

Article

Research on the SDIF Failure Principle for RF Stealth Radar Signal Design

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Abstract: Radio frequency (RF) stealth is one of the essential research hotspots in the radar field. The anti-sorting signal is an important direction of the RF stealth signal. Theoretically speaking, the anti-sorting signal design is based on the failure principle of the radar signal sorting algorithm, and the SDIF algorithm is a core sorting algorithm widely used in engineering. Thus, in this paper, the SDIF algorithm is first analyzed in detail. It is pointed out that the threshold function of the SDIF algorithm will fail when the signal pulse repetition interval (PRI) value obeys the interval distribution whose length is 20 times larger than the minimum interval of PRI. Secondly, the correctness of the failure principle of SDIF threshold separation is proved by the formula. Finally, the correctness is further verified by the signal design case. The principle of SDIF sorting threshold failure provides theoretical support for anti-sorting RF stealth signal design. It also complements the shortcoming of the casual design for the anti-sorting signal. Furthermore, the principle of SDIF sorting threshold failure helps improve anti-sorting signal design efficiency. Compared with the Dwell & Switch (D&S) signal and jitter signal, the anti-sorting ability of the signal designed by using the sorting failure principle is notably enhanced through simulation and experimentation.

Citation: Jia, J.; Han, Z.; Liu, L.; Xie, H.; Lv, M. Research on the SDIF Failure Principle for RF Stealth Radar Signal Design. *Electronics* **2022**, *11*, 1777. <https://doi.org/10.3390/electronics11111777>

Academic Editor: Massimiliano Pieraccini

Received: 7 April 2022

Accepted: 31 May 2022

Published: 3 June 2022

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Keywords: radio frequency stealth; sequence difference histogram; principle of sorting failure; pulse repetition interval; interval distribution

1. Introduction

With the increasing use of radio equipment, electronic countermeasures based on electronic reconnaissance are vital in modern warfare [1–3]. According to the signal detection process of the electronic reconnaissance system, the radio frequency (RF) stealth [4] of radiation sources mainly includes anti-interception [5–7], anti-sorting [8], and anti-identification. Due to the extensive applications of low SNR receivers and the rapid development of digital signal processing technology, radiation source anti-interception technology cannot be used to completely counter electronic reconnaissance from the enemy. Hence, it is critical for the anti-electronic reconnaissance system to weaken the sorting and identification abilities of the electronic reconnaissance system of the enemy [9]. To obtain information about radiation sources in the environment, the electronic reconnaissance system sorting and identifying radiation source signal separates the pulse sequence of each radiation source from the random and staggered pulse stream received by the intercepted receiver [10,11]. The main sorting is the core of radiation source signal sorting, and the pulse repetition interval (PRI) and modulation mode of each radiation source in an electromagnetic environment are usually obtained by processing the arrival time of each pulse [12,13]. Therefore, it is necessary to combat PRI-based sorting to weaken the signal sorting and identification of the electronic reconnaissance system of the enemy. We will study the sorting algorithm in the sorting field and the countermeasures against PRI-

based sorting in order to weaken the signal sorting and to identify the electronic reconnaissance system of the enemy.

At present, the field of signal sorting mainly focuses on the improvement of the signal sorting algorithm and the design of the anti-PRI sorting method. On the one hand, the signal sorting algorithm mainly puts forward the corresponding improved SDIF algorithm based on SDIF for different signal sorting failure situations. The literature [14] points out that because time of arrival (TOA) is easily affected by the jitter of PRI, the SDIF algorithm cannot effectively sort the PRI jitter signal. Therefore, an improved algorithm is proposed based on the SDIF algorithm. The sorting efficiency of the algorithm for jitter signals is notably improved by using overlapping PRI bins. Furthermore, the search speed is also improved. In reference [15], an improved SDIF algorithm was proposed to solve the problem of “increasing batch” in the signal sorting of multi-function radars (MFRs) with various work modes. The improved method utilizes a limited penetrable visibility graph to construct the network from interleaved radar pulse sequences and then employs a label propagation algorithm and density peak clustering to detect community structures, thus fulfilling the deinterleaving of pulses from several MFRs. The above methods can effectively solve the problem of increasing batch in the process of sorting. The authors in [16] compared several commonly used sorting algorithms and obtained an optimal sorting algorithm under different circumstances. With the extensive application of radio equipment, a single sorting algorithm is not enough to sort high density pulse current in complex electromagnetic environments. Therefore, the authors in [17] comprehensively used the PRI transform and SDIF algorithm to sort signals, achieving good sorting effects for all kinds of signals. The authors in [18] comprehensively applied clustering and SDIF sorting methods to improve the sorting speed and accuracy and meet the real-time requirements of sorting. The above is a brief introduction to the development of the signal sorting algorithm. The above literature mainly focuses on the failure of the SDIF sorting algorithm caused by different signal sorting situations. Then SDIF is analyzed. Finally, improved sorting algorithms based on the SDIF algorithm are obtained. However, starting with the work flow of the SDIF algorithm, this paper studies the failure principle of the threshold function in the SDIF algorithm in order to provide theoretical support for anti-sorting signal design. On the other hand, the research on anti-PRI sorting mainly focuses on the design technology of anti-sorting signals. There are three design methods for anti-sorting signals. Firstly, jamming pulses are added to the radar signal to disrupt the interception and recognition of the PRI pulse signal by the enemy interception receiver [19–22]. Then, jitter is added to the PRI of the pulse signal, and every pulse has a different PRI. Thus, it is difficult for the enemy intercepting receiver to sort the radar signal [21,23,24]. At last, the PRI of the pulse or signal system is optimized, and the accurate and quantitative design of the PRI is required only, without the additional design of interference pulses [25,26]. Although the above methods have achieved a certain effect, the stability of the anti-sorting performance of the designed signal needs to be further verified. The method of signal design relies more on the experience of researchers and lacks the strict sorting failure principle as a theoretical guide.

The failure mechanism of the classical sequential difference histogram (SDIF) in the PRI sorting algorithm is studied in this paper to establish a theoretical basis for the design of an anti-PRI sorting signal. It is proposed for the first time that the SDIF algorithm threshold function will fail when the signal PRI values obey the interval distribution whose length is more than 20 times of the minimum interval PRI, as will be proved by formula derivation. The rest of this paper is organized as follows: Section 2 analyzes the SDIF sorting algorithm in detail. Section 3 discusses the failure principle of SDIF sorting; the signal parameters are designed according to the sorting failure principle, and the designed signal is simultaneously verified by the simulation and experiment in Section 4. In Section 5, the full paper is summarized.

2. Sequential Difference Histogram (SDIF)

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

In engineering, histogram sorting is the most commonly-used method to estimate the PRI value of the radiation source signal based on statistical principles. After the difference of time of arrival (TOA) is counted, the histogram of the difference is formed. Then, the appropriate sorting threshold and sorting strategy are set. In the 1980s, the most traditional histogram sorting algorithm could be used to calculate the TOA difference of any two pulses, and the histogram of all TOA differences was formed. The PRI estimate can be obtained by comparing each histogram with the threshold function. The traditional histogram sorting method contains all the information of the pulse flow. Thus, it is insusceptible to pulse loss and other adverse effects. However, this method is time-consuming, with a large calculation amount and a lack of real-time performance. Therefore, researchers improved the traditional histogram method. The Cumulative Difference Histogram (CDIF) and Sequential Difference Histogram (SDIF) are two improved algorithms commonly used in engineering.

In essence, both SDIF and CDIF belong to TOA difference histogram sorting methods [27,28]. The TOA difference of pulses is counted by the two sorting algorithms according to certain rules, and PRI estimation is analyzed. Then, the impulse train search is performed based on the PRI estimate. At last, the radiation source pulse trains are extracted. Compared with the traditional histogram sorting algorithm, SDIF and CDIF algorithms greatly reduce the computational amount and are real-time. SDIF and CDIF algorithms can sort PRI fixed, PRI stagger, and jitter radiation source signals and are widely used in the engineering field [29–31].

