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РАЗРАБОТКА МЕТОДА ОЦЕНИВАНИЯ СКОРОСТИ ВЕТРА В ПОЛЕТЕ С ИСПОЛЬЗОВАНИЕМ ВОЗДУШНОЙ СКОРОСТИ САМОЛЕТА

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Рассматривается проблема оценки скорости ветра в полете. Предлагаемый метод дает оценки для трех проекций скорости ветра в нормальной земной системе координат с использованием данных спутниковых навигационных систем (СНС), а также бортовых барометрических измерений скорости полета. Предполагается, что для участка полета продолжительностью 50—60 с ветер имеет постоянную скорость и направление. Это означает, что для данного временного интервала значения проекций скорости ветра на оси нормальной земной системы координат постоянны. Далее представлены модели объекта и наблюдений, а также характеристики точности алгоритма идентификации, полученные при обработке данных, полученных на пилотажном стенде. Обсуждается влияние погрешности измерения скорости на оценку скорости ветра. Приведены результаты, показывающие точность оценки скорости ветра в зависимости от погрешностей измерения постоянной скорости.

Анализ показывает, что горизонтальные проекции скорости ветра оцениваются с высокой точностью (относительные погрешности 1—3%), но для получения надлежащей степени идентифицируемости необходим определенный временной интервал. После этого точность оценки горизонтальных проекций скоростей ветра сохраняется на хорошем уровне и не сильно зависит от увеличения погрешности измерения скорости. При этом точность оценки вертикальной проекции ветра составляет 30—40% даже при нулевой ошибке скорости полета и значительно увеличивается при росте погрешности измерения скорости. Таким образом, предложенный метод обеспечивает хорошую точность оценки горизонтальных проекций скорости ветра и не применим для оценки вертикальной составляющей.

Ключевые слова: параметрическая идентификация, воздушная скорость, оценивание скорости ветра в полете, постоянная погрешность измерения воздушной скорости.

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DEVELOPMENT OF WIND VELOCITY ESTIMATION METHOD USING THE AIRSPEED

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Abstract

The method suggested in this paper provides estimates for the three projections of wind velocity in earth's normal coordinate system using satellite navigation systems (SNS) data, as well as on-board barometric airspeed measurements. The wind speed and its direction are assumed constant for a flight leg of 50-60 s duration. This means, that for the given time interval projections of the wind velocity values on the axis of the normal earth coordinate system are constant. Further, the object and observation models are presented, as well as the identification algorithm accuracy characteristics, obtained from the simulation data processing. The airspeed measuring error effect on the wind velocity estimation is also under discussion. The results, showing the accuracy of wind velocity estimation depending on the constant velocity measurement errors, are presented.

The analysis shows that horizontal projections of wind velocities are estimated with high accuracy (relative errors of 1—3%), but a certain time interval to obtain the proper degree of identifiability is necessary. After this, the accuracy of estimating the horizontal projections of wind velocities remains at a decent level, and does not depend heavily on the increase of the speed measurement error. The wind vertical projection estimation herewith leaves something to be desired. It makes 30—40% even at zero flight speed error, and increases considerably with an increase of speed measuring error. Thus, we may conclude that the suggested method can ensure the good accuracy for estimating the wind velocities along the horizontal coordinate axes, and it is not applicable for estimating the vertical component of wind velocity.

Keywords: parametric identification, air speed, wind speed estimation in flight, constant error of air speed measuring.

Introduction

In flight tests practice of aeronautical engineering, atmospheric parameters and the aircraft motion parameters monitoring is of great importance [1]. The system identification approach may be employed to estimate the measurement errors [2—5]. Recently, the parameter identification algorithms have been proposed to deal with systematic measurement errors of aircraft angle of attack and slide [6], orientation angles [7] and airspeed [8]. At the same time, the issues of determining the actual values of wind velocity are problematic while performing flight test modes. With satellite navigation systems application in flight tests, the possibilities for developing methods for the wind velocity estimation increased considerably, especially if compared with conventional technologies of optical flight path measuring [9]. The precise estimates of the wind velocity are necessary for numerous tasks while aircraft flight tests [1, 10—14]. More detailed information on the wind velocity estimation problem can be found in [15—20].

