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Research on the Sequential Difference Histogram Failure Principle Applied to the Signal Design of Radio Frequency Stealth Radar

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Abstract: As electronic warfare becomes the core of modern warfare, radio frequency (RF) stealth radar is becoming the focus of modern electronic warfare. The anti-sorting strategy of RF stealth radar is a new effective method of the anti-enemy electronic reconnaissance system. Hence, research on the failure mechanism of sorting algorithms has become the cornerstone of anti-sorting technology. In this paper, the mechanism of algorithm failure is studied because the SDIF algorithm is widely used in engineering practice throughout the whole workflow of the sequential difference histogram (SDIF) algorithm, from the estimation of pulse repetition interval (PRI) destroyed by the algorithm and algorithm analysis to the staggered signal. Firstly, the working steps of the SDIF histogram sorting algorithm are considered. Key steps of signal sorting by the algorithm are analyzed, and the failure principle of the sorting algorithm is proposed. It is pointed out that if the PRI signal center value of the two groups of radars is within the tolerance range of the sorting algorithm, when the two signal center values are not of the same order of magnitude, the difference is more than 10 times, and the signal variation is less than 30% of the center value, the sorting error of the algorithm for the radar signal is at least 25%. The sorting algorithm fails to sort signals. At the same time, for the sorting failure of the staggered signal, the sub-PRI design formula of the staggered signal is proposed, and the staggered signal satisfying the design formula can make the sorting algorithm invalid. Finally, the correctness of the SDIF failure principle is further verified by formula derivation, signal design simulation and experiment. The principle of sorting failure provides theoretical support and foundation for the design of anti-sorting RF stealth signal. The principle of sorting failure makes up for the shortcomings of random signal design and improves the design efficiency of RF stealth signal.

Keywords: electronic countermeasure; radio frequency stealth radar; sorting failure; sequential difference histogram (SDIF); pulse repetition interval estimation; staggered signal design

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1. Introduction

With the extensive use of radio equipment, electronic countermeasures have gradually become the core of modern warfare [1]. The prerequisite for electronic countermeasures is electronic reconnaissance [2]. As the function of electronic reconnaissance systems becomes increasingly comprehensive and precise, radio frequency (RF) stealth radar is becoming a research hotspot to counter the electronic reconnaissance systems in modern electronic countermeasures [3]. According to the signal detection process of electronic reconnaissance systems, RF stealth radar [4] mainly has three countermeasures, anti-interception [5–7], anti-sorting [8] and anti-identification, to achieve RF stealth. In the anti-interception strategy, radar realizes RF stealth mainly by power control of radiation sources and directional antennas [9]. The anti-sorting strategy is primarily through the anti-sorting signal design technique to achieve RF stealth [10], and the anti-identification strategy is mainly through the complex signal design. Even if the signal is intercepted and sorted, there is no relevant signal data in the radar database to match and identify the signal, failing to achieve RF stealth.

Due to the extensive application of low SNR receivers and the rapid development of digital signal processing technology in modern warfare, RF stealth radar using a low intercept strategy to achieve RF stealth is insufficient to completely counter electronic reconnaissance from the enemy. Therefore, the RF stealth anti-sorting strategy becomes another important research direction of RF stealth radar. The signal sorting and identification of the radiation source by electronic reconnaissance systems is mainly to sort the pulse sequences of each radiation source from the random staggered pulse stream received by the intercepted receiver to obtain information about radiation sources in the environment [11,12]; the steps include pre-sorting and main sorting. The main sorting acts as the core of the signal sorting of radiation sources. Usually, the pulse repetition interval (PRI) and its modulation mode of each radiation source in the electromagnetic environment are obtained by processing the arrival time of each pulse [13,14]. Therefore, enhancing the performance of RF stealth radar in terms of the anti-sorting strategy focuses on its ability to resist PRI-based sorting. At present, PRI-based anti-sorting research is mainly concentrated on anti-sorting signal design technology. There are two design methods for anti-sorting signals. First, jamming pulses are added to the radar signal to disrupt the interception and recognition of the PRI pulse signal by the enemy intercept receiver [15–18]. Second, jitter is added to the PRI of the pulse signal, and each pulse has a different PRI. Thus, it is difficult for the enemy intercept receiver to sort radar signals [17,19,20]. Although the methods above have been effective, the stability of the anti-sorting performance of the designed signals needs to be further verified. The method of signal design relies more on the experience of researchers. A strict sorting failure principle is lacking as a theoretical guide.

In this paper, we studied the failure principle of the SDIF algorithm widely used in signal sorting. It is proposed for the first time that if the PRI center value of two groups of radar signals is within the tolerance range of the sorting algorithm and the difference is more than 10 times, and the signal variation is within 30% of the center value, the sorting error of the sorting algorithm for the radar signals is at least 25%, which makes the sorting algorithm invalid. At the same time, a formula for the precise design of the PRI value for a staggered signal is presented. If the PRI value of the staggered signal is designed according to the formula, the SDIF sorting algorithm will incorrectly sort the staggered signal into a fixed PRI signal, and the sorting algorithm cannot sort signals. The sorting failure principle provides a theoretical basis for the anti-PRI sorting signal design and avoids the blindness of signal design. The paper is structured as follows: The SDIF sorting algorithm is analyzed in detail in Section 2. The principle of SDIF sorting failure is discussed in Section 3. In Section 4, the signal parameters are designed according to the principle of sorting failure, and the designed signals are compared and verified by simulation and experiments. Section 5 presents the summary of the paper.

2. SDIF Algorithm

Radar signal source sorting, also known as deinterleaving of radar radiation source signals, refers to the process of separating various radar pulse sequences from randomly interlaced pulse streams. In essence, it is the matching of parameters for each signal pulse. Researchers treat the most similar pulses as the pulse sequences produced by the same signal source, using characteristic parameters extracted in different domains or measured between or within pulses and matching them in databases or with each other. Otherwise, they are regarded as the pulses generated by various radiation sources to complete the deinterlacing of the pulse flow.

In engineering, histogram sorting is the most commonly used method that estimates the PRI value of radiation source signals based on the statistical principle. The cumulative difference histogram (CDIF) and sequential difference histogram (SDIF) are two improved algorithms commonly used in engineering.

Essentially, both SDIF and CDIF belong to TOA difference histogram sorting methods. The two sorting algorithms count the TOA difference of pulses according to certain rules and analyze PRI estimation. Then, the pulse sequence is searched based on the PRI estimate. Finally, the radiation source pulse sequences are extracted [21,22]. Compared with the traditional histogram sorting algorithm, SDIF and CDIF algorithms greatly reduce the computational amount and are real-time. Additionally, the two algorithms can sort PRI fixed, PRI stagger, and jitter radiation source signals. They are widely used in the engineering field [23–25].

In this paper, mainly the failure mechanism of the SDIF algorithm is studied. The SDIF sorting algorithm mainly includes TOA difference histogram analysis and pulse sequence search. The TOA difference histogram analysis is used to estimate PRI values. The histogram statistics method is used to calculate the number of TOA differences on a level-by-level basis. If the number of TOA difference statistics exceeds the detection threshold, then the TOA difference corresponding to the peak divided by the statistical series of the TOA difference is the possible PRI value. Therefore, the determination of the threshold equation is critical.

SDIF threshold formula is shown in (1):

$$T_{thre}(\tau) = x(E - C)e^{-\tau/kQ} \tag{1}$$

where E is the total number of pulses; C is the order of the histogram; k is a constant within $[0, 1]$; Q is the number of cells counted in the histogram; x is a tunable constant, usually determined by the pulse loss rate.

In the actual signal sorting process of the SDIF sorting algorithm, the influence of the intercept receiver on the pulse TOA measurement needs to be avoided to enhance the sorting performance of the algorithm for jitter signals. Therefore, the tolerance ε of the signal PRI value T is set in SDIF and its improved sorting algorithm. The interval T is determined by the tolerance, i.e., the PRI interval or the small box of PRI. The upper and lower limits of the small box can be expressed as:

$$T_{\max} = T + \varepsilon \tag{2}$$

$$T_{\min} = T - \varepsilon \tag{3}$$

Then the box range of the PRI value is $T_{\min} \leq T \leq T_{\max}$. The PRI value of the histogram is the weighted average of the values that fall into the PRI box. Hence, the weighted average function $\overline{T}$ should be:

$$\overline{T} = \sum_{i=1}^{n} (x_i/S) \cdot T_i \tag{4}$$

where S denotes the sum of the pulse number corresponding to adjacent PRI values $T_1, T_2, \cdots, T_i$ within tolerance; x_i is the number of the PRI value T_i corresponding to pulses within tolerance.

The above is a detailed description of the PRI estimates in the first step. Then, the signal sequence search is analyzed in the second step of the algorithm. The sequence search extracts the radiation source pulse sequence from the PRI estimate obtained in the first step. First, the PRI estimate is used to judge whether three pulses can be continuously searched in the staggered pulse stream. If it is useful, it is a true PRI. Then, with these three pulses as the starting point, the remaining pulses of the radiation source whose arrival time difference is close to each other are searched backward successively. If it is useless, it is a false PRI, and the PRI estimate is discarded. In addition, we can use other PRI estimates that exceed the threshold of sequence search. The estimated PRI obtained in the first step can also be screened, and the real value of PRI can be obtained by pulse sequence search.

3. SDIF Sorting Failure Principle

The study of the SDIF sorting failure mechanism should focus on the whole process of the SDIF sorting algorithm. Then, the corresponding sorting failure principle is studied by analyzing the defects in the sorting process. The SDIF workflow is shown in Figure 1.

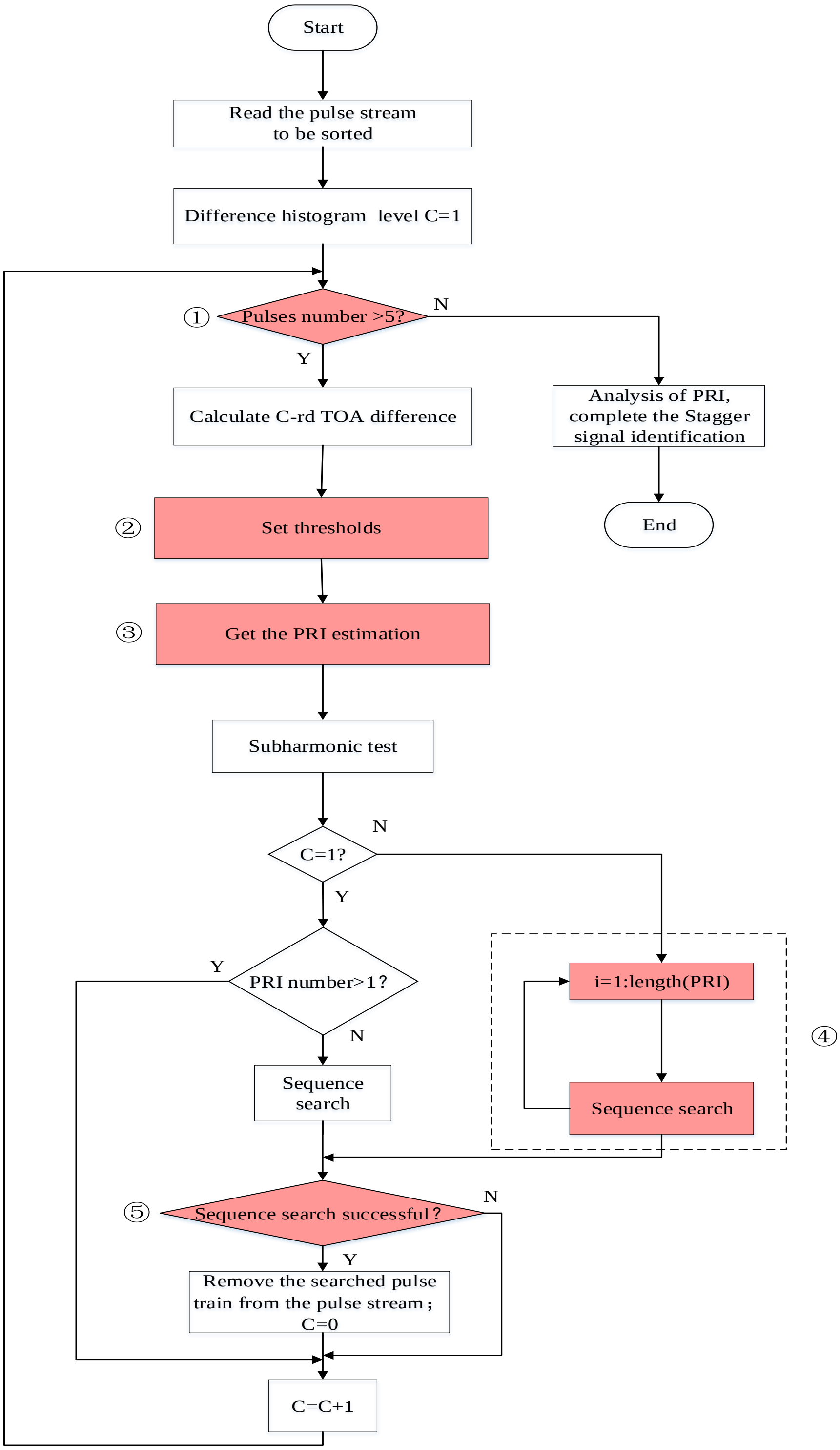

Figure 1. SDIF sorting flow chart.