Compared with the CDIF algorithm, the SDIF algorithm has the following advantages: SDIF only analyzes the histograms of the current level without the histogram statistics of different levels and the $2\times$ PRI test. It requires less computation and has a faster processing speed. In addition, the SDIF algorithm has an optimized threshold function. In combination with sub-harmonic detection, false detection is avoided in the SDIF algorithm. Therefore, SDIF is more widely used than is CDIF. In this paper, the failure mechanism of the SDIF algorithm is mainly studied. SDIF algorithm flows are as follows.

According to Algorithm 1, the SDIF histogram mainly includes two parts: TOA difference histogram analysis, and impulse sequence search. TOA difference histogram analysis is mainly used to estimate PRI values. The histogram statistics method is used to calculate the number of TOA differences from level one to a higher level. If the number of TOA difference statistics exceeds the detection threshold, the TOA difference corresponding to the peak divided by the statistical series of the TOA difference is the possible PRI value.

Algorithm 1 Deinterleaving signal via SDIF

Input: Time of arrival (TOA)
Initialization: difference level C
1: Judge the TOA number of level C
2: Calculate the TOA difference of level C
3: Count the TOA difference of level C and form a histogram
4: Determine the detection threshold and obtain the PRI estimation
5: Subharmonic check
6: Determine the unique PRI estimate
7: Sequence search
8: Removes the searched pulse train from the pulse stream
9: The remaining pulses are sorted until the number of pulses is less than 5 or the number of PRI in the first-level histogram exceeding the threshold is not unique
10: Increase difference level C and repeat the above steps until the sorting is over

Therefore, it is essential to determine the threshold formula. In the analysis of the entire signal intercept, the TOA difference between two adjacent pulses approximates a random event because of the receiver obtaining signals from multiple sources during the sampling time of the SDIF histogram. Hence, the TOA distribution of each pulse approximates the Poisson distribution. It can be expressed as:

$$P(x=k) = \frac{\lambda^k}{k!} e^{-\lambda} (k=0,1,\dots) \quad (1)$$

where λ is the average number of signal pulses reaching the intercepted receiver per unit time; x indicates the actual arrival number of signal pulses per unit time. Then, the probability that there are w pulses in the time interval $\tau = t_2 - t_1$, namely $x = w$, can be expressed as:

$$P(x=w) = \frac{(b\tau)^w}{w!} e^{-b\tau} (w=0,1,\dots) \quad (2)$$

where b is the pulse current density, $b=n/t$ and n is the total number of pulses, and T is pulse duration. According to the meanings of parameters in (1) and (2), we get $b\tau = \lambda$ in (2). If τ is the time interval between adjacent pulses, namely, having zero pulses in the time interval ($w=0$), the probability is

$$P(x=0) = e^{-b\tau} \quad (3)$$

In the level c histogram, there are $E - C$ time intervals if the number of pulses is E . The parameter of the Poisson process is $b=1/kN$ [28]. We can conclude that the optimal function of the detection threshold is expressed as:

$$T_{thre}(\tau) = a(E - C)e^{-\tau/kN} \quad (4)$$

where E is the total number of pulses; C is the order of the histogram; k is a positive constant less than 1; N is the total number of bins in the histogram. The optimum values of the constants a and k are experimentally determined. According to mathematics, a function graph of a dependent variable that changes with an independent variable is given in Figure 1, in which the threshold function is a monotonically decreasing exponential function with the signal PRI value as an independent variable.

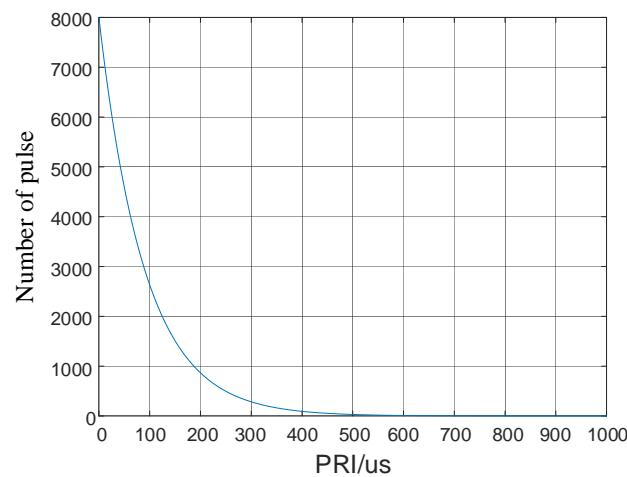


Figure 1. Schematic diagram of the threshold function.

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

$$\tau_{\max} = \tau + \varepsilon \quad (5)$$

$$\tau_{\min} = \tau - \varepsilon \quad (6)$$

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

$$\bar{\tau} = \sum_{i=1}^n (x_i / S) \cdot \tau_i \quad (7)$$

where S is the sum of the pulse number corresponding to adjacent PRI values $\tau_1, \tau_2, \dots, \tau_i$ within the tolerance; x_i is the number of PRI values τ_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 in the second step of the algorithm is analyzed. The sequence search extracts the radiation source pulse train from the PRI estimate obtained in the first step. In the first place, the PRI estimation is used to judge whether three pulses can be continuously searched in the staggered pulse stream. If it is useful, it is true PRI. Then, the remaining pulses of the radiation source whose arrival time difference is close to each other are searched backward successively, with these three pulses as the starting point. If it is useless, it is false PRI, and the PRI estimation is discarded. In addition, we can use other PRI estimates that exceed the threshold of the sequence search. The estimated PRI obtained in the first step can also be screened, and the real value of PRI can be obtained via the pulse sequence search.

3. SDIF Sorting Failure Principle

According to the analysis in the previous section, SDIF sorting is based on the estimation of the PRI value in the first step. The important step to determine whether the PRI value can be used as the PRI estimate of the sorting algorithm is to compare the pulse number of histogram statistics with the pulse number threshold of the sorting algorithm.

If the pulse number counted by the histogram exceeds the threshold value, the sorting algorithm is a possible PRI estimate. Then, we can check the sub-harmonics and enter other subsequent stages. In contrast, if the pulse number counted by the histogram is less than the threshold, it is not a possible PRI estimation.

Induction and proofs are mainly used in this paper. Firstly, the accuracy of the SDIF sorting algorithm for fixed PRI is verified by the special case level histogram of signal sorting. Then, signal PRI values increase from one fixed value to two or more when the total number of pulses is constant. In addition, the PRI critical condition that invalidates the sorting algorithm is proved correct. Thirdly, the sorting results of the algorithm are discussed when signal PRI values obey the interval distribution. At last, the sorting results of the signal PRI obeying the interval distribution by a multistage histogram are discussed. The logic diagram of the derived SDIF separation failure principle is given in Figure 2.

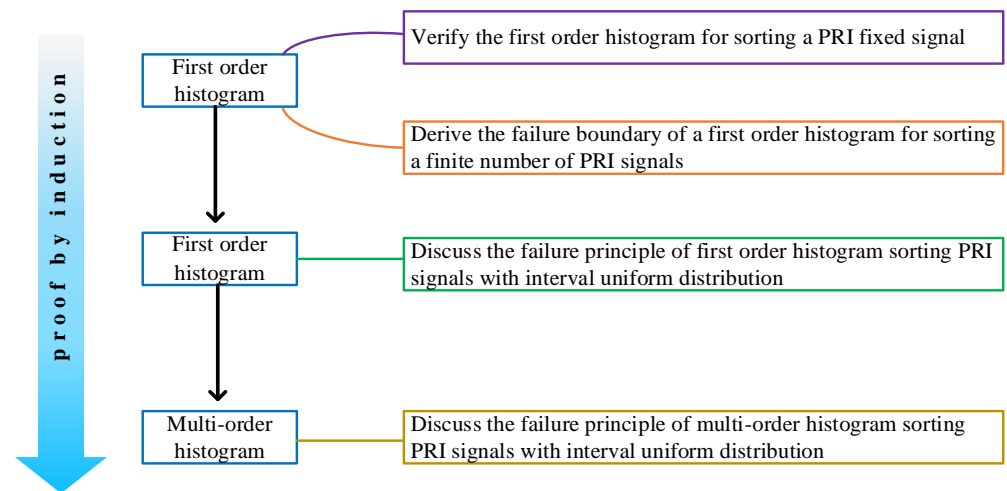


Figure 2. Logic diagram of the derived SDIF separation failure principle.