The method suggested in this paper provides estimates for the three projections of wind velocity in earth's normal coordinate system using satellite navigation systems (SNS) data, as well as on-board barometric airspeed measurements. Further, the algorithm is presented, as well as its accuracy characteristics, obtained from the simulation data processing. The effect of airspeed measurement error on the wind velocity estimation is also discussed.

The problem formulation

The wind speed and its direction are assumed constant for a short flight leg of 50—60 s duration. This means, that the values of the wind velocity projections on the axis of the normal earth coordinate system are constant for this time interval. To define the sequence of operations to generate estimates of components of wind speed, it is necessary to develop the object model. The equations for the aircraft airspeed projection on the normal earth coordinate system are defined as follows:

$$\begin{aligned} V_{xg\_a}(t_i) &= V_{xg\_SNS}(t_i) + V_{xg\_W} \\ V_{yg\_a}(t_i) &= V_{yg\_SNS}(t_i) + V_{yg\_W} \\ V_{zg\_a}(t_i) &= V_{zg\_SNS}(t_i) + V_{zg\_W} \end{aligned} \tag{1}$$

where $t_i = 1, 2, ..., N$ — discrete time moments,

$V_{xg\_SNS}(t_i), V_{yg\_SNS}(t_i), V_{zg\_SNS}(t_i)$ — projections of the aircraft earth related velocity on the axes of the normal earth coordinate system, measured by satellite navigation system,

$V_{xg\_W}, V_{yg\_W}, V_{zg\_W}$ — projections of wind velocity on the axes of the earth coordinate system, which have to be estimated.

It is assumed that they are constant on the processed section of the flight. The airspeed projections in the associated coordinate system, are obtained by multiplying the values of airspeed (1) by known transition matrix from the normal earth coordinate system to the associated coordinate system:

$$\begin{bmatrix} V_{x_a} \\ V_{y_a} \\ V_{z_a} \end{bmatrix} =$$

$$= \begin{bmatrix} \cos\psi\cos\vartheta & \sin\vartheta & -\sin\psi\cos\vartheta \\ \begin{matrix} \sin\psi\sin y - \\ -\cos\psi\sin\vartheta\cos y \end{matrix} & \cos\vartheta\cos y & \begin{matrix} \cos\psi\sin y + \\ +\sin\psi\sin\vartheta\cos y \end{matrix} \\ \begin{matrix} \sin\psi\cos y + \\ +\cos\psi\sin\vartheta\sin y \end{matrix} & -\cos\vartheta\sin y & \begin{matrix} \cos\psi\cos y - \\ -\sin\psi\sin\vartheta\sin y \end{matrix} \end{bmatrix} \times$$

$$\times \begin{bmatrix} V_{x_{g\_a}} \\ V_{y_{g\_a}} \\ V_{z_{g\_a}} \end{bmatrix} \tag{2}$$

In equation (2) the matrix includes the aircraft orientation angles, i.e. pitch , roll and yaw .

The aircraft airspeed value, i.e. the speed relative to the air, is defined as follows

$$V_a(t_i)=\sqrt{V^2_{x\_a}(t_i)+V^2_{y\_a}(t_i)+V^2_{z\_a}(t_i)} \tag{3}$$

So, the equations (1)-(3) form the object model. The parameter $V_a(t_i)$ may be called the airspeed value predicted from the object model. This predicted value depends on the value of wind velocity. The observation model in this case is scalar:

$$z_1(t_i)=\ V_a(t_i)+\xi_V(t_i) \tag{4}$$

where $z_1(t_i),\ i=1,2,...,N$ — onboard aircraft airspeed barometric measurements,

$\xi_V(t_i)$ — random measurement errors.

The vector of estimated parameters is presented as follow:

$$\alpha^T=\left[V_{xg\_W}\ \ V_{yg\_W}\ \ V_{zg\_W}\right] \tag{5}$$

Thus, estimation of three components of wind velocity is realized as a parameter identification problem [2—5].

