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A new method of measuring optical turbulence of atmospheric surface layer at Antarctic Taishan Station with ultrasonic anemometer

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Abstract To find the optimal location for large-aperture telescopes is a goal of astronomy. Chinese Antarctic astronomy has begun to flourish in recent years, and it is an urgent need in basic astronomical work to measure and analyze the optical turbulence spatiotemporal distribution in the Antarctic region. We analyzed turbulence data measured by a mobile atmospheric parameter measurement system from 30 December 2013 to 10 February 2014 at Antarctic Taishan Station. Because there is a discrepancy between the refractive index structure constant C_n^2 measured by an ultrasonic anemometer with a single-point temperature structure function method and by micro-thermometer, a new method to measure C_n^2 with a temperature spectrum method is proposed herein. Through comparing long-term continuous C_n^2 data derived from ultrasonic anemometer with those via the new method and micro-thermometer, trend, magnitude and measured weak turbulence of ~2×10^{-16}m$^{-2/3}$ are generally satisfactory. The reason for the discrepancy in C_n^2 measurement between the ultrasonic anemometer with the old method and micro-thermometer is investigated.

Keywords **optical turbulence, ultrasonic anemometer, temperature spectrum method, Antarctic Taishan Station**

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1 Introduction

The main effects on the performance of ground-based astronomical telescopes are sky background, transmittance, and optical turbulence and so on[1-2]. Atmospheric turbulence is the major reason for the serious decline of imaging quality of the astronomical optical telescope. Random refractive index fluctuations associated mainly with temperature fluctuations are called optical turbulence. The sky background and transmittance limit telescope sensitivity, and optical turbulence limits resolution. Given the influence of atmospheric turbulence on astronomical parameters, seeing is not only one of the important factors in site location decision-making but is also a major measurement parameter. It is an important indicator in evaluating astronomical site quality. Turbulent intensity in the near-surface layer and its rate of decrease with height are closely related to the quality of potential sites. Quoted from Pant's measurement result in Devasthal[3], seeing of the near-surface 6–12 m layer is 1.28″, but it is down sharply to 0.32″ in the 12–18 m layer. In the circumstance where boundary layer and free atmosphere turbulence at

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candidate astronomical sites are equivalent, as an indicator of seeing, one must compare turbulent intensity of the surface layer and rate of decrease with height to quantify which site is the best for astronomical applications.

Continuous observation of atmospheric optical turbulence of the surface layer is usually achieved using a meteorological mast equipped with several-layer micro-thermometers. Because dust readily causes probe contamination and strong wind, insects and other factors damage the probe, the micro-thermometer probes need regular replacement and cannot be used in unattended operation in adverse environments. We have proposed measuring the refractive index structure constant C_n^2 with a single-point temperature structure function method, involving analysis of temperature fluctuation time-series data from an ultrasonic anemometer[4-5]. This method was coded into the data acquisition system of a mobile atmospheric parameter measuring system[6-7], so C_n^2 could be measured in real time. This instrument was installed at Antarctic Taishan Station by the 30th Chinese National Antarctic Research Expedition (CHINARE) team for astronomical site testing. Major stations that are currently used for astronomical observation in the Antarctic are Amundsen-Scott at the South Pole, Concordia at Dome C, Kunlun at Dome A, and Fuji at Dome F. At the South Pole, the mean visual seeing, measured by 15 balloon flights in 1997, was 1.86″, of which the free atmosphere component was only 0.37″[8]. At Dome C, the summer site testing median seeing based on a Differential Image Motion Monitor (DIMM) was 0.54″[9]. In 2004, by combining free-atmosphere C_n^2 values determined by the Multi-Aperture Scintillation Sensor[10] with surface boundary layer turbulence determined by Sonic Detection and Ranging, atmospheric seeing above 30 m was 0.27″. In 2005 seeing, isoplanatic angle and coherent time above 30 m based on *in situ* balloon measurement[11] was 0.36″, 4.6″, and 7.9 ms, respectively. In this paper, we analyze turbulence data obtained by a mobile atmospheric parameter acquisition system at Antarctic Taishan Station, and compare several methods of optical turbulence measurement. We found a value of C_n^2 derived from a structure function analysis previously proposed with a sonic anemometer was different from that of micro-thermometer measured. Thus, a new method to measure C_n^2 with a temperature spectrum analysis is proposed. C_n^2 data derived from an ultrasonic anemometer with the new method and micro-thermometer were mainly the same in magnitude and trend.

