

# The essential digital signal processing in HF radar target detection

Qianzhao Lei

School of Physics and Electrical Engineering, Weinan Normal University, Weinan 714000, China

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**Abstract:** The moving target detection with HF radar must go through four steps of signal processing, namely pre-processing, range processing, azimuth processing and subsequent processing. Pre-processing is mainly the low-pass filtering and signal sampling. Range processing, which is used to produce the initial distance information, mainly includes the low-pass filter processing and fast Fourier transform (FFT). Azimuth processing is by using the adaptive beamforming, which in compliance with the linearly constrained minimum variance benchmark, to do the weighted processing; then by doing another FFT, to get a formula with a delta function and a Sinc function, this formula contains the moving target distance, direction and frequency informations. Subsequent processing should use some of the high-resolution processing or CFAR technique. These steps of signal processing were verified by measured data. Understanding these processing steps, we can optimize certain aspects according to actual needs, to realize the purpose of high frequency radar monitoring large area.

**Keywords:** Target detection, range processing, azimuth processing, Sinc function, high-resolution processing.

## 1. Introduction

High-frequency radar (HF radar) usually must meet a higher average transmit power to achieve its long-range detection capability and effective target discrimination [1]; in addition to the transmitting and receiving antenna array with special requirements, the radar generally uses the linear frequency modulation continuous wave signal [2, 3], by using these emission signals, HF radar digital signal processing in the course of target detection will be discussed; it will also be tested and verified with the measured data by HF sky wave radar.

## 2. Essential basic signal processing for HF radar target detection

The signal processing flow of HF radar as shown in Figure 1, it can be divided into four processes, namely (a) pre-processing; (b) distance processing; (c) azimuth processing; (d) subsequent processing.

2.1. *Digital signal pre-processing for HF radar system*  
In the flow chart of Figure 1, any a signal received by an

antenna, after mixing with the local oscillator signal, then successively through digital receiver, analog to digital converter and low-pass filter, transforms into a secondary intermediate frequency signal about a few MHz; then by doing signal sampling with 25 kHz sampling rate, got a discrete signal. Setting that radar linear frequency modulation signal  $S_0$  can be expressed as the following function:

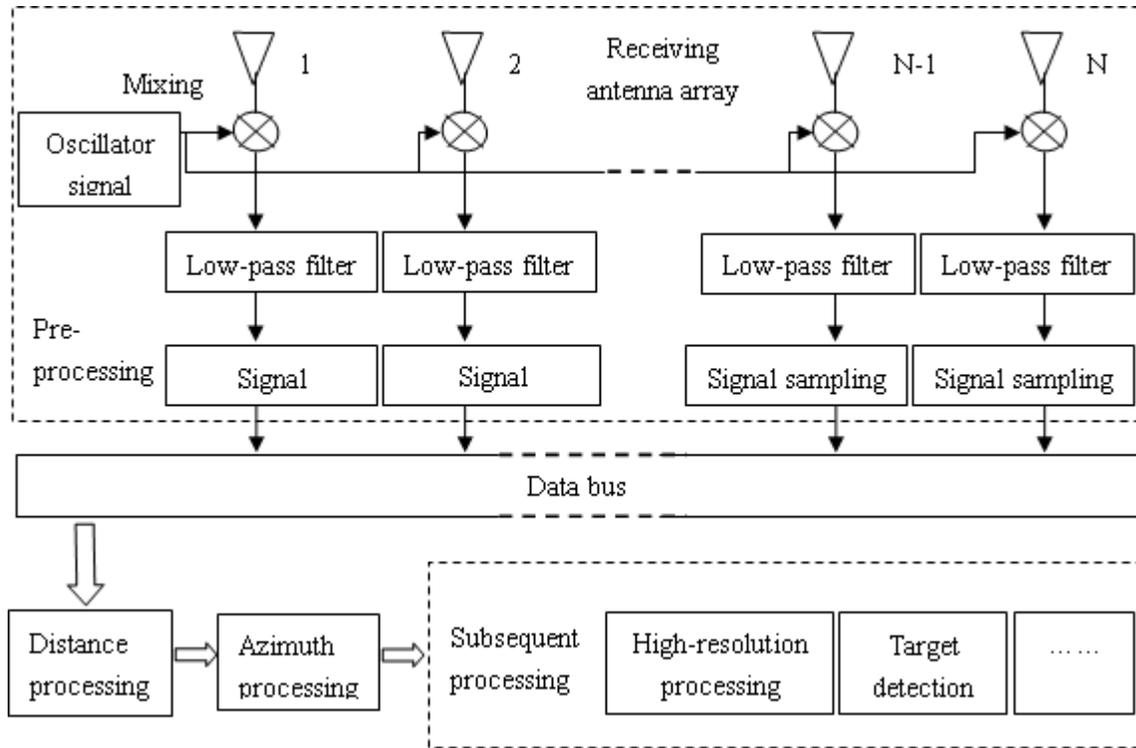
$$S_0 = A \exp(j2\pi f_0(t)) \sum_{m=0}^{M-1} u(t - mT)$$