The workflow analysis in Figure 1 shows that sorting failure occurs in the marked five links.

① The number of pulses less than or equal to five will abort sorting. The sorting object of the SDIF algorithm is the pulse stream processed by clustering and other pre-sorting algorithms.

② The number of accumulated pulses in the histogram is less than the threshold value, resulting in no output of the algorithm. In the sorting algorithm, the histogram statistics compare with the threshold function to obtain the potential PRI estimate. The interval distribution of PRI causes the number of accumulated pulses in the histogram to be less than the threshold value.

③ The SDIF sorting algorithm generates incorrect PRI estimates. To address the measurement error of the arrival time of signal pulses by the electronic reconnaissance receiver, a tolerance range is usually set in the sorting algorithm. However, due to the non-cooperation between radar and electronic reconnaissance systems and unreasonable algorithm tolerance settings, the sorting algorithm tends to generate wrong PRI estimates.

④ The SDIF sorting algorithm based on second-level to multi-level histogram over-threshold statistical peaks performs the wrong pulse search, leading to sorting failure. For special signal systems such as staggered signals and pulse repetition interval slide signals, since multiple statistical peaks exceed the threshold in the first-order histogram, the second-order histogram is used to count pulses. The precise design of signal PRI leads to the error of pulse search in the sorting algorithm.

⑤ The SDIF sorting algorithm cannot satisfy the real-time search of signal pulse sequences, resulting in sorting failure. In the complex electromagnetic environment, millions or even tens of millions of pulses arrive at the electronic reconnaissance receiver every second. With such a large number of pulses, sequence search can easily lead to pulse blocking, which greatly reduces the real-time search, thus leading to sorting failure.

After analysis, scholars have researched three aspects: ① signal frequency-hopping design, time-varying pulse width, and pulse arrival angle deception [8,26–28]; high-density pulse flow leads to the ③ failure of threshold function [10] and ⑤ sorting algorithm in real-time sequence search [13,29]. Therefore, the above three aspects are not studied in this paper. The failure principles of SDIF sorting are mainly studied from two perspectives: the estimation of the PRI value in step ② and the pulse search of the staggered signal in step ④.

3.1. Failure Principle of SDIF Sorting Based on PRI Estimation

In the actual working environment, the sorting algorithm usually needs to sort hundreds or thousands of radiation source signals simultaneously. Although pre-sorting is carried out, dozens of radiation source signals still need to be sorted by the SDIF main sorting algorithm. By analyzing the workflow of the SDIF algorithm, it can be seen that the sorting principle of the algorithm for more than two radar signals is the same. Therefore, to simplify the analysis process while remaining general, the SDIF sorting algorithm for two radar signals is taken as an example to analyze the failure principle of SDIF sorting.

Without loss of generality, it is assumed that there are two radar transmitting signals, and the signals of each radar comprise a set of pulse sequences with the same signal system but different PRIs. The pulse sequence of the first radar consists of N pulses. The pulse sequence of the second radar signal is composed of M pulses, as shown in Figure 2.

Therefore, the expressions of the PRI value T of the two groups radar signals are:

$$T_{1i} = T_{10} + \Delta T_{1i}(i = 1, \cdots, N) \tag{5}$$

$$T_{2j} = T_{20} + \Delta T_{2j}(j = 1, \cdots, M) \tag{6}$$

where, T_{10} and T_{20} are the central values of signal PRI; ΔT_{1i} and ΔT_{2j} are the increments of signal PRI and the elements of signal PRI variation sets ΔT_1 and ΔT_2, namely $\Delta T_{1i} \in \Delta T_1$, $\Delta T_{2j} \in \Delta T_2$.

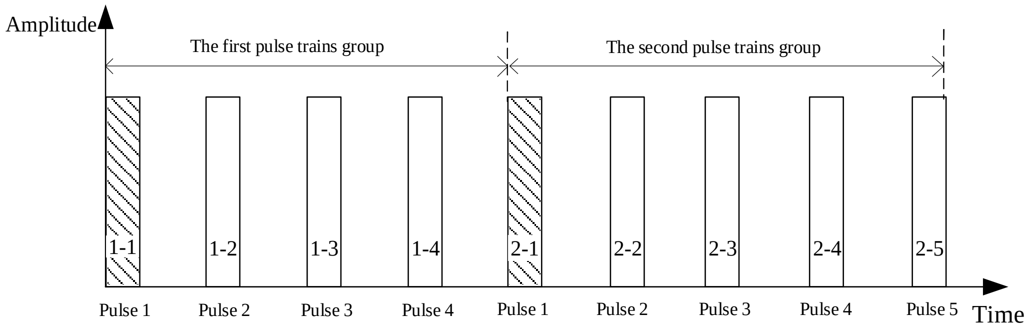

Figure 2. Schematic diagram of the radar transmitting signals with four sub-pulses as an example.

The principle of SDIF separation failure is deduced. Two groups radar signals are sorted by the SDIF sorting algorithm. It is necessary to judge whether the radar signals are within the tolerance range of the same sorting algorithm, i.e., the relationship between the difference in the center value of the radar signal and the tolerance of the algorithm. According to the relationship between the tolerance range and the difference in the signal center value, this paper mainly discusses two aspects: the difference between the center values of two groups' radar signals is greater and less than the tolerance. The difference is shown in Equation (7).

$$T_{12\text{diff}} = |T_{10} - T_{20}| \tag{7}$$

3.1.1. The Difference between the Center Values of Two Groups' Radar Signals Is Greater than the Tolerance

When $T_{12\text{diff}} > \varepsilon$, the sorting algorithm sorts the two signals separately. Therefore, in the first-order histogram sorting process, it can be known from Equation (4):

$$\overline{T_{1i}} = \sum_{i=1}^{N} T_{1i} \div N = T_{10} + \frac{1}{N}\sum_{i=1}^{N} \Delta T_{1i} \tag{8}$$

$$\overline{T_{2j}} = \sum_{j=1}^{M} T_{2j} \div M = T_{20} + \frac{1}{M}\sum_{j=1}^{M} \Delta T_{2j} \tag{9}$$

Therefore, the SDIF sorting algorithm can accurately sort the corresponding two radar signals.

3.1.2. The Difference between the Center Values of Two Groups' Radar Signals Is Greater than the Tolerance

When $T_{12\text{diff}} < \varepsilon$, the following equations can be expressed according to Equation (7):

$$\overline{T} = \left(\sum_{i=1}^{N} T_{1i} + \sum_{j=1}^{M} T_{2j}\right) \div (M+N) \tag{10}$$

According to Equations (5) and (6), Equation (11) can be expressed:

$$\sum_{i=1}^{N} T_{1i} + \sum_{j=1}^{M} T_{2j} = NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} \tag{11}$$

Therefore,

$$\overline{T} = \left(NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j}\right) \div (M+N) \tag{12}$$

Essentially, different signal systems are manifested by the different sets ΔT_1 and ΔT_2 of the PRI variation of the signal. Therefore, PRI increment sets A and B are the main variables of Equation (12). Three cases are discussed by analyzing the composition of elements in sets ΔT_1 and ΔT_2. ① The elements in sets ΔT_1 and ΔT_2 are all 0, and the signal is a fixed repetition signal. ② The elements in sets ΔT_1 and ΔT_2 are finite elements arranged repeatedly, and the signal is the jagged signal. In the special case, if the finite elements in sets ΔT_1 and ΔT_2 are arranged in an equal difference and repeated cyclically, the signal is a PRI slide signal. ③ The elements in sets A and B are pseudo-random code sequences or random sequences, and the signal is a random PRI signal. In the special case, if the elements in sets ΔT_1 and ΔT_2 are random sequences that obey a small interval distribution, the signal is a PRI jitter signal. Different situations are discussed as follows.

① The elements of the signal PRI variation set are all 0

The elements in sets ΔT_1 and ΔT_2 are all 0, i.e., the PRI of the signal does not change, and it belongs to a fixed repetition signal. Therefore,

$$\sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} = 0 \tag{13}$$

Equation (12) can be simplified as follows:

$$\overline{T} = (NT_{10} + MT_{20}) \div (M + N) \tag{14}$$

Under normal circumstances, the number of the sub-signals M and N of radar signals is not more than 10, and M is approximately equal to N. Therefore,

$$\begin{aligned} \overline{T} &= (NT_{10} + MT_{20}) \div (M + N) \\ &= \tfrac{T_{10}+T_{20}}{2} \end{aligned} \tag{15}$$

The sorting result for the signal is $\overline{T} \in [T_{10}, T_{20}]$. From the perspective of sorting results, the sorting algorithm sorts two radars into one. However, the PRI value of the sorting result is between the two fixed PRIs, and the sum is within the same tolerance range. Combined with the tolerance range, the radar signal pulse can still be searched out, thus realizing signal sorting.

② The elements of the signal PRI variation set are a finite sequence of values

The elements of the PRI variation set of the signal are cyclically repeated arrangements of finite elements, and the signal is a staggered signal. The PRI slide signal is the corresponding radar signal when the isometric sequence is arranged repeatedly. Under normal circumstances, the number of the sub-signals M and N of radar signals is no more than 10, and the elements in the PRI variation set of signals are all less than 0.3 times of the signal center value. Therefore,

$$\sum_{i=1}^{N} T_{1i} = NT_{10} + \sum_{i=1}^{N} \Delta T_{1i} < (N+3)T_{10} \tag{16}$$

$$\sum_{j=1}^{M} T_{2j} = MT_{20} + \sum_{j=1}^{M} \Delta T_{2j} < (M+3)T_{20} \tag{17}$$

Combining Equations (11), (16) and (17) can obtain:

$$NT_{10} + MT_{20} < NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} < (N+3)T_{10} + (M+3)T_{20} \tag{18}$$

According to Equation (12), the sorting result is related to the size–scale relationship of the central value of the two radar signals.

a The center values of the two radar signals are in the same order of magnitude

Considering that the center values of the two radar signals are in the same order of magnitude,

$$T_{10} \approx T_{20} \tag{19}$$

Therefore, Equation (18) is transformed into:

$$NT_{10} + MT_{10} < NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} < (N + M + 6)T_{10} \tag{20}$$

The sorting results of the algorithm combined with Equations (10) and (20) are as follows:

$$T_{10} < \overline{T} < \left(1 + \frac{6}{M+N}\right) T_{10} \tag{21}$$

According to the above analysis, when the PRI center values of two radar signals are in the same order of magnitude, the signal sorting result of the sorting algorithm is $\overline{T} \in [T_{11}, T_{1N}]$. Although the sorting algorithm sorts two radars into one, the PRI value of the sorting is within the PRI variation range of one of the radars. Electromagnetic attack weapons, such as anti-radiation missiles, can still take the sorting result as an important parameter to attack radars.

b The centers of the two radar signals are not in the same order of magnitude

Because the center values of the two radar signals are not in the same order of magnitude, T_{20} is usually about 10 times larger than T_{10}.

$$T_{10} \ll T_{20} \tag{22}$$

Therefore,

$$(N + 3)T_{10} \ll (M + 3)T_{20} \tag{23}$$

Equation (18) is transformed into:

$$MT_{20} < NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} < (M + 3)T_{20} \tag{24}$$

By combining Equations (10) and (24), the sorting results of the SDIF algorithm are obtained.

$$5T_{10} \approx \frac{1}{2} T_{20} \approx \frac{M}{M+N} T_{20} < \overline{T} < \frac{(M+3)}{M+N} T_{20} \approx T_{20} \tag{25}$$

To analyze the error of the sorting results more specifically, the repeated frequency slip signal is taken as an example, i.e., the elements in sets A and B are arithmetic sequences. Since M and N are no more than 10 under normal circumstances, the maximum value of the signal PRI of the first radar is:

$$\begin{aligned} T_{1i\max} &= T_{110} \\ &= T_{10} + \sum_{i=1}^{9} \Delta T_{1i} \\ &< 4T_{10} \end{aligned} \tag{26}$$

The sorting error of the SDIF algorithm is:

$$\eta = \frac{\overline{T} - T_{1i\max}}{T_{1i\max}} = \frac{5T_{10} - 4T_{10}}{4T_{10}} = 25\% \tag{27}$$

It can be seen from Equation (25) that when the element in the change set of signal PRI is greater than 30%, the right half $\frac{(M+3)}{M+N} T_{20} \approx T_{20}$ of Equation (25) cannot meet the approximation condition. Therefore, the element value in the variation set of signal PRI cannot exceed 30% of the central value.