3.1. Analysis of Sorting Failure Principle of the First-Order Histogram

When the signal is a fixed-period signal, namely, $\tau = \tau_0$, we assume that the number of pulses E is $E_0; e^{\frac{\tau}{kN}}$ and a are the positive constant less than 1 when $\tau > 0$ in the threshold Formula (4). The number of pulses is $E_0 \gg 1$ in the actual situation. Therefore, the right part of the threshold formula is $a(E_0 - C)e^{\frac{\tau}{kN}} < E_0$, and the threshold formula is $T_{thre}(\tau_0) < E_0$ when $\tau = \tau_0$. The signal PRI value $\tau = \tau_0$ can be sorted out.

3.1.1. The Number of PRI Values Increases from One to a Finite Number

The number of PRI values increases from 1 to 2, assuming the total number of pulses $E = E_0$ is constant, which means the signals are two stagger signals. In addition, the value of PRI is τ_0 or τ_1 ($\tau_0 < \tau_1$). There are $\frac{E_0}{2}$ pulses in each value of PRI. The relationship between the number of corresponding pulses and the threshold value $T_{thre}(\tau_0)$ is discussed when the PRI value and pulse number have changed.

According to Formula (4), when the PRI value is $\tau = \tau_0$, the threshold of the algorithm should be:

$$T_{thre}(\tau_0) = a(E_0 - 1)e^{-\tau_0/kN} \quad (8)$$

When the PRI value is $\tau = \tau_1$, the threshold of the algorithm can be expressed as

$$T_{thre}(\tau_1) = a(E_0 - 1)e^{-\tau_1/kN} \quad (9)$$

When the threshold of the algorithm is $\frac{E_0}{2}$, namely, $T_{thre}(\tau') = \frac{E_0}{2}$, the PRI critical value of sorting failure can be calculated by Formula (10).

$$a(E_0 - 1)e^{-\tau'/kN} = \frac{E_0}{2} \quad (10)$$

E_0 represents the total number of pulses, which is usually in the tens of thousands, namely, $E_0 \gg 1$. Therefore, Equation (10) can be simplified as:

$$aE_0e^{-\tau'/kN} = \frac{E_0}{2} \quad (11)$$

Therefore, after taking the natural logarithm of the above formula, we can obtain τ' :

$$\tau' = kN \ln(2a) \quad (12)$$

With the monotonically decreasing property of the threshold function, it can be known that:

The SDIF algorithm can sort out the pulses of PRI τ_0 when $\tau_0 \geq kN \ln(2a)$, namely, $\frac{E_0}{2} \geq T_{thre}(\tau_0)$. The SDIF algorithm can also sort out the pulses of PRI due to $\tau_0 < \tau_1$. The SDIF algorithm cannot sort out the pulses of PRI τ_0 when $\frac{E_0}{2} < T_{thre}(\tau_0)$. However, if $\tau_1 \geq kN \ln(2a)$, the SDIF algorithm can sort out the pulses of PRI τ_1 , $\frac{E_0}{2} \geq T_{thre}(\tau_1)$ and if $\tau_1 < kN \ln(2a)$, the SDIF algorithm cannot sort out them. Consequently, the SDIF algorithm cannot sort the signal pulse whose PRI is less than the critical value $kN \ln(2a)$ when the number of PRI values increases from 1 to 2.

According to the above analysis, the actual signal sorting situation is extended, and the derivation condition is assumed as follows:

- (1) The total number of pulses is still E_0 .
- (2) The number of the PRI value increases to a limited number, which means the signals are multiple stagger signals.
- (3) The values of PRI are $\tau_1, \tau_2 \dots \tau_n$ ($\tau_1 < \tau_2 < \dots < \tau_n$).
- (4) The number of pulses corresponding to each PRI value is $\frac{E_0}{n}$.

The derivation process is the same as that of Equations (8)–(12). Hence, we will not repeat it here. The PRI critical value of sorting failure is solved as:

$$\tau' = kN \ln(na) \quad (13)$$

At last, the SDIF algorithm cannot select the signal pulse whose PRI is less than the critical value $kN \ln(na)$ when the number of PRI signals increases to a finite number.

3.1.2. The Signal PRI Value Follows an Interval Distribution

We assume that the number of pulses E is E_0 . The signal PRI value follows an interval distribution $\tau \in [\tau_0, \tau_1]$. The design of transmitting signals and the processing of echo

signals need to be considered in the radar field. Hence, the PRI value of the radar signal does not obey completely random disordered distribution. Thus, the PRI values of signals are discussed with uniform distribution in this section. For any given interval, the number of pulses E' is:

$$E' = \frac{E_0}{(\tau_1 - \tau_0)/z} \quad (14)$$

where E_0 is the total number of pulses, τ_1 and τ_0 are the maximum and minimum values of the distribution interval, respectively, and z is the minimum interval of PRI values within the interval distribution. When PRI is τ' , the threshold calculation formula of the algorithm is shown in Equation (4).

When $T_{thre}(\tau') = E'$,

$$a(E_0 - 1)e^{-\tau'/kN} = \frac{E_0}{(\tau_1 - \tau_0)/z} \quad (15)$$

where E_0 is the total number of pulses, $E_0 \gg 1$. Therefore, the above formula can be simplified as:

$$aE_0e^{-\tau'/kN} = \frac{E_0}{(\tau_1 - \tau_0)/z} \quad (16)$$

Thus, the PRI critical value of sorting failure is solved as:

$$\tau' = kN \ln \left(\frac{a \cdot (\tau_1 - \tau_0)}{z} \right) \quad (17)$$

When $\tau_1 < \tau'$, the number of pulses corresponding to PRI values in the interval $[\tau_0, \tau_1]$ is less than the threshold value. Hence, the SDIF algorithm sorting fails. When $\tau_0 < \tau' < \tau_1$, the number of pulses corresponding to the PRI value in interval $[\tau_0, \tau']$ is less than the threshold value. Thus, SDIF algorithm sorting also fails in the interval $[\tau_0, \tau']$. The number of pulses corresponding to the PRI value in the interval $[\tau_0, \tau']$ is larger than the threshold value. The signal can be sorted successfully. When the PRI value of the signal follows the interval distribution, the SDIF algorithm cannot select the signal pulse

whose PRI is less than the critical value $kN \ln \left(\frac{a(\tau_1 - \tau_0)}{z} \right)$.

The conditions in the actual signal sorting process are described as follows:

- (1) N is the number of cells counted in the histogram and is usually above 1000.
- (2) z is the minimum interval of PRI. In general, z , τ_1 , and τ_0 have the same size scale, all of which are in the microsecond level.
- (3) $a, k \in (0, 1)$ in Equation (4).

Therefore, when the interval length is 20 times larger than z , we can know that $\ln \left(\frac{a \cdot (\tau_1 - \tau_0)}{z} \right) > 1$. Thus, the threshold value is much larger than any value in the interval $[\tau_0, \tau_1]$, namely, $\tau' \gg \tau_1$.

In conclusion, when signal PRI values obey the interval distribution, and the interval length is 20 times larger than z , the number of pulses corresponding to any PRI value in the interval $[\tau_0, \tau_1]$ is less than the threshold value of the sorting algorithm in the analysis

of the sorting failure principle of the first-order histogram. Hence, the SDIF algorithm fails in signal sorting.

