemy via the spectrum. EW system monitors the electromagnetic spectrum by measuring the parameters of intercepted signals, and uses this data to identify the intercepted emitters.

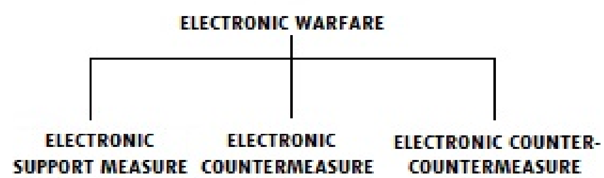

Fig.1a. Classification of electronic warfare system

Electronic Support Measure (ESM) is an important radar reconnaissance equipment that performs **area surveillance** and **threat detection** to determine the identity and capability of the surrounding radar emitters. Classification of radars is possible by using their unique characteristics, some of which may be directly measured and some are derived from the measured parameters. Once the characteristics of radars are determined, they can be identified. One possible task of an EW system is to sort and classify received pulses from dense environment of hostile radars so that the pulses can be processed; this process is known as pulse **deinterleaving**. The main aim of the deinterleaving process [2] is to detect and extract repeating structures.

A simplified block diagram of a typical ESM system is given below :

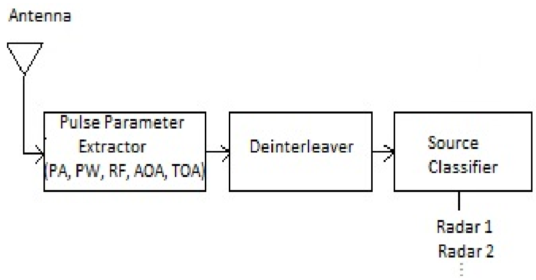

Fig.1b. ESM System

The ESM system shown in Fig.1b, receives signals via the antenna to give it to the pulse parameter extractor, which extracts the characteristics of the received signal/pulses, like pulse amplitude, pulse width, time of arrival, etc. Once the pulse characteristics are identified, the deinterleaver uses one or more of the pulse parameters to identify the individual source emitters. The source classifier then classifies each signal indicating which signal belongs to which radar emitter.

The ESM system surveys the surrounding environment and keeps track of the number of surrounding radar emitters in that region and alerts the host system when a threat emitter is detected .

The major pulse-radar emitter characteristics / pulse descriptor words (PDWs) that an ESM system can measure include :

1. Radio Frequency (RF)
2. Amplitude (power)
3. Angle of Arrival (AOA)
4. Time of Arrival (TOA)
5. Pulse Repetition Interval (PRI)
6. Pulse Width (PW)

In this project, we make use of the TOA data of the incoming interleaved pulse sequence to extract the PRI of the individual signals using the sequential difference (SDIF) histogram method and then perform sequence searching to retrieve the individual signals. The extracted PRIs are then subjected to stagger-analysis to detect the presence of any staggered PRI (level-2).

II. CONCEPT OF INTERLEAVING & DEINTERLEAVING

A periodic pulse train consists of a sequence of periodically spaced pulses. Often a single channel receiver will receive periodic pulse trains from a number of sources concurrently. The act of combining / coming together of all the received pulse sequences results in what is known as an **interleaved** pulse sequence. The process of retrieving the individual signals from the received interleaved pulse sequence is known as pulse train **deinterleaving**. This process is demonstrated in Fig.2a.

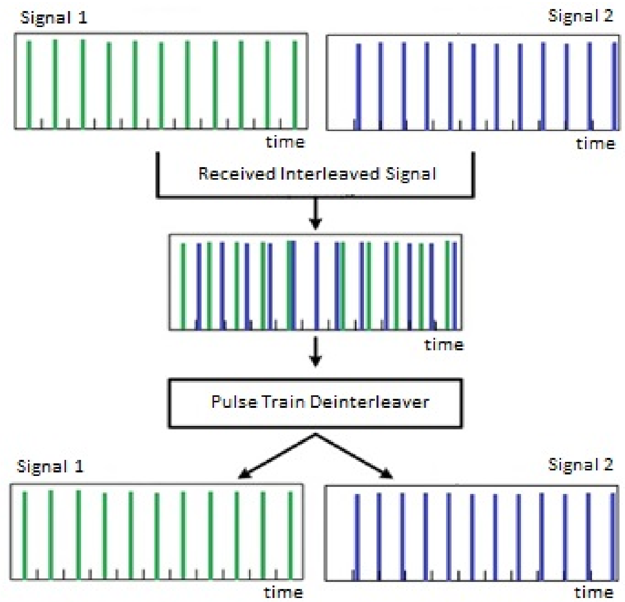

Fig.2a. Concept of Interleaving and Deinterleaving

In the figure above, the two plots at the top represent periodic pulse trains emitted from two individual radars. The center plot shows how the interleaved signals will appear at the EW receiver. The plots at the bottom represent the successful deinterleaving of the received signal, which in a perfect scenario, should identically match the top plots.