Identification Algorithm

The problem of wind velocity estimation may be solved by the maximum likelihood estimation (MLE) algorithm [2, 4, 6]. In the general vector form, the object and observation models are presented as follows:

$$y(t_i)=f(y(t_i),a,u(t_i)) \tag{6}$$

$$z(t_i)=h(y(t_i),a,u(t_i))+\eta(t_i) \tag{7}$$

where

$y(t),u(t)$ — vectors of the object output and input signals with respective dimensions of *n* and *m*,

$z(t_i)$ — vector of observation with dimension of *r*,

a — vector of the unknown parameters which have to be estimated,

$\eta(t_i)$ — noise of observations, i.e. a vector of a normal discrete random sequence with zero mean and known variance matrix $R(t_i)$.

It is assumed, that the input signal *u*(*t*) is a known function of time. The initial conditions $y(t_0)$ are also assumed to be known.

Noise observations are normal and independent random vector variable. It is well known, that the maximum likelihood method under the specified assumptions on the properties of noise leads to unbiased and efficient estimates [2]. The minimized functional of the maximum likelihood method is expressed in the following form:

$$J(a)=\sum_{i=1}^{N}((z(t_i)-h(y(t_i),a,u(t_i)))^T R^{-1}(t_i)\times$$
$$\times((z(t_i)-h(y(t_i),a,u(t_i))) \tag{8}$$

It is easy to see that (8) is a functional of the least squares method with the matrix of weight coefficients $R(t_i)^{-1}$.

For minimization of (8), it is suggested to use modification of the classical Newton method

$$a_{k+1}=a_k-\left(\frac{d^2J(a_k)}{da_k^2}\right)^{-1}\frac{dJ(a_k)}{da_k}$$

where

$$\frac{dJ(a_k)}{da_k}=-2\sum_{i=1}^{N}\frac{dz^T(t_i,a_k)}{da_k}R^{-1}(t_i)(z(t_i)-z(t_i,a_k)) \tag{9}$$

$$\frac{d^2J(a_k)}{da_k^2}\approx 2\sum_{i=1}^{N}\frac{dz^T(t_i,a_k)}{da_k}R^{-1}(t_i)\frac{dz(t_i,a_k)}{da_k} \tag{10}$$

The derivative estimates are determined numerically for the discrete time $t_i,\ i=\overline{1,N}$ according to the equations:

$$\frac{dz(t_i,\ a)}{da}=\left[\frac{\partial z(t_i,\ a)}{\partial a_1}\ \ \frac{\partial z(t_i,\ a)}{\partial a_2}\ \ \cdots\ \ \frac{\partial z(t_i,\ a)}{\partial a_p}\right]_{(r\times p)} \tag{11}$$

$$\frac{\partial z(t_i,a)}{\partial a_j}=\frac{z(t_i,a+\varepsilon e_j)-z(t_i,a)}{\varepsilon} \tag{12}$$

where

e_j — vector of dimension *p*, which all elements are equal to zero except *j* element, and *j* element is equal to 1,

ε — a small number, usually specified at the level of 0.001...0.1% from the nominal parameter values.

Estimates $z(t_i,a),\ i=\overline{1,N}$ are determined by numerical solution of equations of the object and observations in $\eta(t_i)=0.$ Identification is completed when the condition $\left|a_{k+1}-a_k\right|<\delta\left|a_k\right|$ is met, where $\delta=0{,}005.$

Results and Error Analysis

To study the features of the suggested algorithm, it was applied to the simulation data. The detailed description of the wind and aircraft models is given in [8]. A turn at constant altitude of 2000 m with the roll angle of 30 degrees was simulated. The aircraft earth related velocity was 100 m/s, the wind velocity horizontal projections were 5 m/s and 7 m/s, and the vertical projection was 2 m/s. The aircraft airspeed constant measurement errors (CV) were simulated as 0.0 m/s, 0.1 m/s, 0.2 m/s, 0.4 m/s, 0.7 m/s, and 1.0 m/s.

The estimation process was performed for each of airspeed measurement value constant error CV. The length of the processing interval was also variable. The starting point was always at zero time, and the set of values for the processing interval length was 1, 2, 3, 4, 5, 8, 10, 12, 16, 18, 28, 38, 58, 68 s. The estimates of wind velocity would change, and its changing was expressed in results and errors' analysis.

To monitor the wind velocity estimates changes, the relative estimation errors were introduced. The following equation was used for calculation:

$$Relative\ Error = \frac{\hat{a} - a_{true}}{a_{true}} \cdot 100\% \qquad (13)$$

where

$$\hat{a} = Parameter\ estimate; \ a_{true} = Parameter\ true\ value$$

The obtained relative errors for different airspeed measurement constant errors are shown in figures 1—6. On these graphs, the abscissa axis presents the length of processing interval in seconds.

