P4.9 Measurement of Eddy Dissipation Rate by a Mini-sodar for Aviation Application: Comparison with Tower Measurement

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1. INTRODUCTION

Low-level turbulence is caused by irregular motion of the air, bringing about rapid bumps or jolts to aircraft. In severe turbulence, abrupt changes in the altitude and attitude of the aircraft may occur and the aircraft may suffer a momentary loss of control. The availability of turbulence measurements in the first hundred metres or so above an airport would be very useful for timely issuance of turbulence alerts for arriving or departing aircraft.

Turbulence can be calculated from the velocity spectrum measured by fast-responding anemometers, such as sonic anemometers. Due to airport height restriction requirements and potential interference with the air navigation signals, it is however not practical to set up a meteorological tower near the runway to make in situ anemometer measurement of the vertical profile of turbulence. Remote sensing devices, such as sodars and wind profilers (Chan and Chan, 2004), are viable alternatives.

This paper describes the use of a mini-sodar to measure turbulence up to an altitude of 100 m. The quality of these data is studied by comparing with measurements of sonic anemometers installed on a 50-m tower in the vicinity of the mini-sodar. Following the intensity thresholds adopted for automatic aircraft turbulence reporting by the International Civil Aviation Organization (ICAO, 2001), turbulence intensity in this study is defined in terms of eddy dissipation rate (EDR) with the unit of $m^{2/3}s^{-1}$, which is equal to the cubic root of the turbulent kinetic energy (TKE) dissipation rate.

2. EQUIPMENT

The mini-sodar in this study (AeroVironment model 4000) operates at acoustic frequencies near 4.5 kHz. It measures the three components of the wind using a vertical beam and two oblique beams at about 15 degrees from the vertical. Wind data are available up to 200 m, but the mini-sodar in this study is configured to measure up to 100 m only in order to get more frequently updated wind data (at about 0.5 Hz) to produce the wind spectrum for calculating the EDR. The minimum measurement height is 15 m. Because of acoustic reflection by buildings and other nearby structures at the measurement site (Figure 1), the wind data at the lowest two range gates have been found to be rather unreliable (e.g. the presence of clutter-related acoustic returns at these range gates). So only the data at 25 m or above are considered here. The other operating parameters for the mini-sodar, such as percentage of acceptable data and signal-to-noise ratio threshold, basically follow the suggested values in other studies (e.g. Antoniou et al., 2003).

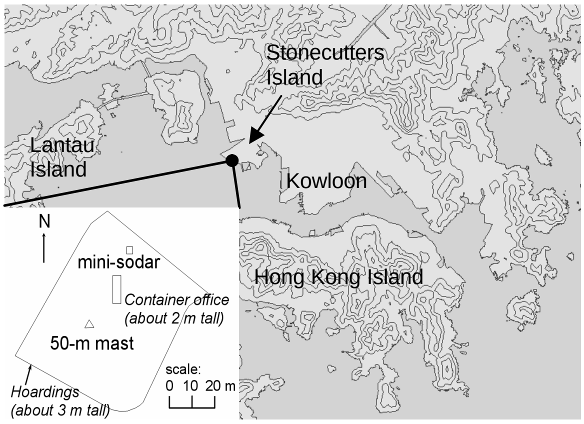

Figure 1 Map of Hong Kong (height contours: 100 m) and location of the measurement site (black dot). Inset shows equipment setup at the site.

The 50-m wind measuring mast is located at about 40 m to the south-southwest of the mini-sodar (Figure 1). Sonic anemometers (Gill model R3-50) are installed at 30 m and 50 m above ground. The three components of wind are sampled at 100 Hz and output at 10 Hz, i.e. each output datum is the average of 10 measurements.

3. COMPARISON OF MEAN WINDS AND WIND VARIANCES

Performance of the mini-sodar in the environment of the measurement site is firstly studied by comparing its standard output products, namely, 10-minute mean wind and variances of the three components of the wind, against the data of the sonic anemometers. When there is rain, the mini-sodar data (which have unreasonably large mean wind speeds) are excluded.