Block Diagram of Deinterleaver:

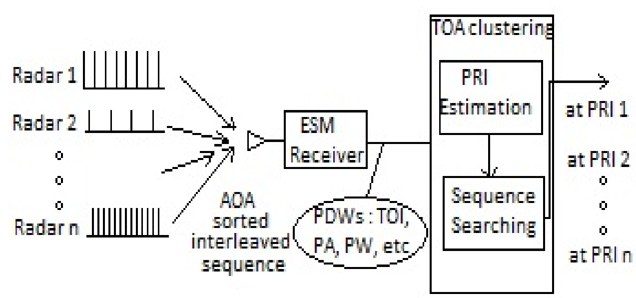

Fig.2b. Typical deinterleaver

Fig.2b. illustrates the structure of a typical deinterleaver. Each emitter emits pulses at a certain interval, or pulse repetition interval (PRI).

As these signals approach the receiver, they are mixed by the channel, AOA sorted to form clusters, and present themselves as an interleaved sequence depending on their times of arrival.
Once the pulse descriptor words are extracted, TOA deinterleaving is performed on the received pulse sequence. TOA deinterleaving is performed in two steps:
a) PRI estimation & **b)** Sequence searching.

The deinterleaver obtains a possible PRI and begins sequence searching to seek pulses to form a pulse sequence matching the estimated PRI. If searching succeeds, the deinterleaver extracts the matched pulses from the mixture. The deinterleaver repeats the two steps repeatedly until the remaining pulses cannot form any PRI sequence.

III. SDIF HISTOGRAM FORMING

SDIF Histogram:
The SDIF histogram algorithm is a type of time-of-arrival (TOA) difference algorithm. It is a modified and improved version of the cumulative difference histogram (CDIF). It perfoms simple but efficient computations and helps to extract the PRIs successfully in the EW environment.
Assume that N pulses are collected over a particular time period. The difference between the TOA for adjacent pulses is calculated resulting in N−1 values. For example, the jth difference, dj, is calculated as :

$$dj = |TOA(j) - TOA(j+1)|$$

A histogram of the difference values is constructed against bin heights, where each bin height corresponds to each unique calculated difference. Bins with heights exceeding a particular threshold are taken as valid PRIs. And, the sequence search at this PRI is conducted. If no sequences are extracted , we upgrade the SDIF order, i.e. go for the next level difference (second-level), where the TOA differences between each pulse and the next but one is calculated and the same procedure is carried on till all the PRIs are extracted or till the end of the observation time.

Mathematically, the optimal threshold takes the form of the exponential function described in equation below [14] :

$$\mathrm{Thr}(\tau) = x*(E\text{-}c)\}*e^{\frac{-\tau}{kN}}$$

$$\text{where,} \quad p(\tau) = \frac{x*E}{\tau}$$

τ is the bin number, E is the number of observed pulses, and x is a constant less than 1. N is the total number of bins in the histogram, and c is the difference level.
Compared to the cumulative difference (CDIF) histogram technique of TOA difference algorithm, SDIF techniqueis less sensitive to interference and missing pulses [14], and the SDIF technique has been successful in high pulse density radar environments for different types of pulse repetition intervals.

For the received interleaved sequence (formed by the superposition of 3 input signals), the SDIF histogram of difference-level one is shown in the figure below. The time of arrival difference values corresponding to 1350, 5112 and 7068 have greater (distinct) bin heights i.e. they form the primary, secondary and tertiary peaks in the histogram. These are taken as the valid PRI values, and will be used for sequence searching.