3.2. Analysis of Sorting Failure Principle in Multi-Order Histogram

Sometimes, the SDIF sorting algorithm has multiple PRI values exceeding the threshold in the first-order histogram. We must count the secondary, tertiary, and advanced histograms to produce PRI estimates. Therefore, it is also necessary to analyze the sorting failure principle of the histograms from secondary to advanced.

We assume that the number of pulses E is E_0 . The signal PRI value follows an interval distribution $\tau \in [\tau_2, \tau_3]$. Because the design of the transmitting signal and processing of the echo signal need to be considered together in the radar field, the PRI value of the radar signal will not be a completely random and disordered distribution. Hence, the PRI values of signals are discussed with a uniform distribution in this section. For any given interval, the number of pulses E' is:

$$E' = \frac{E_0}{(\tau_3 - \tau_2)/z} \quad (18)$$

where E_0 is the total number of pulses, τ_3 and τ_2 are the maximum and minimum values of the distribution interval, respectively, and z is the minimum interval of PRI values within the interval distribution. When the value of PRI is τ' , the threshold calculation formula of the algorithm is shown in Equation (4).

When $T_{thre}(\tau') = E'$:

$$a(E_0 - C)e^{-\tau'/kN} = \frac{E_0}{(\tau_3 - \tau_2)/z} \quad (19)$$

where E_0 represents the total number of pulses, and C represents the histogram sorting series. In the actual sorting process, $E_0 \gg C$, although $C > 1$. Equation (19) is simplified to:

$$aE_0e^{-\tau'/kN} = \frac{E_0}{(\tau_3 - \tau_2)/z} \quad (20)$$

Thus, the PRI critical value of sorting failure is solved as:

$$\tau' = kN \ln \left(\frac{a \cdot (\tau_3 - \tau_2)}{z} \right) \quad (21)$$

The PRI values distribution and signal sorting results are shown in Table 1.

Table 1. Signal PRI value distribution and sorting results.

Serial Number	The Magnitude of τ' and τ_3	PRI Interval	Sorting Result
1	$\tau_3 < \tau'$	$[\tau_2, \tau_3]$	Failure
2	$\tau_2 < \tau' < \tau_3$	$[\tau_2, \tau')$	Failure
3		$(\tau', \tau_3]$	Success
4	$\tau' < \tau_2$	$[\tau_2, \tau_3]$	Success

The conditions in the actual signal sorting process are described as follows:

- (1) N is the number of cells counted in the histogram and is usually above 1000.

- (2) z is the minimum interval of PRI. In general, z , τ_3 , and τ_2 have the same size scale, all of which are in the microsecond level.
- (3) $a, k \in (0,1)$ in Equation (4).

Therefore, when the interval length is 20 times larger than z , we can know that $\ln\left(\frac{a \cdot (\tau_3 - \tau_2)}{z}\right) > 1$. Thus, the threshold value is much larger than any value in the interval $[\tau_3, \tau_2]$, namely, $\tau' \gg \tau_3$.

In conclusion, when signal PRI values obey the interval distribution, and the interval length is 20 times larger than z , the number of pulses corresponding to any PRI value in the interval $[\tau_2, \tau_3]$ is less than the threshold value of the sorting algorithm in the analysis of the sorting failure principle of the high-order histogram. Hence, the SDIF algorithm fails in signal sorting.

4. Simulation and Experiment

In this section, three aspects of simulation and experiment are carried out. The first aspect is to design the signal according to the sorting failure mechanism, and then to verify its anti-sorting performance by simulation. The second aspect compares the anti-sorting performance of the D&S signal and the signal designed in this paper. The third aspect is to use the signal reconnaissance system to carry out the signal sorting experiment to the signal designed in this paper and the PRI jitter signal.

4.1. Signal Sorting Simulation Verification Based on MATLAB

4.1.1. Signal Parameter Design

According to the analysis in Section 3, when the PRI of the radar signal is changed from a fixed value to an interval evenly distributed, the SDIF sorting algorithm will have no output result because the arbitrarily-determined PRI value does not have enough pulses exceeding the threshold value. Therefore, a radar signal is designed with the PRI value of the signal that is evenly distributed between $[100\mu s, 200\mu s]$.

4.1.2. Simulation

The simulation parameters are set as follows:

- (1) The number of pulses is 1000.
- (2) The TOA measurement error is 50 nanoseconds.
- (3) Sequence search tolerance is 1 microsecond.
- (4) The histogram analysis range is 0 to 1250 microseconds, and the statistical interval of the histogram is 0.5 microseconds.
- (5) SDIF statistical threshold is shown in Equation (4) where $N = 2500$, $k = 0.1$, $a = 0.8$.

The following simulation cases are considered, and the summary of each simulation case is shown in Table 2.

Table 2. Summary of the simulation case.

Simulation Case	PRI Value (μs)	Total Number of Pulses	Number of Pulses per PRI
1	100	1000	1000
	100, 210	1000	500
2	150, 210	1000	500
	100, 110	1000	500

3	100, 150, 190	999	333
	100, 150, 240	999	333
	150, 240, 270	999	333
	230, 250, 270	999	333
4	[100,200]	1000	—

Simulation case 1: The PRI value of the radar signal is fixed, and the signal PRI is $100\mu s$.

Simulation case 2: The PRI value of the radar signal is increased from one fixed value to two fixed values. The PRI combinations of signals are $100\mu s$ and $210\mu s$; $150\mu s$ and $210\mu s$; $100\mu s$ and $110\mu s$. The total number of pulses in each combination is 1000. Each PRI in the combination has 500 pulses.

Simulation case 3: The PRI value of the radar signal is increased from one fixed value to three fixed values. The PRI combinations of signals are $100\mu s$, $150\mu s$, and $190\mu s$; $100\mu s$, $150\mu s$, and $240\mu s$; $150\mu s$, $240\mu s$, and $270\mu s$; and $230\mu s$, $250\mu s$, and $270\mu s$. The total number of pulses in each combination is 999. Each PRI in the combination has 333 pulses.

Simulation case 4: The PRI value of the radar signal changes from a fixed value to a uniform distribution between $[100\mu s, 200\mu s]$. The total number of pulses in each combination is 1000.

The histogram of statistical results under different conditions is shown in Figure 3.

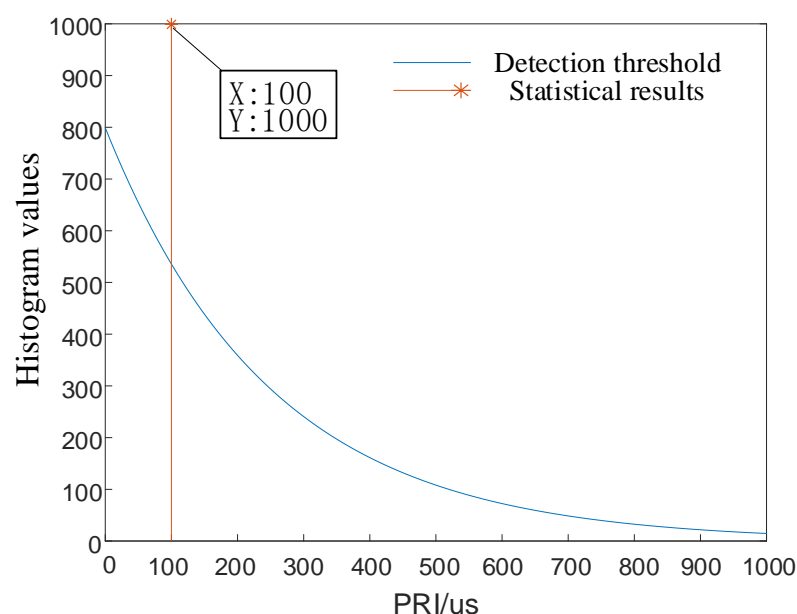


Figure 3. Histogram of the first-order TOA difference in simulation case 1.