Data collected during the period 12 December 2003 to 6 May 2004 are used in this study. Comparison of the key parameters between the mini-sodar data and the sonic anemometer data are shown in Table 1. For variances of the horizontal wind components, we only consider the square root of their sum. The results of comparison for horizontal wind speed, wind direction and the variance of vertical velocity (s_w) are generally consistent with those in the previous studies (Crescenti, 1997). The correlation for the mean vertical velocity *w* is relatively low, which is also noted in other studies (Kallistratova et al., 2003). But this should not affect the results of the EDR study as discussed later because the mean value would be removed from the time series of *w*

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(de-meaning) in the standard procedure of constructing the velocity spectrum.

The wind variances from the two instruments compare reasonably well, despite a slight offset (as an example, the comparison of s_w is shown in Figure 2). The next step is to explore whether the "raw" measurements from the two instruments (0.5 Hz data from the mini-sodar and 10 Hz data from the sonic anemometer) show similar variation with time and give comparable EDR values, despite the difference in the sampling frequency. This will be discussed in the following sections.

Element	R	A	B
30 m			
V	0.90	0.90	0.65
q	0.94	0.96	3.52
$\sqrt{s_u^2 + s_v^2}$	0.86	1.24	-0.06
w	0.60	0.64	0.02
s_w	0.89	1.09	-0.06
50 m			
V	0.92	0.92	0.56
q	0.93	0.95	-1.94
$\sqrt{s_u^2 + s_v^2}$	0.88	1.21	-0.10
w	0.66	0.70	0.03
s_w	0.91	1.16	-0.11

Table 1 Comparison of the mini-sodar data (X) and sonic anemometer data (Y) at 30 m and 50 m above ground of the measurement site. The five elements for each height (from top to bottom) are horizontal wind speed (V), wind direction (q), the square root of the sum of variances of the horizontal wind components ($\sqrt{s_u^2 + s_v^2}$), vertical velocity (w) and its standard deviation (s_w) respectively. Least square linear fit is made to the data from the two instruments. R is the correlation coefficient. A and B are the slope and y-intercept of the linear fit respectively (Y = A*X + B).

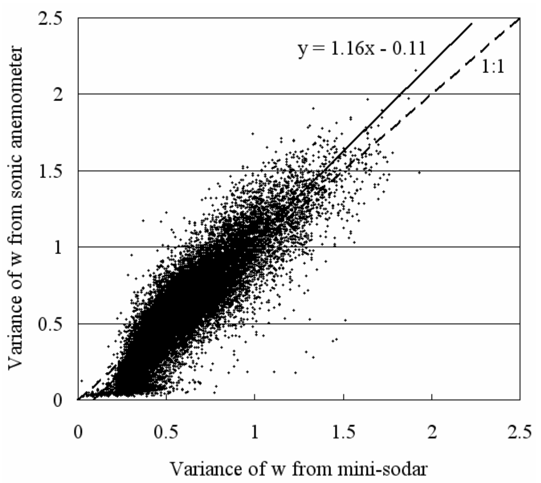

Figure 2 Scatter plot of the variance of vertical velocity w for the mini-sodar and for the sonic anemometer at 50 m. Dotted line is the 1:1 line. Solid line is the least square linear fit.

4. CALCULATION OF EDR

The mini-sodar takes about 2 seconds to complete each cycle of beaming into the 3 directions. One may argue that the 3 radial velocities may be used together to construct the 3 components of the "instantaneous" wind. Turbulence calculation then involves transformation of the spatial co-ordinates with respect to the mean wind over a period (e.g. 1 hour) and evaluation of the 3 components of the instantaneous wind in this transformed co-ordinate system. However, the wind may have changed quite significantly during this 2-second measurement cycle of the mini-sodar (especially for turbulent airflow, which is the subject of this paper) and the 3-components of the wind so determined cannot be taken together to represent the wind at a particular instance. As a result, we just use a single wind component, namely, the vertical velocity w (which is directly measured by the vertical beam of the mini-sodar) to study turbulence. The vertical velocity is mostly an order of magnitude smaller than the horizontal velocity and the effect of co-ordinate transformation should be insignificant.

