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A simple method to estimate the eddy dissipation rate from SODAR/RASS measurements

Michael Frech
Institut für Physik der Atmosphäre
German Aerospace Centre (DLR) Oberpfaffenhofen
D-82234 Wessling, Germany

1. Introduction

Traffic throughput at major airports is in part limited by prescribed ICAO wake vortex separation standards where aircraft are grouped into three weight classes. Wake vortices are generated inevitably by an aircraft as a consequence of lift, where the vortex strength mainly depends on aircraft weight, approach speed and span. A wake vortex is hazardous because of the rolling moment it may impose on a following encountering aircraft (Gerz et al. 2002). The ICAO separation standards are considered to be often too conservative because favorable atmospheric condition can often mitigate the wake vortex hazard (Frech and Zinner, 2004). In order to increase capacity and to reduce related delay costs, wake vortex avoidance systems are being developed (see Gerz et al. 2002)). A wake vortex avoidance system aims at monitoring and predicting the wake vortex behavior in the flight corridor in order to propose safe separations to the air traffic controller. Atmospheric conditions significantly influence the transport and decay characteristics of wake vortices. Turbulence, stable static stratification and shear influence the decay of a wake vortex (Holzäpfel et al., 2002). Today, all state-of-the-art wake vortex models parameterize the decay due to turbulence in terms of the turbulent eddy dissipation rate (Sarpkaya 2000, Holzäpfel, 2003) . The dissipation rate is suggested to be known within an accuracy of a factor four, which is sufficient to predict wake behavior with a probabilistic wake vortex model (Holzäpfel, pers. communication). From an operational point of view situations are relevant where the cross wind is not sufficient to clear the glide path from vortices and where vortices may persist for a long time due to calm environmental conditions. There are observations of vortices with substantial circulation up to 4 minutes (radar separation $\approx$ 60 sec). This will be the case when turbulence is weak and the atmosphere is neutral stratified. In order to predict wake vortex persistence the turbulence level is one key quantity that has to be predicted and diagnosed. A complicating aspect may appear, if we have to quantify small eddy dissipation rates ϵ, where turbulence models can fail because basic assumptions are not fulfilled. Pragmatic parameterizations of ϵ may be acceptable for operational solutions as long their limits are understood.

Often the dissipation rate is determined from indirect methods when data of sonic anemometer with sufficient high temporal resolution are available. Commonly, Kolmogorv's 5/3rd law is employed, where the power spectrum of velocity components are analyzed for a 5/3rd slope in a log/log representation. The 5/3rd slop is expected in the inertial subrange. As an alternative the structure function may be employed which also requires the presence of an inertial subrange. The indirect determination of ϵ is less dependent on the averaging scale as compared to the estimation of turbulent kinetic energy e. More important, ϵ in general is determined at length scales which presumably most effectively trigger instability mechanisms, which subsequently lead to the rapid decay of a wake vortex.

In order to estimate a dissipation rate profile we have to rely on remote sensing techniques which are robust enough to provide continuous real-time estimates of ϵ in an operational environment. In this paper we compare eddy dissipation rate estimated from SODAR/RASS with LIDAR measurements taken during two European wake measurement campaigns. The standard quality controlled output from SODAR/RASS is used for analysis. In addition data from a sonic anemometer are analyzed.

2. Data analysis

A METEK DSDPA.90-24 SODAR together with a MERASS at 1274 MHz was deployed during two wake vortex measurement campaigns in spring 2002 and autumn 2003 in Tarbes, France. The instrument settings were set to provide 10 minute averaged profile of wind components and temperature at a vertical resolution of 10-20 m. The typical measurement range was 500 m starting at $z = 40$ m. A sonic anemometer with a sampling frequency of 20 Hz was mounted on a 10 m mast close to the SODAR/RASS system. A 2μm LIDAR was used to characterize the wake vortices of a large transport aircraft (Köpp et al., 2004). The line-of-sight (LOS) spatial resolution of this instrument is 3 m at a sampling rate of 500 MHz. In addition, the LIDAR provided background information on the atmospheric LOS velocity field. The flight tests with wake measurements were scheduled to be carried out under calm conditions of low turbulence and wind. Most of the measurements took place in the evening hours between 18:00 and 22:00 local time. In the following plots the lowest measurement height at $z = 10$ m is based on the sonic anemometer measurement.

The dissipation rate determined from LIDAR system is computed from the second order structure function at lags between 120 and 160 m (Banakh et al., 1997). An assumption is that the outer scale of turbulence is larger than the length scale from which the dissipation rate is estimated. This assumption will be investigated in another study in more detail. As a first check, we have computed the integral length scale from sonic anemometer measurements at a height of 10 m above ground. In total we have analyzed 56 cases with corresponding wake measurements.