It can be seen from Figure 3 that in simulation case 1, the SDIF sorting algorithm can accurately sort a PRI fixed radar signal.

Signal sorting by the SDIF algorithm in simulation case 2 is shown in Figure 4a–c. According to Formula (12), the PRI critical value of separation failure can be obtained as $\tau' = 117.5$. When the PRI values of both signals are smaller than the critical value, and the number of signal pulses is smaller than the threshold value, the SDIF sorting algorithm fails to sort signals. When there is a PRI value larger than the critical value, the number of signal pulses is greater than the threshold value, and therefore the SDIF algorithm can accurately sort the signal. When both PRI values are greater than the critical value, and the number of pulses of the two signals is greater than the threshold value, the SDIF sorting algorithm then works normally.

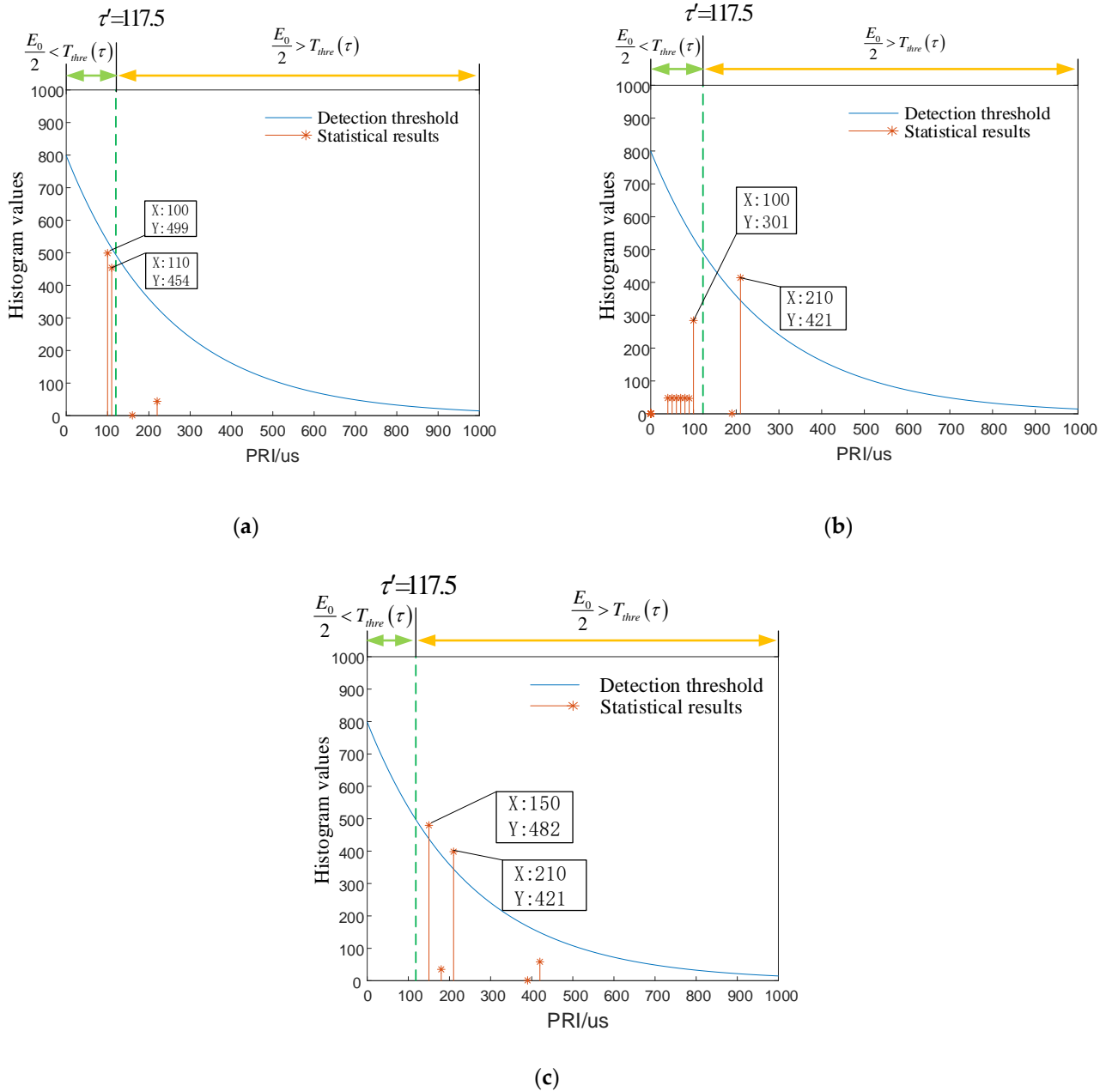
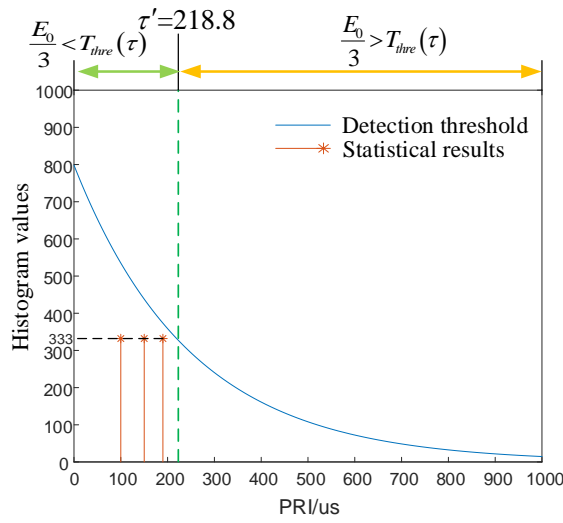
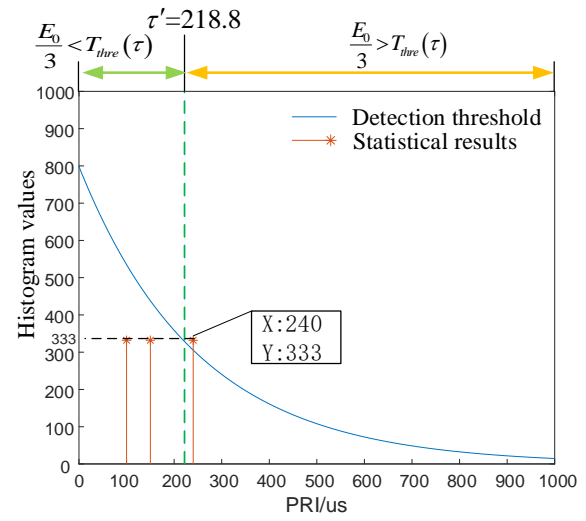


Figure 4. Histogram of first-order TOA difference in simulation case 2. (a) The PRI values of both signals smaller than the sorting failure critical condition; (b) a signal with a PRI value larger than the sorting failure critical condition; (c) the PRI values of both signals larger than the sorting failure critical condition.

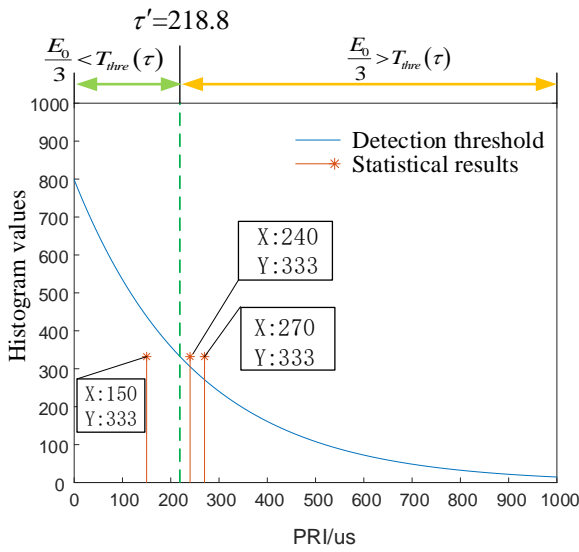
Signal sorting by the SDIF algorithm in simulation case 3 is shown in Figure 5a–d. According to Formula (13), the PRI critical value of separation failure can be obtained as $\tau' = 218.8$. When the values of three signals are all smaller than the critical value, the number of signal pulses is smaller than the threshold value, and the SDIF sorting algorithm fails to separate the signals. When there are signals whose PRI values are greater than the critical value, the number of such signal pulses is greater than the threshold value. The SDIF sorting algorithm can still correctly sort such signals.



