On the Use of Hot-Wire Anemometers for Turbulence Measurements in Clouds

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ABSTRACT

The use of a hot-wire anemometer for high-resolution turbulence measurements in a two-phase flow (e.g., atmospheric clouds) is discussed. Experiments in a small wind tunnel (diameter of 0.2 and 2 m in length) with a mean flow velocity in the range between 5 and 16 m s$^{-1}$ are performed. In the wind tunnel a spray with a liquid water content of 0.5 and 2.5 g m$^{-3}$ is generated. After applying a simple despiking algorithm, power spectral analysis shows the same results as spectra observed without spray under similar flow conditions. The flattening of the spectrum at higher frequencies due to impacting droplets could be reduced significantly. The time of the signal response of the hot wire to impacting droplets is theoretically estimated and compared with observations. Estimating the fraction of time during which the velocity signal is influenced by droplet spikes, it turns out that the product of liquid water content and mean flow velocity should be minimized. This implies that for turbulence measurements in atmospheric clouds, a slowly flying platform such as a balloon or helicopter is the appropriate instrumental carrier. Examples of hot-wire anemometer measurements with the helicopter-borne Airborne Cloud Turbulence Observation System (ACTOS) are presented.

1. Introduction

Atmospheric turbulence is characterized by extremely large Reynolds numbers. This means that the turbulent cascade extends over a large range of spatial scales and that the turbulence at the smallest scales tends to be highly intermittent (e.g., Wyngaard 1992). These general features are thought to hold true for turbulence in clouds also, but there the problem becomes more complex. It is suggested, for example, that the presence of droplets in a turbulent flow can modify the energy dissipation rate and, when gravitational sedimentation is significant, can introduce anisotropy at small spatial scales and lead to a reverse energy cascade (Elghobashi and Truesdell 1993; Ferrante and Elghobashi 2003). Furthermore, growth and evaporation of cloud droplets is associated with a large phase-change enthalpy and it is therefore possible to inject energy at small scales, also modifying the dynamics of the turbulent cascade near the dissipation scale (Andrejczuk et al. 2004). Unfortunately, however, it has not been possible to study these processes in natural clouds because of the difficulty of making fine-scale turbulence measurements in a two-phase system. Quantifying the rich interactions thought to occur in clouds at centimeter scales remains an experimental challenge.

The fundamental measurement challenge is to obtain a high-spatial-resolution measurement of turbulence in the presence of cloud droplets (and possibly ice crystals and precipitation). Most aircraft-based flow measurements are made with five-hole probes, yielding spatial resolutions on the order of several meters. Much of our experimental understanding of the turbulent structure of clouds, therefore, is based on measurements that are only able to resolve the largest eddies of the turbulent flows. Higher-resolution measurements with ultrasonic anemometers in clouds have been made (Cruette et al. 2000; Siebert et al. 2006) but are limited in general to a resolution of around 10 cm because of line averaging over the pathlength (Kaimal et al. 1968). To obtain local statistical parameters, such as local energy dissi-
pation rates $e_s$, a record of at least 100 samples is needed for a statistically stable estimation (Frehlich et al. 2004). With ultrasonic anemometer data, a spatial resolution for $e_s$ of only ~10 m is possible, which is often too low to resolve the turbulent cloud structure. Therefore, turbulence probes with much higher sampling frequencies are needed to obtain $e_s$ with higher spatial resolution. Furthermore, spectral deviations from classical Kolmogorov turbulence resulting from droplet growth/evaporation and sedimentation are expected to be present at centimeter scales (e.g., Korczyk et al. 2006) and therefore cannot be observed directly in cloud with the current instrumentation.

The sensor of choice for many decades in wind tunnel experiments and atmospheric boundary layer studies is the hot-wire anemometer (HWA). State-of-the-art sensors for high-resolution turbulence measurements have a bandwidth up to 100 kHz and are, therefore, suitable for turbulence measurements well within the dissipation range. High-resolution measurements with hot wires in the atmosphere have been made, for example, with a sensor package carried by a tethered balloon (Muschinski et al. 2001) or based on a tower (Shaw and Oncley 2001). However, even though the application of hot wires for measurements in two-phase flows is discussed in textbooks (e.g., Bruun 1995; Goldstein 1996), measurements with HWA in the cloudy atmosphere are rare.