2 Introduction to measurement system

The Antarctic mobile atmospheric parameter measurement system[6] includes a CR5000 data logger, CSAT3 three-dimensional ultrasonic anemometer, micro-thermometer, temperature and relative humidity probe, wind monitor, 485 communication module, power module, and a 3-m tower. Two levels of air temperature, relative humidity and wind speed, and one level of air pressure, surface temperature, atmospheric optical turbulence intensity and other atmospheric parameters can be measured. Taishan Station is located in Princess Elizabeth Land between the Chinese Antarctic Zhongshan and Kunlun stations, 76°58’E, 73°51’S, at altitude 2621 m. Figure 1 shows the mobile atmospheric parameter measurement system at Chinese Antarctic Taishan Station. The site testing experiments were carried out during the 30th CHINARE. Part of the data from 30 December 2013, when the system was installed, to 10 February 2014, when the expedition staff returned, were analyzed here.

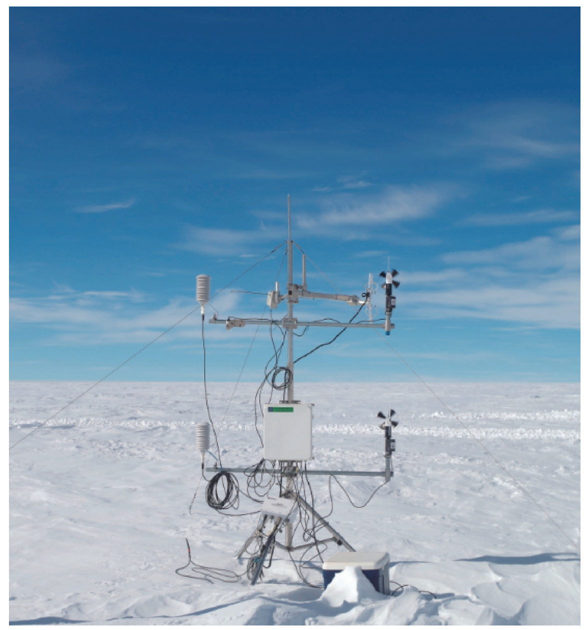

Figure 1 Mobile atmospheric parameters measurement system installed at Antarctic Taishan Station.

3 Measurement methods of C_n^2

For Kolmogorov turbulence, the refractive index structure constant and the temperature structure constant are defined as[11]

$$C_n^2 = \langle [n(\vec{x}) - n(\vec{x}+\vec{r})]^2 \rangle r^{-2/3}, \quad l_0 << r << L_0 \tag{1}$$

$$C_T^2 = \langle [T(\vec{x}) - T(\vec{x}+\vec{r})]^2 \rangle r^{-2/3}, \quad l_0 << r << L_0 \tag{2}$$

where $\vec{x}$ and $\vec{r}$ denote the position vector, r is the magnitude of $\vec{r}$, angle brackets represent the ensemble average, and l_0 and L_0 are the inner and outer scales of the optical turbulence, respectively. For visible and near-infrared light, the refractive index fluctuation is mainly caused by temperature fluctuation. Conversion of C_T^2 to C_n^2, depends on local pressure and temperature, and it is customary to use the following equation[12]:

$$C_n^2 = \left(79\times10^{-6}\frac{P}{T^2}\right)^2 C_T^2, \tag{3}$$

where T is air temperature (K) and P is air pressure (hPa). Therefore, C_n^2 can be calculated through Equations (2) and

(3) by measuring the square and average of the temperature difference given by two sensors separated by a known distance r in the inertial region. This is called the structure function method of temperature differences between two points.

The relationship between temperature and wire resistance is

$$R=R_0[1+\alpha(T-T_0)]. \quad (4)$$

Thus, the ΔR and ΔT relationship is

$$\Delta R=\alpha R_0 \Delta T, \quad (5)$$

where R_0 is the resistance at reference temperature T_0 and α is the coefficient of thermal resistivity of the wires.

