Insect speed extraction method based on a high resolution and full polarisation radar with vertical-looking mode

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Abstract: This study introduces a novel insect speed extraction method based on a high resolution and full polarisation radar with vertical-looking mode. The insect echo model of the high resolution and full polarisation radar is first established. Then, an iterative algorithm for estimating the horizontal speed of insects is derived based on the second-order polynomial approximation. Finally, experimental results show the effectiveness and feasibility of this algorithm in extracting the horizontal speed of insects. Compared with the traditional method, the method here is more simple and effective and greatly reduces the computation.

1 Introduction

Entomological radar has become a powerful tool for monitoring insect migration and has realised long-term automatic observations [1]. Until now, the most widely used entomological radar is the vertical-looking radar (VLR), which uses the techniques of rotating polarisation and beam nutation to extract characteristic parameters of insects [2–4]. The obtained parameters can be used for insect species identification and migration direction prediction, which is of great significance for insect pest forecast and the study of insect migration [5].

In order to get the insect migration parameters, Smith et al. established an echo model when an insect traversed the beam based on the VLR. By setting system parameters such as polarisation rotation speed and nutation angle, a curve of insect echo intensity can be obtained over time. In parameters extraction, first, the complex Fourier transform of the echo amplitude is considered. Then using a ‘three-peak’ or ‘five-peak’ approximation method, the speed and displacement direction, the body orientation, and the three cross-section parameters which are related to the size and shape of the insect can be extracted [2]. However, the algorithm for solving parameters in this literature is rather complicated.

In this paper, a novel insect speed extraction method is proposed based on a high resolution and full polarisation radar with vertical-looking mode. High range resolution can be achieved by using a stepped frequency technique, which helps to improve the measurement accuracy of the target [6, 7]. By transmitting and receiving a pair of electromagnetic waves with an orthogonally polarised state simultaneously, the full polarisation information of the target can be obtained [8]. First, the insect echo model of the stepped frequency radar system is established based on a hypothetical scenario. Then, an iterative algorithm is used to estimate the horizontal speed of insects. Finally, a Ku-band high resolution and full polarisation radar is used to observe insect migration. The experimental results verify the effectiveness and feasibility of this algorithm. Literally, the method in this paper is more simple and effective and greatly reduces the computation.

2 Echo model and parameters estimation

To accurately measure the density and behavioural parameters of insects, we used a high resolution and full polarisation radar system to observe insect migration. The basic parameters of the radar system are shown in Table 1.

The general modes of the radar can be divided into the scanning mode and vertical-looking mode. Among them, the scanning mode is mainly used to measure the statistical density of insects, while the vertical-looking mode is mainly used to measure the behavioural parameters of insects. This paper mainly focuses on the vertical-looking mode.

2.1 Echo modelling

2.1.1 High resolution range image: The stepped frequency signal is made up of \( N \) chirp signals which have the bandwidth \( B \) and pulse width \( T_p \). The frequency step is \( \Delta f \), thus the synthesised bandwidth will be \( B \times \Delta f \) after signal processing. The transmit signal can be written as [7]

\[
s(t) = \sum_{n=0}^{N-1} \left[ \text{rect}\left( \frac{t - nT_r}{T_r} \right) \times \exp\left\{ jnK_r(t - nT_r) \right\} \right] \\
\times \exp\left[ j2\pi(f_s + n\Delta f)(t - nT_r) \right]
\]  

where \( \text{rect}(\cdot) \) is the rectangular function, \( f_s \) is the centre frequency of the first sub-pulse, \( T_r \) is the pulse repetition time, \( K_r = B/T_p \) is the frequency modulation rate of the chirp signal.

During the operation of the entomological radar, the antenna alternately transmits and receives stepped chirp signals. The reference signals are also frequency stepped when demodulated. The baseband echo model for a single point target at distance \( R \) is given by

| Table 1 Basic parameters of the radar system |
|---------------------------------------------|
| Parameters                          | Value       |
| centre frequency                    | 16.2 GHz    |
| beam width                         | 1.5°        |
| pulse repetition frequency         | 40 kHz      |
| pulse width                        | 1 µs        |
| number of sub-pulses               | 40          |
| synthetic bandwidth                | 800 MHz     |
| polarisation modes                 | HH, HV, VH, VV |
\[ s_i(t) = \sigma \times \sum_{n=0}^{N-1} \left[ \text{rect} \left( \frac{t-nT_c-2R/c}{\Delta f} \right) \right] \times \exp \left[ j\frac{4\pi R}{c} (f_i + n\Delta f) \right] \times \exp \left[ j\frac{2\pi}{N} \left( f_i - nT_c - \frac{2R}{c} \right) \right] \] 

(2)

where \( \sigma \) is the scattering coefficient of the target.