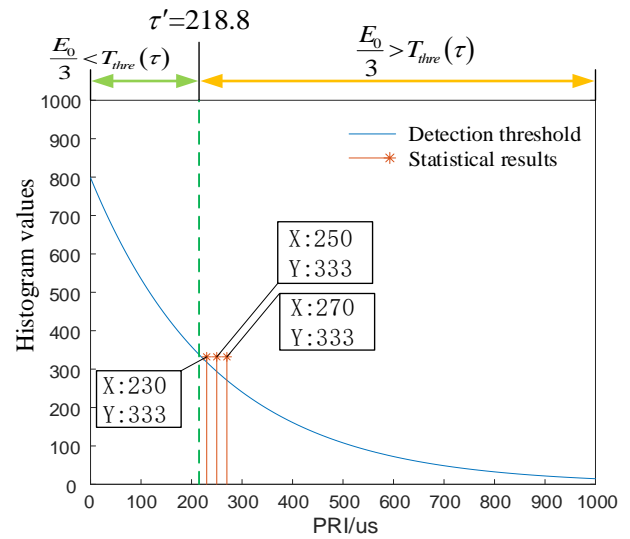
(a)



(b)



(c)



(d)

Figure 5. Histogram of first-order TOA difference in simulation case 3. (a) The PRI values of the three signals all less than the sorting failure critical condition; (b) a signal whose PRI value is larger than the sorting failure critical condition; (c) two signals whose PRI values are larger than the sorting failure critical condition; (d) the PRI values of three signals larger than the sorting failure critical condition.

Signal sorting by the SDIF algorithm in simulation case 4 is shown in Figure 6a–d. When the PRI values of the signal are evenly distributed in an interval, the number of pulses corresponding to each PRI is smaller than the threshold value, and therefore the sorting fails.

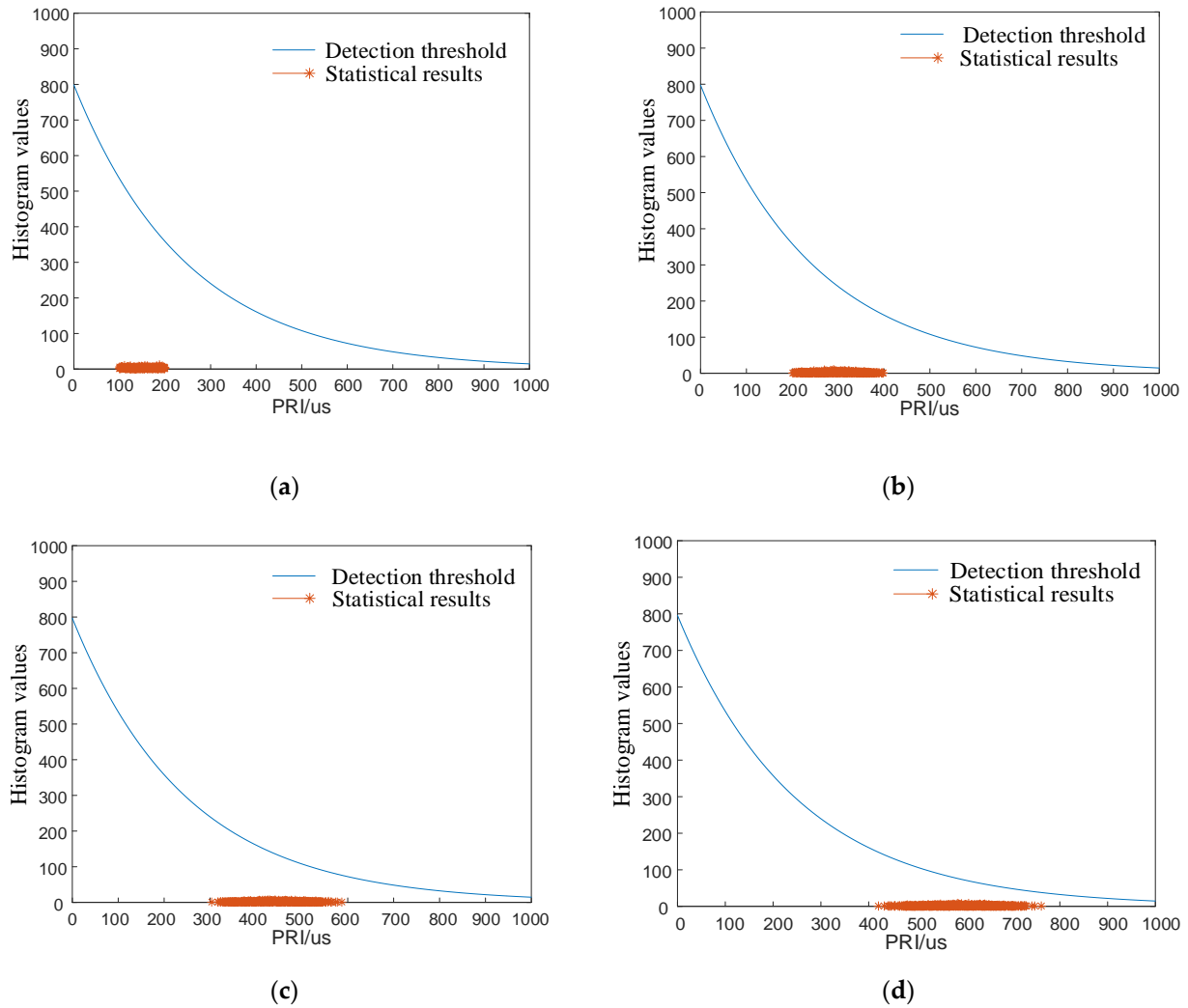


Figure 6. Histogram of first- and multi-order TOA differences in simulation case 4. (a) The histogram of the first-order TOA difference in signal PRI values uniformly distributed in an interval; (b) the histogram of the second-order TOA difference in signal PRI values uniformly distributed in an interval; (c) the histogram of the third-order TOA difference in signal PRI values uniformly distributed in an interval; (d) the histogram of the fourth-order TOA difference in signal PRI values uniformly distributed in an interval.

4.2. Signal Comparison Simulation Based on MATLAB

In order to eliminate the range ambiguity and speed ambiguity of radar, the D&S PRI signals are commonly used in practical engineering applications and also have certain anti-sorting ability. The PRI of the signal can be expressed as:

$$PRI_i = \begin{cases} PRI_1, & \text{if } \lceil i / M \rceil \bmod K \equiv 1 \\ PRI_2, & \text{if } \lceil i / M \rceil \bmod K \equiv 2 \\ \dots & \\ PRI_K, & \text{if } \lceil i / M \rceil \bmod K \equiv K \end{cases} \quad (22)$$

where K is the number of pulse groups in D&S signal, and M is the number of pulses in each pulse group.

In this section, the sorting simulation is carried out on a D&S signal and anti-sorting signal designed according to the sorting failure principle, respectively, based on

MATLAB. The PRI values of the D&S signal and the signal designed are shown in Table 3.

Table 3. The PRI values of the D&S signal and the signal designed in this paper.

Signal Types	PRI Values
Dwell & Switch signal	$K = 5, M = 10;$ $PRI1 = 100, PRI2 = 130, PRI3 = 150, PRI4 = 170, PRI5 = 190$
Signal designed in the paper	$[100\mu s, 200\mu s], z = 1\mu s$

The number of pulse groups of the D&S signal is 5, each pulse group contains 10 pulse signals, the PRI value is set in total to 5, and there are 1000 pulses in total. The anti-sorting signal PRI designed according to the failure mechanism is $[100\mu s, 200\mu s]$, and the minimum interval of the signal PRI is $1\mu s$. The PRI interval length of the signal is 100 times the minimum interval, which meets the requirements of Section 3. The sorting results of the SDIF sorting algorithm on D&S signals are shown in Figure 7.