$$\text{where } u(t) = \begin{cases} \exp(j\pi\beta t^2), & 0 \leq t \leq T \\ 0, & \text{else} \end{cases} \quad (1)$$

Here  $A$  is the signal amplitude,  $f_0$  radar working frequency,  $T$  its pulse cycle,  $M$  the number of continuously emitted pulse,  $\beta$  frequency modulation slope,  $\beta t$  is the frequency changing linearly with time.

2 Supposing a moving target's initial position has the relative distance  $R$  away from a launch radar, an azimuth angle  $\alpha$  diverging from the normal direction of the receiving antenna array, and the moving targets radial velocity is  $v_R$ , its Doppler frequency  $f_T$ ; assuming the radar working wavelength  $\lambda$ , the spacing between antenna array elements

\* Corresponding author: e-mail: leiqzh@126.com



**Figure 1** The signal processing flow chart of HF radar system

*d.* By formula (1), while the  $n$ -th antenna unit receives the  $(m+1)$ -th pulse echo signal  $S_{n,m}(t)$  from the moving target,  $S_{n,m}(t)$  as:

$$S_{n,m}(t) = A \exp\left(j2\pi \frac{(n-1)d \sin \alpha}{\lambda}\right) \cdot \exp(j2\pi f_0(t-\tau))u(t-mT-\tau), \quad (2)$$

Where  $\tau$  is the delay of the radar received signal from it emitted one.

$$\tau = \frac{2(R+v_R \cdot t)}{c} = \left(\frac{2R}{c} + \frac{f_T \cdot t}{f_0}\right) \quad (3)$$

In Figure 1, the local oscillator signal  $S_0(t)$  only has a time delay  $\tau_0$  compared with the radar emitted signal, written as [4]

$$S_0(t) = A \exp[j2\pi f_0(t-\tau_0)]u(t-mT-\tau_0). \quad (4)$$

Where  $\tau_0 = 2R_0/2c$ . After the signal mixing with the radar echo signal in formula (2), the following formula is got

$$S_{n,m}(t) \cdot S_0^*(t) = A^2 \exp\left(j2\pi \frac{(n-1)d \sin \alpha}{\lambda}\right) \exp\left(j4\pi f_0 \frac{R_0-R}{c}\right) \cdot \exp(-j2\pi f_T \cdot t) \cdot u(t-mT-\tau) \cdot u^*(t-mT-\tau_0) \quad (5)$$

## 2.2. Digital signal processing in the distance processing

Using  $t_{m'}$  to replace  $t-mT$ ,  $t_m$  to do  $mT$  in formula (5), as for  $u(t-mT-\tau) \cdot u^*(t-mT-\tau_0)$ , its instant frequency  $f(t)$  is as the following on the basis of formula (1),

$$f(t) = \begin{cases} -\beta(\tau-\tau_0), & \dots, \\ -\beta(\tau-\tau_0) + \beta T, & \dots, \end{cases} \quad \dots \begin{cases} t_{m'} \in [\max(\tau_0, \tau), T + \min(\tau_0, \tau)] \\ t_{m'} \in [\min(\tau_0, \tau), T + \max(\tau_0, \tau)] \end{cases} \quad (6)$$