Through the above analysis, when the center values of the PRI of the two radar signals are not in the same order of magnitude, the output of the sorting algorithm is not in the PRI variation range of the transmitted signal. Moreover, the output of the sorting algorithm differs from the maximum PRI of the first radar signal by at least 25%. Wrong sorting results will directly lead to the failure of the electronic jamming system to jam the radar system and make the anti-radiation missile bind wrong parameters, which cannot attack the radar accurately and ensure the safe operation of the radar system.

③ Elements in the signal PRI variation set are random sequences

According to the previous derivation, the sorting results of signals are shown in Equation (15), which is rewritten as follows:

$$\overline{T} = \left(NT_{10} + MT_{20} + \sum_{i=1}^{N} \Delta T_{1i} + \sum_{j=1}^{M} \Delta T_{2j} \right) \div (M+N) \tag{28}$$

Under normal circumstances, the number of the sub-signals M and N of radar signals does not exceed 10, and the mean of the signal PRI ΔT is less than 0.3 times the signal center value.

$$E(x_{1i}) = 0.3T_{10} \tag{29}$$

$$E\left(x_{2j}\right) = 0.3T_{20} \tag{30}$$

Hence,

$$\sum_{i=1}^{N} T_{1i} = NT_{10} + \sum_{i=1}^{N} \Delta T_{1i} = NT_{10} + 0.3NT_{10} < (N+3)T_{10} \tag{31}$$

$$\sum_{j=1}^{M} T_{2j} = MT_{20} + \sum_{j=1}^{M} \Delta T_{2j} = MT_{20} + 0.3MT_{20} < (M+3)T_{20} \tag{32}$$

Therefore,

$$NT_{10} + MT_{20} < \sum_{i=1}^{N} T_{1i} + \sum_{j=1}^{M} T_{2j} < (N+3)T_{10} + (M+3)T_{20} \tag{33}$$

According to Equation (33), the sorting result is related to the relationship between the magnitude and scale of the center values of two radar signals. The next step is to distinguish the two cases in which the center values of two radar signals are in and not in the same order of magnitude. The derivation process is the same as that of Equations (19)–(27) in Step ②. Therefore, we do not repeat it here.

To sum up, no matter whether the signal PRI numerical sequence variation is limited or random, if two radar signal PRI values are within the tolerance range of the sorting algorithm, when the two signal center values are not in the same order of magnitude, the difference is more than 10 times, signal variation is within 30% of the center value, and sorting algorithm for radar signal sorting error is at least 25%. In this way, the radar signal cannot be accurately sorted and identified, which directly leads to the failure of the electronic jamming system to jam the radar system. The anti-radiation missile cannot carry out accurate attacks, which guarantees the safe operation of radar systems.

3.2. Sorting Failure Principle Based on the Precise Design of Staggered Signals

3.2.1. SDIF Algorithm for Staggered Signal Analysis

For radar signals with staggered PRI, multiple radar signals with a similar angle, frequency and pulse width, close PRI value, and fixed PRI are sorted out after using SDIF. The PRI value is equal to the skeleton period, i.e., the sum of the PRI of the staggered signal. According to this characteristic, the radiation source pulse sequences with close PRI in the separation results can be combined. Then, TOA is ordered from small to large to perform first-order histogram statistics. If multiple PRIs with similar peak values can be obtained, and the sum of PRI is equal to the skeleton period, the signal is judged to be a staggered signal, and each PRI is the sub-PRI of the staggered signal. The specific analysis is as Algorithm 1 follows:

Algorithm 1 Staggered signal sorting via SDIF

Input: Multiple radar pulse sequences with close PRI parameters (all skeleton period T)
Initialization: Difference level C
1: Perform first-level TOA difference histogram statistics on the input radar pulse sequence
2: Judge whether there is more than one peak value in the histogram and they are similar in magnitude
3: Extract the corresponding PRI at the peaks $T_1, T_2, \ldots, T_n$
4: Determine whether the sum of $T_1,\ T_2, \ldots, T_n$ extracted in the third step is equal to the skeleton period. If the sum of $T_1,\ T_2, \ldots, T_n$ is equal to the skeleton period, it is a staggered radar signal; otherwise, multiple PRI fixed signals.

3.2.2. Sorting Failure Principle

According to the analysis in Section 3.2.1, there are two key steps in staggered signal sorting. Firstly, the SDIF algorithm selects multiple radar signals with the PRI value equal to the skeleton period T. Secondly, the stagger analysis of multiple radar signals with similar PRI values in the first step is carried out. Therefore, the sorting failure principle of the SDIF algorithm is to reasonably set up the sub-PRI of the staggered signal so that multiple radar signals with PRI values equal to the skeleton period T cannot be sorted out in step 1, leading to the failure of the analysis of the uneven signal in step 2. In addition, according to the sorting process of SDIF, multiple statistical peaks exceed the threshold in the first-level histogram of the staggered signal. Then, the second-level histogram statistical process is automatically transferred. Therefore, taking the three adjacent staggered sub-signal PRIs as a design group, the values of the three staggered sub-signal PRIs in each design group are accurately designed. Therefore, there are corresponding non-skeleton periods in the histograms of the second level and above. False peaks and sequence search can be successfully performed using the PRI corresponding to the false peaks. Based on the above analysis, the sub-PRI of the staggered signal is precisely designed. The sorting fails when the PRI of the staggered signal meets the following conditions. When the PRI of the sub-staggered signal increases, the PRI design equations are shown in Equations (34) and (35):

$$T_{i-1} + T_{i-2} = T_i,\ \mathrm{mod}(i,3) = 0,\ 3 \le i \le j \text{ and } \mathrm{mod}(j,3) = 0 \text{ or } 1 \tag{34}$$

$$\begin{array}{l} T_{i-1} + T_{i-2} = T_i \\ T_{j-1} + T_{j-2} + T_{j-3} + T_{j-4} = T_j \end{array},\ \mathrm{mod}(i,3) = 0,\ 3 \le i \le j \text{ and } \mathrm{mod}(j,3) = 2 \tag{35}$$

where i is the ith sub-staggered signal, and j is the total number of the staggered signals.

When the PRI of the sub-staggered signal decreases, the PRI design equations are shown in Equation (36):

$$T_i = T_{i+1} + T_{i+2},\ \mathrm{mod}(i+2,3) = 0,\ 1 \le i \le j \tag{36}$$

where i is the ith sub-staggered signal, and j is the total number of the staggered signals.

The specific analysis is as follows:

① The precise design equation for staggered signals is not applicable to two uneven signals

When SDIF sorts two staggered signals, the histogram of the TOA difference in the ideal state without pulse loss is shown in Figure 3.

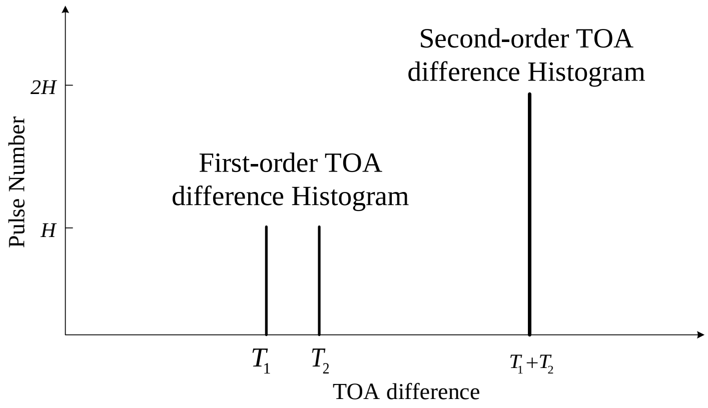

Figure 3. Histogram of the TOA difference in the ideal state of two staggered signals.

As shown in Figure 3, two statistical peaks exceed the threshold in the first-order histogram of the two staggered signals. There is a unique statistical peak at the skeleton period $T_1 + T_2$ in the secondary histogram. According to the sorting process of SDIF, when there is more than one over-threshold peak in the first-order histogram, no sequence search is performed. Next, is the statistical process of second-level histogram signal sorting. In the second-order histogram, a unique statistical peak exists, i.e., the skeleton period of two staggered signals $T = T_1 + T_2$. According to the skeleton period T, a fixed PRI of radar signals can be sorted out, and the corresponding pulse sequence can be searched. The PRI fixed radar pulse sequence with period T can still be searched by re-sorting the remaining pulse sequences with the first-order histogram, as shown in Figure 4.

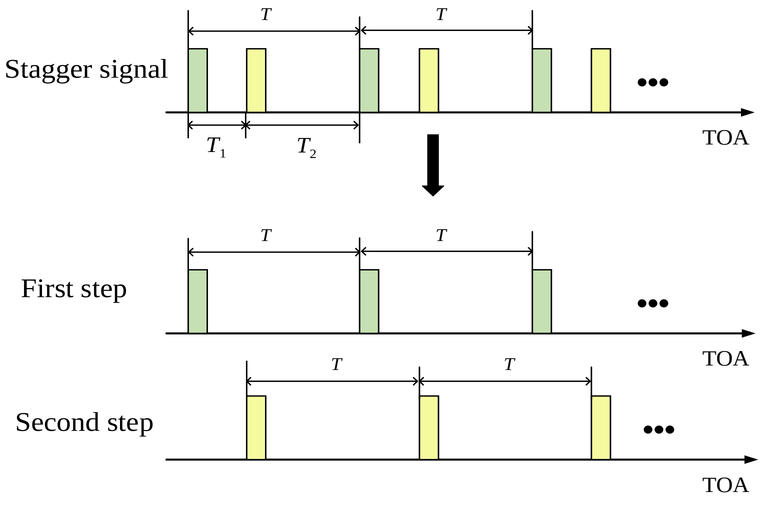

Figure 4. Schematic diagram of the pulse search of two staggered signals.

In Figure 4, T is the skeleton period of two staggered signals, T_1 is the first and T_2 is the second sub-staggered signal. At this point, the requirements of the key step 1 have been satisfied, and two radar signals with PRI equal to the skeleton period are selected to enter the second step and start the staggered signal analysis. Finally, staggered signals with periods T_1 and T_2 can be obtained. Through the above analysis, the SDIF sorting algorithm can always obtain the skeleton period of the two staggered signals but cannot realize the false peaks of the non-skeleton period in the secondary histogram. Therefore, the precise design equation of the staggered signal is not applicable to two staggered signals.

② The sub-staggered signal PRI increases

When the PRI of the sub-staggered signal is in an increasing state, two cases are distinguished. In the first case, the total number of sub-staggered signals is exactly an integer multiple of 3, or the remainder is 1 after taking the remainder of 3. In the second case, the total number of sub-staggered signals is divided by 3, and the remainder is 2. The three and five staggered signals are taken as examples below to analyze Equations (34) and (35), respectively. In the ideal case of no pulse loss for three staggered signals, the statistical results of the TOA difference histogram are shown in Figure 5.