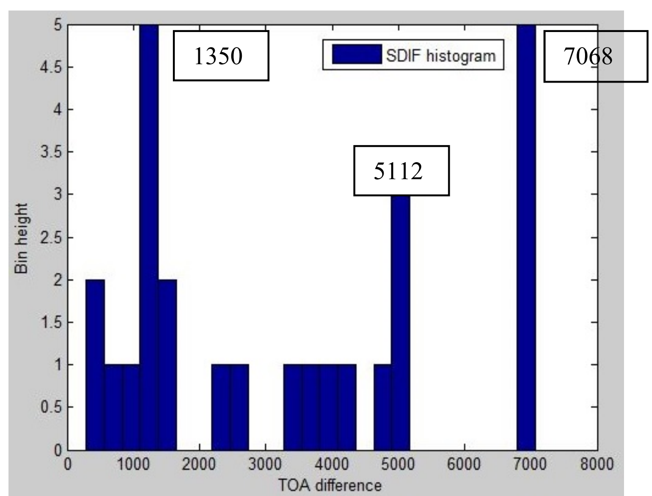

Fig.3 SDIF Histogram 1

Once the potential PRI is identified, the program performs sequence search i.e. it looks for a group of pulses that form a periodical pulse train, with periods equal to PRI. If the search is successful, the PRI sequence will be extracted from the input buffer. If there is no detection (i.e. pulses do not form the PRI sequence), or if none of the histogram values exceeds the set threshold, the next difference will be calculated and the process is repeated till all the pulse sequences are successfully extracted. If more than one histogram value exceeds the set threshold, the sequence search is performed for every potential PRI value, starting from the lowest.

IV. DEINTERLEAVING ALGORITHM

Assuming that the ESM receiver has received radar signals from a particular AOA, observed over an observation interval ‘nt’, the proposed algorithm in this study uses TOA information for deinterleaving these signals. In the first stage of the project, The TOA data is sorted, and an SDIF histogram is formed for the different difference-levels and based on set threshold. As the histogram bin for a particular difference-level exceeds the set threshold value, the particular interval is noted as a valid PRI and sequence search for this PRI is performed. If the extraction of PRI sequence is successful, the process is repeated until the extraction of pulse train. If the sequence search cannot extract a PRI sequence, next difference is calculated and the whole process is repeated (Fig.4a). In the second stage of the project, the extracted PRI values in that particular time frame are subject to stagger PRI analysis (level-2 stagger) to check for the presence of any staggered PRI pattern. The algorithm detects and displays the PRIs that form the stagger PRI pattern coming from a radar emitter.(Fig.4b).