Since the frequency  $|\beta(\tau-\tau_0) + \beta T|$  less than  $|\beta(\tau-\tau_0)|$ , after a low-pass filter, only the former keeps. Using formula (1) to deduce the  $u(t-mT-\tau) \cdot u^*(t-mT-\tau_0)$  of formula (5), after passing through the low-pass filter, got

$$S_{n,m \text{ mixing (after low-pass)}} = A^2 \exp\left(j2\pi \frac{(n-1)d \sin \alpha}{\lambda}\right) \cdot \exp(j\varphi) \cdot \exp\left(-j2\pi\beta\left(\frac{f_T}{f_0}\right)t_{m'}^2\right) \text{rect}(t) \cdot \exp\left(-j2\pi\beta\left(\frac{2(R-R_0)}{c} + \frac{f_t \cdot t_m}{f_0} + \frac{f_T}{\beta} - \frac{2R}{cf_0}f_T - \left(\frac{f_T}{f_0}\right)^2 t_m\right)t_{m'}\right) \cdot \exp\left(-j2\pi\left(1 - \frac{2\beta R}{cf_0}\right)f_T \cdot t_m\right) \quad (7)$$

here,  $\exp(j\varphi) = \exp(j4\pi f_0 \frac{2(R-R_0)}{c}) \cdot \exp(j\pi\beta \frac{4R^2-4R_0^2}{c^2})$ .

Then doing fast Fourier transform (FFT) for  $t_{m'}$  in formula (7), got

$$S_{n,m(low-pass)}(f_R) = A^2 \exp(j2\pi \frac{(n-1)d \sin \alpha}{\lambda}) \cdot \exp(j\varphi) \cdot T_P \cdot \exp(j\varphi_R) \cdot \exp\left(-j2\pi\left(1 - \frac{2\beta R}{cf_0}\right)f_T \cdot t_m\right) \cdot \text{Sinc}\left(\pi T_P \left(f_R + \beta \left(\frac{2(R-R_0)}{c} + \frac{f_t \cdot t_m}{f_0} + \frac{f_T}{\beta} - \frac{2R}{cf_0} f_T - \left(\frac{f_T}{f_0}\right)^2 t_m\right)\right)\right) \quad (8)$$

Where  $T_P = T - \tau - \tau_0$ , is the filtered pulse width,  $\varphi_R$  is the phase corresponding to the distance  $f_R$  of a moving target. At the narrow pulse position of the 'Sinc' function contains the distance information, but when  $f_T$  isn't known, it is still not a certain distance.

2.3. Digital signal processing in the azimuth processing

Adaptive beamforming, which complying to the guidelines of linearly constrained minimum variance, is used to do azimuth processing. The adaptive beamforming is to do weighted summation for the signals received by each antenna element, and when the constraint is constant to a signal gain at a certain direction, to make the antenna array has a minimum output power. Assuming that an antenna received signal sequence  $X(t)$  is  $N \times M$  dimensional matrix, i.e.

$$X(t) = [x_1(t), x_2(t), \dots, x_M(t)] \quad (9)$$

Which  $N$  is the vibrators number of antenna array,  $M$  the number of snapshot, and setting the array covariance matrix  $R = E[X(t_i)X^H(t_i)]$ . Optimal weights  $W$  can be got by doing linear constraints optimization for the following equation [5]

$$\begin{cases} \min W^H \hat{R}_x W \\ s.t. W^H S_\gamma(\theta) = 1 \end{cases} \quad (10)$$