A few measurements in clear air with HWAs fixed on a slow-flying research aircraft were reported by Lenschow et al. (1978), but on fast-flying aircraft with typical high true airspeed (TAS) on the order of 100 m s$^{-1}$, hot wires with a diameter of several micrometers likely are too fragile. Merceret (1976) showed that hot-film probes are useful for airborne small-scale turbulence measurements with better than centimeter resolution. Measurements were suggested for clear-air turbulence but also in the presence of rain (Merceret 1970). It was found that ice would damage the hot-film probes and that flights in clouds were harmless, but the true velocity signal cannot be recovered in clouds because of the large numbers of droplet impacts. More recently, Henze and Bragg (1999) made flow measurements in a wind tunnel with spray generators using hot-wire anemometers. They developed a digital acceleration threshold filter to remove distinct spikes from the hot-wire data caused by droplet impaction. Given this experience over the last decades, it seems worthwhile to explore the possible use of hot-wire anemometry in clouds in greater detail.

The aim of this paper is to investigate the feasibility of using hot-wire anemometers for finescale turbulence measurements in clouds or other two-phase flows. To extend previous work (e.g., Henze and Bragg 1999), the influence of the droplet spikes on the signal statistics and the efficiency of the despiking filter have to be analyzed in more detail. To accomplish this we have tested a hot-wire anemometer under various flow conditions in a controlled laboratory setting, which are representative of typical cloud conditions. The laboratory experiments are described in section 2. Specifically, we discuss the wind tunnel setup (section 2a), the nature of droplet–hot-wire interactions and the implications for the quality of the turbulence measurements (section 2b), the hot-wire signal (HW) despiking filter (section 2c), and examples of data for three different flow conditions (section 2d). In section 3 we present results from hot-wire measurements made in an atmospheric cloud, using a helicopter-borne payload Airborne Cloud Turbulence Observation System (ACTOS). In this configuration, hot-wire measurements were possible in natural clouds because true airspeeds were sufficiently low. Finally, our findings are summarized and discussed in section 4.

2. Wind tunnel experiments

2a. Wind tunnel and experimental setup

The wind tunnel consists of a horizontal Plexiglas tube that is 2 m long and 0.2 m in diameter. A sketch of the setup is shown in Fig. 1, in which the flow direction is from right to left. The ratio between tube length $l$ and tube diameter $d$ that is necessary for fully developed turbulence can be approximated by $l/d = (A) Re^B$, with the flow Reynolds number $Re = \pi d v/\nu$ and two constants $A = 0.6$ and $B = 0.25$ for turbulent flows (Bohl 1998). Here $\pi$ is the mean flow velocity, $v = \mu/\rho_a = 1.5 \times 10^{-5}$ m$^2$s$^{-1}$ is the kinematic viscosity of air, $\mu$ is the dynamic viscosity of air ($1.81 \times 10^{-5}$ kg m$^{-1}$s$^{-1}$), $\rho_a$ is the air density, and $d$ is the tube diameter. With $\pi = 10$ m s$^{-1}$, it follows that $Re \sim 10^5$ and $(A) Re^B \sim 11$. Therefore, $l/d \sim 8$ and the conditions for fully developed turbulence are nearly met. This conclusion is also supported by power spectral analysis (discussed in Fig. 8).

The spray in the wind tunnel is created by an injector nozzle. The basic operating principle and location of this nozzle is shown in Fig. 1. The injector nozzle is designed to create a spray with a median droplet diameter of 10 $\mu$m. Purified water was used to protect the wire of the HWA from any further material remaining at the surface. The tube to the water reservoir can be closed by a manual valve and since no additional compressed air passes through this tube, this valve has no influence on the flow speed. Thus, identical flow situations with or without spray can be established.
of 1/4-in. tubes are placed side by side with the mixing nozzle. The maximum pressure for the nozzles is 5 bars each. For the 1/4-in. tubes the pressure can be roughly adjusted to vary the flow speed. However, it was found that stable flow conditions exist only for completely opened valves; that is, experiments with three different stable flows could be performed. The three different flow cases are denoted in the text by subscripts describing the valve settings (cf. Table 1).