On these graphs, the notion Wind_x relates to the wind velocity over the x coordinate, Wind_z relates to

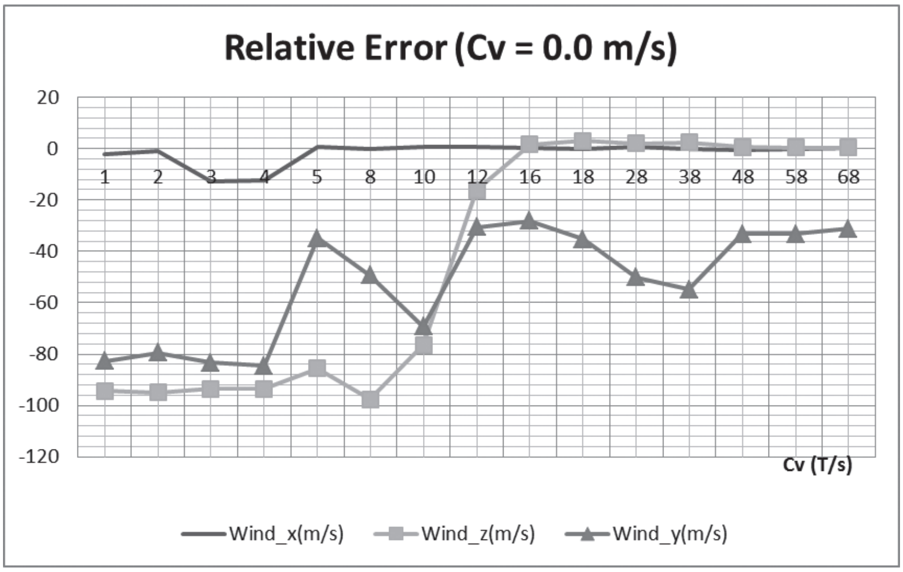

Fig. 1. Relative errors of wind velocities for constant airspeed error CV = 0.0 m/s

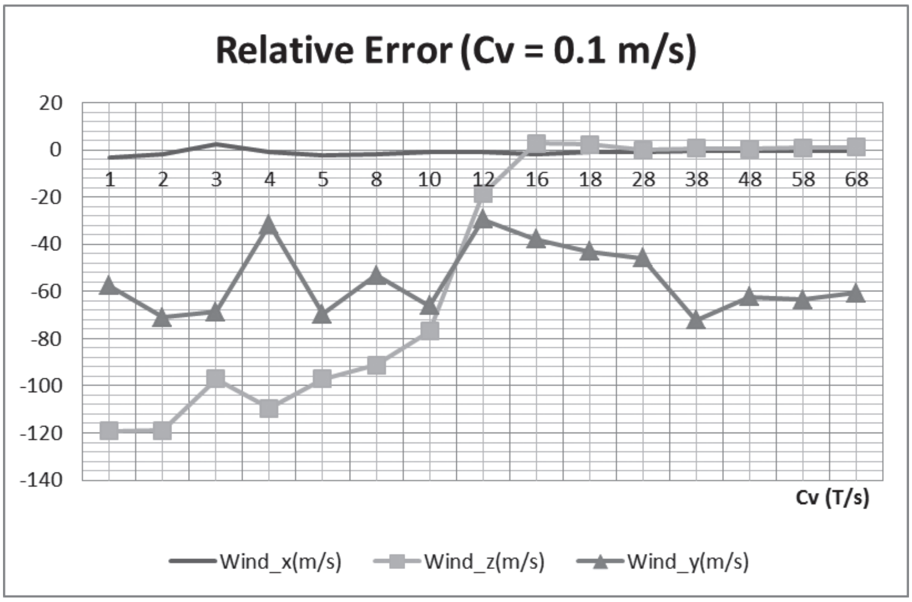

Fig. 2. Relative errors of wind velocities for constant airspeed error CV = 0.1 m/s