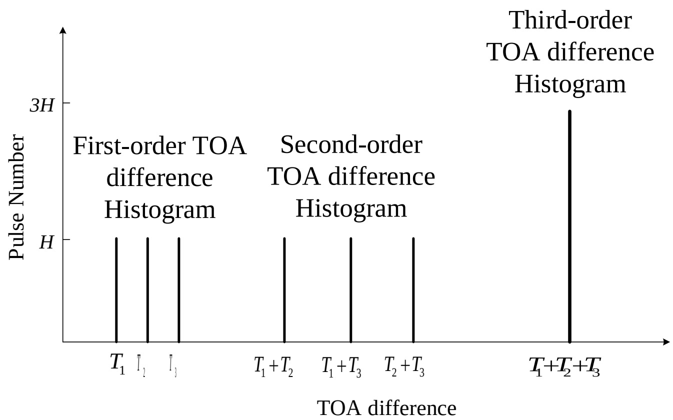

Figure 5. Histogram of TOA difference under the ideal conditions of three staggered signals.

As shown in Figure 5, three staggered signals have three statistical peaks in the first-level histogram. According to the SDIF sorting process, the second-level histogram statistics are started instead of entering the pulse search process. There are also three statistical peaks in the secondary histogram. Since the sub-PRI of the staggered signal increases, the secondary histogram has statistical peaks that exceed the threshold at $T_1 + T_2$, $T_1 + T_3$ and $T_2 + T_3$ in turn. The PRI fixed radar signal pulse sequence with the period $T_1 + T_2$ is first extracted in the order from small to large. The sequence search diagram is shown in Figure 6. Then the remaining pulses are counted again by the first-level histogram, which will form a unique peak at the skeleton period $T_1 + T_2 + T_3$, and the sequence search will select a radar with a PRI of $T_1 + T_2 + T_3$. Therefore, SDIF sorts this staggered signal into two fixed PRI radars with the pulse repetition periods $T_1 + T_2$ and $T_1 + T_2 + T_3$, respectively.

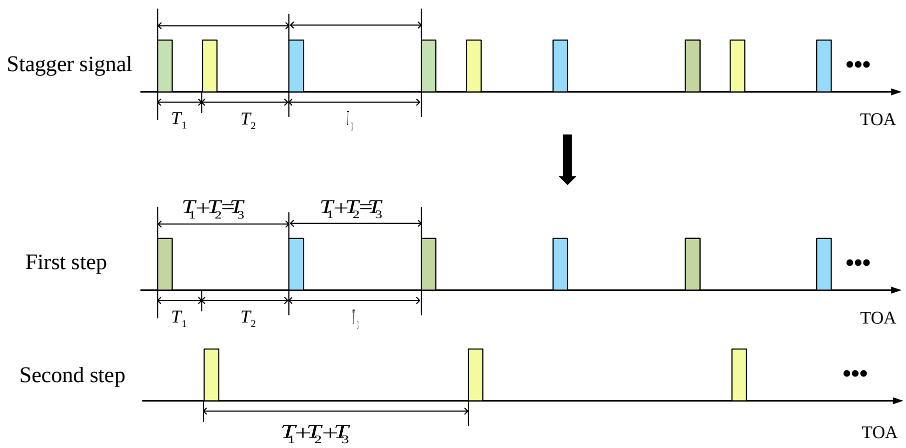

Figure 6. Schematic diagram of the pulse sequence search of three staggered signals.

In Figure 6, T is the skeleton period of three staggered signals, T_1 is the first, T_2 is the second and T_3 is the third sub-staggered signal. The above shows the analysis of the failure principle of the SDIF sorting algorithm for the accurate design of the three staggered signals. For the five staggered signals, since the precise design of PRI is based on the PRI of three adjacent staggered sub-signals as a design group, the remaining two sub-staggered signals can be combined with the phase after the five staggered signals and the remainder of the three sub-staggered signals remain two sub-staggered signals. After the previous group of neighbors is parametrically selected, the remaining sub-signals are precisely designed. In the ideal case of the five staggered signals without pulse loss, the TOA difference histogram has five statistical peaks in the first-level histogram, starting with the second-level histogram statistics without pulse retrieval. There are also five statistical peaks in the secondary histogram. According to the sub-PRI incremental assumption of the staggered signal, the secondary histogram has statistical peaks above the threshold at $T_1 + T_2$, $T_2 + T_3$, $T_3 + T_4$, $T_4 + T_5$ and $T_1 + T_5$ in turn. The schematic diagram of the sequence search is shown in Figure 7.

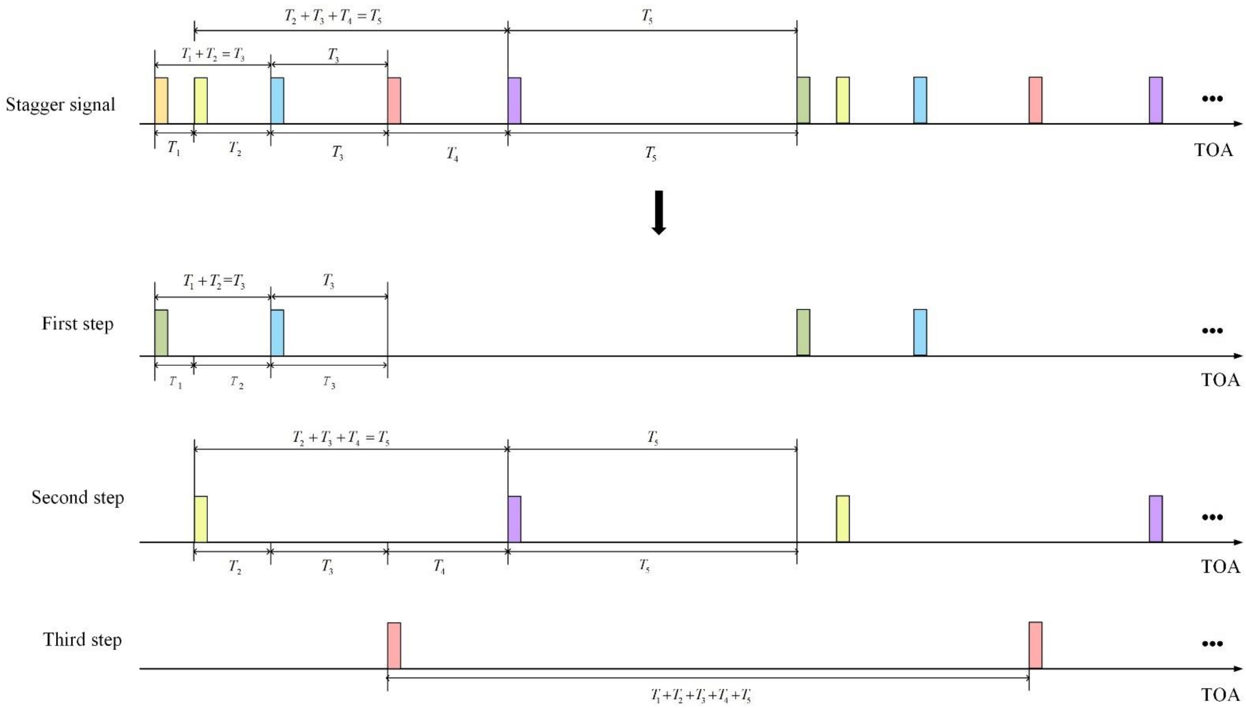

Figure 7. Schematic diagram of the pulse search of five staggered signals.

In Figure 7, T is the skeleton period of three staggered signals, T_1 is the first, T_2 is the second, T_3 is the third, T_4 is the fourth and T_5 is the fifth sub-staggered signal.

The PRI fixed radar pulse sequences (green and blue pulses) with the period $T_1 + T_2$ are firstly extracted in descending order. Then the rest pulse sequences are repeated for first-level histogram statistics, which will form statistical peaks at $T_2 + T_3$, T_4 and T_5, and then enter the second-level histogram statistics process again, forming peaks at $T_2 + T_3 + T_4$, $T_2 + T_3 + T_5$ and $T_4 + T_5$ successively. The pulse sequence with PRI at $T_2 + T_3 + T_4$ is also extracted in descending order. At this point, PRI fixed radar pulses (yellow and purple pulses) with the period $T_2 + T_3 + T_4$ are extracted because of $T_2 + T_3 + T_4 = T_5$. Only the PRI fixed radar pulse (red pulse) with the skeleton period $T_1 + T_2 + T_3 + T_4 + T_5$ is left in the pulse sequence. To sum up, the SDIF sorting algorithm classifies the five staggered signals into three PRI fixed radars with the pulse repetition period $T_1 + T_2$, $T_2 + T_3 + T_4$ and $T_1 + T_2 + T_3 + T_4 + T_5$. An accurate and reasonably designed radar signal PRI can still cause the sorting failure of the SDIF algorithm.

③ The sub-staggered signal PRI decreases

When the sub-staggered signal PRI decreases, the analysis process is the same as that in the first case, where the sub-staggered signal PRI increases and is not repeated here.

To sum up, by accurately designing PRI of uneven signals, the SDIF algorithm can make errors in sorting the nature of radar signals and PRI values, increasing the number of radar targets and eventually causing SDIF sorting to fail.

4. Signal Simulation and Experiments

4.1. Failure Principle of SDIF Sorting Based on PRI Estimation

4.1.1. Signal Parameter Design

According to the analysis in Section 3, the PRI center values of two radar signals are not of the same order of magnitude. Only when the difference is more than 10 times can SDIF sorting fail. In this paper, two radar signals are designed by taking the element of the signal PRI variation set as a finite arithmetic sequence, namely the PRI slide signal. The first radar signal has a PRI starting value of 100 μs and a fixed PRI increment of 30 μs. The second radar signal has a PRI starting value of 1000 μs and a PRI increment of a fixed value of 200 μs. The number of sub-pulses of both radar signals is 10, and the equations of the two signals are shown as follows.

$$PRI_{i+1} = 100 + 30 \cdot i(i = 1, \cdots, N-1) \tag{37}$$

$$PRI_{i+1} = 1000 + 200 \cdot i(i = 1, \cdots, N-1) \tag{38}$$

4.1.2. Signal Simulation Verification

Simulation parameter setting: there are 1000 pulses in the signal, and two groups' radar signals are transmitted repeatedly according to different simulation situations below. The TOA measurement error is 50 ns, and the sequence search tolerance is 1 microsecond. Histogram analysis ranges from 0 to 2000 microseconds, and the statistical interval of the histogram is 0.5 microseconds. Additionally, the SDIF statistical threshold is shown in Equation (1), where, $Q = 4000$, $k = 0.1$, and $x = 0.8$.

The main simulation cases are as follows:

Case 1: The radar signal is a fixed PRI signal with 100 μs.
Case 2: The radar signal is a fixed PRI signal with 1000 μs.
Case 3: The radar signal is repeated 100 times by a set of PRI slide signals. The initial value of the repeated frequency slip signal is 100 microseconds, the PRI increment is fixed at 30 microseconds, and the number of sub-pulses in the group is 10.
Case 4: The radar signal is transmitted 50 times by two groups of PRI slide signals alternately. In the first group, the initial value of the PRI slide signal is 100 microseconds, the PRI increment is fixed at 30 microseconds, and the number of sub-pulses in the group is 10. The initial value of the second group is 1000 microseconds, the PRI increment is fixed at 100 microseconds, and the number of sub-pulses in the group is 10.

Among the above four simulation scenarios, simulation case 1 and simulation case 2 are to verify that the SDIF sorting algorithm and sorting test system can sort fixed carrier frequency signals. Simulation case 3 is to prove that the SDIF sorting algorithm and sorting test system can still successfully separate signals when the conditions mentioned in sorting failure principle, namely two sets of signals, are not met. In simulation case 4, the SDIF sorting algorithm and the sorting test system cannot successfully sort signals by setting PRI design conditions that meet the requirements of Section 3.1 sorting failure principle. Simulation cases 1 and 2 are to show that the SDIF sorting algorithm and the sorting test system can work normally. Simulation cases 3 and 4 are to form a comparative experiment, which fully demonstrates that separation failure can be realized as long as the conditions required by sorting failure principle are met. In simulation case 4, the starting values of signal PRI were set as 100 microseconds and 1000 microseconds, respectively, in order to make the difference of PRI values between the two groups of signals 10 times, so as to meet the conditions of sorting failure principle.

The statistical results of the histogram in different simulation cases are shown in the figure below (Figures 8–11).