b. Hot-wire anemometer

Turbulence was measured with a one-dimensional HWA (Dantec Dynamics A/S, Denmark, type 54T30) that was located about \( l_2 \approx 160 \text{ cm} \) behind the inlet of the wind tunnel (cf. Fig. 1). The HWA system is a constant temperature anemometer with a platinum-plated tungsten wire (type 55P01) with a diameter of 5 \( \mu \text{m} \) and an overall length of around 3 mm, whereas the sensing part is only 1.25 mm long. Essentially, an HWA measures the convective heat transfer between the heated wire and the flow that is described by the Nusselt number \( \mathrm{Nu} \) with the Reynolds number \( \mathrm{Re} = \frac{\pi d_{\text{HW}}}{v} \) (Goldstein 1996; Bruun 1995).

Here, \( C \) and \( D \) are empirical constants and \( d_{\text{HW}} \) is the diameter of the hot wire. The electrical power input \( P \) is \( \frac{V^2}{2} = \frac{\eta_{\text{Nu}}}{\eta_{\text{Re}}} \) therefore, the output voltage \( V_p \) of the HWA is \( \eta_{\text{Re}}^{1/4} \eta_{\text{Re}}^{1/4} \). The bandwidth of the system is 10 kHz.

To calibrate the HWA over the range of the three different flow speeds, a few measurements for varying speeds were made simultaneously with a Pitot tube placed slightly behind the hot wire, so as not to disturb the turbulence measurements. The sampling frequency \( f_s \) was set at 1 kHz for all devices. A correlation plot of the flow velocity \( u_{\text{Pitot}} \) measured with the Pitot tube and the HWA output \( V_{\text{HW}} \) is shown in Fig. 2. To reduce the scatter, the hot-wire signal was averaged over nonover-

<table>
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<th>Dataset</th>
<th>( \pi ) (m s(^{-1}))</th>
<th>( \sigma_{\pi} ) (m s(^{-1}))</th>
<th>( \sigma_{\sigma_{\pi}} ) (m s(^{-1}))</th>
<th>( \sigma_{\sigma_{\pi}} ) (m s(^{-1}))</th>
<th>( \eta_{\text{K}} ) (10(^{-4}) m)</th>
<th>( \eta_{\text{K}} ) (10(^{-4}) m)</th>
<th>( a_i ) (m s(^{-1}))</th>
<th>( a_i ) (m s(^{-1}))</th>
<th>( N_{\text{tot}} ) (s)</th>
<th>( N_{\text{HW}} ) (c m(^{-3}))</th>
<th>( N_{\text{FSSP}} ) (c m(^{-3}))</th>
<th>( \phi' ) (10(^{-4}))</th>
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lapping flow velocity ranges of 1 m s$^{-1}$. A fit with a third-order polynomial was made to estimate the calibration coefficients.

c. Characterization of the spray

To study the effects of droplets on the HWA signal it was necessary to characterize the spray under the three flow conditions. A particle volume monitor (PVM-100A) was placed at the end of the wind tunnel to measure the liquid water content (LWC) of the spray (cf. Fig. 1). An internal low-pass filter for antialiasing was set at around 100 Hz. Details of this optical probe can be found in Gerber et al. (1994).

The droplet size distribution $\Delta N/\Delta d_d$ is derived from measurements performed with an M-Fast Forward Scattering Spectrometer Probe (FSSP; Schmidt et al. 2004), which was located at the end of the tube (instead of the PVM). The integral over $\Delta N/\Delta d_d$ gives the droplet number concentration $N$. Figure 3 depicts the size distributions for the three different flow states. For the two situations with the highest flow velocities (110 and 111), both distributions have nearly the same shape with a mean diameter around 9 $\mu$m and a long tail toward large droplet sizes. The ratio of both distributions and number concentrations ($\sim$2) is similar to the ratio of the flow velocities. For the third case with low flow velocities, the number concentration reaches very high values and the M-Fast FSSP is near saturation. Thus, the M-Fast FSSP measurements for this case should be interpreted with caution.

d. Influence of droplet–hot-wire collisions on the velocity signal

When a droplet impacts the hot wire, the system reacts so as to evaporate the water and maintain the wire at a constant temperature. As a result a sudden spike in the voltage is observed. This spike must be distinguished from voltage variations due to turbulent velocity fluctuations. Essentially, the result is a continuously sampled signal interrupted by random spikes. The usefulness of the velocity signal is inversely related to the fraction of signal lost because of droplet–hot-wire collisions. In the following we attempt to estimate that fraction.