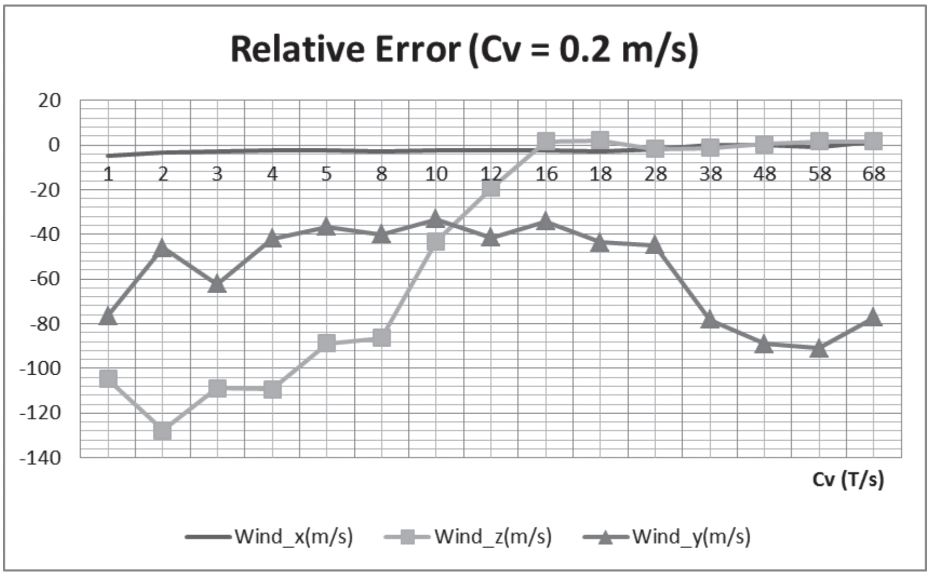

Fig. 3. Relative errors of wind velocities for constant airspeed error CV = 0.2 m/s

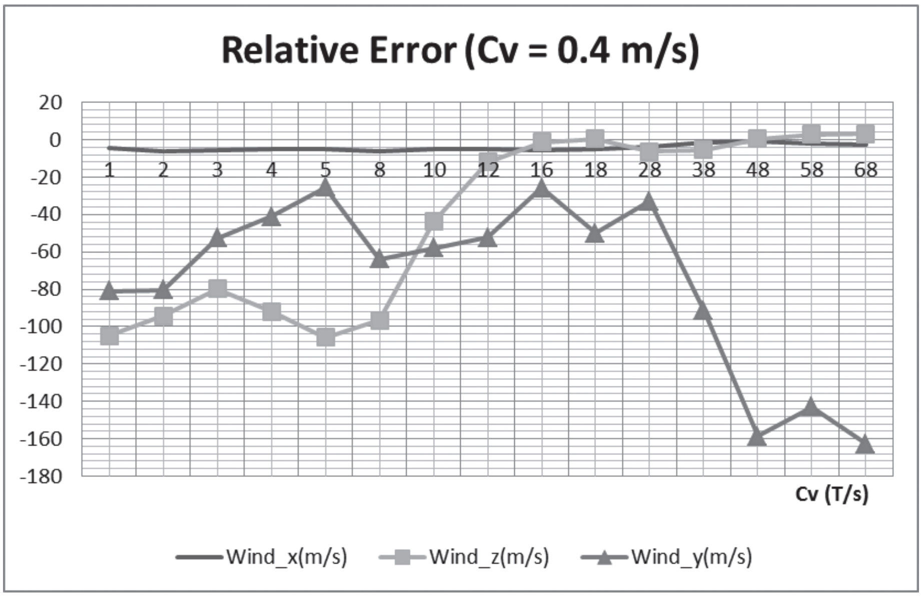

Fig. 4. Relative errors of wind velocities for constant airspeed error CV = 0.4 m/s