The two resistance sensors are legs of a Wheatstone bridge that generates a voltage difference ΔV proportional to the temperature difference ΔT:

$$\Delta V=C\cdot\Delta T. \quad (6)$$

Here, C is the calibration coefficient.

The principle of micro-thermometer measurement is the same as in the last paragraph. C_n^2 is deduced from a pair of horizontally separated micro-temperature probes. The frequency response range of the micro-thermometer is 0.1–30 Hz, and the standard deviation of minimum temperature fluctuation is < 0.002°C[13].

The triaxial ultrasonic anemometer measures temperature from transit times t_1 and t_2 measured along a known distance path of the anemometer' probe. The speed of sound in moist air is a function of temperature and humidity. Sonic temperature T_s and air temperature T have the following relationship[14]:

$$T_s=\frac{d^2}{1612}\left(\frac{1}{t_1}+\frac{1}{t_2}\right)^2+\frac{V_n^2}{403}, \quad (7)$$

$$T=\frac{T_s}{1+0.51q}. \quad (8)$$

Here, t_1 and t_2 are the transit times in seconds for sound pulses traveling in opposite directions along acoustic path length d, and V_n is the magnitude of the horizontal wind vector normal to d. q is specific humidity. In dry conditions, the diference of T_s and T is very small.

For the temperature fluctuation time series data measured by the ultrasonic anemometer, Taylor's frozen turbulence hypothesis was used to convert a time series of a fluctuating quantity into a spatial series of fluctuations along the direction of the mean wind. Therefore, C_n^2 is deduced via Equations (9) and (3) by measuring the square and average of the temperature difference between two time points in the inertial region. This method is known as single-point temperature structure function method.

$$C_T^2=\langle[T(t)-T(t-\tau)]^2\rangle(V\tau)^{-2/3}, \quad (9)$$

where τ is the time interval, determined by the average wind speed and the known space length (typically 1 m).

C_T^2 can be determined by the one-dimensional temperature spectrum of the turbulence inertia region. For Kolmogorov turbulence, the one-dimensional temperature wave number spectrum $\Psi_T(k)$ is

$$\Psi_T(k)=0.25C_T^2k^{-5/3}, \quad (10)$$

where k is the wave number. For the power spectrum, temporal and spatial frequencies are related by $f=\frac{V}{2\pi}k$. It is easy to show that the relationship between the temporal and spatial one-dimensional spectra is

$$\Psi_T(k)=\frac{V}{2\pi}\Psi_T(f). \quad (11)$$

We can write

$$C_T^2=\frac{1}{0.25}\left(\frac{2\pi}{V}\right)^{2/3}\Psi_T(f)f^{5/3}. \quad (12)$$

This method is called the single-point temperature spectrum method.

More generally, the form of $\Psi_T(f)$ can be expressed as

$$\Psi_T(f)=Af^{-\alpha}. \quad (13)$$

Here, A is the coefficient related to the generalized temperature structure constant $\widetilde{C}_T^2$ [15], and α is the spectral power law of one dimension. On a logarithmic scale, Equation. 13 is written as

$$\lg(\Psi_T(f))=\lg(A)-\alpha\lg(f). \quad (14)$$

can be estimated via linear regression.

4 Measurement results and discussion

4.1 Comparison of C_n^2 between ultrasonic anemometer with single-point temperature structure function method and micro-thermometer

Figure 2 is an example of derived from the ultrasonic anemometer with structure function analysis and those from micro-thermometer at Taishan Station on 6 January 2014. The sampling frequency of the ultrasonic anemometer was 50 Hz and the average time for calculating C_n^2 was 20 s. It is seen that C_n^2 values from the ultrasonic anemometer are several times greater than those of the micro-thermometer, sometimes even one order of magnitude greater. The characteristic C_n^2 diurnal cycle with minima near sunrise (about 0900) and sunset (about 1900) is not obvious. The other time data also have similar characteristics. No matter the order of magnitude and trend of C_n^2, the data measured with the single-point temperature structure function method cannot be used to explain the C_n^2 characteristics at Taishan Station. However, although the order of magnitude of C_n^2 measured by the two methods had a few differences from other field experiments[4-6,16], trends were basically the same, with a correlation coefficient > 0.9.