To calculate EDR, first of all we need to construct the times series of the "raw" w from each instrument. The mini-sodar measurement is susceptible to contamination by wind noise and environmental noise (e.g. moving vehicles and machinery at the measurement site) and only the "raw" wind data obtained from sufficiently strong atmospheric return (signal-to-noise ratio of 8 or above, with an arbitrary unit used by the mini-sodar system in this study) are considered to be valid. A mean frequency of the valid "raw" w data (f_0) is calculated as a reference of the quality of the EDR derived later because the EDR cannot be calculated accurately by using too little "raw" data. A time series of 1-second w in a 1-hour period is then generated by including all the valid "raw" data in this period. When the 1-second w data are not available (either there is no measurement by the mini-sodar at that second or the "raw" data are invalid), it is filled in by linear interpolation between the two nearest valid "raw" w.

The time series of 1-second w is then processed through the standard procedures of de-meaning (removing the mean value in an hour, as in Greenhut and Mastrantonio, 1989) and de-trending (removing the linear trend). Frequency spectrum of the resulting data series (an example shown in Figure 3) is derived by using fast Fourier transform. The part of the spectrum with the frequency larger than f_0 is neglected because it arises from the artificial 1-second w generated from linear interpolation of the valid "raw" data of the mini-sodar.

The inertial subrange of the frequency spectrum is found by looking for the largest range of frequency in which the slope of the spectrum is close to -5/3 (Stull, 1988). This frequency range has to span at least 0.5 unit in the logarithm scale of the frequency, namely, between $\log_{10}(f_0)$ and $\log_{10}(f_0) - 0.5$, as in Greenhut and Mastrantonio (1989). Otherwise, the frequency spectrum is not considered to include sufficient data points in the inertial subrange and would not be used to calculate EDR. Concerning the slope of the frequency spectrum, because of instrumental errors and airflow disruptions by the

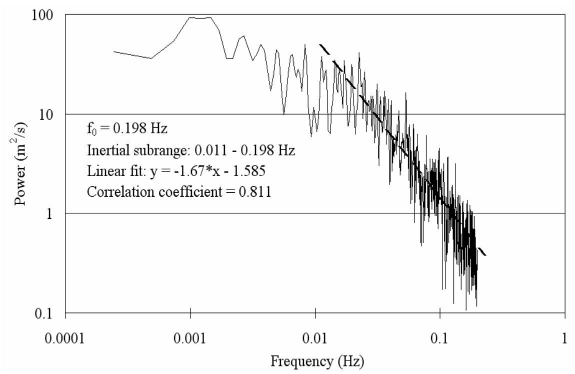

Figure 3 Frequency spectrum at 09:10 a.m., 23 March 2004 as measured by the mini-sodar. The dotted line refers to the least square linear fit to the inertial subrange.

structures at the measurement site, it may not be close to -5/3 at times. The frequency spectrum is taken to have sampled the inertial subrange if the slope lies between -1.5 and -1.7. In fact, as found out in this study, the slope is mostly within this range.

Least square linear fit is then made to the inertial subrange of the frequency spectrum in a log-log plot (Figure 3). Let *a* and *b* be the slope and y-intercept of this linear fit respectively. TKE dissipation rate (*r*) is then given by (Greenhut and Mastrantonio, 1989)

$$r = \frac{11.2}{V} 10^{3b/2} f^{(5+3a)/2}, \qquad (1)$$

where *V* is the mean horizontal velocity and *f* is frequency. If *a* exactly equals -5/3, *r* will be independent of *f*. When *a* is not exactly equal to -5/3, *f* is taken to be the central frequency of the part of the inertial subrange in the measured frequency spectrum. For example, in the frequency spectrum of Figure 3, *f* equals to (0.011+0.198)/2 = 0.105 Hz. EDR (e) is then calculated from

$$e = r^{1/3}. \qquad (2)$$

In the case of Figure 3,

$$e = \left(\frac{11.2}{5.71} 10^{3x(-1.585)/2} x 0.105^{(5+3x(-1.67))/2} \right)^{1/3} = 0.203$$

The calculation of EDR from sonic anemometer data is very similar. Because of the higher data sampling rate (10 Hz), the resulting frequency spectrum covers a larger range of frequency. In determining the inertial subrange, the frequency range has to include at least 0.1 to 1 Hz, i.e. spanning at least 1 unit in the logarithm scale of the frequency (vs. 0.5 unit in the log-frequency scale for the mini-sodar, which has a lower data sampling frequency).