The frequency-domain spectrum reconstruction (FDSR) method is used to synthesise the sub-pulses into the ultra-wideband signal [9]. After matched filtering, oversampling, frequency shift, and coherent accumulation, a high resolution range image may be written as

\[ s_i(t) = \sigma \times \sin \left[ \pi N\Delta f \left( t - \frac{2(R - R_{\text{init}})}{c} \right) \right] \times \exp \left[ -j\frac{4\pi R}{c} f_i \right] \] 

(3)

where \( R_{\text{init}} \) is the initial sample distance, \( f_i \) is the centre frequency of the whole stepped chirp signals, and \( f_i = f_p + ((N - 1)/2)\Delta f \).

2.1.2 Insect echo intensity model: Radar has the ability of simultaneous full polarisation measurement, which can obtain high resolution range images of targets under different polarisation states. By extracting the echo information of the target at each high resolution range image, the echo intensity of the target under different polarisation states can be obtained. The echo intensity depends on the scattering properties and the position of the target in the beam. It is assumed that the scattering properties remain unchanged during the insect overflight. However, the beam gain incident upon the insect is not a constant because the insect is moving. The off-axis beam gain is usually approximated by a Gaussian function [10]

\[ E(\theta) = E_0 \exp \left[ - \frac{1}{2} \left( \frac{\theta}{\theta_0} \right)^2 \right] \] 

(4)

where \( E_0 \) is the on-axis voltage gain, \( k = 8\ln 2 \), \( \theta_0 \) is the half-power beam width and \( \theta \) is the angle between the beam axis and the line connecting the target and the radar.

Suppose that the insect I is flying along a straight line \( P \) with constant speed \( V \) and the body orientation of the insect I is along a straight line \( Q \). The angle between the straight line \( P \) and the positive x-axis is \( a \). Fig. 1 shows the three-dimensional image and horizontal projection of the insect I as it traverses the beam [2]. In Fig. 1b, the straight line \( P' \) is the horizontal projection of the straight line \( P \), and the straight line \( Q' \) is the horizontal projection of the straight line \( Q \). Moreover, the horizontal component of the three-dimensional speed \( V \) is \( V_h \). The angle between the straight line \( P' \) and the positive x-axis is \( \beta \), and the angle between the straight line \( Q' \) and the positive x-axis is \( \phi \). In addition, \( p \) is the minimum distance from the point \( O' \) to line \( P' \). Suppose that the insect I passes the point A at the moment \( r \). The instantaneous distance \( r \) from the insect I to the beam axis is given by

\[ r' = p^2 + V_h^2(t - r) \] 

(5)

When the insect overflies the beam, the distance \( R \) from the insect to the radar is approximately equal to its flight height \( H \) due to the narrow beam width. Thus, the instantaneous angle \( \theta \) can be written as

\[ \theta = \tan(\theta) \times \frac{r}{H} \times \frac{r}{R} \] 

(6)

When the full polarisation radar is working properly, the echo data of the four polarisation modes can be obtained simultaneously, and the difference between each polarisation echo data is due to the different scattering properties of the target at different polarisation states. Therefore, the following derivation takes a certain polarisation mode as an example. Considering the signal changes in the slow time, the sinc function in (3) can be equivalent to 1. Combined with the antenna bidirectional voltage gain and the stepped frequency synthesis processing, the insect echo intensity can be written as

\[ S_i(t) = C_0 \times \exp \left[ - \frac{1}{2} \frac{V_h^2(t - r)^2}{R \theta_0^2} \right] \times \exp \left[ -j\frac{4\pi R}{c} f_i \right] \] 

(7)

where \( C_0 \) is a constant related to antenna gain and target scattering properties.

2.2 Iterative algorithm

Echo model in (7) contains three unknown parameters \( p, V_h, \) and \( \tau \). Among them, the shortest distance \( p \) cannot be solved with this type of radar system. However, \( V_h \) and \( \tau \) can be estimated by an iterative algorithm. By normalising the time-invariant parts in (7), (7) can be rewritten as

\[ g(t) = \exp \left[ - \frac{1}{2} \frac{V_h^2(t - r)^2}{R \theta_0^2} \right] \] 

(8)

Obviously, \( g(t) \) represents the echo envelope when the insect is moving in the beam.

To reduce the amount of computation, taking the logarithm of (8), the observation data model in the iterative algorithm is given by

\[ u(t) = 20 \log_{10}(g(t)) = -10 \log_{10} \frac{V_h^2(t - r)^2}{R \theta_0^2} \] 

(9)

The two unknown parameters \( V_h \) and \( \tau \) in (9) are arranged as a vector \( \theta = [V_h, \tau]^T \) and the elements in this vector are represented by \( \theta_i(i = 1, 2) \).

Now, suppose the radar observation data vector is denoted as \( w = [w_1, w_2, \ldots, w_M] \), and the data length is \( M \). The theoretical data vector in (9) is denoted as \( u(\theta) = [u_1(\theta), u_2(\theta), \ldots, u_M(\theta)] \) under the same conditions. Hence, the optimisation problem is to estimate \( \theta \) by minimising the cost function as follows [11, 12]

\[ J(\theta) = (w - u(\theta))^H(w - u(\theta)) \] 

(10)

where the superscript \( H \) denotes complex conjugate and transpose.