The estimate of ϵ is based on a parameterization proposed by Kramar and Kouznetsov (KK, 2002) where a simplified budget equation is proposed to estimate turbulence properties from SODAR/RASS. The parameterization is restricted to neutral stratification and assumes that the local mechanical production of turbulent kinetic energy e is balanced by dissipation of e. The eddy dissipation at a given height z is written as:

$$\epsilon(z) = \frac{e(z)\partial U/\partial z}{C_{KP}^2} \tag{1}$$

with $C_{KP} = (e/\overline{-u'w'})^{1/2}$, where $C_{KP} \approx 2$ under neutral conditions. In our application we fix this value to $C_{KP} = 2$. We estimate the TKE from the SODAR measurements as $e = 3/2\sigma_w^2$. The dissipation rate from the sonic anemometer measurement is computed from the 3rd order structure function of the along wind component, $D(r)^3 = -4/5\epsilon r$, where we check for the constant skewness assumption $S(r) = D(r)^3/(D(r)^2)^{3/2}$, to be in the range of $|S(r)| = 0.25 - 0.45$ (Katul et al. 1995).

The initial implementation of the parameterization by KK indicated a systematic overestimation of ϵ compared to the LIDAR measurement. This is attributed to an overestimation of TKE due to atmospheric motions at larger scales not attributable to turbulence during mostly near neutral and stable situations. For these situations we apply a simple empirical scaling factor to the SODAR estimated TKE, $e_{scaled} = c_m e$, with $c_m = e(l < 100m)/e$. This scaling factor is computed from a multiresolution decomposition of TKE from the sonic anemometer data considering length scales smaller ≈ 100 m (Howell and Mahrt, 1997) from 10 min averages.

We first show as an example the intercomparison of mean quantities computed from SODAR/RASS and LIDAR, 19:30 UTC, 17.6.2002. There is a very good agreement between the standard deviation of vertical wind obtained from SODAR and the line-of-sight (LOS) standard deviation from LIDAR (Fig. 1). The virtual potential temperature profile indicates a stable stratified surface layer and a layer between 150 and 300 m with near neutral stratification. This layer corresponds to the larger standard deviations of vertical velocity and LOS winds which may be attributed to a residual layer. The stability parameter $z/L = 3.9$ at $z = 10$ (Table 1) is in agreement with observed temperature profile close to the surface. The profiles of cross wind from SODAR and LIDAR nicely agree. For this case we observe a maximum in wind speed close to the surface (≈ 4 m/s), which decreases with height (Fig. 2).

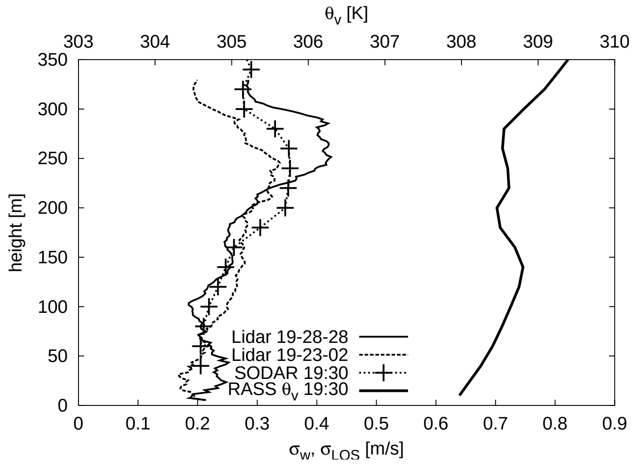

Figure 1: Profiles of the standard deviation of vertical wind speed (SODAR), the LOS velocity standard deviation from LIDAR and the virtual potential temperature from the RASS, 17.06.2002. SODAR profile are 10 minute averages, LIDAR profiles are 5 minute averages.

Table 1: Stability parameter z/L, integral length scale l and dissipation rate ϵ computed from sonic anemometer data based on 10 and 30 min averages, 17.06.2002 at 19:30 UTC.

Variable	30 min average	10 min average
z/L	3.9	6.1
l (m)	39	20
ϵ (m^2/s^3)	$8.7 \cdot 10^{-4}$	$8.4 \cdot 10^{-4}$

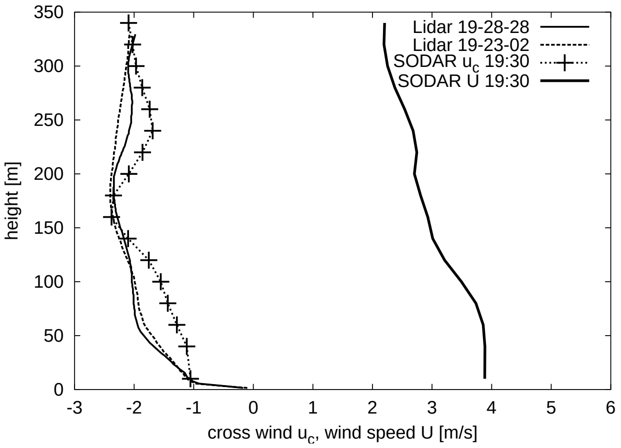

Figure 2: Profiles of wind speed (SODAR) and cross wind (SODAR and LIDAR), 17.06.2002.