4.2 Comparison of C_n^2 between ultrasonic anemometer with single-point temperature spectrum method and micro-thermometer

Using Equations (10)–(12) we measured C_n^2 by the single-point temperature spectrum method. Triaxial sonic anemometer sampling frequency was 50 Hz and the sampling period was 16.4 min. This yielded 49200 data points per run. A fast Fourier transform was carried out and the power

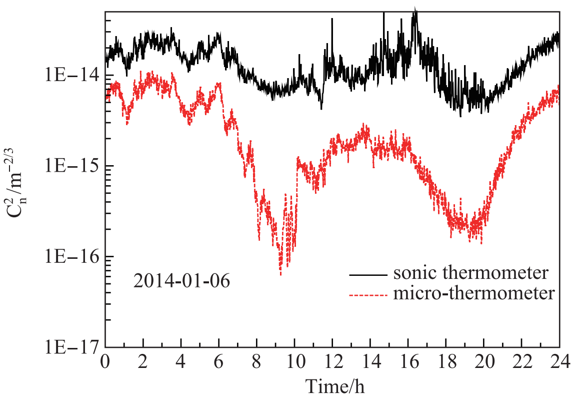

Figure 2 Comparison of C_n^2 derived from ultrasonic anemometers with structure function analysis and those from micro-thermometer.

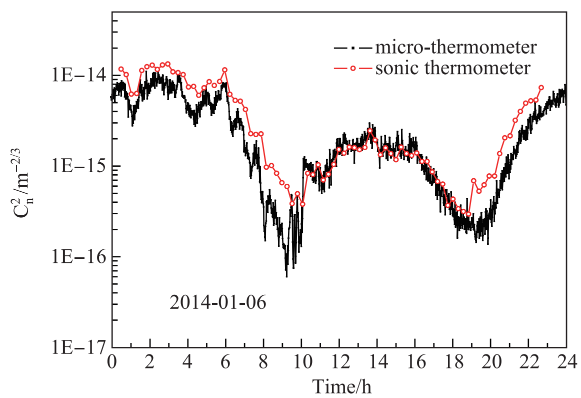

Figure 3 Comparison of C_n^2 derived from ultrasonic anemometers with spectrum analysis and micro-thermometer.

spectrum of 25 Hz was obtained. The power spectrum was smoothed and combined with wind speed, and the approximate inertial range was determined. After the median C_T^2 of a set of values in the inertial region was calculated by the formula (12), C_n^2 was obtained. Figure 3 is a comparison of C_n^2 values derived from the ultrasonic anemometers with spectrum analysis and micro-thermometer, using Figure 2 dataset. In comparison with Figure 2, C_n^2 values derived from the ultrasonic anemometer with spectrum analysis are closer to those from the micro-thermometer. The former was smoother than the latter, and was only sensitive over $2\times10^{-16}m^{-2/3}$, but the micro-thermometer was sensitive about $2\times10^{-18}m^{-2/3}$. To confirm the data reliability by ultrasonic anemometer at Taishan Station in an adverse environment, and the possibility of measuring C_n^2 from ultrasonic anemometer instead of micro-thermometer, we

