Simulation on Multichannel Navigation Satellite Reflected Signal Detection Algorithm Based on Uniform Plane Array Digital Beamforming

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***Abstract*—Passive radar systems based on navigation satellite reflected signal achieve the target detection and location by receiving and processing very weak Globe Navigation Satellite System (GNSS) reflected signal efficiently. During the multi-channel signal processing of navigation satellite reflected signals, digital beamforming (DBF) has been introduced to form automatically array antenna beam pointing to optimize navigation satellite receiving reflected signals. Finally, simulations have been on the results and performance of the detection algorithm simulation, the results show that the algorithm is efficient enough to achieve the goal of detecting the weak reflected signal.**

Keywords—Digital Beamforming; Array Signal; Weak Signal Detection

I. INTRODUCTION

Global Navigation Satellite System (GNSS) is Earth satellite constellation to provide positioning and timing information for the user on the Earth or in the space. US Global Positioning System (GPS) is the most widely used GNSS[1]. In addition, GNSS also includes Russia's GLONASS, the EU's Galileo Navigation system and China's Beidou satellite navigation system (COMPASS). Passive target detection systems using GNSS signal have been a hot issue these years[2-6]. This kind of target detection systems have high battlefield survival ability which work in radio silence mode with the advantage of anti-radiation missile attack, anti-jamming and anti-stealth and other unique advantages.

NSS weak signal detection technology is mainly to consider how to effectively improve the SNR of the receiving system which can usually be considered from the detection of the received signal strength and reduced noise power. On the one hand, a high gain antenna can be used to receive the reflected weak signal [7-11], but this makes the system design complexity increases, and the ability of enhance the signal strength is limited. On the other hand, the different characteristics of signal noise auto-correlation can be used to improve the SNR of the weak reflected signal receiving system by autocorrelation processing [12-16].

Under normal circumstances, GNSS satellite signal power is very weak near the Earth, the power of reflected GNSS signals after reflection from targets and space transmission loss is further decreased, resulting in the serious challenges for the detection of the reflected signal. Since the time-domain accumulation algorithm is influenced by calculation, the Doppler frequency shift and the length of the received data, it cannot meet the actual demand. In order to realize the receiving and processing the very weak reflected navigation efficiently, the paper introduce digital beamforming (DBF) into the multi-channel GNSS reflected signal processing using accumulation time-domain algorithm. The DBF can automatically adjustment array antenna beam pointing to optimize the receiving of the reflected GNSS signals. Because DBF also has an effect of spatial filter which can effectively suppress noise and weaken the adverse effects of the interference signal, and ultimately makes the further detection of the reflected GNSS signals possible.

II. ARRAY SIGNAL MODEL

Since the linear array can only process one dimension beamforming, apply to the more general case, consider the receiving array as uniform plane array, the array structure shown in Figure 1[17].

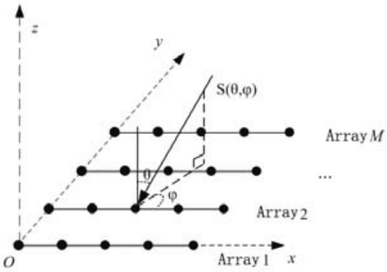


Fig. 1. Schematic Diagram of Uniform Plane Array

Let uniform array plane array element number is M × N, the number of source is P. θ_p、ϕ_p representing the source of the p-th elevation and azimuth (p = 1,2, ..., P), the wave path difference between the i-th array element and the array element reference (reference array elements is the original matrix element) is:

$$\beta = 2\pi(x_i \cos\phi \sin\theta + y_i \sin\phi \sin\theta + z_i \cos\theta) / \lambda \tag{3}$$

Wherein, x_i and y_i is the i-th array element coordinates. Since the plane array is generally in the xy plane, z_i is generally zero. Easy to know that the corresponding guide matrix for N array elements on the x-axis is:

$$A_x = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{-2\pi d\cos\phi_1\sin\theta_1/\lambda} & e^{-2\pi d\cos\phi_2\sin\theta_2/\lambda} & \cdots & e^{-2\pi d\cos\phi_p\sin\theta_p/\lambda} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-2\pi d(N-1)\cos\phi_1\sin\theta_1/\lambda} & e^{-2\pi d(N-1)\cos\phi_2\sin\theta_2/\lambda} & \cdots & e^{-2\pi d(N-1)\cos\phi_p\sin\theta_p/\lambda} \end{bmatrix} \quad (4)$$