5. COMPARISON OF EDR

EDR is calculated every 10 minutes by using the “raw” *w* data accumulated in the last 60 minutes. Only the EDR data satisfying the following criteria are selected for further study:

(a) f_0 is at least 0.1 Hz, to make sure that the inertial subrange is covered;
(b) correlation coefficient of the least square linear fit of the inertial subrange is at least 0.7, so that there are sufficient number of data points;
(c) horizontal wind speed is at least 6 knots, because low-level turbulence experienced by aircraft, which is the interest of this study, occurs at least in moderate winds.

The EDRs from the mini-sodar and the sonic anemometer are compared. Results are summarized in Table 2 and an example of scatter plot of the EDRs from the two instruments is shown in Figure 4. The two measurements are found to correlate reasonably well. The correlation is better at 50 m than at 30 m, which may be related to the following factors: (i) the spatial variation of the wind fluctuations at higher frequencies (between the locations of the mini-sodar and the 50-m tower) should be larger at a lower altitude due to variation of topography and artificial structures on the ground, and (ii) the effect of airflow disruption by the 50-m mast itself is stronger in the sonic anemometer measurement at 30 m.

Height	R	A	B
30 m	0.67	0.74	0.04
50 m	0.85	1.12	-0.03

Table 2 Comparison of the EDR from the mini-sodar (X) and the sonic anemometer (Y). Least square linear fit is made to the two sets of data. R is the correlation coefficient. A and B are the slope and intercept of the linear fit respectively (Y = A*X + B).

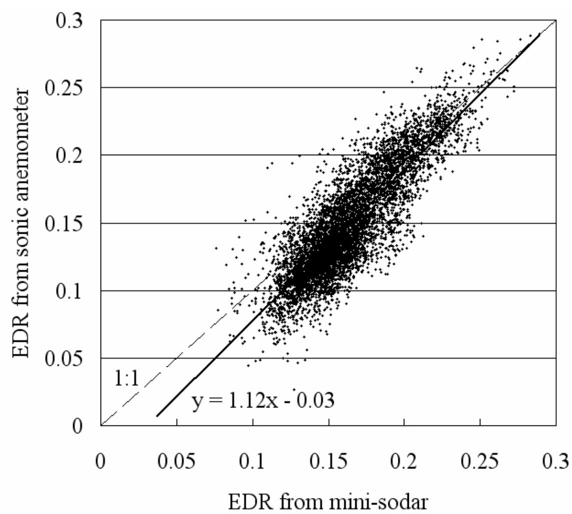

Figure 4 Scatter plot of the EDR from the mini-sodar and the sonic anemometer at 50 m. Dotted line is the 1:1 line. Solid line is the least square linear fit.

It is noted that the correlations of EDR are smaller than those of s_w for both heights. This is probably due to the fact that, whilst s_w only considers the deviation of *w* from the mean value, EDR is calculated from the variation of *w* over a range of frequencies (spanning at least 0.5 unit in the logarithm scale of the frequency), which is a more demanding comparison between the mini-sodar and sonic anemometer measurements. Moreover, as shown in equation (1), EDR is related to the exponents of *a* and *b*, which are deduced from the least-square linear fit of the velocity spectrum. Small errors of *a* and *b* would result in a much larger error in EDR.

The EDR in this study only ranges between 0.1 and 0.3, i.e. light to moderate turbulence conditions according to ICAO definition (ICAO, 2001). The quality of the EDR data from the mini-sodar in severe turbulence (e.g. airflow disrupted by terrain under high wind conditions) requires further study.

6. EXAMPLE OF VERTICAL PROFILE OF EDR

The mini-sodar measures the wind from 25 m up to 100 m at 5 m interval. EDR can be calculated at each height to give the vertical turbulence profile.

As an example, the vertical profile of EDR on 19 December 2003 is shown in Figure 5. The southern part of China was under the influence of the northeast monsoon on that day (Figure 6). Winds were mainly moderate to fresh northerlies up to 100 m as measured by the mini-sodar. The weather was fine in Hong Kong with the temperature at the measurement site rising from 13 degrees at 6 a.m. (Hong Kong Time, which is 8 hours ahead of UTC) to a maximum of 17 degrees at 2 p.m. As shown in Figure 5, the EDR above 50 m or so did not change very much during the day and it generally decreased with height. On the other hand, the EDR below 50 m showed greater variation. For example, the EDR at 25 m increased from 0.15 $m^{2/3}s^{-1}$ at 6 a.m. to 0.25 $m^{2/3}s^{-1}$ at noon, and then decreased to 0.19 $m^{2/3}s^{-1}$ at 6 p.m. The air closer to the ground seems to become more turbulent in the day-time as a result of solar heating.