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**Fig. 2.** (a) The correlation between the raw hot-wire signal $V_{HW}$ and the flow velocity $u_{Pitot}$ measured with the Pitot tube. A fit with a third-order polynomial is included. (b) A time series of the flow velocity measured with the Pitot tube and the signal of the calibrated hot wire.
1) Impact Rate of Droplets on the Hot Wire

The particle Stokes number for a 10-μm droplet interacting with a hot wire is

$$St = \frac{d_d^2 \rho_w \overline{u}}{9 \mu w d_{HW}^2} \approx 1200,$$

where \(\rho_w\) is the density of liquid water. This Stokes number is much higher than the critical Stokes number required for impaction (\(St \approx 0.3\)); therefore, we can safely use the geometric cross section in determining the droplet–hot-wire collision rate.

The hot wire has a cross section \(\sigma\) for a typical cloud droplet with an average diameter of \(d_d = 10\, \mu m\) of \(\sigma = L(d_{HW} + d_d) \approx 1.25\, mm \times (5\, \mu m + 10\, \mu m) \approx 1.9 \times 10^{-8}\, m^2\). With a droplet number concentration of \(N = 675\, cm^{-3}\), the mean free path is \(1/(N\sigma) \approx 8\, cm\). Furthermore, with a mean flow velocity of \(\overline{u} \approx 10\, m/s\) we obtain an average arrival time of \(\tau = 1/(N\sigma\overline{u}) \approx 8\, ms\). In fact, if the droplets are randomly distributed in the turbulent flow, we expect that the probability density function for the (random) droplet interarrival time \(\tau\) is exponential, \(p(t) = \tau^{-1} \exp(-t/\tau)\). This is observed to be a reasonable approximation, as illustrated in Fig. 4, which shows the probability density function (PDF) of interarrival times under flow conditions 110. As a result of the skewness of the exponential function, we expect there will be a significant number of velocity data segments that remain uninterrupted for times several times larger than \(\tau\) (e.g., see Fig. 4 where it can be seen that approximately 1% of the interarrival times are \(\geq 5\tau\)). Thus, the natural tendency of random droplet arrivals to be clustered improves the ability to extract meaningful data.

2) Duration of a Droplet Impact in the Hot-Wire Signal

If we wish to know the fraction of useable signal we must estimate the typical duration of a voltage spike in the hot-wire signal due to a droplet impact. We proceed by considering the time required for a spherical droplet to evaporate after coming into contact with the hot wire.

![Fig. 4. PDF for droplet interarrival time (points), as determined from the hot-wire voltage spikes for flow state 110. The interarrival time is plotted relative to the mean interarrival time, \(\tau = 108\, ms\). An exponential curve (solid line) is shown for comparison.](image-url)
wire. Of course, after a collision the droplet may no
longer be a sphere, but we expect the analysis to give a
satisfactory estimate for the purpose of a scale analysis.

The ratio of energy required to evaporate a droplet
with radius \( r_d \) and the energy required to increase
the droplet temperature by approximately \( \Delta T = 80 \text{ K} \) (e.g., from a labora-

tory temperature around 20°C to \( T_m =
100^\circ\text{C} \)) is \( \alpha = L_v/(c_p \Delta T) = 2.2 \times 10^6 \text{ J kg}^{-1} \text{K}^{-1} \times 80 \text{ K} \) \( \approx 7 \), where
\( L_v \) is the latent heat of vaporization for water and
\( c_p \) is the specific heat capacity
at constant pressure for water. Therefore, as a first-
order approximation we consider only the evaporation
time scale of a droplet with a uniform, constant
temperature of 100°C. The evaporation of a droplet is
described by (e.g., Pruppacher and Klett 1997)

\[
\frac{dr_d}{dt} = -\frac{M_w D_v}{\rho_v R} \left[ \frac{E(T_w)}{T_w} - \frac{e_v}{T_w} \right],
\]

