A New Method for Parameter Estimation of Cross-Channel Ultra-Wideband LFM Signal

Xiaolei Fan¹*, Bing Li²

¹ National Key Laboratory of Science and Technology on ATR, National University of Defense Technology, Changsha, Hunan, 410073, China
² Information Communications College, National University of Defense Technology, Xi’an, Shanxi, 710106, China

*Corresponding author’s e-mail: xiaolei_zeno@126.com

Abstract. Aiming at the reconnaissance of ultra-wideband (UWB) LFM signal, a method using dual-channel joint working mode is introduced and a parameter estimation algorithm of cross-channel signal is proposed in this paper. Short time Fourier transform (STFT) is carried out to extract time-frequency curve firstly. Then least-square (LS) algorithm is used to roughly estimate the parameters of signal in single channel and whether it is a cross-channel signal is determined. Finally, random sample consensus (RANSAC) iteration is applied to construct the model of the chirp line and obtain the accurate parameters. Simulation results confirmed the effectiveness of the proposed method.

1. Introduction
As one of the most commonly used wideband radar signals, the waveform design and implementation technology based on LFM signal has been very mature. In recent years, the use of LFM signals has a trend towards wider bandwidth and higher frequency band. For example, TIRA, a broadband imaging radar recently developed by the German Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR), uses a LFM signal with a bandwidth of 2.1 GHz[1]. Lincoln Laboratory's newly upgraded ultra-wideband (UWB) satellite imaging radar HUSIR has a signal bandwidth of 8 GHz[2]. How to detect and process such LFM signals is a difficult problem in the field of electronic signal reconnaissance. It is hard to fundamentally solve the problem of UWB signal detection by using higher speed analog-to-digital converter (ADC). Moreover, the current level of ADC device technology development is very mature, and it is difficult to achieve major breakthroughs in the short term[3]. To solve this problem, a dual-channel synchronous reconnaissance technology is explored in this paper, and a cross-channel signal parameter estimation method is proposed to realize the reconnaissance and processing of UWB LFM signal.

2. Channel splicing
Figure 1 shows the two-dimensional time-frequency distribution of an UWB LFM signal, in which the signal frequency ranges from 900 MHz to 3900 MHz. It is to be detected by two receivers with 4.8 GHz sampling rate and 2 GHz effective bandwidth. Traditionally, the receiver center frequencies will be set to 1.2 GHz and 3.6 GHz, as shown in figure 2 and figure 3. In order to facilitate the subsequent analysis and processing of the signal, the receiver transition band is omitted in this paper, and only its effective bandwidth is used for channel splicing. The central frequency of the receiver in channel one...
is set to 1.2 GHz and that of channel two is set to 3.2 GHz. It ensures that at any time, the signal can be effectively received by one of the receiving channels without falling into the transition zone.

![Time-frequency distribution of a UWB LFM signal](image1)

Figure 1. The time-frequency distribution of a UWB LFM signal.

![Time-frequency distribution in channel one](image2)

Figure 2. The time-frequency distribution in channel one.

![Time-frequency distribution in channel two](image3)

Figure 3. The time-frequency distribution in channel two.

3. Parameter estimation algorithm of cross-channel LFM signal

3.1. Rough estimation of signal parameters in single channel

Under the condition of dual-channel reconnaissance, it is necessary to judge whether the signal crosses two channels. That is to say, for the signals detected in the two channels, determine whether they are the same signal or not. So, the first task is to detect and estimate parameters of LFM signal in each channel. In this paper, a parameter estimation method based on STFT[4] and least-square (LS)[5] fitting is adopted and the process is shown in figure 4. Firstly, STFT is carried out to the signal and the corresponding frequency of the spectrum peak in each window is extracted to form a time-frequency sequence. Then median filter is applied to the sequence to reduce the clutter interferences. Finally, the LS method is used to fit the two-dimensional time-frequency series, and the modulation slope, the initial frequency and the cut-off frequency of the signal are roughly estimated.

