# DETECTION OF SMALL TARGETS BASED ON DUAL-RECEIVE CHANNELS RADAR

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## ABSTRACT

With the widespread application of unmanned aerial vehicles, higher requirements have been put forward for the detection of small targets moving at high speed. In this paper, we implement a millimeter wave Frequency Modulated Continuous Wave (FMCW) radar system with dual-receive channels to detect target motion parameters. In the radar system, a novel signal is designed to be composed of two FMCW signals whose instantaneous frequencies are symmetrical about carrier frequency, so as to get the estimation value of the targets' distance and radial velocity using doppler shift. Besides, signals of different periods are transmitted alternately to facilitate the removal of virtual targets. Furthermore, the height information of the target can be obtained through the interference of the signals received by the two channels. Based on the theory above, simulation results are provided to validate the effectiveness of the proposed approach and evaluate the performance of the radar system.

***Index Terms—*** Small target, velocity measurement, height measurement, dual-Receive channel

## 1. INTRODUCTION

Small targets are becoming increasingly ubiquitous[1] which the RCS of is comparable to that of flying birds, such as unmanned aerial vehicles (UAVs). Although UAVs have made significant social contributions in some fields like express delivery, aerial photography and environmental exploration, there still exists increasing concern about theirs inappropriate use for terrorist attacks and reconnaissance activities not permitted by law[2]. Then, it is extremely necessary for us to carry out technological innovation to make up for the deficiencies of existing technologies in dealing with the movement parameters of UAVs to guarantee not only the timeliness but also the correctness of the detection of the UAVs' movement status in case of emergencies caused by UAVs.

In recent years, many achievements have been made in the field of UAVs detection technology, of which FMCW is the most commonly used technology. FMCW is characterized by no blind zone, high resolution and low cost, which can well implement short-range detection. At present, there exist relatively mature FMCW measurement solutions. In [3], the paper aimed to design and developed a low-cost customized 24 GHz FMCW radar prototype to implement the detection of nano-target and extract the Doppler signal. In [4], this paper focused on the design and development of K-band FMCW radar prototype for nano-UAVs detection. In addition, bistatic interferometric radar is often used for the detection of target motion characteristics. [5] introduced a new method to reduce the signal distortion in interferometric angular velocity measurement, and proposed two waveform methods: long-wavelength signal and short-pulse signal. [6] proposed that the radial velocity and angular velocity of the target can be measured by using the interferometric radar with dual-receive channels, and [7] based on this, combination of distance parameters, realized the path prediction of UAVs. A new method based on dual frequency Interferometric Radar was proposed in [8]. In this method, the radar can transmit high-frequency waveforms for radial velocity measurement and low-frequency waveforms for suppressing cross-correlation between different objects to provide lateral velocity. The NetRAD proposed in [9] can improve the resolution of clutter and target by analyzing the real data.

In this paper, based on the dual-receive channel radar, we propose a signal which is composed of two FMCW signals whose instantaneous frequencies are symmetrical about carrier frequency to meet the complex detection requirements of targets. This allows us not only to measure the target distance and radial velocity parameters, but also to use the interference of the echo signals of the two channels to obtain the height information of the target, which plays an important role in accurately detecting the spatial position of the target. We will focus on this principle in section II, and verify the feasibility of the theory with a simple multi-object simulation example in section III, and evaluate the correctness of the theory, and finally make a conclusion in section IV.