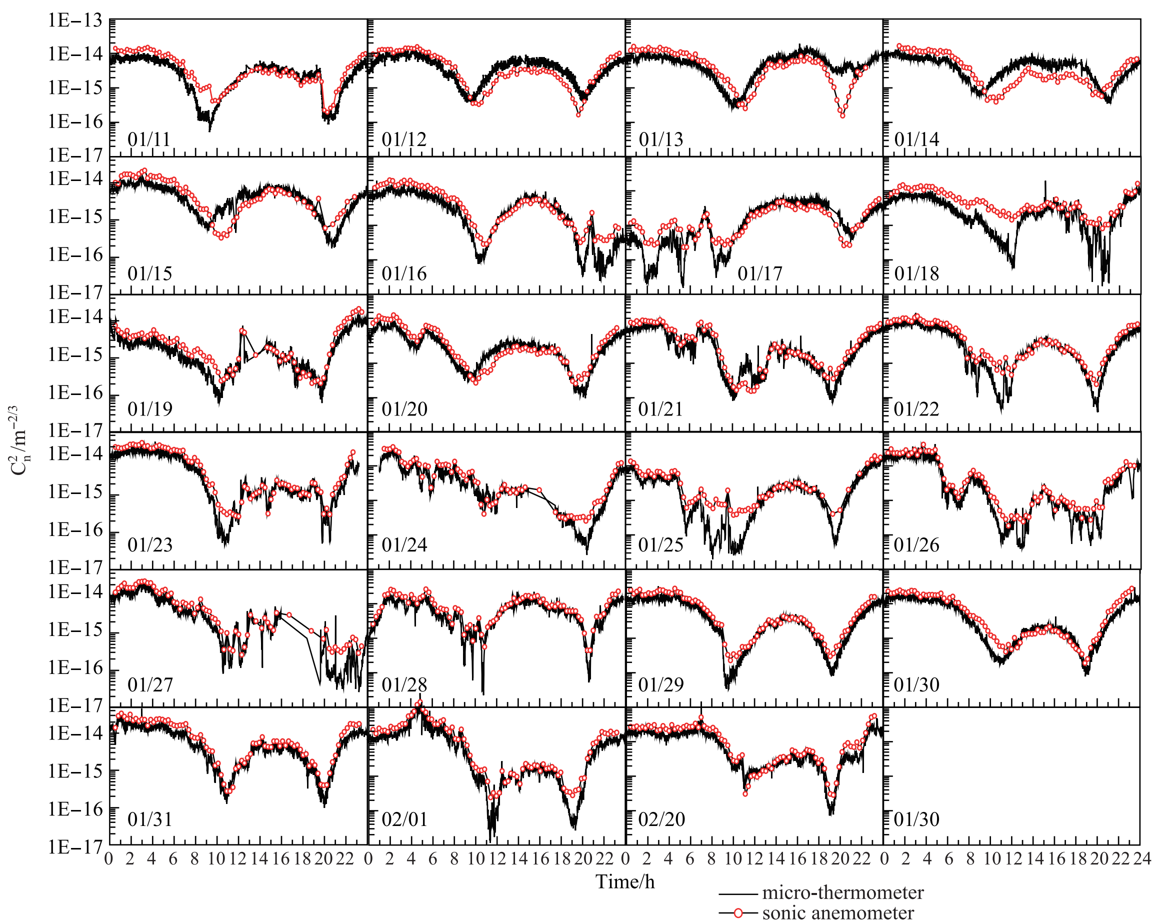

Figure 4 Comparison of C_n^2 derived from ultrasonic anemometers with spectrum analysis and micro-thermometer during field experiment.

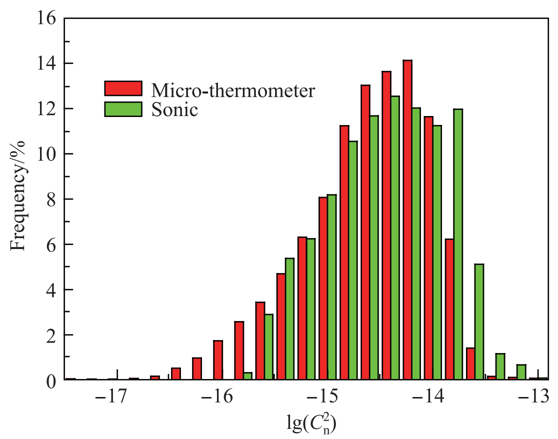

Figure 5 Comparison of C_n^2 frequency distribution derived from ultrasonic anemometer with spectrum analysis and micro-thermometer during field experiment.

compared both instruments for long time. After abnormal data owing to the broken wire being eliminated, a 23-day dataset was used. Figure 4 is a comparison of C_n^2 values from spectrum analysis of sonic anemometer data and micro-thermometer data from 11 January through 2 February 2014. In this dataset, under various meteorological conditions and regardless of day or night, the comparison was satisfactory.

Figure 5 compares a C_n^2 frequency distribution from spectrum analysis with the sonic anemometer and micro-thermometer data on 30 December 2013 to 10 February 2014. Sample numbers were 3446 and 59175, respectively. Table 1 is a C_n^2 frequency distribution from the micro-thermometer and anemometer in three frequency ranges. In the $-15<\lg(C_n^2)<-13.8$ range, the frequencies of the two are both 78%. Frequencies in the $\lg(C_n^2)>-13.8$ range are 1.7% and 6.9%, respectively, and those in the $\lg(C_n^2)<-15$ range are 20.3% and 14.8%. During the experiment, 78% optical turbulence at Taishan Station was concentrated in the range $10^{-15}<C_n^2<1.6\times10^{-14}$. In this range, the C_n^2 frequency distributions of both anemometer and micro-thermometer were consistent. Frequency statistics within the scope of strong and weak turbulence measured by the two instruments had a 6% difference. This may be attributable to smoothing, because the time for those statistics of the ultrasonic anemometer was 16.4 min whereas that for the micro-thermometer was only 20 s.