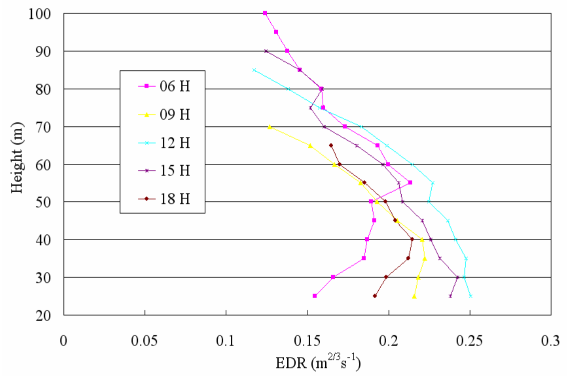

Figure 5 Evolution of the vertical profile of EDR on 19 December 2003.

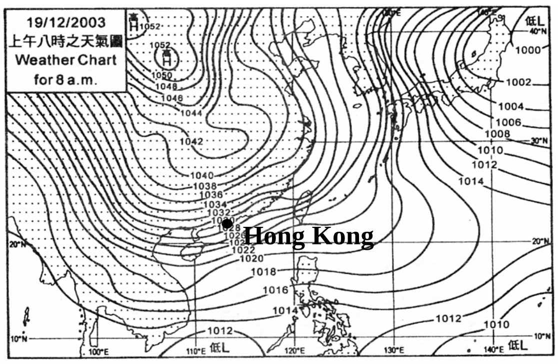

Figure 6 Surface isobaric chart at 8 a.m., 19 December 2003.

7. CONCLUSION

A mini-sodar with a central frequency of 4.5 kHz was used in this study to measure EDR directly. It was firstly confirmed to operate satisfactorily by comparing its 10-minute mean wind and wind variances with the data from two sonic anemometers installed at 30 m and 50 m above ground on a tower. The correlation was around 0.9 for horizontal wind speed, wind direction, the sum of variances for horizontal wind components and the variance of vertical velocity, and between 0.6 and 0.7 for the mean vertical velocity. The "raw" vertical velocity data of the mini-sodar (with a sampling frequency of about 0.5 Hz) were then used to calculate EDR. The mini-sodar and the sonic anemometers were found to give comparable values of EDR, with a correlation coefficient of at least 0.67.

The mini-sodar appears to have the potential of providing reasonably accurate EDR profile for the monitoring of low-level turbulence at the airport in light to moderate turbulence conditions. It would be relocated to the Hong Kong International Airport later for a further study of its performance separately under high wind conditions.

Acknowledgement

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References

Antoniou, I., H.E. Jørgensen, F. Ormel, and S. Bradley, 2003: On the theory of SODAR measurement techniques. Risø National Laboratory, Roskilde, Denmark, 59 pp.

Chan, P.W., and S.T. Chan, 2004: Performance of eddy dissipation rate estimates from wind profilers in turbulence detection. *11th Conference on Aviation, Range, and Aerospace Meteorology*, American Meteorological Society, Massachusetts (this CD-ROM).

Crescenti, G. H., 1997: A look back on two decades of Doppler sodar comparison studies. *Bulletin of the American Meteorological Society*, **78**, 651-673.

Greenhut, Gary K., and G. Mastrantonio, 1989: Turbulence kinetic energy budget profiles derived from Doppler sodar measurements. *J. Appl. Meteor.*, **28**, 99-106.

ICAO, 2001: Meteorological Service for International Air Navigation, Annex 3 to the Convention on International Civil Aviation.

Kallistratova, M.A., R.D. Kouznetsov, G.A. Kourbatov, E.A. Shourygin, and V.P. Yushkov, 2003: On accuracy of remote acoustic measurements in the atmospheric boundary layer (ABL). *XIII Session of the Russian Acoustical Society*.

Stull, R.B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers, 666 pp.