![Parameter estimation method in single channel based on STFT and LS](image4)

Figure 4. Parameter estimation method in single channel based on STFT and LS.
3.2. Frequency modulation linear fitting based on RANSAC iteration

If signals are detected in both channels and identified as the same LFM signal, further processing is needed to obtain its accurate parameters. Using the time-frequency sequence set obtained in section 3.1, a method based on random sample consensus (RANSAC) iteration is applied to extract the accurate signal parameters by cross-channel frequency modulation (FM) line fitting.

RANSAC was proposed by Fischler and Bolles for the first time[6]. It is a steady algorithm for model parameter estimation. Denote inliers as the samples that can be depicted by the model, and outliers are the ones far off normal range because of noise, interferences and wrong assumptions. The basic idea of RANSAC is to estimate the model parameters through iterations [7-8].

The model in this paper is the chirp line \( f = f_0 + kt \). The purpose of RANSAC iteration is to fit an optimal linear equation and obtain the accurate estimations of \( \hat{k} \) and \( \hat{f}_0 \). Assume the equation is \( f = f_{10} + k_{1}t \) after \( l \) iterations, the distance of point \((t_i, f_i)\) to the line can be obtained by

\[
d_{ii} = \frac{|f_{10} + k_{1}t_i - f_i|}{\sqrt{k_{1}^2 + 1}}
\]  

(1)

Define \( Th_d \) as the threshold. If \( d_{ii} > Th_d \), label the point as an outlier. Otherwise, label it as an inlier. According to the relabeled inliers and outliers, construct a more accurate linear model. Repeat the process until the model can satisfy the requirement or the iterations reach the maximum number.

3.3. The flow of the whole algorithm

Combining the advantages and disadvantages of LS method and RANSAC iteration, we propose a new method to estimate parameters of cross-channel LFM signal. The flow chart of the algorithm is shown in figure 5.

The two receiving channels are marked as CH_A and CH_B, and the frequency band covered by CH_A is lower than that of CH_B. The processing steps can be described as follows.

(1) First, signal detection is performed on the sampling data of CH_A and CH_B separately. If signals are detected in both of the two channels and \( |t_{b0} - t_{a1}| < \delta_f \), that is, the start time of the signal in CH_B and the end time of the signal in CH_A are continuous (\( t_{a1}, t_{b0} \) are the end time of the CH_A signal, and the start time of the CH_B signal respectively), it is considered that the signal may be a cross-channel LFM signal and it will be sent for subsequent processing. Otherwise, the signals are classified as single-channel signals.

(2) Then, the FM straight lines are extracted from the signals in CH_A and CH_B based on the method in section 3.1, and the FM slopes of them are estimated, which are recorded as \( k_a, k_b \). If \( |k_b - k_a| < \delta_k \), consider the signal as a cross-channel LFM signal and go on to step (3).

(3) Then, the cut-off frequency of CH_A signal (named as \( f_{a1} \)) and the start frequency of CH_B signal (named as \( f_{b0} \)) are compared. If \( |f_{b0} - f_{a1}| < \delta_f \), it is confirmed that the signal is a cross-channel LFM signal and the following processing in step (4) will be carried out.

(4) Finally, the time-frequency point sets obtained in the two channels are fitted by RANSAC iteration, and the precise parameters of the signal are estimated.
In the algorithm, $\delta_t$, $\delta_k$, $\delta_f$ are the parameters for controlling the discrimination of the two-channel signals, and are determined according to the actual application situation. Estimating the parameters of the signals in each channel separately is to judge whether the signals in the two channels are the same signal or not, so it is only necessary to estimate the rough parameters. Therefore, the LS method which is simple and need few computations is applied. If the signal is confirmed as a cross-channel signal, the more accurate signal parameters can be obtained with the linear fitting method based on RANSAC iteration.

4. Simulation and analysis

In order to verify the effectiveness of the algorithm, the simulation experiment is carried out based on Matlab platform. The LFM signal with a starting frequency of 900 MHz, a bandwidth of 3 GHz and a pulse width of 100 us is generated. The signal amplitude is normalized to 1, the initial phase is 0, and the signal-to-noise ratio (SNR) is -15 dB. The signal is sampled by two receiving channels with a sampling rate of 4.8 GHz. The parameters $\delta_t$, $\delta_k$, $\delta_f$ are set to 0.5 us, 1 MHz/us and 10 MHz respectively.