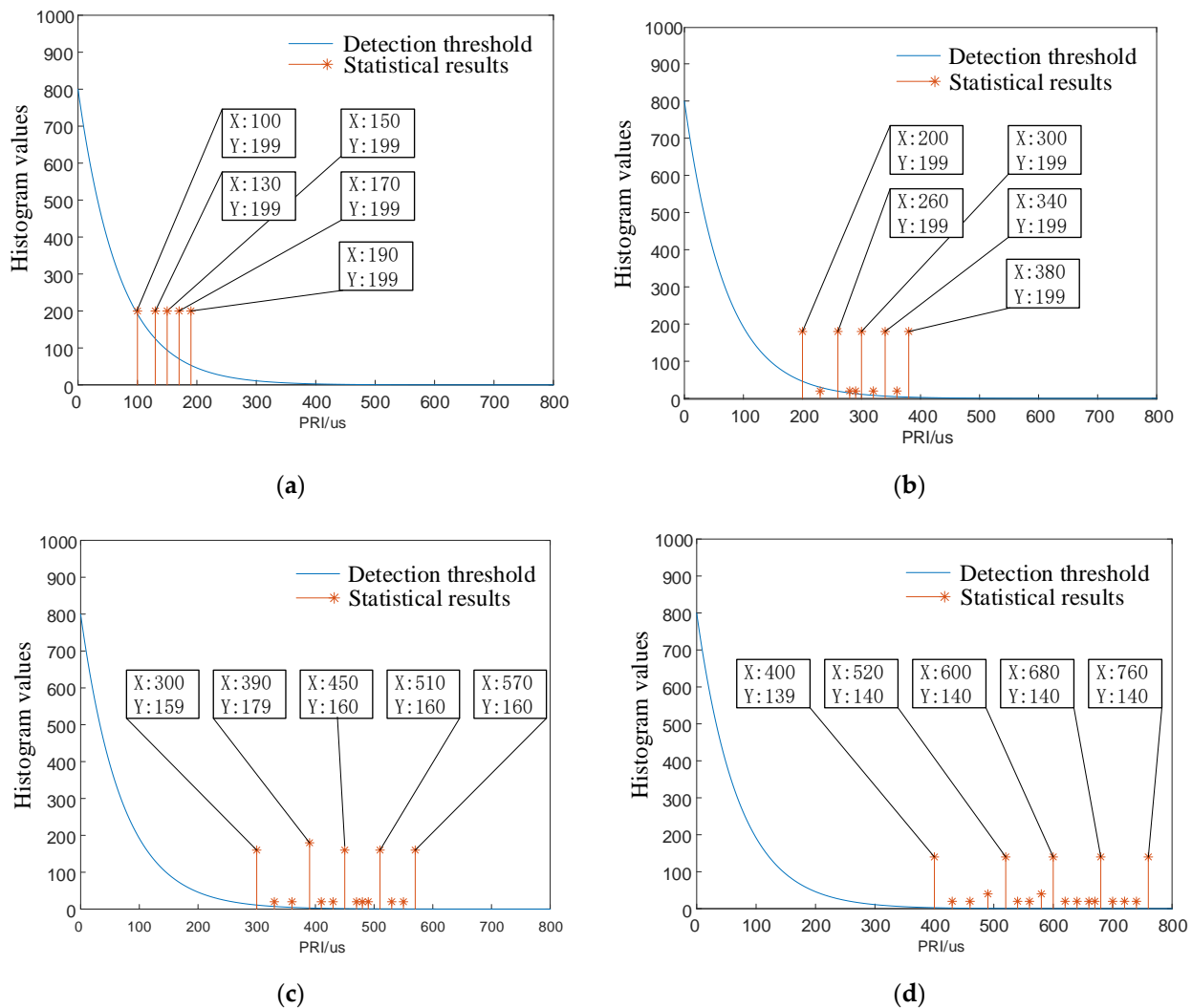


Figure 7. SDIF algorithm for the D&S signal first-to-fourth-order histogram sorting results. (a) The histogram of first-order TOA difference in the D&S signal; (b) the histogram of second-order TOA difference in the D&S signal; (c) the histogram of the third-order TOA difference in the D&S signal; (d) the histogram of the fourth-order TOA difference in the D&S signal.

Figures 6 and 7 respectively show the sorting results of the anti-sorting signal designed in this paper and the D&S signal by the SDIF sorting algorithm. Figure 7a shows that the SDIF sorting algorithm could sort D&S signals in the first-order histogram. Similarly, the SDIF sorting algorithm could successfully sort D&S signals in the second-order histogram, third-order histogram, and fourth-order histogram. The analysis of Figure 6 shows that no statistical value exceeded the threshold function from the first-order histogram to the advanced histogram, so the radar signal designed according to the sorting failure principle could resist SDIF sorting.

4.3. Contrast Experiment of Signal Sorting Based on the Experimental System

4.3.1. Introduction to the Experimental System

The experimental system was mainly composed of two parts, the first part being the signal transmission subsystem, and the second part the signal reconnaissance subsystem. The signal transmission subsystem was mainly composed of a vector signal source, a signal digital–analog conversion board, and control and signal processing board, and a display terminal. The signal transmitting subsystem mainly used remote-control technology to integrate the signal digital–analog conversion, signal processing, and signal generation into a system. Then the vector signal source transmitted a waveform file prepared by MATLAB code. The structure and composition of the signal transmission subsystem is shown in Figure 8. Furthermore, the signal reconnaissance subsystem was mainly composed of a receiving antenna, an electronic equipment host, a display control host, power extension, a triangle bracket, and several cables. It was used for real-time measurement, processing, sorting, and identification of carrier frequency, pulse width, amplitude, and TOA parameters of the radar target radiation source signal. A schematic diagram is shown in Figure 9.

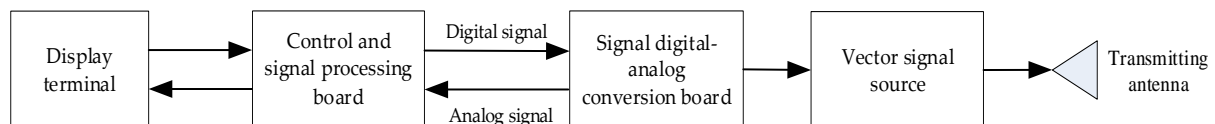


Figure 8. Diagram of the signal transmitting system structure.

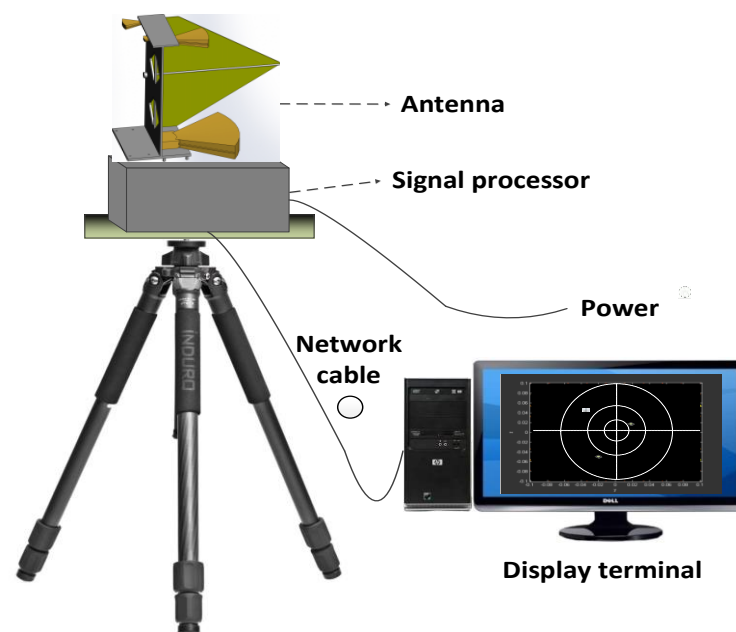


Figure 9. Schematic diagram of the signal reconnaissance system.