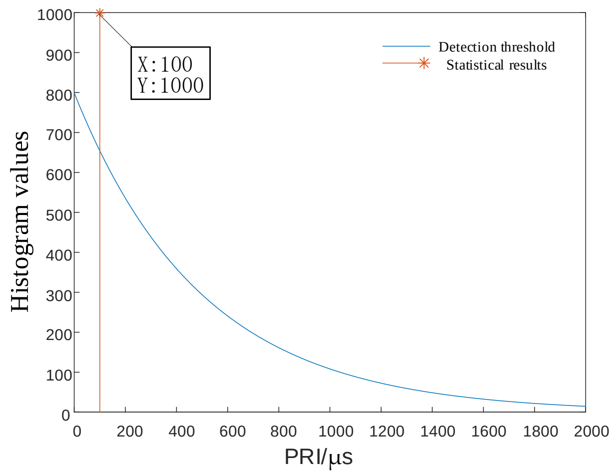

Figure 8. Histogram of first-order TOA difference in case 1.

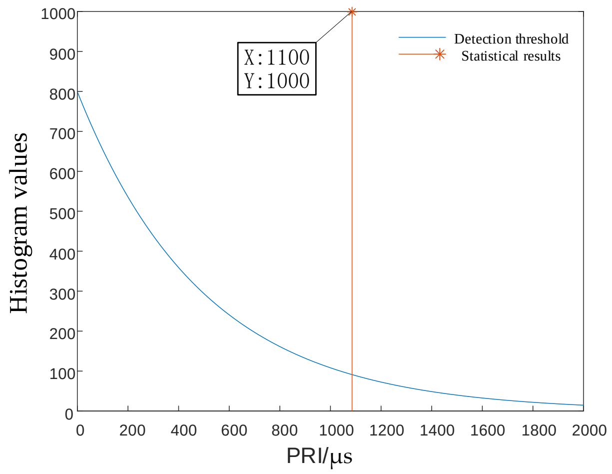

Figure 9. Histogram of first-order TOA difference in case 2.

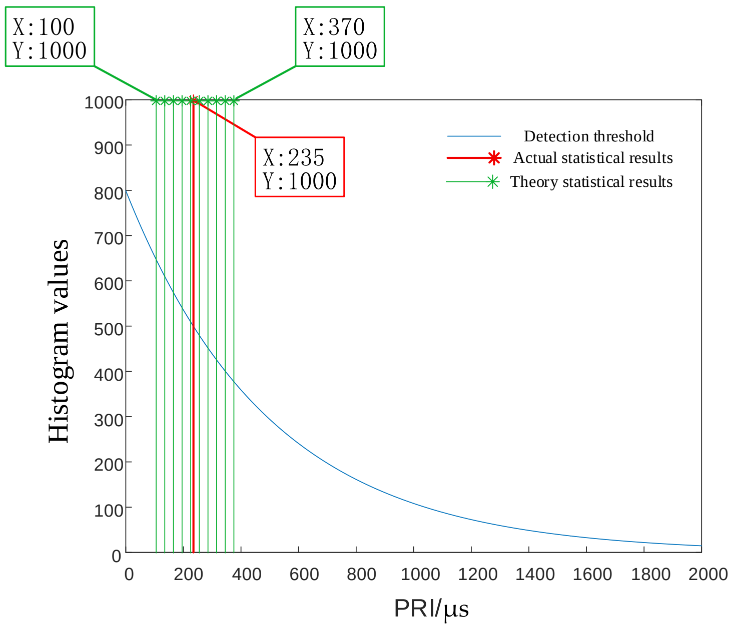

Figure 10. Histogram of first-order TOA difference in case 3.

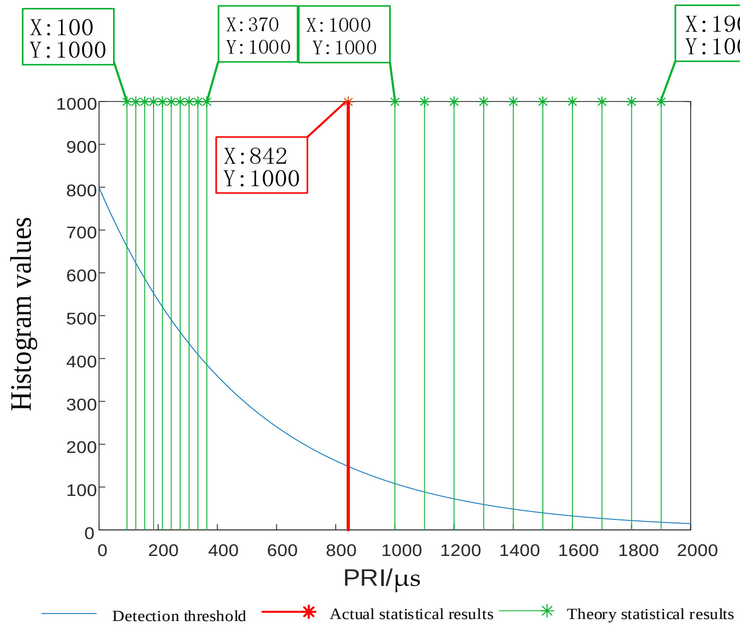

Figure 11. Histogram of first-order TOA difference in case 4.

For cases 1 and 2, the SDIF sorting algorithm can accurately sort the radar signal with fixed PRI, as shown in Figures 8 and 9. Table 1 shows the signal PRI values in case 3.

Table 1. Signal PRI values in case 3.

series number	1	2	3	4	5
PRI(μs)	100	130	160	190	220
series number	6	7	8	9	10
PRI(μs)	250	280	310	340	370

Figure 10 shows the simulation results in case 3. The first-order difference histogram shows a threshold peak at the estimated PRI value of 235 μs. The value is within the PRI variation range of the pulse group signal. The SDIF sorting algorithm combined with the tolerance setting can conduct a sequence search on the signal and then extract the signal. In case 4, signal PRI values are shown in Table 2.

Table 2. Signal PRI values in case 4.

First radar	series number	1	2	3	4	5
	PRI(μs)	100	130	160	190	220
	series number	6	7	8	9	10
	PRI(μs)	250	280	310	340	370
Second radar	series number	1	2	3	4	5
	PRI(μs)	1000	1100	1200	1300	1400
	series number	6	7	8	9	10
	PRI(μs)	1500	1600	1700	1800	1900

Figure 11 shows the simulation results in case 4. The first-order difference histogram presents a threshold peak at the estimated PRI value of 842 μs. The green statistical histogram is the theoretical statistical result of the SDIF algorithm for PRI slide signals, and the red statistical histogram is the actual statistical result. As shown in Table 2 and Figure 11, 842 μs is neither within the PRI range of the first radar signal nor the second radar signal. The SDIF algorithm cannot search the signal sequence, and SDIF algorithm sorting fails.

4.1.3. Signal Sorting Experiments

① Introduction of the signal sorting system

The experimental system is mainly divided into the signal transmission subsystem and the signal reconnaissance subsystem. The signal transmission subsystem mainly comprises a vector signal source, signal digital–analog conversion board, control and signal processing board and display terminal. The digital-to-analog conversion, signal processing and signal generation are integrated into a system by the remote-control technology of vector signal sources. The transmitting waveform file of the vector signal source is prepared by MATLAB code. Figure 12 shows the structural composition of the signal transmission subsystem. The signal reconnaissance subsystem is mainly composed of a receiving antenna, electronic equipment host, display control host, power extension, triangle bracket and several cables. The signal reconnaissance subsystem measures, processes, sorts and identifies the carrier frequency, pulse width, amplitude and TOA parameters of radar target radiation source signal in real-time. Then the threat alarm function is complete. Figure 13 shows the schematic diagram of the signal reconnaissance subsystem.

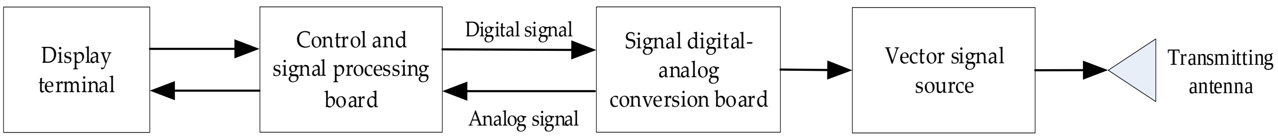

Figure 12. Structural diagram of the signal transmission subsystem.

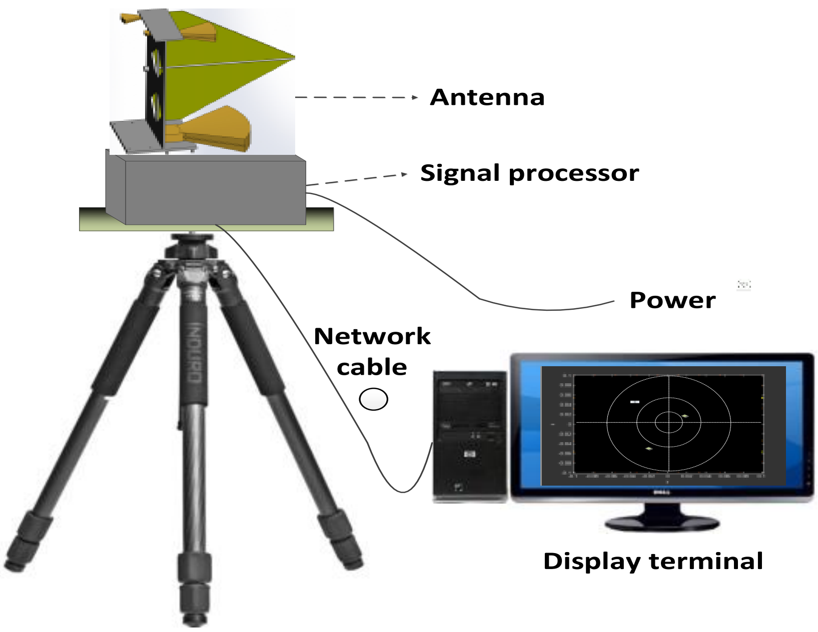

Figure 13. Schematic diagram of the signal reconnaissance subsystem.

② Experimental process and results

To avoid the influence of environmental noise on experimental results, the signals transmitted by the vector signal source were directly transmitted to the receiving antenna of the signal reconnaissance subsystem through cables. Figure 14 shows the connection of each experimental subsystem.

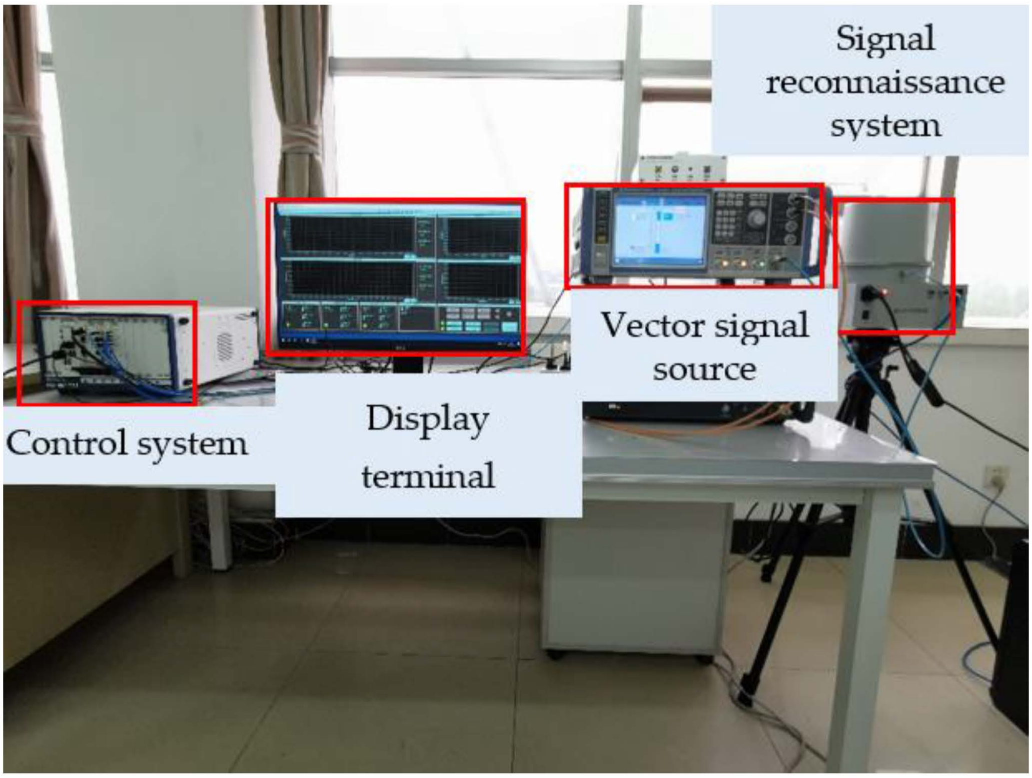

Figure 14. Experimental system connection diagram.