## 2. METHOD

### 2.1. VELOCITY MEASUREMENT

As shown in Fig.1, a periodic signal is continuously transmitted at a carrier frequency $f_0$ that consists of two FMCW signals whose instantaneous frequencies are symmetrical about carrier frequency. The transmitting signal can be expressed

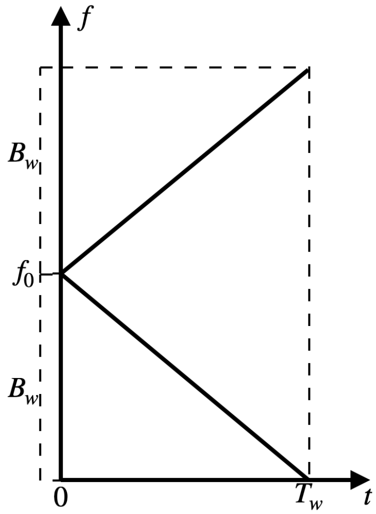


**Fig. 1**. Instantaneous frequencies of the signal.

as

$$S(t)=A_0\left[exp(j2\pi(f_0t+\frac{\mu t^2}{2}))+exp(j2\pi(f_0t-\frac{\mu t^2}{2}))\right] \quad (1)$$

Where $A_0$ is the amplitude, $B_w$ is the bandwidth, $T_w$ is the duration of a period, and $\mu = B_w/T_w$ is the linear frequency modulation slope.

Let us consider $N$ small targets located at an distance of $R_k$ and moving with a relative radial velocity of $v_k$ along radar LoS($k = 0, 1, \ldots, N-1$). Then time delay of $k$th target' echo is $\tau_k = \frac{2R_k}{c}$. The echo signal can be expressed as:

$$\begin{aligned}S_r(t)=&\sum_{k=0}^{N-1} K_k A_0\left[exp(j2\pi(f_0(t-\tau_k)+\frac{\mu(t-\tau_k)^2}{2}))\right.\\&\left.+exp(j2\pi(f_0((t-\tau_k)-\frac{\mu(t-\tau_k)^2}{2}))\right]\end{aligned} \quad (2)$$

Where $K_k$ represents the reflection coefficientof each different target, k=0,1,. . . ,N-1, the echo signal will pass the upper and lower limit cutoff frequency band stop filter with $\omega_1$ and $\omega_2$, where $\omega_1 = f_0 - (2v_{min})/\lambda$, $\omega_2 = f_0 + (2v_{min})/\lambda$, $v_{min}$ is the maximum radial velocity of the fragment target, which can separate the up and down sweep echo signals, and then the echo signal and the transmitted signal are conjugate mixed Get the beat signal of the up and down sweep. Supposed that B = $\frac{1}{2}k_k A_0^2$, the expression is as follows

$$S'_{up}(t) = \sum_{k=0}^{N-1} B\exp(j2\pi(f_0\tau_k - \frac{\mu{\tau_k}^2}{2} + \mu\tau_k t)) \quad (3)$$

$$S'_{down}(t) = \sum_{k=0}^{N-1} B\exp(j2\pi(f_0\tau_k + \frac{\mu{\tau_k}^2}{2} - \mu\tau_k t)) \quad (4)$$

Because the speed of light c is very large, the relevant terms of $c^{-2}$ and the $t^2$ term containing the coefficient of $c^{-1}$ are ignored, and the echo delay $\tau_k$ is substituted into the simplified result

$$S'_{up}(t) = \sum_{k=0}^{N-1} B\exp(j2\pi((\frac{2\mu R_k}{c} + \frac{2v_k f_0}{c}) + \frac{2f_0 R_k}{c})) \quad (5)$$

$$S'_{down}(t) = \sum_{k=0}^{N-1} B\exp(j2\pi((-\frac{2\mu R_k}{c} + \frac{2v_k f_0}{c}) + \frac{2f_0 R_k}{c})) \quad (6)$$

The parameters of the up and down sweep beat signal are as follows: Center frequency:

$$f_{bk,up} = \frac{2\mu R_k}{c} + \frac{2v_k f_0}{c}, k = 0, 1, ...N-1 \quad (7)$$

$$f_{bk,down} = -\frac{2\mu R_k}{c} + \frac{2v_k f_0}{c}, k = 0, 1, ...N-1 \quad (8)$$

Additional phase:

$$\phi_{bk,up} = \phi_{bk,down} = \frac{2f_0 R_k}{c}, k = 0, 1, ...N-1 \quad (9)$$

