SCIENCE CHINA
Information Sciences

• LETTER •

October 2018, Vol. 61 109306:1–109306:3
https://doi.org/10.1007/s11432-018-9484-2

Insect flight speed estimation analysis based on a full-polarization radar

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Received 4 May 2018/Accepted 28 May 2018/Published online 21 August 2018

Citation Hu C, Li W Q, Wang R, et al. Insect flight speed estimation analysis based on a full-polarization radar. Sci China Inf Sci, 2018, 61(10): 109306, https://doi.org/10.1007/s11432-018-9484-2

Dear editor,
As most migratory insects are nocturnal, the entomological radar with the advantage of all-time and all-weather application is the most effective technique for insect migration observation [1]. Generally, the current entomological radar could be categorized into the scanning radar and vertical-looking radar (VLR). The aerial density of migration could be measured by the scanning radar, while the flight speed, displacement direction, body orientation, and three cross-section parameters related to the size and shape of the insect could be obtained by the VLR, which can contribute significantly to the scientific research of insect migration. Many fascinating phenomena have been revealed, such as the layer formation and common orientation of aerial insects [2].

The current entomological radars are single-polarized radars and the VLR achieves the flight behavioral parameter measurements using the polarization rotation and beam nutation [3]. In particular, these parameters are retrieved based on the three peaks or five peaks of the echo spectrum [4], and the algorithm for solving the parameters is relatively complicated. With the development of radar techniques, the instantaneous full polarization can be realized and the full-polarization information of the insects can be measured directly [5].

A typical radar can measure the Doppler speed of a target; however, its displacement speed is difficult to measure. Herein, an insect flight speed estimation method is proposed based on a full-polarization radar with a vertical-looking beam. First, a full-polarization echo signal model is established. The insect flight speed is estimated using an iterative algorithm based on the second-order polynomial approximation. To validate the proposed method, the observation experiment of an aerial flight insect was performed using a Ku-band high-resolution and full-polarization radar system, and the experimental data were analyzed. The four polarization channel data of insect targets and the eigenvalue of the polarization scattering matrix (PSM) could be used to estimate the speed. However, because the accuracy of the speed estimation was influenced severely by the signal-to-noise ratio (SNR), the polarization channel data or the eigenvalue data with the highest SNR were used in the experimental data processing. Finally, the experimental results show the effectiveness and feasibility of the proposed method.

Echo signal model. Herein, the insect flight speed estimation is based on the full-polarization radar with a vertical-looking beam; the observation geometry is shown as Figure 1(a). With the full-polarization radar, the four polarization channels data can be obtained simultaneously, and one polarization channel data are selected for analysis. The stepped frequency signal waveform is adopted to realize a high range resolution. After the high-resolution range processing, the target signal in

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the slow time can be written as [6, 7]

$$S_{r,ij}(\tau) = C\sigma_{ij} \cdot \exp\left\{-\mathrm{j}\frac{4\pi R(\tau)}{\lambda}\right\} G(\tau), \quad (1)$$

where C is a constant related to the system gain, τ is the slow time, $R(\tau)$ is the range between the target and the radar, λ is the radar wavelength, and $G(\tau)$ represents the antenna beam gain that depends on the relative angle between the radar line of sight and the beam axis. σ_{ij} is the scattering coefficient of the target where i and j represent the horizontal or vertical polarization of the receiving and transmitting electromagnetic wave, respectively.

Next, the antenna beam gain of $G(\tau)$ is formulated. The off-axis antenna beam gain is typically approximated by a Gaussian function as follows:

$$G(\theta) = G_0 \exp\left(-\frac{1}{2}k\frac{\theta^2}{\theta_{1/2}^2}\right), \quad (2)$$

where G_0 is the on-axis gain, $k = 8\ln 2$, θ is the relative angle between the radar line of sight and the beam axis, and $\theta_{1/2}$ is the half-power beam width.

Because the insect I is moving in the beam, θ is variational and related to the flight trajectory. As shown in Figure 1(b), the flight trajectory of insect I is along the line P; moreover, it is assumed in the horizontal plane with constant speed V, which is typically used in the VLR. The radar beam width is typically narrow; therefore, θ can be written as

$$\theta \approx \tan(\theta) = \frac{r(\tau)}{H} = \frac{\sqrt{p^2 + V^2(\tau-\delta)^2}}{H}, \quad (3)$$

where H is the flight height, $r(\tau)$ represents the instantaneous distance from insect I to the beam axis in the horizontal flight plane at moment τ. Suppose that at moment δ, insect I is located at point A, which has the minimum distance p from point O to line P.

Substituting (2) and (3) into (1), the target signal in the slow time can be rewritten as

$$\begin{aligned} S_{r,ij}(\tau) = CG_0\sigma_{ij} \cdot \exp\left\{-\mathrm{j}\frac{4\pi R(\tau)}{\lambda}\right\} \\ \cdot \exp\left\{-\frac{1}{2}k\frac{p^2 + V^2(\tau-\delta)^2}{H^2\theta_{1/2}^2}\right\}. \end{aligned} \quad (4)$$

Speed estimation method. The insect flight speed estimation and accuracy analysis are performed in this section. Using the amplitude of (4) and normalizing, we obtain

$$g(\tau) = \exp\left\{-\frac{1}{2}k\frac{V^2(\tau-\delta)^2}{H^2\theta_{1/2}^2}\right\}. \quad (5)$$

Subsequently, using the logarithm of (5), the following relationship can be obtained

$$\begin{aligned} u(\tau) &= 10\log_{10}(g(\tau)) \\ &= -5k\frac{V^2(\tau-\delta)^2}{H^2\theta_{1/2}^2}\log_{10}(\mathrm{e}), \end{aligned} \quad (6)$$

where e is the natural logarithm.