Figure 15 shows the display terminal interface of the signal reconnaissance subsystem.

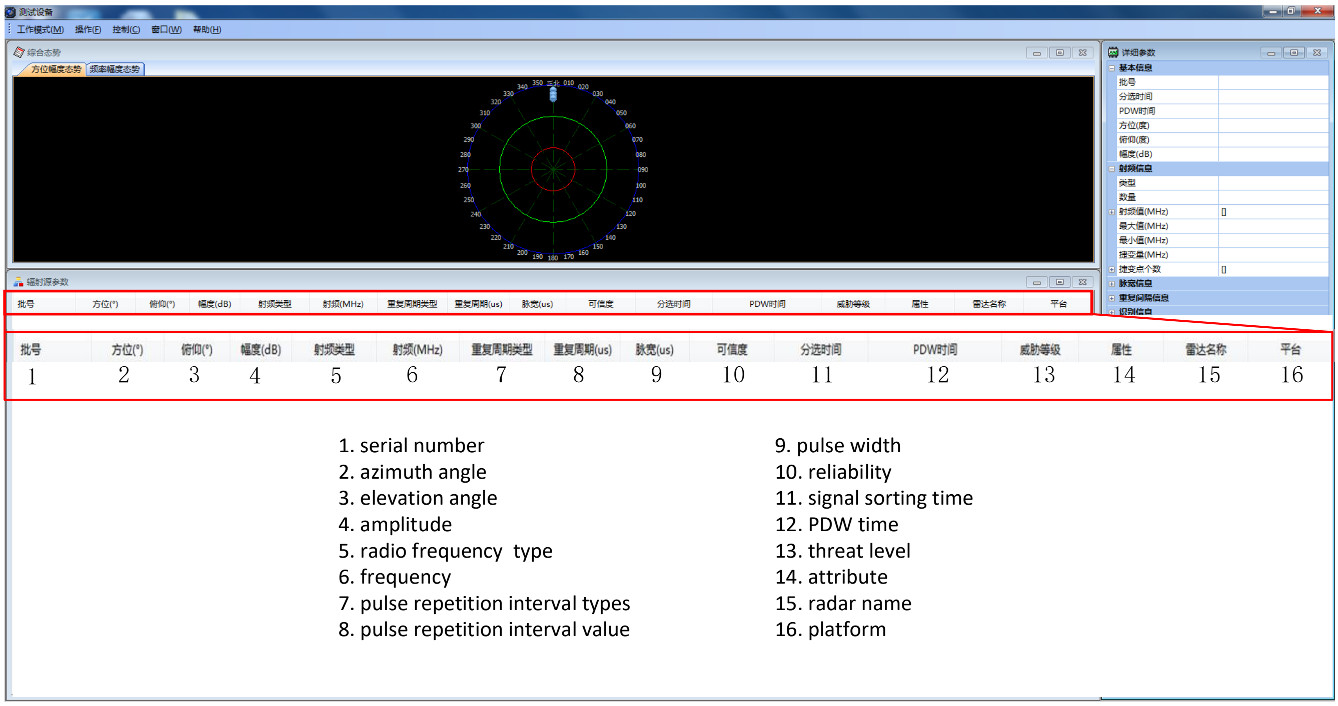

Figure 15. Display terminal interface of the signal sorting system.

Figures 16–19 show the experimental results of each simulation case.

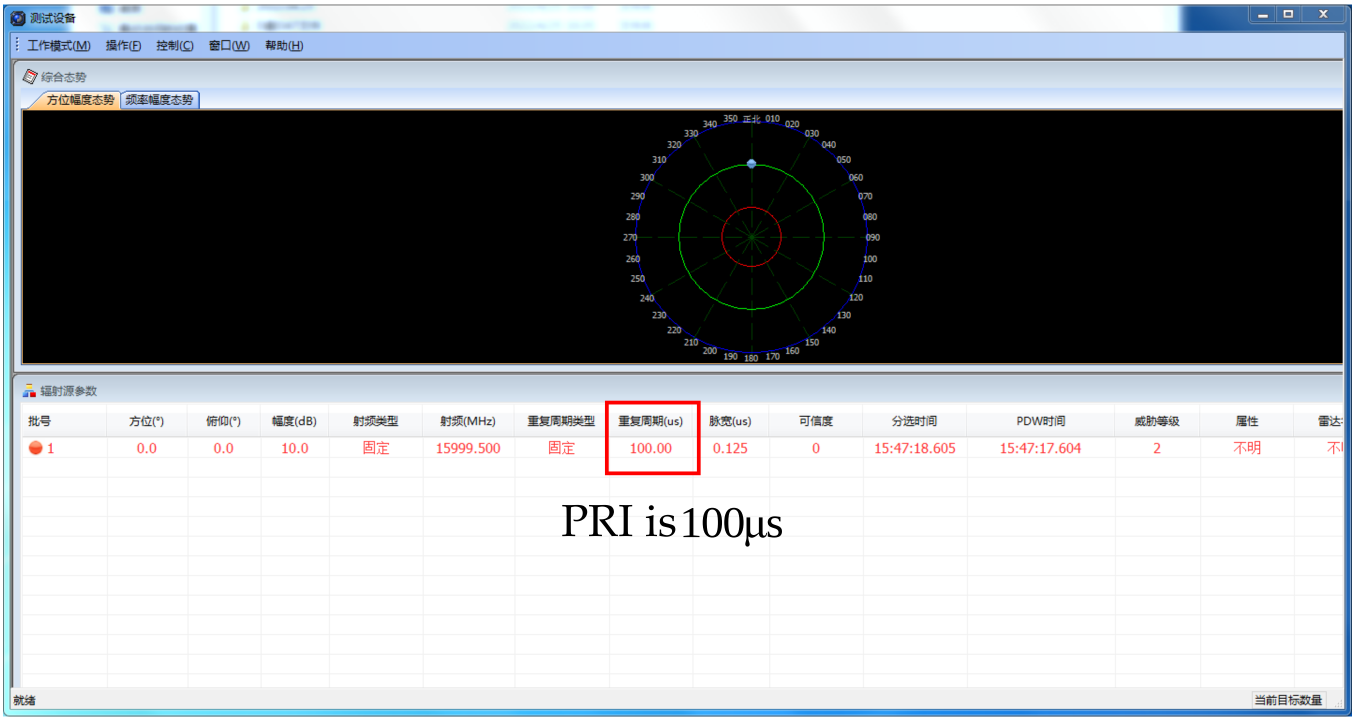

Figure 16. Experimental system sorting interface in case 1.

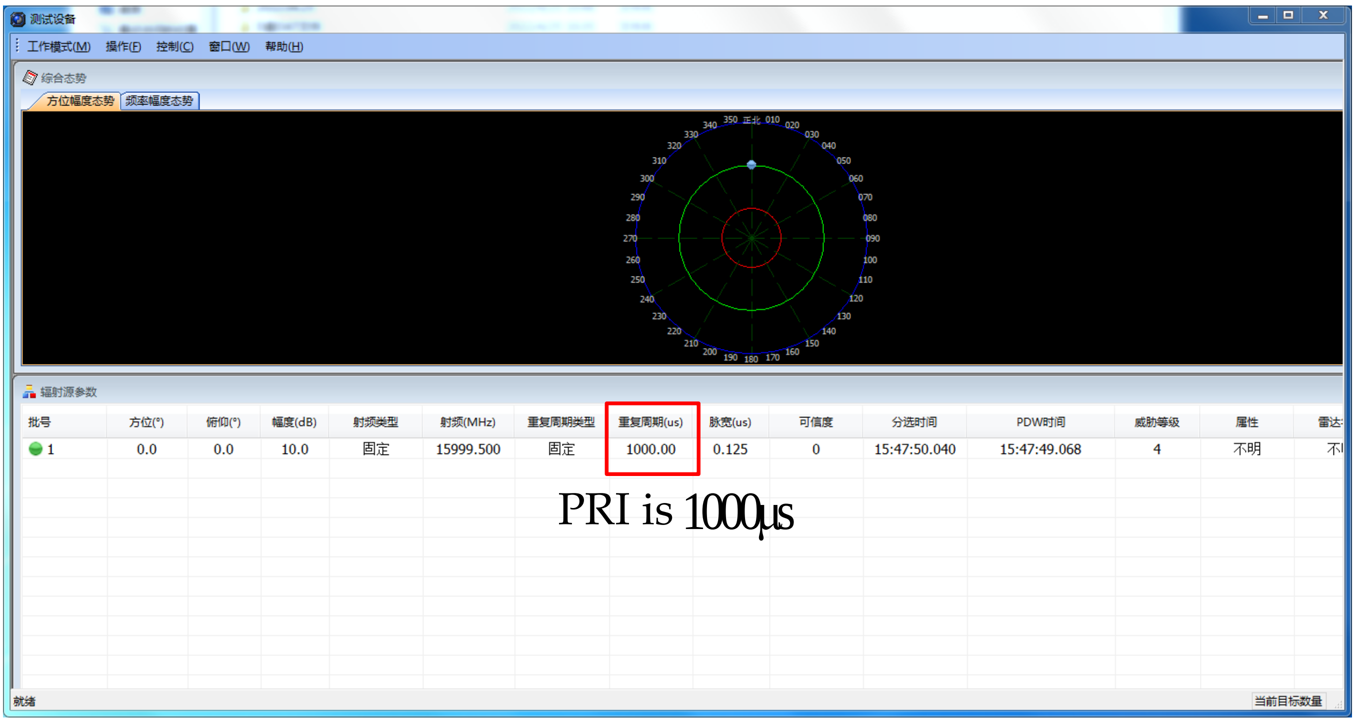

Figure 17. Experimental system sorting interface in case 2.

From the red box in the figure, we can know that the PRI value of the signal measured by the signal sorting experiment is 100 µs.

From the red box in the figure, we can know that the PRI value of the signal measured by the signal sorting experiment is 1000 µs. According to Figures 16 and 17, the sorting experimental system could accurately identify and classify radar signals in cases 1 and 2.

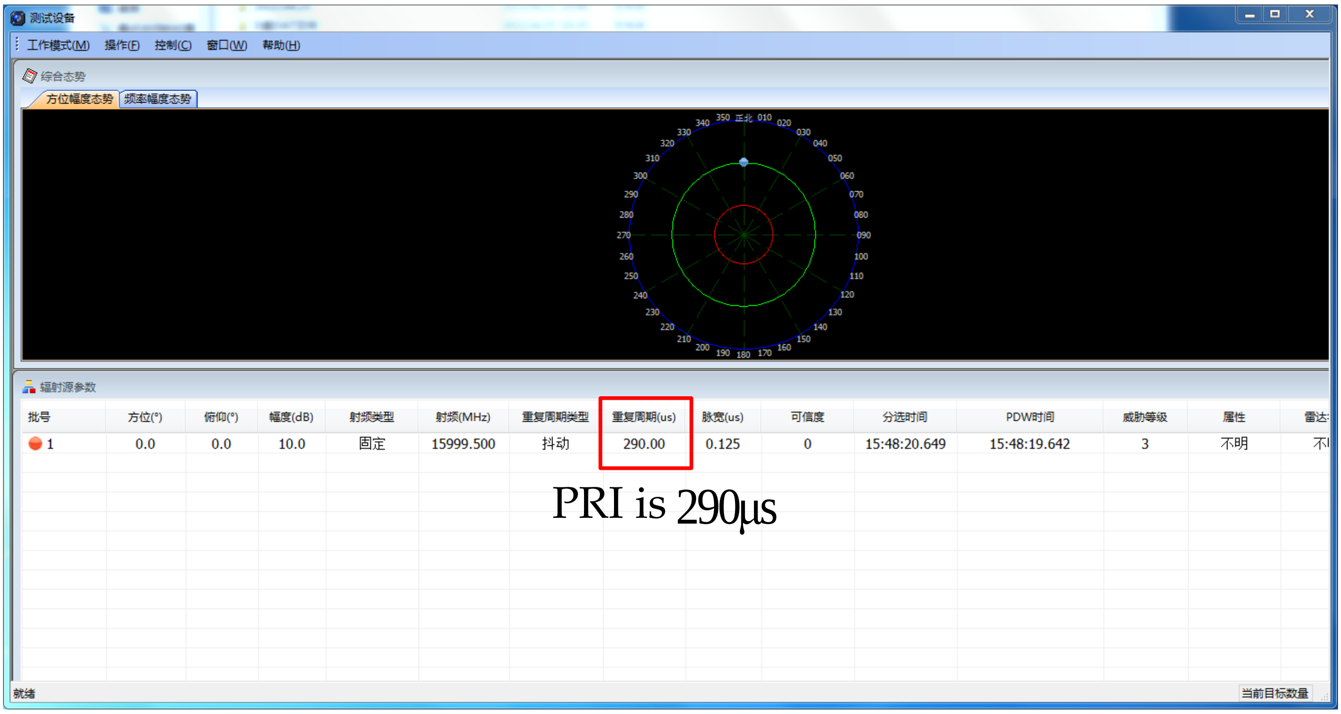

Figure 18. Experimental system sorting interface in case 3.