The corresponding guide matrix for M array elements on the y-axis is:

$$A_y = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ e^{-2\pi d\sin\phi_1\sin\theta_1/\lambda} & e^{-2\pi d\sin\phi_2\sin\theta_2/\lambda} & \cdots & e^{-2\pi d\sin\phi_p\sin\theta_p/\lambda} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-2\pi d(M-1)\sin\phi_1\sin\theta_1/\lambda} & e^{-2\pi d(M-1)\sin\phi_2\sin\theta_2/\lambda} & \cdots & e^{-2\pi d(M-1)\sin\phi_p\sin\theta_p/\lambda} \end{bmatrix} \quad (5)$$

A_x , A_y in (4) and (5) are Vandermonde matrix. In figure 2, the sub-array 1 can be represented by guide the matrix A_x .Sub-array steering matrix 2 can be seen as a result of the translation by the sub-array 1 along the y-axis, where each array element with respect to the reference beam path length difference can be considered as wave path difference of sub-array 1 plus $-2\pi d\sin\phi\sin\theta/\lambda$. And so on, so that the i-th sub-array-oriented matrix is:

$$A_i = A_x \cdot D_i(A_y) \quad (6)$$

$D_i(\cdot)$ is a diagonal matrix constructed by an m-th row of the matrix A_y , empathy sub-arrays may be regarded as the y-direction, and so get the guide matrix plane array. Similarly available, the entire receive data plane array is:

$$x(t) = \left[A_1 s(t) + n^1(t) \quad A_2 s(t) + n^2(t) \quad \cdots \quad A_M s(t) + n^M(t) \right]^T \quad (7)$$

In the formula, $\boldsymbol{n}^m(t) = [n_1^m(t), n_2^m(t), \ldots, n_N^m(t)]^{\mathrm{T}}$, $n_n^m(t)$ is the n-th background noise of the m-th sub-array.

In terms of T_s sampling period for sampling an array of received data, the temporal snapshot data model can be obtained:

$$\boldsymbol{x}(n) = \boldsymbol{x}(t)\Big|_{t=nT_s} \quad (8)$$

Thus, the formula (8) can be rewritten as M × N-dimensional matrix, namely:

$$x(n) = \left[A_1 s(n) + n^1(n) \quad A_2 s(n) + n^2(n) \quad \cdots \quad A_M s(n) + n^M(n) \right]^T \quad (9)$$

III. Reflected Signal Processeing Algorithm

Because the wave direction of the signal is unknown, the range of scene is divided into several areas. When the data processing, an equivalent narrow beam is produced to each target region successively by DBF processing to receive the reflected signals correspond to each area, the main steps of the algorithm as follows:

(1) Calculate the weight coefficient matrix, signal synthesis

According to the structure of the array antenna, calculate the receiving antenna space-time steering matrices $\boldsymbol{A}$ and taking the conjugate transpose $\boldsymbol{A}^*$ too, it will be multiplied by the echo signal, the signal $\boldsymbol{x}'(t)$ obtained after the beam former.

(2) Data Block Processing

$\boldsymbol{x}'(t)$ is divided into *K* segment data ($K \geq 2$), the length of each piece data is *N*ms data, which *N*ms is the coherent accumulation time, usually no more than 20ms;

(3) Removing the Carrier

The locally generated carrier wave is divided into two Orthogonal-phase signals, and is multiplied with each *N*ms signal; to obtain in-phase signal I_k and the quadrature-phase signal Q_k , and then the complex signal $I_k + jQ_k$ does FFT transform and take its Conjugate;

(4) Local CA-code Processing

The locally generated 1 ms C / A code is extended to *N*ms and does FFT transform, and multiplying the result of step 3 after the Doppler frequency compensation to local C / A code in the frequency domain, then the results do IFFT transform, That is $y_k = IFFT(FFT(CA)\square(FFT(I_k + jQ_k))^*)$, and the last does the single-cycle Superposition;

5) Non-coherent Accumulation

Do non-coherent accumulation of coherent processing results to *N*ms data segment for *K* coherent processing results, that is $Y = y_1 + y_2 + \cdots + y_K$ and storage;

(6) Loop Processing, Output Results.

For reflected signals received in each region are processed in step 1 to 5, takes a maximum value of the final result of all the received signal from all detection region and outputs the results.

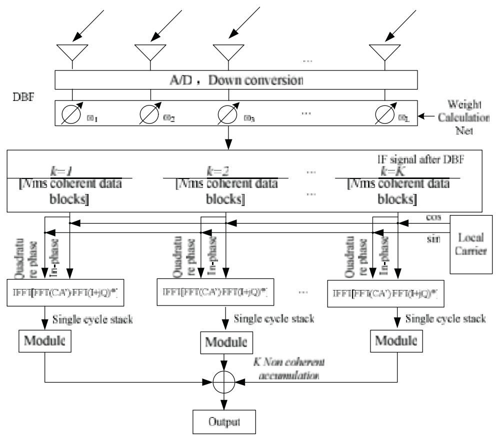


Fig. 2. Schematic Diagram of Multi-channel DBF Reflection Signal Detection Algorithm

In summary, the multi-channel digital beamforming reflection signal detection algorithm is shown as Figure 3.