Where  $\hat{R}_x$  is a covariance array,  $S_\gamma(\theta)$  is the array vector to the direction of angle  $\theta$ ,

$$S_\gamma(\theta) = [s_1(\theta), s_2(\theta), \dots, s_M(\theta)] = \left[1, \exp\left(\frac{j2\pi d \sin \theta}{\lambda}\right), \dots, \exp\left(\frac{j2\pi d(M-1) \sin \theta}{\lambda}\right)\right]^T \quad (11)$$

Using Lagrange method, the optimal adaptive weight coefficient  $W$  can be derived as

$$W = \frac{\hat{R}_x^{-1} S_\gamma(\theta)}{S_\gamma^H(\theta) \hat{R}_x^{-1} S_\gamma(\theta)} \quad (12)$$

Weighted by  $W$ , the output  $Y$  of the adaptive beamforming is got by using  $Y(t) = W^H \cdot X(t)$  [6].

With the optimal weight coefficient  $W$ , then back to formula (8), range, azimuth processing can be continued. Within the m-pulse, the echoes received by antenna elements, from the same range gate, are weighted and then combined, so got the following

$$S_m(f_R, \theta) = W^H [S_1(f_R), S_2(f_R), \dots, S_M(f_R)]^T = A^2 T_P W^H \left(1, \exp\left(j2\pi \frac{d \sin \alpha}{\lambda}\right), \dots, \exp\left(j2\pi \frac{(M-1)d \sin \alpha}{\lambda}\right)\right)^T \cdot \exp(j\varphi_R) \exp(j\varphi) \exp\left(-j2\pi\left(1 - \frac{2\beta R}{cf_0}\right)f_T \cdot t_m\right) \cdot \text{Sinc}\left(\pi T_P \left(f_R + \beta \left(\frac{2(R-R_0)}{c} + \frac{f_t \cdot t_m}{f_0} + \frac{f_T}{\beta} - \frac{2R}{cf_0} f_T - \left(\frac{f_T}{f_0}\right)^2 t_m\right)\right)\right) \quad (13)$$

In the above formula, when the angle  $\theta$  is equal to  $\alpha$  of formula (2), the strongest signal of the target, then the orientation of the radar beam scanning is the position of a moving targets at that moment. The  $t_m$  in (15) for discrete Fourier transform, i.e. doing FFT for the  $m$ -th pulse echo sampling, in the same range gate there are the same target distance and azimuth, formula (15) is changed into

$$S_m(f_R, \theta, f_m) = A^2 T_P W^H \left(1, \exp\left(j2\pi \frac{d \sin \alpha}{\lambda}\right), \dots, \exp\left(j2\pi \frac{(M-1)d \sin \alpha}{\lambda}\right)\right)^T \cdot \exp(j\varphi) \cdot 2\pi\delta\left(f_m + \left(1 - \frac{2\beta R}{cf_0}\right)f_T\right) \cdot \text{Sinc}\left(\pi T_P \left(f_R + \beta \left(\frac{2(R-R_0)}{c} + \frac{f_t \cdot t_m}{f_0} + \frac{f_T}{\beta} - \frac{2R}{cf_0} f_T - \left(\frac{f_T}{f_0}\right)^2 t_m\right)\right)\right) \quad (14)$$

Using the above equation, the moving target distance, azimuth and Doppler informations can be got. Where,  $\delta$  function determines the position of a target Doppler frequency; the location of the Sinc-shaped pulse and the maximum energy orientation do the distance and orientation of the moving target.

2.4. Digital signal processing in the subsequent processing

The following processes, usually with the help of high-resolution spectral estimation techniques or sea clutter cycle elimination method [7,8], reverse engineering [9], further reduce the atmospheric noise and sea clutter, thereby highlighting the moving target, to achieve HF radar moving target detection, identification. The sea clutter is generally non-steady, but the sea state bears little change in adjacent distance-azimuth units, their clutter spectrums have

a similarity [10]. Averaging the clutter power spectrums of adjacent distance-azimuth units as a real-time threshold level [11], comparing any a distance gate of the adjacents with the threshold level, if there being any moving target, it must be highlighted, this is so called constant false alarm rate (CFAR) technique [12, 1]. CFAR has proved effective not only in lessening sea clutter but in decreasing the broadened ionosphere pollution, which is similar in the same threshold level [13].