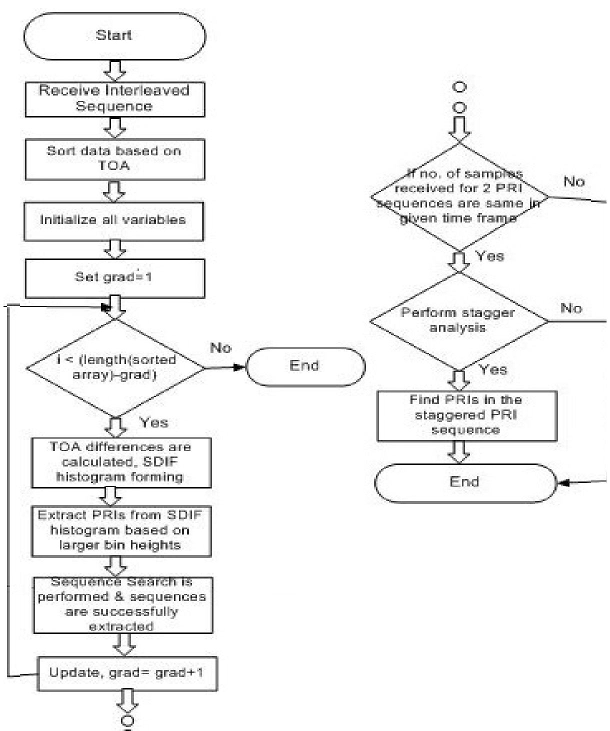

Fig.4a. Flowchart for PRI extraction

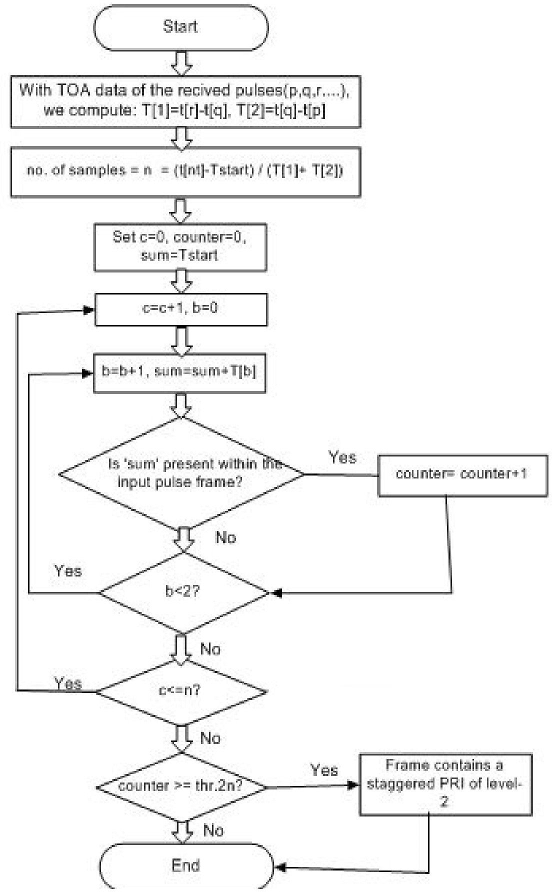

Fig.4b. Flowchart for stagger PRI detection

This algorithm is implemented using MATLAB. MATLAB is chosen because of its ability to handle big matrices and also for fast implementation of the scenario and new sorting algorithms.

V. RESULTS

Using the developed program code based on SDIF histogram method in MATLAB, the following results were obtained:

A. Constant PRI

Example 1: For 3 radar emitters

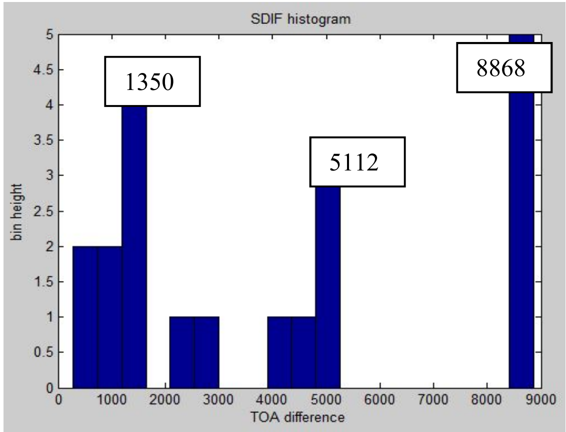

Fig. 5.1a SDIF histogram 1

The SDIF histogram (difference level 1) for constant PRI signals is shown in Fig.5.1a. It was obtained on running the program code (Refer flowchart in Fig. 4a) in MATLAB to identify and extract the valid PRIs. The valid PRIs were found to be 1350, 5112, 8868 (which correspond to the primary and secondary and tertiary peaks in the SDIF histogram. Sequence search was performed to obtain the pulse sequences corresponding to the above mentioned PRI, and the pulse sequences were successfully extracted.

Example 2: For 4 radar emitters

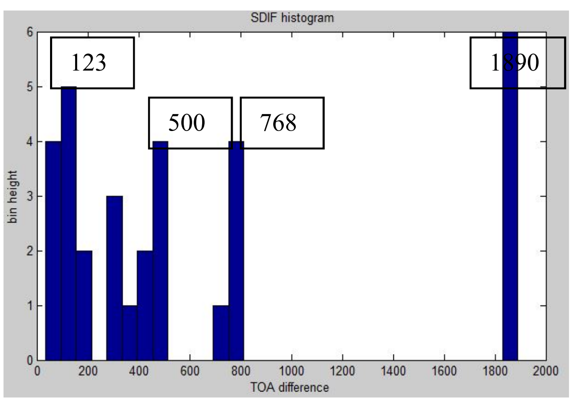

Fig. 5.1b SDIF histogram 2

The SDIF histogram (difference level 1) for constant PRI signals is shown in Fig.5.1b. It was obtained on running the program code (Refer flowchart in Fig.4a) in MATLAB to identify and extract the valid PRIs. The valid PRIs were found to be 123, 500, 768, 1890 (which correspond to the primary and secondary peaks in the SDIF histogram). Sequence search was performed to obtain the pulse sequences corresponding to the above mentioned PRI, and the pulse sequences were successfully extracted.