Figure 6 shows the time-frequency points distribution of the signal after pre-processing (STFT and median filtering). The blue points represent the data distribution in CH_A, and the red points represent the data distribution in CH_B. It can be seen from the figure that in the condition of -15 dB SNR, the time-frequency points in the two channels can still gather along the FM line, but there are also a large number of erroneous interference-points, i.e. outliers.
Through LS fitting, it is preliminarily estimated that the FM slopes of LFM signals in CH_A and CH_B are 29.979 MHz/us and 29.986 MHz/us, respectively. The signal cut-off frequency of CH_A is 2401 MHz, and the signal start frequency of CH_B is 2396.8 MHz. After discrimination, it is considered that this signal is a cross-channel LFM signal with super wide bandwidth.

Next, the data in CH_A and CH_B are combined to fit the FM line through RANSAC method, and the precise parameters of the signal are estimated. Figure 7 shows the fitting result. The green crosses and the red crosses in the figure represent the inliers and the outliers in the initial state, respectively. The green boxes represent the inliers that are finally identified after iterations. Correspondingly, the red boxes represent the final identified outliers. The dark blue dashed line is the final fitted line. Through the changes of inliers and outliers, it can be seen that the algorithm can well exclude the interference points and obtain accurate linear model parameters. Under this condition, the final estimated FM slope of LFM signal is 29.998 MHz/us, and the initial frequency is 899.3169 MHz.

Assume that it is a correct estimation if the error of parameter estimation is within ±1% of the true parameter and define the correct rate of estimation (CRE) as the division between the times estimated correctly and the total trial number. Then the SNR is varied from -20 dB to 0 dB and Monte Carlo simulations with trial number of 500 under each SNR are carried out. Figure 8 and figure 9 show the results of CRE and RMSE.
From the simulation results, it can be seen that the algorithm can achieve nearly 100% CRE and fairly low RMSE when SNR is higher than -18 dB. When the SNR continues to decrease, due to the performance limitation of LS method, the signal is no longer distinguished as a cross-channel LFM signal. As a result, the performance of the algorithm decreases rapidly. In general, the proposed algorithm can effectively process cross-channel LFM signals when the SNR is no less than -18 dB.

5. Conclusions
In this paper, the method of ultra-wideband LFM signal reconnaissance is explored. The related problems of LFM signal reconnaissance using dual-channel joint working mode are studied. A parameter estimation algorithm cross-channel LFM signal is proposed. The simulation results show that the method can accurately estimate the parameters of cross-channel LFM signals under the condition of -18 dB SNR. Moreover, the algorithm has good adaptability and robustness.

References
[1] Li Y.S. (2009) Development and revelation of space target detection radar technology. The 22th space detection workshop in China, pp. 349-354.
[2] Coutts, S., Cuomo, K., Mcharg, J., Robey, F., Weikle, D. (2006) Distributed Coherent Aperture Measurements for Next Generation BMD Radar. In: Fourth IEEE Workshop on Sensor Array and Multichannel Processing. Waltham. pp. 390-393.
[3] Li, R., Chen D.R. (2015) Multi-component LFM signal detection and parameter estimation algorithm based on synchronous Nyquist folding receiver with dual local oscillator. Journal of Electronics & Information Technology, 37: 91-96.
[4] Czerwinski, R.N., Jones, D.L. (1997) Adaptive short-time Fourier analysis. IEEE Signal Processing Letters, 4: 42-45.
[5] Wang, J.Z., Su, S.Y., Chen, Z.P. (2015) Parameter estimation of chirp signal under low SNR. Science China: Information Sciences, 58: 1-13.
[6] Fischler, M.A., Bolles, R.C. (1981) Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. Communications of the ACM, 24: 381-395.
[7] Yuan, Q.K., Zhang, Z.Y., Bi, Q. (2015) Linear fitting application based on the improved RANSAC algorithm. Modular Machine Tool & Automatic Manufacturing Technique, 1: 125-125.
[8] Liu, X.Q., Li, T., Fan, X.L., Chen, Z.P. (2019) Nyquist zone index and chirp rate estimation of LFM signal intercepted by Nyquist folding receiver based on random sample consensus and fractional fourier transform. Sensors, 19, 1477.