(2)

with the diffusivity for water vapor \( D_v = 0.211(T/
T_0)^{1.85}(p_0/p) \times 10^{-4} \sim 3.6 \times 10^{-7} \text{ m}^2 \text{s}^{-1} \) (with \( T_0 = 273
\text{ K}, T = 373 \text{ K}, \) and \( p_0/p \approx 1 \)), the
universal gas constant \( R = 8.31 \text{ J mol}^{-1} \text{K}^{-1} \), the molecular weight of water
\( M_w = 18 \times 10^{-3} \text{ kg mol}^{-1} \), the saturation water vapor
pressure at droplet temperature \( E(T_w) = 10^5 \text{ Pa}, \) and the ambient water vapor pressure
\( e_v \) at ambient temperature \( T_w \). The ambient

temperature is much lower than the droplet tempera-
ture and, therefore, \( e_v (T_w) \sim E(T_w) \), such that
the second term in the brackets of Eq. (2) is negligible.
Since the right-hand side of Eq. (2) is constant \( \left[ C = [M_w D_v/p_v R][E(T_w)/T_w] \approx 2.1 \times
10^{-8} \text{ m}^2 \text{s}^{-1} \right] \), the integration reveals the
time \( \tau \) necessary for the complete evaporation of
the droplet of initial radius \( r_d \):  

\[
\tau = \frac{r_d^2}{2C}.
\]

(3)

Because of the large relative speeds between the air
and the hot wire, the evaporation time is slightly
smaller because of “ventilation,” or advection of the
vapor field away from the droplet by the flow. The
Reynolds number–dependent ventilation coefficient
(e.g., Pruppacher and Klett 1997) does not exceed 1.5
for our flow conditions. For droplet sizes commonly
observed in this experiment (e.g., 1–10 \( \mu \text{m} \)) our analysis
suggests that evaporation times are approximately
in the range \( 1 \leq \tau \leq 10 \text{ ms} \). Actual voltage spikes resulting
from droplet impact are observed to be on the order of
0.5 ms (cf. Fig. 6). We speculate that the difference is
due to enhanced evaporation due to the increase in
surface area when droplets wet the hot wire. Never-
theless, the analysis provides an upper bound for the
duration of voltage spikes resulting from droplet–hot-wire
collisions.

This section may be summarized by specifying the
fraction of time during which the velocity signal is
influenced by droplet evaporation. The fraction can be
estimated as the ratio of the droplet evaporation time \( \tau \)
and the mean interarrival time \( \tau^* \):

\[
\phi = \frac{\tau}{\tau^*} = \frac{Nd^2_{HW} + d_d}{8C}.
\]

(4)

From Eq. (4) it can be seen that for a constant \( \pi \), \( \phi \)
varies approximately as \( Nd^2_{HW} \), which is proportional
to the liquid water content. It follows, therefore, that
in order to maximize the fraction of useful turbulent
velocity signal from a given hot-wire system, the product
LWC \( \times \pi \) should be minimized.

e. Hot-wire measurements and despiking method

To describe and test the despiking method, we choose
flow and cloud conditions similar to those that
would likely be encountered with low-true-airspeed
cloud research platforms (see section 3). Specifically,
we begin with flow conditions for state 110, with a mean
flow of \( \pi = 9 \text{ m s}^{-1} \) and a mean LWC \( = 0.8 \text{ g m}^{-3} \). The complete time series is 30 s long. The first 12 s were
without droplets; for the last 18 s the spray was added.

Figures 5a–c show the time series of the calibrated
hot-wire signal \( u_{HW} \), the LWC, and the first time derivative
\( a_{HW} = \partial_t u_{HW} \), respectively. Two subsequences labeled
“Part I” and “Part II” are used for further comparison
of drop-free and cloudy conditions. The spikes of the
impacting droplets are most evident in the time series of
\( a_{HW} \) (cf. Fig. 5c).

A typical signal of a droplet spike (cf. spike in the
dashed box in Fig. 5c) is enlarged in Fig. 6. The signal
has a duration of approximately 0.5 ms (five samples);
the amplitude change of \( \Delta u = 20 \text{ m s}^{-1} \) corresponds to
an acceleration of nearly \( 10^5 \text{ m s}^{-2} \), which is about one
order of magnitude higher than the maximum values
observed for the drop-free flow. Therefore, the spikes
can be clearly distinguished from natural turbulence
and a threshold can be defined. The signal during the
droplet impact is then linearly interpolated for a dura-
tion of five samples (cf. dashed line in Fig. 6).