4.3.2. Sorting Contrast Experiment

Firstly, signals were generated by the signal transmitting subsystem in this experiment. Secondly, in order to avoid the impact of the noise in the natural environment on the experiment, the signal generated by the vector signal source was not transmitted by the horn antenna and received by the antenna and transmitted to the signal processing engine, but directly transmitted to the signal processing host of the signal sorting subsystem through the cable. The specific connection of the experimental system is shown in Figure 10.

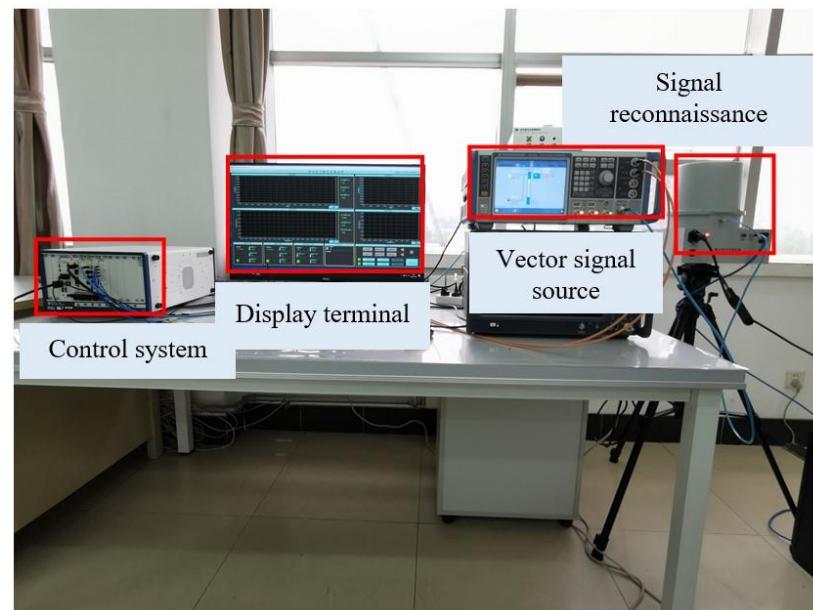


Figure 10. Signal sorting experiment equipment connection diagram.

As the photo format is limited, the display terminal interface of the signal sorting system is shown in Figure 11.

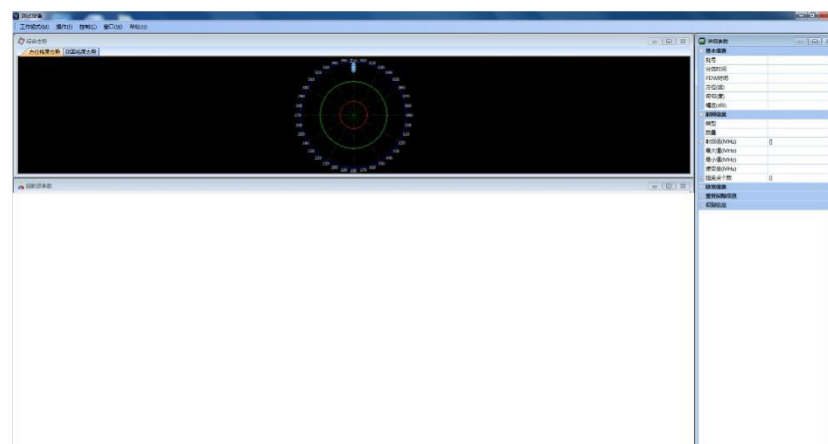


Figure 11. Display terminal interface of the signal reconnaissance system.

In the field of anti-sorting, the jitter signal is also considered as one of the better anti-sorting signals. This section takes the PRI jitter signal as an example to compare its sorting resistance with the signal designed in this paper. The signal PRI designed in this paper is $[100\mu s, 300\mu s]$, the minimum interval of signal PRI is $1\mu s$, and the length of the PRI interval is 200 times the minimum interval, which meets the requirements of Section 2. The jitter signal center PRI is $200\mu s$, and the jitter quantity is 50%, that is, the jitter signal PRI

interval is $[100\mu s, 300\mu s]$. In order to ensure the credibility of the experimental results, 1000 experiments were conducted under the same experimental conditions, and the number of signal pulses in every experiment was 1000. In the actual sorting system, a variety of sorting algorithms, not only the SDIF algorithm, are often used for comprehensive sorting of signals. Therefore, the system always outputs a PRI value in the experiment. However, as long as the number of pulses is less than 5, it can be considered to be a sorting failure. Therefore, in each experiment, the percentage obtained by dividing the number of PRI search pulses output by the sorting system from the total number of pulses (1000) is the sorting result, as shown in Equation (23):

$$\eta = \frac{a}{1000} \quad (23)$$

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 specific sorting results are shown in Figure 12.

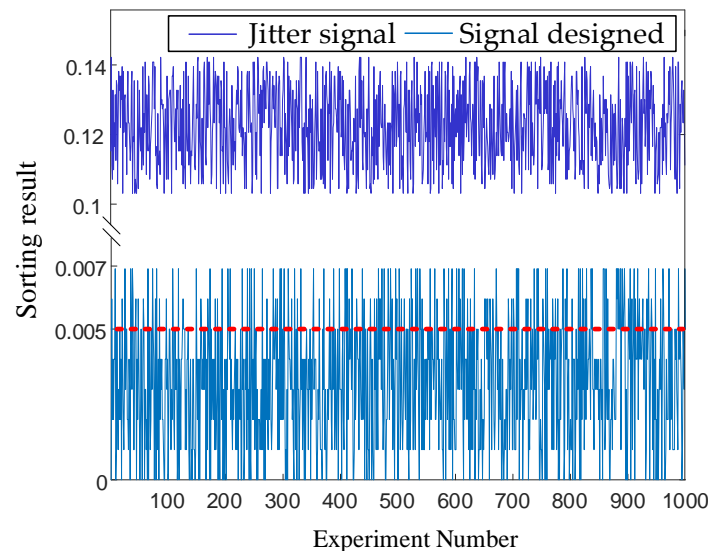


Figure 12. Comparison diagram of sorting results.

Figure 12 shows that with 1000 sorting times, signals designed according to the principle of sorting failure are searched for 163 times with more than 5 pulses according to the output results of the sorting system, which is 16.3% of the total number of experiments, which is 1000 times, and the success rate of anti-sorting is 83.7%. On the contrary, jitter signals can search more than 5 signal pulses according to the output results of the sorting system in 1000 experiments. Therefore, the success rate of anti-sorting is 0, indicating that jitter signals cannot achieve anti-sorting for an efficient signal sorting system.

5. Conclusions

In this paper, the sorting process of the SDIF sorting algorithm is studied. In particular, the TOA histogram threshold in the process of sorting is investigated in detail. Then the failure principle of SDIF threshold sorting is proposed. When the PRI value of a radar signal obeys the distribution of an interval whose length is more than 20 times that of the minimum PRI interval, the accumulative number of TOA differences of signal pulses at all levels is smaller than the threshold of the sorting algorithm. Therefore, the SDIF algorithm fails to sort the signal. The sorting failure principle is verified theoretically and

experimentally by formula derivation and signal simulation. The sorting failure principle provides theoretical support for the design of anti-sorting signals and helps to improve the efficiency and success rate of signal anti-sorting design.

Author Contributions: Conceptualization, J.J.; software, H.X. and M.L.; writing—original draft preparation, J.J.; writing—review and editing, J.J. and Z.H.; supervision, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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