CA' in figure 2 is the local C/A code after Doppler frequency compensated.

IV. SIMULATION ANALYSES

In order to study the effect of noise jamming to the algorithms, signal to noise ratio of multi-channel receive data would be set, and the data is superimposed corresponding random noise power to realize the goal. Because the paper puts more emphasis on comparison of multi-channel beam former signal processing algorithms to the single-channel time-domain signal processing algorithms to study the detection effect on the received signal, to simplify the analysis, simulation experiments in this chapter will not consider navigate bit symbols affects.

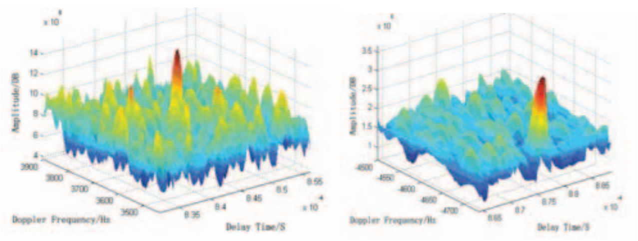
A. Simulation Results

Considering the planar array can provide a two-dimensional beam pointing direction, and multi-channel digital beamforming gain is concerned with the number of signal receiving channel, where the paper uses the uniform surface array-based multi-channel DBF to perform the simulation of the reflected signal detection algorithm. The simulation uses an uniform planar array antenna of 20 × 20 array elements, airborne receiver platform height of 10km, the length of the reflected signal is 200ms, and set a received signal to noise ratio fto -60dB (carrier to noise ratio of 3dB / Hz), while domain accumulation use 20ms coherent accumulation, the 10 times non-coherent accumulation.

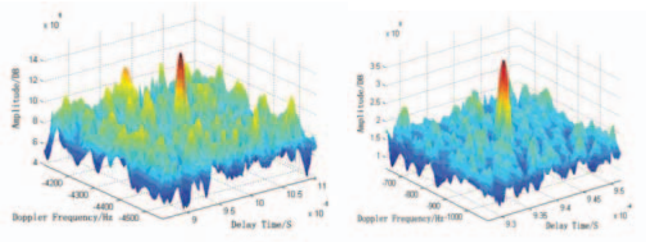
Set a random target in the scene, according to the spatial geometry, using the GPS satellite PRN 16, PRN 19, PRN 22, PRN 23 to analyze. The corresponding Doppler parameters of target to the satellite shows in Table 1, signal detection based on single-channel time accumulation and multi-channel DBF time accumulation results show in Figure 3.

TABLE I. CORRESPONDING DOPPLER PARAMETERS OF TARGET TO THE SATELLITES

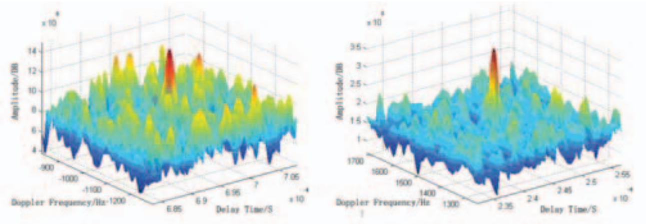
Satellite PRN	16#	19#	22#	23#
Doppler Parameters of Target /Hz	-4734.7	-855.9	1488.3	-3983.8



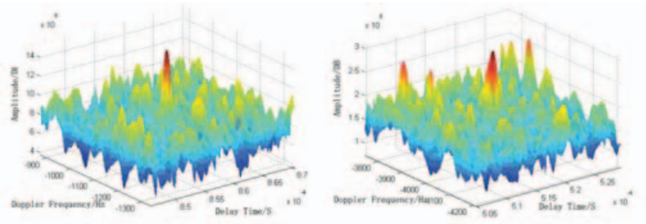
(A) Single-channel result (B) Multi-channel DBF result
PRN 16# Simulation Results



(A) Single-channel result (B) Multi-channel DBF result
PRN 19# Simulation Results



(A) Single-channel result (B) Multi-channel DBF result
PRN 22# Simulation Results



(A) Single-channel result (B) Multi-channel DBF result
PRN 23# Simulation Results

Fig. 3. Comparison Chart of Signal Detection Effects for Single-channel time-domain algorithm and multi-channel DBF Algorithm

Signal detection results of 20 × 20 Uniform plane array multi-channel DBF as Figure4 show. The following conclusions can be drawn from the results:

1. When airborne receivers flight speed is 100m / s, GPS Doppler frequency of the reflected signal is within the range of ± 5kHz .
2. The single-channel time-domain accumulation target detection algorithm failed to detect the reflected signal using 20ms coherent accumulation and 10 time non-coherent time-domain accumulation method under -60dB SNR conditions. The peak appearing in the figure belongs to false alarm phenomenon caused by noise, the main reason is that signal processing gain cannot guarantee ultimate signal to noise ratio only by single channel signal time-domain accumulation detection. The 20 × 20 uniform planar array multi-channel DBF signal detection algorithm can get the correct Doppler and delay information of target reflected signal, test results are correct, because in addition to the accumulate time-domain signal processing gain, the algorithm also won early 26dB gain by multi-channel synthesis
3. Multi-channel DBF based on uniform plane array signal detection algorithm can effectively improve the SNR of the received signal, and it can correctly detect the corresponding correlation peak of target reflected signal.

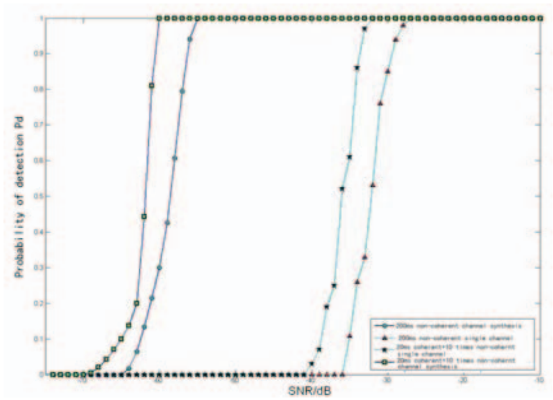
4. Under the same condition of time-domain accumulation time, uniform planar array of multi-channel DBF signal detection algorithm is more efficient to detect weak signals than single-channel time-domain signal detection algorithm.

Although the multi-channel DBF signal detection algorithms can correctly detect corresponding target reflected signal from 23 # satellite, but there are more false peaks, which may be due to the wave direction of # 23 satellite reflected signal is relatively close to the antenna baseline, resulting in digital beamforming main lobe beam generated after cleavage, broadening the main lobe beam width, so that the effect of spatial filtering algorithm deteriorates, not well suppress the noise signal, which is equivalent to the effect of improving the noise floor, and the signal detection effect is slightly worse.

In summary, when the data length is 200ms with 20ms coherent accumulation and 10 times non-coherent time-domain accumulation method, the uniform plane array-based multi-channel DBF detection algorithm is able to detect the signal to noise ratio of -60dB. The algorithm effect will slightly worse when direction of received signal approaching baseline array, but it still able to provide a higher signal processing gain. Compared to single-channel time-domain accumulation algorithm, multi-channel DBF detection algorithm greatly improves the system ability to detect and process weak signals.

Performance Analysis of Algorithms

Simulation parameters unchanged, the performance of single-channel reflection signal detection algorithm and multi-channel uniform plane array DBF signal detection algorithm is studied. Meanwhile, to discuss the coherence accumulation time on the test results, this experiment also used two approaches to process the 200ms of reflected GPS signal simulation data: (1) 1ms coherent accumulation with 200 times non-coherent accumulations; (2) 20ms coherent accumulation with 10 times non-coherent accumulation. Monte Carlo simulation results are shown in Figure 4.



Performance of uniform planar array of multi-channel DBF signal detection algorithm

Figure 4 shows:

1. Single-channel signal detection algorithm performance depends primarily on the time length of coherent and non-coherent accumulation. Under the same data length, the method 2 signal detection effect is better than method 1; relative to method 1, processing gain of reflected signal for method 2 is increased by about 5dB.

2. Using the same time-domain accumulation approach, under the same conditions as data length, the processing of the gain uniform planar array of DBF reflected signal detection algorithm is about 26dB higher than the single-channel reflection signal detection algorithm. The gain is mainly provided by the channel synthesis. Under the same conditions of the system, ability to detect weak signals has been enhanced by multi-channel data synthesis.

3. In order to ensure detection performance, the signal processing algorithms provide the required gain is increased accordingly when the SNR of the received data is reduced. Under the same SNR, the time-domain accumulation time is shorter for uniform planar array DBF signal detection algorithm compared with the single-channel signal detection algorithm.

V. Conclusion

In this paper, the reflected GNSS signal multi-channel DBF detection algorithm had been studied. Simulations had been performed using airborne platform configuration. The results showed that, GNSS reflected signal multi-channel DBF algorithm can effectively detect the correlation peak intensity of the received signal, providing a higher signal processing gain, to ensure the effective detection of the faint object reflected signal. When the accumulation length of received data and with the same time method, as compared to single-channel signal detection algorithm, multi-channel DBF algorithm can be further improved target reflected signal intensity received by the system, to improve the detection performance of the system. The algorithm has a certain reference value for the receiving, processing and application of GNSS reflected signal.

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