At Taishan Station, the difference of C_n^2 measured by the single-point temperature structure function method and the sonic anemometer and micro-thermometer is very large. This may be related with factors such as spectral characteristics, turbulent multi-scale spatial and temporal structure, and whether the Taylor assumption is valid. A similar result was found in reference[17]. In that work, an aero thermal series from a cold wire probe mounted on an aircraft was analyzed. C_T^2 from the structure function sometimes agreed well with spectral analysis, but sometimes the difference was very large, five times larger than the spectrum analysis results. The author believed that the large differences were in the regions α where deviated from −5/3, so the structure function estimator was only valid for $-3\leqslant\alpha<-1$. For aero-thermal series data to be used in spectral analysis, it is speculated that C_T^2 must be obtained via the single-point temperature structure function method under the Taylor assumption. To discover why C_n^2 values from the ultrasonic anemometer were several times larger than those of the micro-thermometer at Taishan Station, it is necessary to determine the power frequency distribution of the temperature spectrum during an experiment. Figure 6 is the frequency distribution of the power law of a one-dimensional spectrum. The frequency for $\alpha<-1$ was 36.2%, and that for $\alpha>-1$ was 63.8%. That is, there is nearly two-thirds of spectral power outside the range $-3\leqslant\alpha<-1$, so we cannot use the single-point temperature structure function method to calculate C_n^2. In addition, during the Taishan Station experiment, average wind speed was 7.7 m·s^{-1}, and the maximum was 16.3 m·s^{-1}. Average wind speed from the literature[4-6,15] was not more than 3 m·s^{-1}, so we should consider that this speed has an impact on the single-point measurement of temperature structure function method.

Table 1 C_n^2 frequency distribution derived from spectrum analysis of sonic anemometer and micro-thermometer data

Frequency distribution range	Micro-thermometer	Sonic anemometer
$\lg(C_n^2)>-13.8$	1.7%	6.9%
$-15<\lg(C_n^2)<-13.8$	78.0%	78.3%
$\lg(C_n^2)<-15$	20.3%	14.8%

5 Conclusions

Atmospheric parameters at Taishan Station from 30 December 2013 through 10 February 2014 were obtained by a mobile measuring system, and these data were analyzed. C_n^2 derived from the single-point temperature spectrum method with the sonic anemometers and micro-thermometer was compared. In the range $-15<\lg(C_n^2)<-13.8$, the frequencies of both were 78%. Frequencies for $\lg(C_n^2)>$

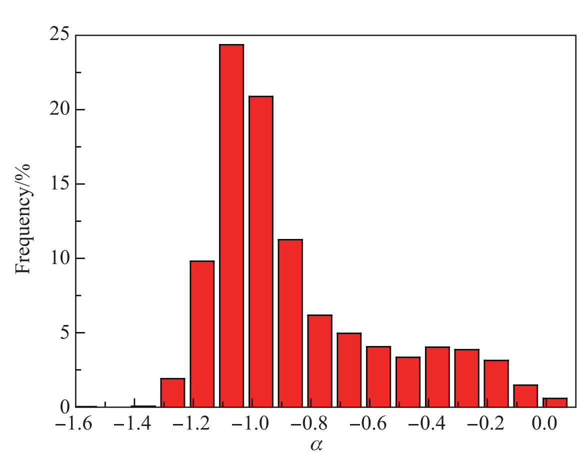

Figure 6 Frequency distribution of power law of one-dimensional spectrum.

−13.8 were 1.7% and 6.9%, respectively, and for lg(C_n^2) < −15 they were 20.3% and 14.8%. Compared with the microthermometer, results of C_n^2 measured by the ultrasonic anemometer from the spectrum analysis method were satisfactory in magnitude and trend.

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