To derive a criterion for the threshold, PDFs of \( u_{HW} \)
and \( a_{HW} \) are calculated and depicted in a semilogarith-
mic plot in Fig. 7. For smaller values, \( u_{HW} \) can be well
approximated with a Gaussian fit whereas the wings of
\( a_{HW} \) are closer to an exponential curve, in agreement
with theory (Frisch 1995). For positive velocities larger
than around 6 m s\(^{-1}\) an increased probability of \( u_{HW} \)
is found because of the spikes. For the derivative \( a_{HW} \) this
effect is symmetric (cf. Fig. 6), and the influence of
the spikes appears as a sharp change in the slope, which is

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 clarified by the dashed lines. This slope change is used to define the threshold \(a_t\) for the despiking algorithm. For this case, \(a_t = 1.5 \times 10^4\ \text{m s}^{-2}\) is chosen.

To illustrate the effectiveness of this simple despiking algorithm, power spectra \(F(k)\) are calculated as a function of the nondimensional parameter \(k\eta\) and shown in Fig. 8, where \(k\) is the wavenumber and \(\eta\) is the Kolmogorov microscale. The spectra are calculated for Part I (drop free) and Part II (raw signal and despiked signal) individually. In general all three spectra follow a \(-5/3\) slope and drop off at around \(k\eta = 0.05\), where dissipation becomes effective. However, it can be clearly seen that the spectrum of the data including the spikes drops off much less rapidly than for the drop-free case (Part I). This effect is significantly decreased by the despiking algorithm. For \(k\eta < 0.03\), there is no difference between the spectra including drops and the despiked spectra.

f. Hot-wire measurements for three different flow states

To confirm the utility of the despiking algorithm over a broad range of cloud conditions, it is tested for the two additional wind tunnel flow states described in section 2a. The mean parameters for all three flow cases are summarized in Table 1. For this investigation the setup was slightly changed, resulting in 20% increased mean flow velocities compared with the calibration (cf. Fig. 2). With the total number of detected spikes \(N_{\text{tot}}\) and the total integration time \(T_i\), the droplet number concentration \(N_{\text{HW}} = N_{\text{tot}}a_T T_i\) can be estimated and compared with the concentration derived from FSSP data \(N_{\text{FSSP}}\). The results are also included in Table 1. For the two cases with higher flow rates (110 and 111), the \(N_{\text{HW}}\) is about 20%–25% lower than the concentration observed from FSSP measurements. There are two possible explanations for this disagreement. First, the collision efficiency between the hot wire and droplets is smaller than one and, second, the signal of small droplets is too low and therefore is interpreted as natural turbulence. The latter argument is supported by the fact that the spectrum of the despiked data lies above the spectrum of the drop-free data. For the low flow case (010), the hot wire “detected” 5 times more droplets than counted with the M-Fast FSSP. In this case, the definition of the threshold was difficult and also high accelerations in the drop-free part were interpreted as droplet spikes. Here, the despiking algorithm reduces natural variance and consequently the spec-
trum of the despiked data is below the spectrum of the drop-free data over a wide frequency range. On the one hand, a lot of droplet spikes would remain in the time series when increasing the threshold; therefore, a compromise had to be found. On the other hand, as described in section 2c, the M-Fast FSSP was near saturation and coincidence counts led to an underestimation of $N_{\text{FSSP}}$.

Fig. 6. A 3-ms-long subsequence of the data shown in Fig. 5 (cf. dashed box) indicating the signature (a) of a striking droplet and (b) in the first derivative. A typical spike due to droplet impact lasted 4–5 samples (0.4–0.5 ms).

Fig. 7. PDFs of $u_{\text{HW}}$ and $a_{\text{HW}}$. In the PDF, the threshold for the despiking algorithm $a_t$ is included.
The ratio \( \phi' \) in Table 1 is equal to Eq. (4), but the factor \( N d_3^2(d_{1w} + d_o) \) is approximated by (LWC) \((4/3 \pi p_m)^{-1}\). The direct measured ratio \( \phi_m = N_{tot} \tau_m / \tau_i \) is the ratio between the total time affected by droplet strikes and the integration time with \( \tau_m = 0.5 \text{ ms} \) as the mean observed evaporation time (e.g., the observed length of the voltage spikes due to droplet impact).