Pairing the center frequencies of the upper and lower beat signals in the frequency domain can get the speed and distance of each fragment target. Because of the Doppler frequency shift, the center frequency has shifted. At this time, there is a distance-velocity coupling phenomenon. Therefore, find the beat frequency $f_b$ corresponding to the real distance of the fragment target:

$$F_{bk} = \frac{f_{bk,up} - f_{bk,down}}{2}, k = 0, 1, ...N-1 \quad (10)$$

So the initial distance is estimated as

$$R_k = \frac{f_{bk}c}{2\mu}, k = 0, 1, ...N-1 \quad (11)$$

The initial velocity is estimated as

$$V_k = \frac{(f_{bk,up} + f_{bk,down})c}{4f_0}, k = 0, 1, ...N-1 \quad (12)$$

### 2.2. TARGET MATCHING

The frequency pairing described in the previous section will cause the generation of many virtual targets. In order to remove these virtual targets, we further adopt a variable-period frequency-domain symmetric triangular wave signal which has the same bandwidth and different period.

The radar continuously transmits two frequency-domain symmetrical triangular wave signals with different sweep periods. Assuming that there are N targets in front of the radar, the center frequency of the target k obtained by sweeping up echo beat signal in the nth period is:

$$f_{bk,up} = \frac{2v_k f_0}{c} + \frac{2\mu R_k}{c} \tag{13}$$

Similarly, the center frequency of the target m obtained by sweeping down the frequency signal in the nth cycle is

$$f_{bm,up} = \frac{2v_m f_0}{c} - \frac{2\mu R_m}{c} \tag{14}$$

Then we can get

$$R_{nkm} = \frac{1}{2}(R_k + R_m) + \frac{1}{2}f_0\mu(v_k - v_m) \tag{15}$$

$$V_{nkm} = \frac{1}{2}(v_k + v_m) + \frac{1}{2}\mu f_0(R_k - R_m) \tag{16}$$

If the target k and m are the same target, the target distance and speed obtained by matching the beat frequency of the upper and lower scan frequency bands in different triangle wave periods are the same: $R2$, the real target distance and speed of the target have nothing to do with $\mu$, they are the same in two triangle wave periods, and the calculated value of the speed and distance of the false target is related to . If the two sets of distance and speed values in the two cycles are the same, the set value is considered to be the distance and speed parameter values of a certain target.

### 2.3. HEIGHT MEASUREMENT

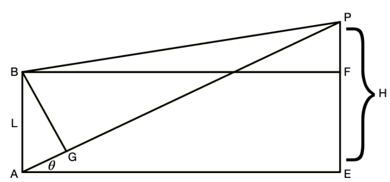


**Fig. 2**. The diagram of elevation space geometric Suppose.

Assuming that the distance between the target and the two receiving antennas A and B is $R_A$ and $_B$, respectively, then the echo signal of the frequency sweep signal undergoes Fourier transform to obtain the phase information. Taking a period of up-sweep signal as an example, the phase information of the target can be expressed as

$$\phi_A(t) = 2\pi(f_0 t - \frac{2R_A}{\lambda}) + \phi_A \tag{17}$$

$$\phi_B(t) = 2\pi(f_0 t - \frac{2R_B}{\lambda}) + \phi_B \tag{18}$$

where $\lambda$ is wavelength, $\phi_A$ and $\phi_B$ are backscatter phase shift.

It can be deduced from (1) and (2) that the phase after the interference processing reflects the distance difference between the two antennas and the target, and the antenna baseline length is negligible relative to the distance of the receiving antenna from the target. It can be approximated that the target has the same echo scattering characteristics of the two receiving antennas. So the interference phase of the target can be expressed as

$$\Delta\phi = 4\pi\frac{R_A - R_B}{\lambda} = 4\pi\frac{\Delta R}{\lambda} \tag{19}$$

Using geometric relations, we can get

$$H = \frac{R_A^2 - R_B^2 + L^2}{2L} = \frac{1}{2}\left[\frac{\Delta R(2R_A - \Delta R)}{L} + L\right] \tag{20}$$

## 3. EXPERIMENTAL RESULTS

### 3.1. VELOCITY AND DISTANCE

In this part, the MATLAB experiment simulation of the radar signal processing is carried out to verify the correctness of related algorithms and parameters. The radar baseband processing part includes low-pass filtering of the beat signal, AD converter, and a series of high-speed digital signal processor, its function is to be able to extract the speed and distance of the target in real time.