### 3. Measured data validation by HF sky wave radar

By using a sampling frequency of 5.6MHz, then 512 echo-units extracted from each resident beam as a distance gate, finally weighting function of Chebyshev window to suppress side-lobe pulse pressure, after finishing the distance and azimuth processing, the data of every distance gate were saved in the dat files. Selecting 850 distance gate as an example, getting the data from the dat file, doing FFT for it, the power spectra of this distance gate was got, as showing in Fig. 2. In the frequency spectrogram of the 850 distance gate, two left and right Bragg peaks were at -0.44 Hz and 0.43 Hz respectively, midpoint of 2 peaks positions was at -0.005Hz, which was the point of genuine zero frequency due to the existence of the radar system frequency offset. The sea echo Bragg peak Doppler frequency ( $f_B$ ) and the radar operating frequency ( $f_0$ ) satisfy  $f_0 = \pm 0.102 \sqrt{f_0(MHz)}(Hz)$  [14]. By calculating, the theoretical values of the Bragg peaks is of  $\pm 0.436Hz$ . We can see the theoretical value was basically consistent with that of the measured. Fig. 3 was a case, which averaging 8 adjacent distance gates spectra of the 850 as the threshold level, the spectra of 850 distance gate minus the level, taking into account the radar system frequency offset, the prominent signal was at the actual zero Doppler frequency, this is generally caused by the differences of land-echo peaks between the 850 distance gate and its neighboring, so it isn't a target [13].

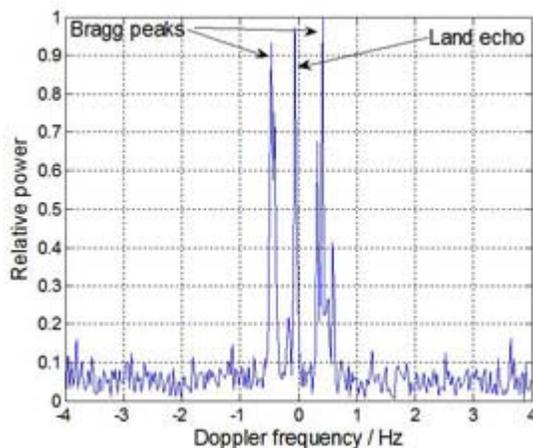


Figure 2 The power spectra of 850 distance gate

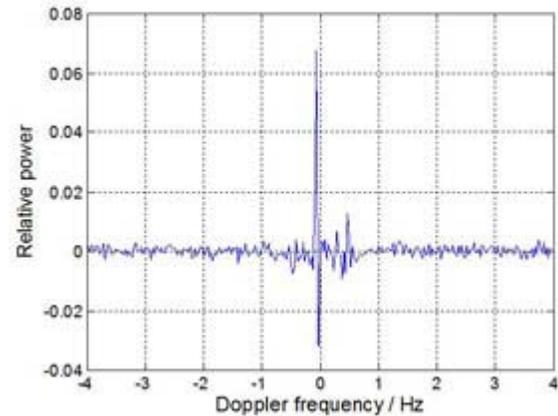


Figure 3 After 850 distance gate minus the threshold level

### 4. Conclusion

In the signal processes for target detection, earlier using low-pass filter to remove some of the clutter, keeping moving target information, reducing the dynamic range of subsequent processing, then the beat signal of a moving target is done FFT. After this, the frequencies contains the atmospheric noise, sea clutter and target informations. Atmospheric noise isotropic, its frequency spectrum is in the Gaussian distribution. For the echoes of the sea clutter, its first-order and second-order Bragg spectral distribution is also the Gaussian. Due to fast speed, aircraft has high Doppler frequency, big difference from background, relatively easy to detect; but as sea moving target speed is limited, the Doppler frequency of the background sea clutter should not be overlooked, so the follow-up processing of ship detection will be a huge challenge.