Next, an iterative algorithm is derived to estimate \( \theta \). Let \( J_k \) denote the cost function of the \( k \)th iteration and the \( k \)th estimate of \( \theta \) is denoted as \( \theta_k \). The second-order Taylor expansion of the cost function \( J \) at \( \theta_k \) is

\[ J_{k+1} = J_k + \frac{\partial J}{\partial \theta} (\theta_k - \theta) + \frac{1}{2} \frac{\partial^2 J}{\partial \theta^2} (\theta_k - \theta)^2 \] 

(11)
where $\partial J/\partial \theta_0$ and $\partial J/\partial \theta_i$ represent the first and second derivatives about $\theta_0$ and they are given by

$$\frac{\partial J}{\partial \theta_0} = -\left(\frac{\partial J}{\partial \theta_0}\right)^T (w-u) - (w-u)^T \frac{\partial J}{\partial \theta_0}$$

(12)

$$\frac{\partial J}{\partial \theta_i} = -\left(\frac{\partial J}{\partial \theta_i}\right)^T (w-u) + \left(\frac{\partial J}{\partial \theta_i}\right)^T \frac{\partial J}{\partial \theta_0} - (w-u)^T \frac{\partial J}{\partial \theta_i}$$

(13)

To minimise $J_{k+1}$, the derivative of $J_{k+1}$ against $\theta_i$ can be calculated and set it equal to 0. Thus, the corresponding estimated parameter can be expressed as

$$\theta_{i+1} = \theta_i - \frac{\partial J}{\partial \theta_i} \left(\frac{\partial J}{\partial \theta_0}\right)$$

(14)

At last, the appropriate initial values of iteration needs to be chosen for calculation. When the accuracy requirement is satisfied, the current values are the estimated values of the horizontal speed $V_h$ and time $r$, respectively.

3 Results

In the experiment, the full polarisation entomological radar was placed in the field where insects migrated frequently. The antenna was adjusted to make the radar beam vertical to the sky before data acquisition. When the insect passed through the radar beam, the echo data of the four polarisation modes could be obtained simultaneously. To improve the accuracy of the parameter extraction, the echo data of one polarisation mode which had the highest signal-to-noise ratio (SNR) were chosen for the parameter estimation.

The RCS of the insect is related to the angle between the insect body orientation and the antenna polarisation direction. For small insects, the RCS is greatest when the polarisation direction is parallel to the insect body axis, and the RCS is smallest when the polarisation direction is perpendicular to the insect body axis. Compared to the single polarisation radar, the full polarisation radar is easier to obtain echoes with higher SNR. Two insects (insect A, insect B) with different heights were selected from the experimental data for analysis. The SNR of the HH echo data is the highest for insect A, while the SNR of the VV echo data is the highest for insect B. The relative power of the chosen echo data of the insect A and insect B over time are shown in Fig. 2.

When the insect is located in the main lobe of the beam, the beam gain can be approximated by a Gaussian function. When the insect passes right through the beam axis, considering the bidirectional antenna gain, the difference between the maximum power and the minimum power is 6 dB. The area near the peak of the echo data is selected as the valid data area. The second-order polynomial is used to fit the valid data and the valid signal duration is determined to ensure that the difference between the maximum value and the minimum value of the fitting data is slightly <6 dB. The maximum value of the fitting data is subtracted from the echo data as the normalised echo data, that is, the observation data. Meanwhile, the fitting data are also normalised. The normalised observation data and fitting data of the insect A and insect B are shown in Fig. 3.

The observation data of the insect A and insect B are imported into the iteration algorithm, and the estimated horizontal speeds of the insect A and insect B are shown in Table 2.

Two insects picked from the experimental data have different heights and different horizontal speeds. The horizontal speed of the insect A is 3.75 m/s with the height 430 m, while the horizontal speed of the insect B is 5.34 m/s with the height 265 m.

4 Conclusion

In this paper, a novel insect speed extraction method is proposed based on a high resolution and full polarisation radar with vertical-looking mode. Assuming the general insect migration scene, the insect echo model of the high resolution and full polarisation radar system is established for the first time. Then, an iteration algorithm for extracting the horizontal speed of insects is derived. Finally, the Ku-band high resolution and full polarisation entomological radar is used to observe insect migration. The experimental results verify the effectiveness and feasibility of this method. The future research will focus more on the high resolution and full polarisation information of targets due to the precise measurement needs of tiny targets such as insects. Therefore, this algorithm may become an effective tool for insect migration parameters measurement.

6 References

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Fig. 2 The relative power of echoes from two insects
(a) Relative power of the HH echo of the insect A, (b) The relative power of the VV echo of the insect B

Fig. 3 Observation data and fitting data
(a) Observation data and fitting data of the insect A, (b) The observation data and fitting data of the insect B

Table 2 Parameters of the insect A and insect B

| Insect | Height, m | Horizontal speed, m/s |
|--------|-----------|----------------------|
| insect A | 430       | 3.75                 |
| insect B | 265       | 5.34                 |

This work was supported by the National Natural Science Foundation of China under Grant no. 31727901.

J. Eng., 2019, Vol. 2019 Iss. 19, pp. 5889-5892

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