Assuming that the radar's sweep bandwidth $B = 150MHz$, the initial frequency $f_0 = 30GHz$, the sweep period $T_1 = 100s$, $T_2 = 150s$, and the sampling frequency is $35MHz$, we take the movement data of 50 fragmented targets randomly generated by the fragmentation simulation program as the original experimental data.

According to frequency matching algorithms and error judgment requirements, the matching results of speed and distance in different sweep cycles can be obtained.

From the above-obtained data, combined with the actual speed and distance of fragment movement obtained by simulation, we can get the scatter diagram as shown in the figure below.

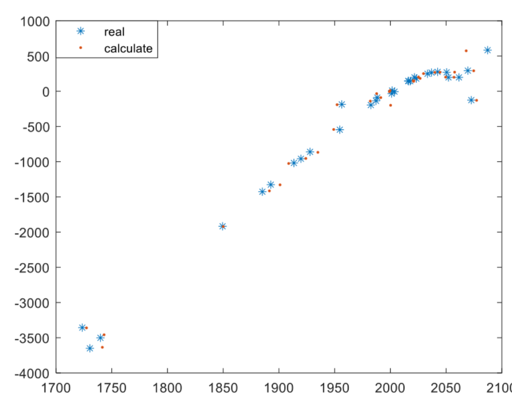


**Fig. 3**. Schematic diagram of speed distance correlation between real data and simulated data.

It can be seen that there is a good correspondence between the calculated speed, distance and the true value. According to this correspondence, we can obtain that the mean speed error at t5 is 6.4m/s and the distance error is 0.87m. In the other words, the errors are both within 1%.

### 3.2. HEIGHT

For the altitude simulation experiment, we randomly generated 5 sets of space coordinates and the corresponding radial velocity, calculated the relative distance to the radar receiver, and used the algorithm to obtain the estimated value of the altitude. The relationship between the real value obtained by the simulation and the estimated value is shown in the figure below, and it can be seen that there is a good correspondence between the two.

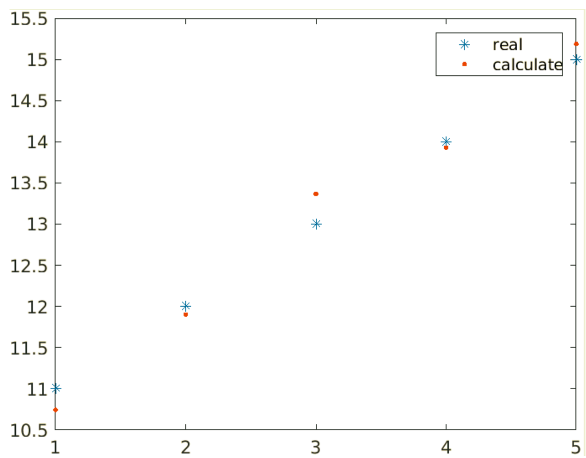


**Fig. 4**. Schematic diagram of height correlation between real data and simulated data.

After many experiments, we get that the algorithm's error of height calculation is kept within 2%

## 4. CONCLUSION

This paper proposed a new FMCW signal and detection algorithm based on target matching of different periodic signals using an interferometric FMCW radar, which we can obtain the target height information at the same time. The experimental results verified the accuracy of the proposed method.

This paper has a very good effect on the detection of a single or fewer targets. However, we also found in experiments that when the number of target is too muchsuch as more than $10^3$), the calculation amount of the target matching algorithm is greatly increased. In the future, it is necessary to further optimize the algorithm capabilities to improve the accuracy of target detection.

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