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### References

- [1] X. GUO, J. L. NI, W. M. SU, G. S. LIU. DEVELOPMENT OF SKY WAVE OVER-THE-HORIZON RADAR, Acta Aeronautica et Astronautica Sinica, 2002, Vol. 23(6): 495-500.
- [2] Zh. Ch. SHAO, Y. H. WU, X. JIA. Detection and Parameter Estimation of LFM Signal Based on Time-frequency Analysis. Journal of the Academy of Equipment Command Technology 2004, Vol. 15(2): 71-75.



**QZh Lei** is an associate professor in School of Physics and Electrical Engineering, Weinan Normal University, China. He received his master degree in radio physics and is working for PhD. His

main research fields include electromagnetic wave propagation in random medium and signal processing. For the last 3 years, he has been author of more than 20 articles, parts of which were published in international journals, others in chinese core journals.

- [3] J. Q. YUAN, F. K. HUANG, Zh. WANG. A New Approach with Wigner-Ville Distribution Based On LFM Signal Detection in the Ocean. *Journal of National University of Defense Technology*, 2002, Vol. 24(4): 73-76.
- [4] Christopher S. Withers, Saralees Nadarajah. Channel capacity for MIMO systems with multiple frequencies and delay spread, *Appl. Math. Inf. Sci.* Vol. 5, No. 3 (Sep. 2011), PP:460-483.
- [5] Y. L. Wang, Y. N. Peng. space time adaptive processing. Beijing China: Tsinghua University Press, 2000.
- [6] Jinfang Liu, Zili Deng, Self-Tuning Weighted Measurement Fusion Kalman Filter for ARMA Signals with Colored Noise, *Appl. Math. Inf. Sci.* Vol. 6, No. 1 (Jan. 2012), PP:1-7.
- [7] J. R. Barnum, Ship detection With high-resolution HF Sky-Wave radar. *IEEE Journal of Oceanic Engineering*, Vol.11, No.2, PP.196 209,1986.
- [8] B. T. Root. HF-over-the-horizon radar ship detection with short dwells using clutter cancellation, *Radio Science*, Vol.33. No.4, July-August 1998, pp.1095 1111.
- [9] Ma Li, Li Jingzhe, Zhang Yongmei, Ge Genyan, Yang Yingang. Error Assessment Method of Ultra-precise Measurement in Reverse Engineering. *Appl. Math. Inf. Sci.* Vol. 5, No. 2S (Mar. 2011, Special Issue), PP:151S-259S.
- [10] A. L. Dzvankovskaya, H. Rohling. Ship Detection with Adaptive Power Regression Thresholding for HF Radar [J]. *Radar Science and Technology*, 2007, Vol. 5(2): 81-85+78.
- [11] Zh. Y. LEI, B. Y. WEN, N. PENG, J. NI, Y. H. HUANG, X.X. CHEN. CFAR-based HFSW radar low Doppler target detection [J]. *Chinese Journal of Radio Science*, 2007, Vol. 22(5): 778+ 789.
- [12] Y. H. HUANG, Zh. Y. LEI, H. F. ZHOU. "The CFAR-based correlative detection algorithm for fluctuant targets". *Radar Ecm*, Vol.3, 2008, pp. 35-4.
- [13] Q. Zh. Lei. Ship Rapid Detection in HF Sky-Wave Radar. *Asia-Pacific Youth Conference on Communication Technology 2010 (APYCCT 2010)*. Scientific Research Publishing, USA, 2010: 554-557.
- [14] X. Guo, J. L. Ni, G. S. Liu. The Ship Detection of Sky Wave Over-the-Horizon Radar with Short Coherent Integration Time [J]. *Journal of Electronics and Information Technology*, 2004. Vol. 26(4): 613-618.