Example 3: For 5 radar emitters

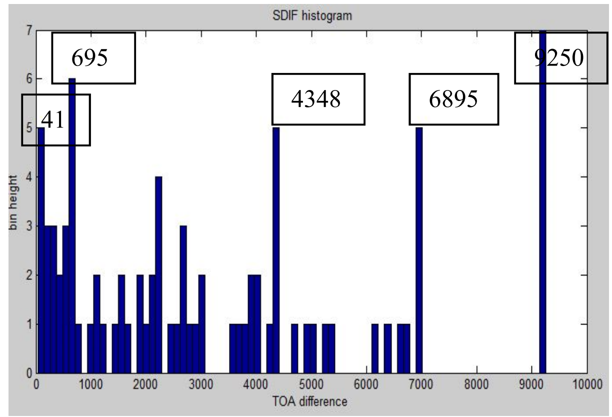

Fig. 5.1c SDIF histogram 3

The SDIF histogram (difference level 1) for constant PRI signals is shown in Fig.5.1c. It was obtained on running the program code (Refer flowchart in Fig.4a) in MATLAB to identify and extract the valid PRIs. The valid PRIs were found to be 41, 695, 4348, 6895, 9250 (which correspond to the primary and secondary peaks in the SDIF histogram). Sequence search was performed to obtain the pulse sequences corresponding to the above mentioned PRI, and the pulse sequences were successfully extracted.

***B.* Staggered + Constant PRI Case**

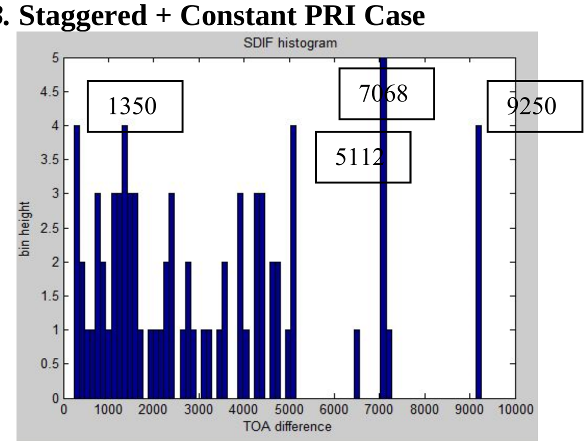

Fig.5.2a SDIF Histogram

output.xls

	A	B	C	D
	Slno	TOA	PRI1	PRI_Type
	Number	Number	Number	Cell
1	Sl no.	TOA	PRI	PRI_Type
2	1	101	1350	Constant
3	2	274	7068	Staggered
4	3	205	9250	Constant
5	4	274	5112	Staggered

Fig.5.2b Tabulated Result

The SDIF histogram (difference level 1) shown in Fig.5.2a. was obtained on running the program code (Refer Fig.4a.) in MATLAB to identify and extract the valid PRIs. The valid PRIs were found to be 1350, 5112, 7068 and 9250. Sequence search was performed to obtain the pulse sequences corresponding to the above mentioned PRI, and the pulse sequences were successfully extracted. Next, to detect the presence of any staggered PRI (level-2) among the extracted PRI, another program code written in MATLAB was used (Refer Fig.4b.) and it confirmed that the frame contains a dual stagger PRI with PRIs 7068 and 5112 and the results were tabulated as shown in Fig.5.2b.

C. Illustration of Effect of Noise

The SDIF histogram (difference level 1) shown in Fig.6.6a. was obtained on running the program code (Refer Flowchart in Fig.4a) in MATLAB to identify and extract the valid PRIs.The valid PRIs were found to be 57, 132, 257 (which correspond to the primary, secondary and tertiary peaks in the SDIF histogram). The workspace containing the extracted PRIs is shown in Fig.6.6b. Sequence search was performed to obtain the pulse sequences corresponding to the above mentioned PRI, and the pulse sequences were successfully extracted.

Fig. 6.6c shows the SDIF histogram obtained on adding random noise signals to an input signal (originally multiples of 257). The PRIs obtained are 57, 132, 258, as shown in the workspace (Fig.6.6d). We observe a slight shift in the PRI value due to the noise added. Appropriate tolerance levels can be chosen as per the need.