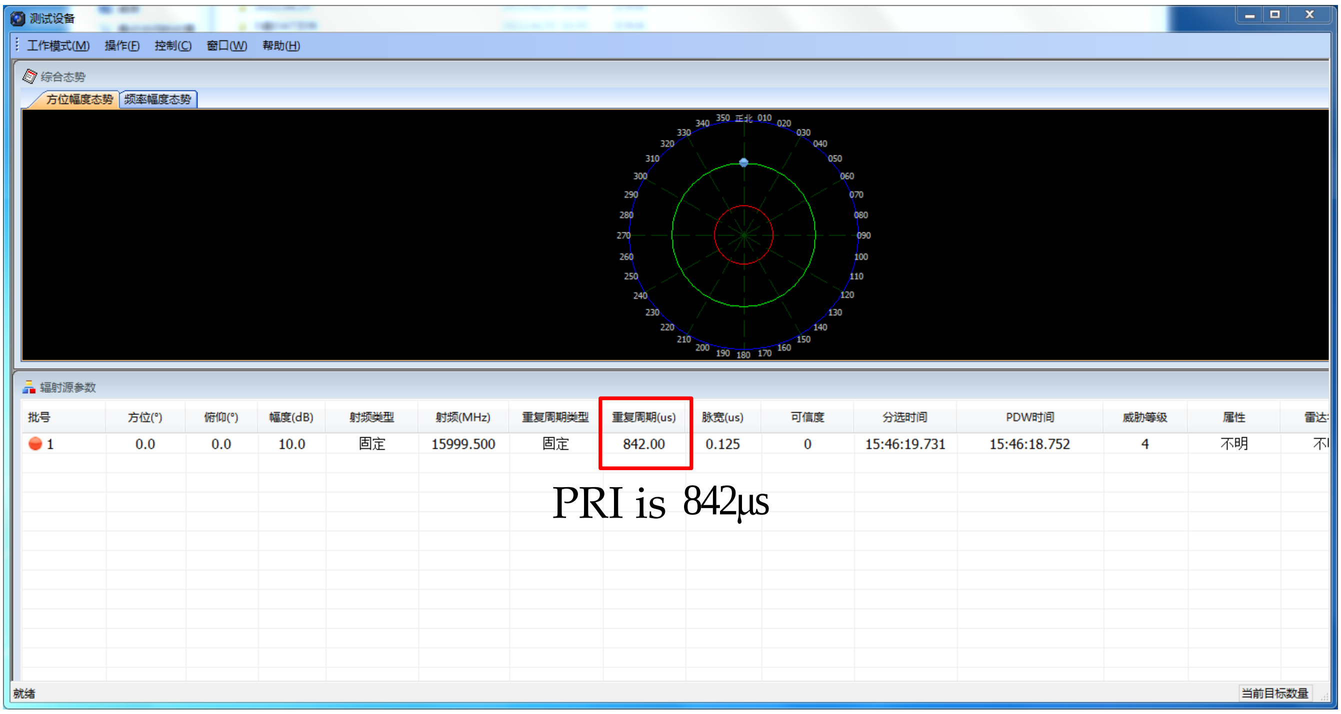

Figure 19. Experimental system sorting interface in case 4.

From the red box in the Figure 18, we can know that the PRI value of the signal measured by the signal sorting experiment is 290 µs, indicating that the signal could be sorted.

From the red box in the Figure 19, we can know that the PRI value of the signal measured by the signal sorting experiment is 842 µs Figure 19 indicates that the sorting result of the radar signal in case 4 by the sorting experimental system is 842 µs, suggesting that the signal could not be correctly sorted.

The above experiments reveal that the sorting system can accurately sort PRI fixed signals. However, the sorting algorithm fails when the difference in PRI center values between the two groups is more than 10 times.

4.1.4. Comparison with PRI Jitter Signal Sorting Experiment

In the field of anti-sorting, jitter signal is also considered as one of the better anti-sorting signals [19]. This section takes PRI jitter signal as an example to compare its sorting resistance with that designed based on PRI estimation sorting failure principle. The jitter signal center PRI is 200 μs, the jitter signal PRI interval is $[100\ \mu s, 300\ \mu s]$, and the jitter amplitude reaches 50%. The anti-sorting signal designed in this paper still uses the signal in simulation case 4 in Section 4.1.1. The sorting system in Section 4.1.3 conducts 1000 sorting experiments on PRI jitter signal and the signal designed in this paper, and the number of signal pulses in each experiment is 1000. In the actual sorting system, a variety of sorting algorithms, not just SDIF algorithm, are often used to comprehensively sort signals. Therefore, in the experiment, the system always outputs a PRI value, but as long as the searched pulses were less than 5, sorting failure could be considered. Therefore, in each experiment, the percentage of dividing the number of PRI search pulses output by the sorting system from the total number of pulses 1000 was the sorting result, as shown in Equation (39):

$$\eta = \frac{a}{1000} \tag{39}$$

where, a is the number of pulses obtained by pulse search based on PRI output of the sorting system, and 1000 is the total number of experimental pulses. If $\eta > 0.5\%$, it is considered that the sorting system has successfully sorted the signals; If $\eta < 0.5\%$, it is considered that the signal sorting system fails. The signal sorting results are shown in Figure 20.

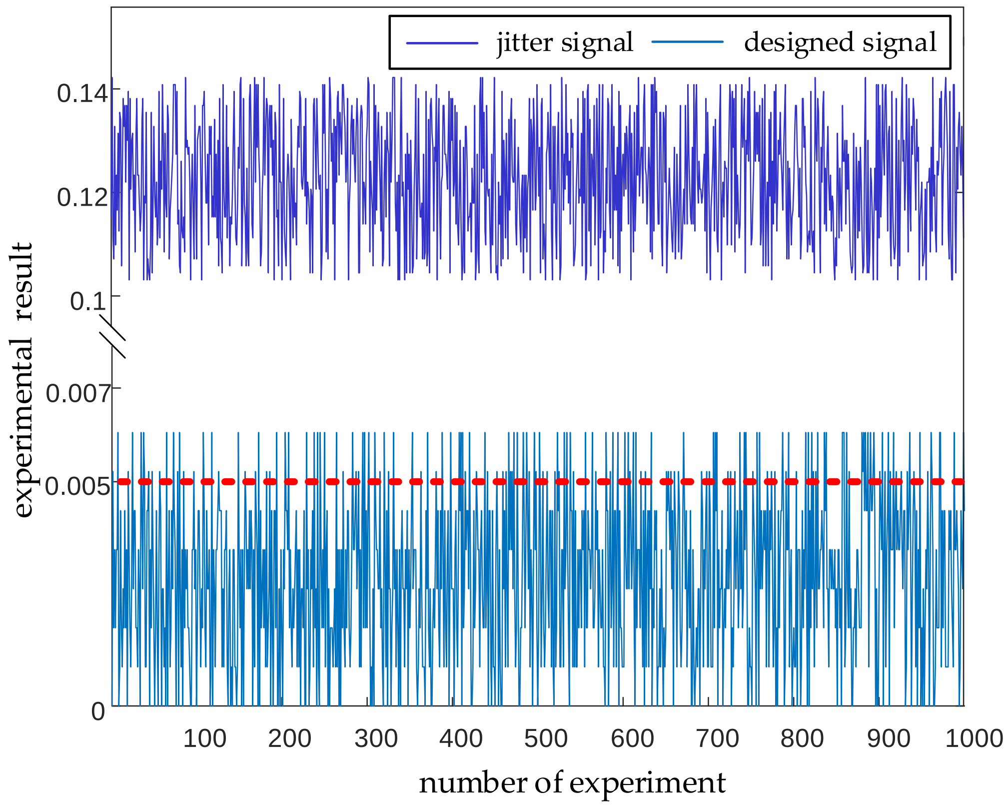

Figure 20. Comparison diagram of sorting results.

It can be seen from Figure 20 that in 1000 times of sorting, the signal designed in this paper had 92 times in total when the number of pulses searched according to the output results of the sorting system exceeded 5, which was 9.2% of the total number of experiments of 1000 times, and the anti-sorting success rate was 91.8%. In contrast, jitter signals in 1000 experiments could search more than 5 signal pulses according to the output results of the sorting system, and the success rate of anti-sorting was 0. The experimental results show that the jitter signal could not realize the anti-sorting function for the efficient signal sorting system.

4.2. Sorting Failure Principle Based on the Precise Design of Staggered Signals

4.2.1. Staggered Signal Design

The method in Section 3.2 was simulated by taking three and five radar staggered signals. The specific PRI settings of the staggered signals are shown in Table 3.

Table 3. The PRI settings of staggered signals.

Simulation Case	PRI1 (μs)	PRI2 (μs)	PRI3 (μs)	PRI4 (μs)	PRI5 (μs)
1	80	100	130		
2	80	100	180		
3	80	100	180	220	
4	80	100	180	190	550
5	150	120	50		
6	150	120	30		

Simulation cases 1 to 4 are the comparison and simulation verification of the increasing condition of staggered signal sub-PRI. Simulation case 1 is the case where the sum of the first and second staggered signal sub-PRI are unequal to the third staggered signal sub-PRI. Simulation case 2 is the case in which the sum of the first and second staggered signal sub-PRI is equal to the third staggered signal sub-PRI. In case 1 and case 2, the comparison experiment proved that when the variable signal sub PRI is increasing, the precise design of the staggered signal PRI could make the sorting algorithm invalid. Simulation cases 3 and 4 designed the child PRI of the staggered signal according to the precise design formula of the staggered signal. Simulation case 3 is the sorting case of four-stagger signal. Simulation case 4 is the sorting case of five-stagger signal. In cases 5 and 6, the comparison and simulation verification were carried out on the condition that the variable signal sub-PRI was decreasing. Simulation case 5 is the case where the sum of the second and third staggered signal sub-PRI is unequal to the first staggered signal sub-PRI. Simulation case 6 is the case where the sum of the second and third staggered signal sub-PRI is equal to the first staggered signal sub-PRI. Cases 5 and 6 were comparative experiments to prove that when the staggered signal sub-PRI was decreasing, the precise design of the staggered signal PRI could make the sorting algorithm invalid.

4.2.2. Simulation Verification

The signal consists of 1200 pulses; the TOA measurement error is 50 nanoseconds; the sequence search tolerance is 1 microsecond; the histogram analysis range is 0 to 1500 microseconds; the statistical interval of the histogram is 0.5 microseconds. The SDIF statistical threshold is shown in Equation (1), where $Q = 3000$, $k = 0.1$, and $x = 0.8$. Figures 21–26 show the statistical results of the histogram in different simulation cases.

As shown in Figures 21 and 22, the second-order histogram of inexact design for three staggered signals in Figure 21 shows statistical peaks above the threshold at 180 μs, 210 μs and 230 μs. When pulse search was carried out at 180 μs, 210 μs and 230 μs in descending order, the searched pulses were all pulse sequences with PRI equal to the skeleton period. Then, the signal sorting process entered the stage of signal stagger analysis. Finally, the SDIF sorting algorithm could correctly sort the three staggered signals. However, the second-order histogram of the precisely designed three staggered signals in Figure 22 shows threshold peaks at 180 µs, 260 µs and 280 µs. When pulse search was carried out with the order of 180 µs from small to large, corresponding pulses could be successfully searched, and then the histogram statistics were performed for the remaining pulses. A PRI fixed radar signal was extracted with a period of 360 µs. To intuitively display the influence of PRI precise design on the SDIF sorting algorithm, the sorting results of cases 1 and 2 were compared, as shown in Table 4.