Therefore, after the discretization of (6), the estimation model can be expressed as

$$h_n = u_n + w_n, \quad (7)$$

where h_n is the observation data, u_n is the discretization of $u(\tau)$, and w_n represents the noise with the mean value of zero.

For a more convenient statement, the estimate parameters are expressed as a vector $\boldsymbol{\alpha} = [V, \delta]^{\mathrm{T}}$, and the elements in this vector are represented by $\alpha_i\ (i = 1, 2)$. The observation data vector is denoted as $\boldsymbol{h} = [h_0, h_1, \ldots, h_{N-1}]^{\mathrm{T}}$, and the model data vector is denoted as $\boldsymbol{u}(\boldsymbol{\alpha}) = [u_1, u_2, \ldots, u_{N-1}]^{\mathrm{T}}$. Hence, the optimization problem is to estimate $\boldsymbol{\alpha}$ by minimizing the cost function as follows:

$$J(\boldsymbol{\alpha}) = (\boldsymbol{h} - \boldsymbol{u}(\boldsymbol{\alpha}))^{\mathrm{T}}(\boldsymbol{h} - \boldsymbol{u}(\boldsymbol{\alpha})). \quad (8)$$

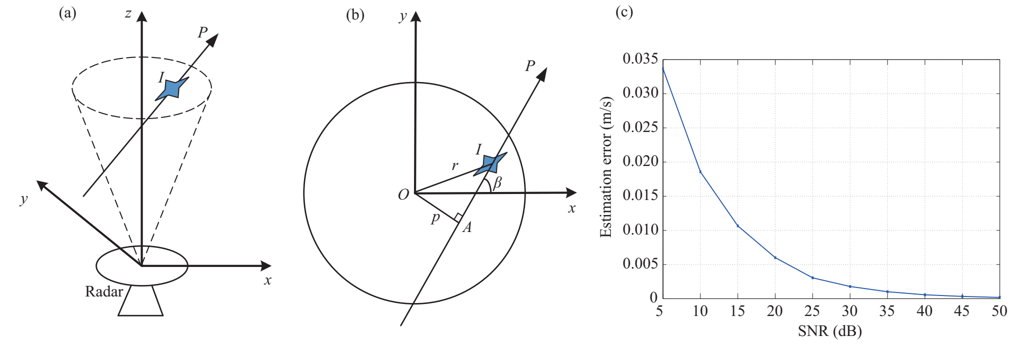
Utilizing the estimation algorithm in [8], the iteration formula is expressed by

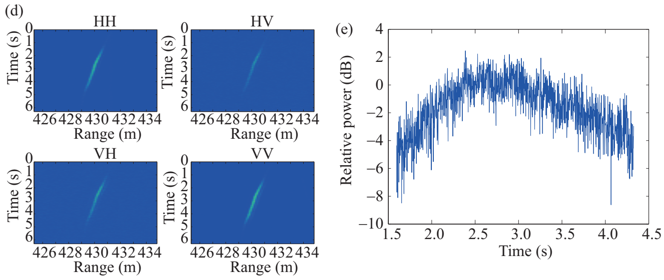
$$\alpha_i^{k+1} = \alpha_i^k - \frac{\partial J}{\partial \alpha_i} \Big/ \frac{\partial^2 J}{\partial \alpha_i^2}, \quad (9)$$

where α_i^k is the kth estimate of α_i, $\partial J/\partial\alpha_i$ and $\partial^2 J/\partial\alpha_i^2$ represent the first and second derivatives of (8) about α_i.

Simulation analysis and experimental validation. To test the estimation performance of the proposed iteration method, a simulation was performed and the influence of the SNR on the accuracy of the speed estimation was analyzed. The insect flight height $H = 300$ m, the speed $V = 5$ m/s, the half-power beam width $\theta_{1/2} = 1.5°$, and the time $\delta = 3$ s. Monte Carlo simulations were performed and the estimation error of insect flight speed versus the SNR is shown in Figure 1(c). As shown, the proposed method has good estimation accuracy even at a lower SNR.

To further validate our proposed method, the experiment was performed using a Ku-band high-resolution and full-polarization entomological radar with the vertical-looking mode. The range resolution is 0.2 m, and the beam width is 1.5°. This entomological radar could achieve an instantaneous full polarization using an orthogonal waveform, and the four polarization data of the insect





(f)

Insect	Height (m)	Speed (m/s)
I_1	265	5.34
I_2	352	8.30
I_3	430	3.75
I_4	600	4.93

Figure 1 (Color online) (a) Observation geometry of the full-polarization radar; (b) the flight trajectory of insect I; (c) simulated estimation error of insect flight speed versus SNR; (d) one-dimensional range profile of four polarization channels of one insect; (e) observation data of the insect; (f) experiment results.

target can be acquired. Subsequently, the PSM of the target and the eigenvalue could be obtained. Through the SNR analysis, the polarization data with the highest SNR are selected for the speed estimation. The one-dimensional range profile of four polarization channels of an insect is shown in Figure 1(d), and the observation data of the insect is shown in Figure 1(e). The experimental results are shown in Figure 1(f). As shown, the insect flight speeds are between 3–9 m/s, which are consistent with the typical flight speeds; thus, it reveals that our proposed method is effective and feasible.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant No. 31727901).

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