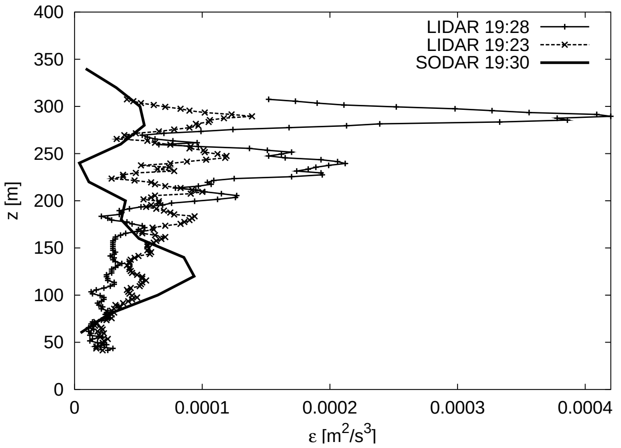

Figure 3: Profiles of dissipation rate estimated from SODAR and LIDAR measurements, 17.06.2002. The scaling factor is $c_m = 0.34$.

The dissipation rates agree quite well up to a height of $z = 250$ m (Fig. 3). There are larger differences in particular for the LIDAR profile at 19:28 UTC above z=250 m. This is likely to be an overestimation of ϵ which can be attributed to the presence of a shear layer which results into additional variance when computing the spatial structure function. The dissipation rate computed from the sonic anemometer (table 1) is roughly a factor 8 larger which may be explained by the larger wind speed close to the surface with larger shear production of TKE.

In a next step, the mean dissipation rate is computed for all 56 cases. We compute the average dissipation rate over the mean decent height of the wake vortex for stable (mostly weakly stable, near neutral) and unstable cases. The typical decent height is on the order of 100-200 m. For comparison we show the results without scaling the TKE. The results are compared to the mean dissipation rate obtained from LIDAR. If we compare the stable (Fig. 4) and unstable (Fig. 5) results we can notice that the scatter is smaller for stable situations. For most of the cases the scatter is reduced if we introduce the scaling of TKE. The accuracy obtained appears sufficient for wake vortex predictions for most of the cases (see introduction). The results for the unstable cases indicates for both cases large scatter. This may not be surprising considering the fact that buoyancy production is not considered in the parameterization.

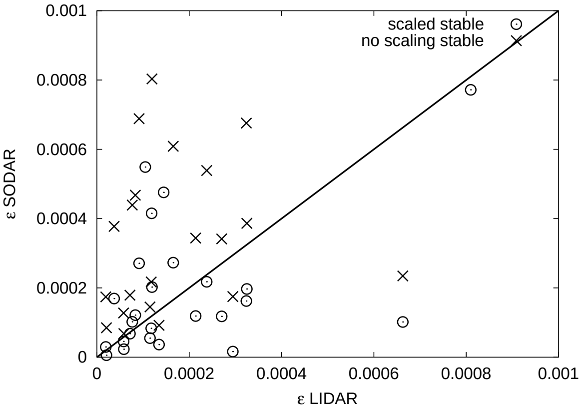

Figure 4: Scatter plot of mean dissipation rates averaged over the mean wake vortex decent height. LIDAR versus SODAR measurements, stable stratification (m^2/s^3).

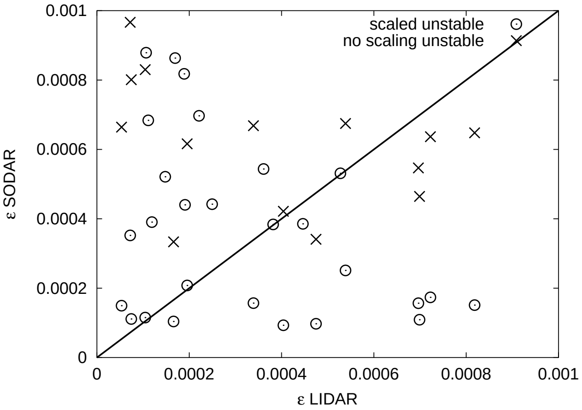

Figure 5: Scatter plot of mean dissipation rates averaged over the mean wake vortex decent height (unstable stratification, in m^2/s^3).

3. Summary

The dissipation rates obtained from SODAR/RASS for the stable/neutral cases using a the scaled TKE show an acceptable agreement with ϵ obtained from LIDAR measurements. For unstable situation, a stability correction needs to be developed which is work currently under way.

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