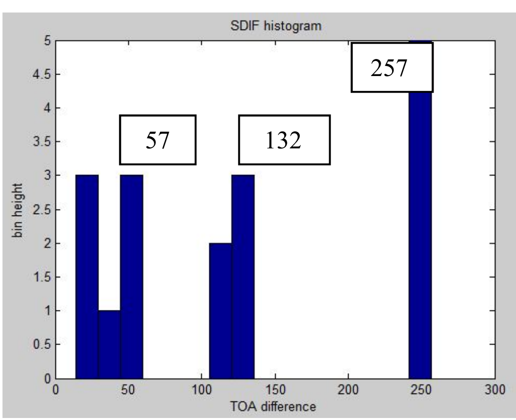

Fig. 6.6a SDIF histogram Without Noise

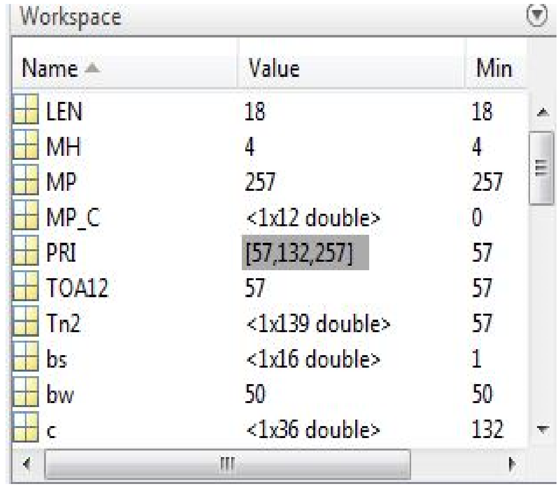

Fig. 6.6b PRI Value (Without Noise)

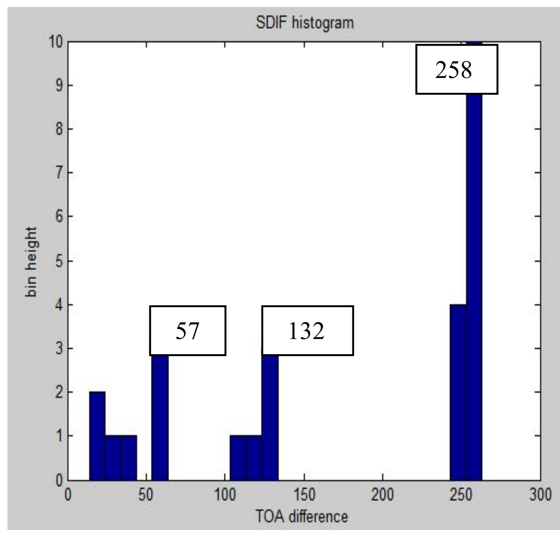

Fig. 6.6c SDIF histogram With Noise

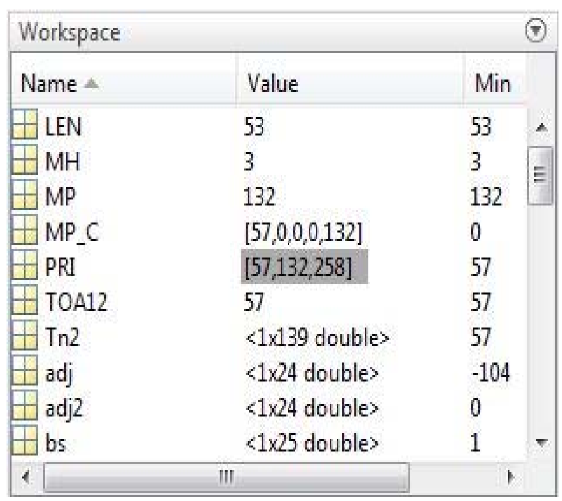

Fig. 6.6d PRI value shifts slightly due to Noise

VI. CONCLUSION & FUTURE WORK

This paper presents an improved algorithm for deinterleaving radar pulses received by the ESM receiver, based on TOA analysis using the SDIF histogram.

The algorithm is implemented using MATLAB, given its ability to handle big matrices, fast implementation of the scenario and new sorting algorithms. The SDIF histogram is a simple and straightforward method to estimate the PRI of the received signal. Here, only current differences exist and there is no need to compare the double PRI with the threshold, like in the CDIF histogram. Thus, the computation time is more than halved. Once the PRIs are extracted, sequence search is performed and the valid PRI sequences are successfully extracted. The extracted PRIs and their respective sequences are then subject to stagger-analysis to check for the presence of any staggered PRI (level-2) among the extracted PRIs.

For future work, the algorithm can be improvised to perform in high-pulse-density radar environments with complex signal types (i.e. higher level of staggering / jittered pulses).

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