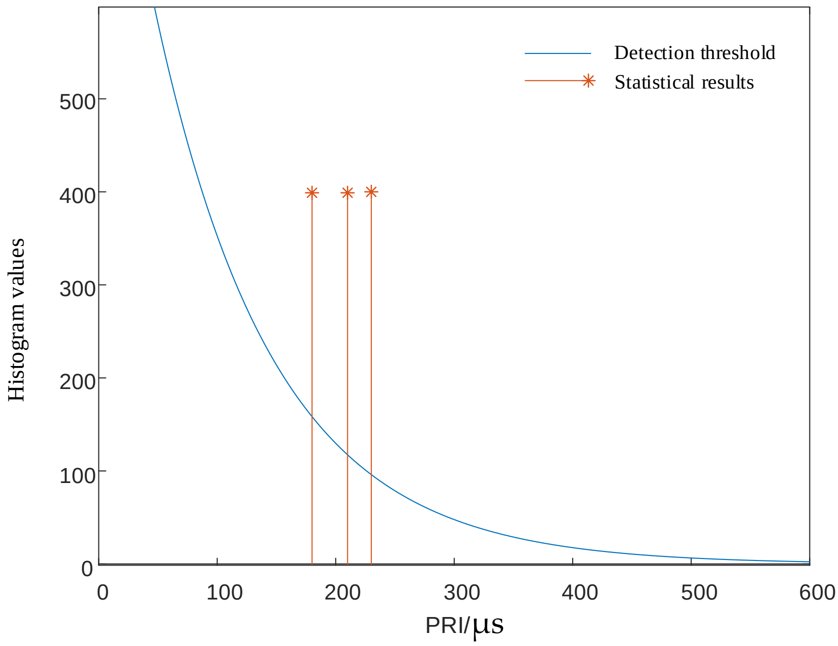

Figure 21. Second-order TOA difference histogram of imprecise design for three staggered signals in case 1.

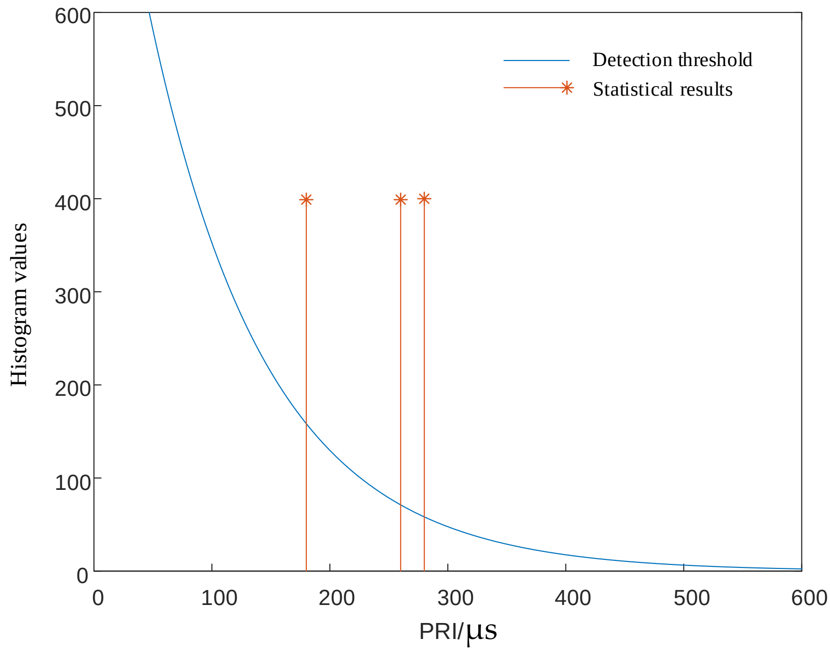

Figure 22. Second-order TOA difference histogram of precise design for three staggered signals in case 2.

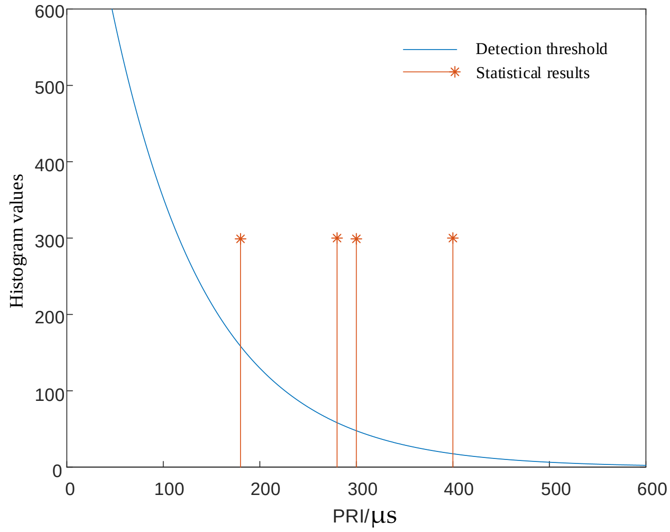

Figure 23. Second-order TOA difference histogram of four staggered signals in case 3.

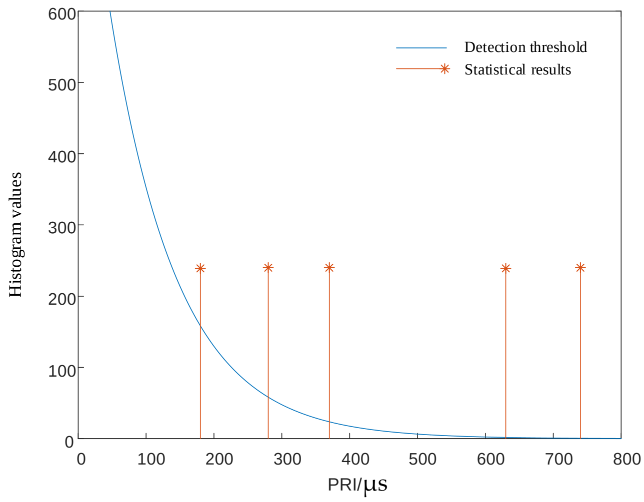

Figure 24. Second-order TOA difference histogram of five staggered signals in case 4.

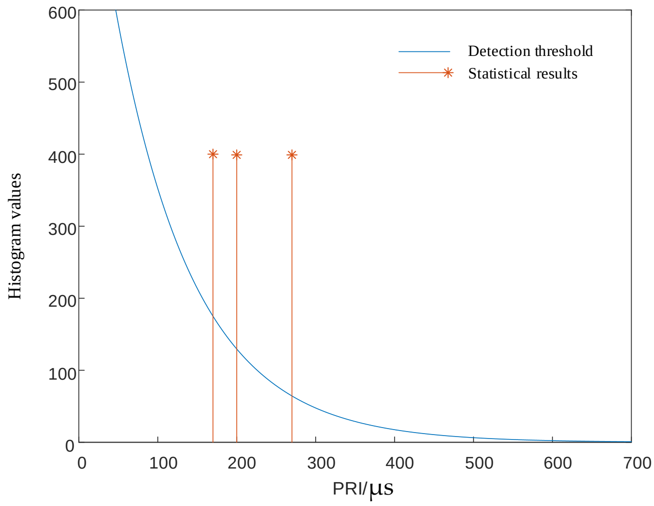

Figure 25. Second-order TOA difference histogram of imprecise design for three staggered signals in case 5.

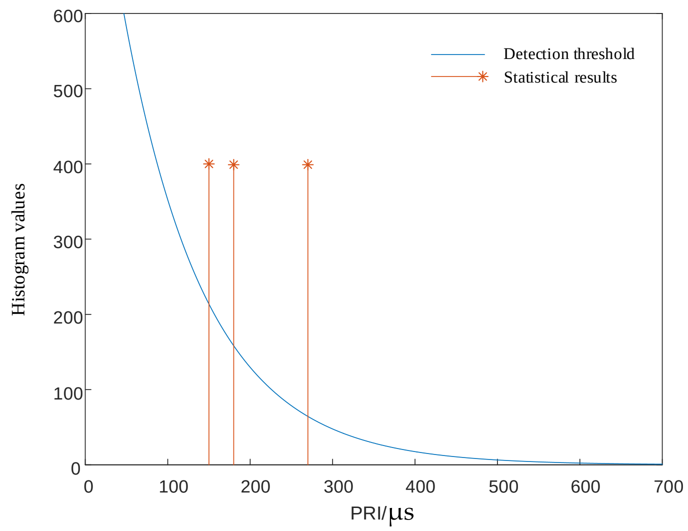

Figure 26. Second-order TOA difference histogram of precise design for three staggered signals in case 6.

Table 4. Comparison of sorting results in cases 1 and 2.

	PRI Incremental Imprecise Design			PRI Incremental Precise Design		
PRI Value	PRI1 80	PRI2 100	PRI3 130	PRI1 80	PRI2 100	PRI3 180
Sorting result	PRI staggered signal, sub-PRIs are 80 μs, 100 μs, and 130 μs			Two PRI fixed signals with 180 μs and 360 μs		
SDIF result	success			failure		

According to the comparison table of the sorting results, after the precise design of the sub-PRI of staggered signals, the SDIF sorting algorithm sorted three staggered signals into two PRI fixed signals. Then, the SDIF signal sorting failed.

As shown in Figure 23, the second-level histogram shows threshold peaks at 180 μs, 280 μs, 300 μs and 400 μs. Firstly, the pulse sequence is searched according to 180 μs. Then the TOA histogram of the remaining pulses is re-counted, and the remaining pulses are further sorted. The detailed sorting process is the same as that of the three staggered signals and is not described here. The final sorting result is a 180 μs PRI fixed radar, a staggered signal radar with 500 μs and 80 μs. There is a gap between the sorting result and the design of staggered signals and SDIF sorting failure.

As shown in Figure 24, the second-level histogram has threshold peaks at 180 μs, 280 μs, 370 μs, 550 μs and 660 μs. The detailed sorting process is the same as that of three staggered signals and is not described here. The final selection results are three PRI fixed radars with the PRI of 180 μs, 550 μs and 80 μs, respectively. There is a gap between the sorting result and the design of staggered signals and SDIF sorting failure.

The above is the simulation verification of the increasing state of staggered signal PRI, and the following is the simulation of the decreasing state of staggered signal PRI. Table 4 shows the design of staggered signal PRI in cases 5 and 6.

As shown in Figure 25, a pulse search is performed for the imprecise design of three staggered signals according to the statistical peak of the thresholds 170 μs, 200 μs and 270 μs in the second-level histogram. The searched pulses are all pulse sequences with PRI equal to the skeleton period. The SDIF algorithm can sort signals successfully. In Figure 26, the pulse search was conducted according to the minimum peak value of 150 over the threshold, and then the remaining pulses were further recalculated. The final sorting results were two PRI fixed radar signals with 150 μs and 300 μs, which is different from the design of staggered signals, indicating that the sorting failed. To show the influence of decreasing

PRI precise design on the SDIF sorting algorithm, the sorting results of cases 5 and 6 were compared and shown in Table 5.

Table 5. Comparison of sorting results in cases 5 and 6.

	PRI Decreasing Imprecise Design			**PRI Decreasing Precise Design**		
PRI value	PRI1 150	PRI2 120	PRI3 50	PRI1 150	PRI2 120	PRI3 30
Sorting result	PRI staggered signal, sub-PRIs are 150 µs, 120 µs, and 50 µs			Two PRI fixed signals with 150 µs and 300 µs		
SDIF result	success			failure		

According to the comparison of sorting results, after a precise design of the sub-PRI of the uneven signal, the SDIF sorting algorithm separates the three uneven signals into two PRI fixed signals, and the sorting failed.

5. Conclusions

In this paper, the estimation of PRI values and the sorting of staggered signals by the SDIF algorithm are studied in detail. Then the principle of sorting failure is proposed. Through equation derivation and signal simulation, the correctness of the separation failure principle is verified theoretically and experimentally, providing theoretical support for the design of anti-sorting signals. The design method of anti-sorting signals, which is used to add interference pulse, make signal jitter and make PRI change randomly, is changed by the demonstration of the sorting failure principle. A preliminary theoretical reference is provided for the design of anti-sorting signals. However, the existing signal processing system found it difficult to handle such signal echoes. Therefore, compression sensing technology is required to preprocess the target echo, followed by conventional radar echo signal processing.

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