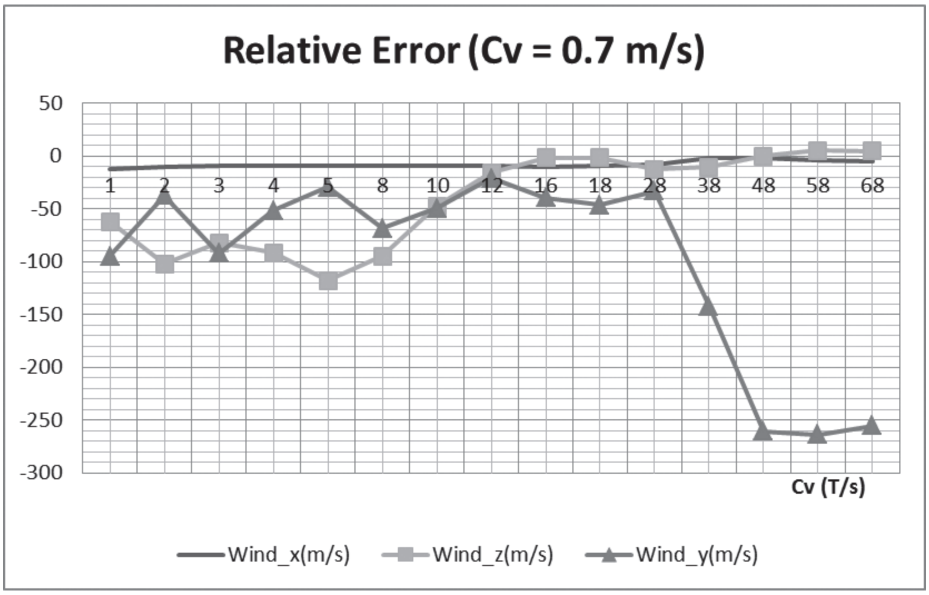

Fig. 5. Relative errors of wind velocities for constant airspeed error CV = 0.7 m/s

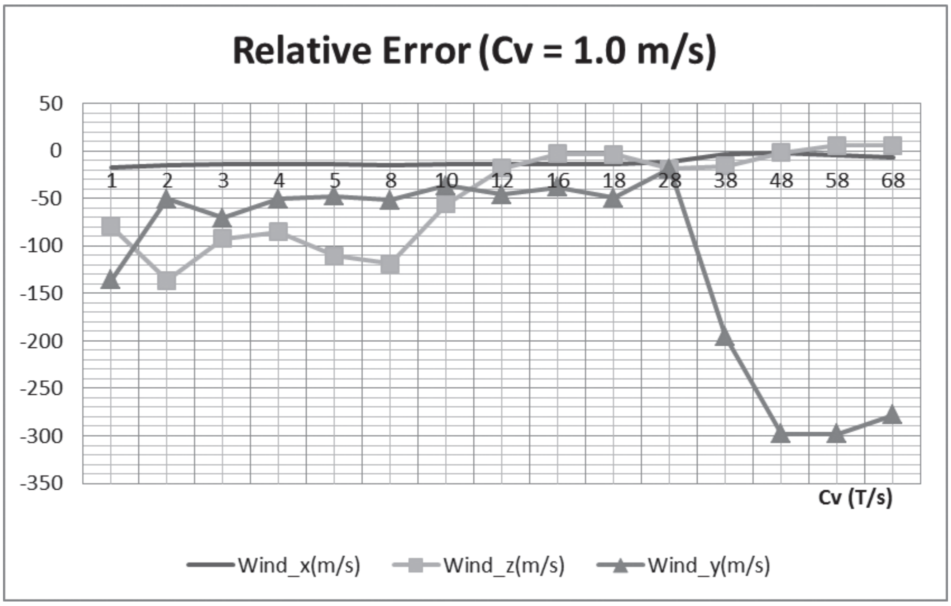

Fig. 6. Relative errors of wind velocities for constant airspeed error CV = 1.0 m/s

the wind velocity over z coordinate, and Wind_y relates to the wind velocity over the y coordinate (vertical), while the notation CV stands for constant errors of airspeed and it is measured in meter per second.

Discussion and Conclusion

The analysis revealed that the wind velocities horizontal projections were estimated with high accuracy (relative errors of 1-5%) only after the processing time interval exeeds 12 s, since a certain amount of yaw angle variation is required to obtain the proper degree of identifiability [2]. After this, the accuracy of estimating the horizontal projections of wind velocities remains at a decent level, and does not depend heavily on the increase of the speed measurement error. At the same time, the estimation of wind vertical projection is poor. It makes 30-40% even at zero airspeed error, and increases drastically up to 300% at airspeed measurement error of 1 m/s. Thus, we may conclude that the proposed method can ensure the good accuracy for estimating the wind velocities along the horizontal coordinate axes and is not applicable to the wind velocity vertical component estimation.

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