In Fig. 9, the power spectral densities (PSDs) \( F(k\eta) \) (hereafter called “spectra”) for all three datasets are shown as a function of \( k\eta \). The spectra of the three

![Fig. 8. PSD functions. A \((k\eta)^{-2/3}\) fit is included as a reference for inertial subrange behavior.](image)

![Fig. 9. PSD functions of all three flow cases. A \((k\eta)^{-2/3}\) fit is included as a reference for inertial subrange behavior. The PSD of set 111 is shifted by a factor of 100, whereas the PSD of set 010 is shifted by a factor of 0.01 for better presentation.](image)
cases are vertically shifted for clearer presentation. For the high flow case (111), nearly no differences can be found between the spectrum of the data including droplets and the despiked data. The spectrum follows a $-5/3$ slope for inertial subrange behavior over a range of nearly 2 decades and starts to drop off at $k\eta = 10^{-3}$ because of the influence of dissipation. Most obvious is the effect of despiking for the low flow case (010) where the spectrum of the droplet-free part drops off significantly at $k\eta = 10^{-1}$, whereas the spectrum of the data including droplets is contaminated at dissipation scales. However, for this case all 3 spectra exhibit much more scatter than observed for the other 2 cases, and the slope in the inertial subrange is slightly steeper than $-5/3$. The spectra of the despiked and drop-free data agree at least qualitatively.

The first 4 statistical moments are calculated for the hot-wire signal and the central difference $\Delta HW = (HW_{i+1} - HW_{i-1})/2$ before and after the despiking algorithm was applied. All moments are summarized for all three datasets in Table 2. The first moment (e.g., the mean value $\mu$) is not influenced by droplet impacts. The mean values differ slightly from the values given in Table 1 since the moments are estimated from the second part (including droplets) of the record only. For higher moments the influence of the despiking algorithm becomes more obvious. In particular, for the kurtosis of the hot-wire signal of set “010,” the despiking leads to a reduction from $K = 8$ to $K = 3$, which is the theoretical value for a Gaussian distribution, which illustrates the efficiency of the despiking algorithm.

Figure 10 shows the time series of the despiked data and the removed spikes (shifted for a better presentation). For set 010, the despiked data still include a few spikes due to coincidences. If the time between two spikes is too short, the linear interpolation fails and ends within the following spike. Since the LWC and the droplet number concentration for set 010 are quite unrealistic for most atmospheric cloud types, we use the despiking algorithm without taking coincidence into account. Compared to Fig. 5 for set “110,” the onset of the spray can hardly be detected in the despiked data in Fig. 10.

### Table 2. First four statistical moments (mean $\mu$, variance $\sigma^2$, skewness $S$, and kurtosis $K$) of the calibrated hot-wire signal $HW$, the central difference $\Delta HW$, the despiked hot-wire signal $HW_{des}$, and the central difference of the despiked signal $\Delta HW_{des}$. 

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3. First field data

An HWA of the same type as used for the wind tunnel investigations was attached to the outrigger of the helicopter-borne version of ACTOS. ACTOS is an autonomous payload with turbulence sensors and several devices that measure cloud microphysical and aerosol properties. The payload is additionally equipped with a navigation unit, a real-time data acquisition system, and a power supply. An overview of a former version of ACTOS can be found in Siebert et al. (2003, 2006b), where ACTOS was carried by a tethered balloon. During a field experiment in April 2005, ACTOS was deployed beneath a helicopter, carried as external cargo from a 140-m-long rope (Siebert et al. 2006a). ACTOS was dipped into cumulus clouds while the helicopter remained outside. The true airspeed was around 15 m s$^{-1}$ (similar to the high flow conditions in the wind tunnel), which is sufficient to avoid the influence of the helicopter downwash. The low TAS of a helicopter compared to the high TAS of typical research aircraft protects the hot wire from being destroyed by impacting droplets, and also reduces $\phi$ by nearly a factor of 10 [see Eq. (4)].

Unfortunately, electronic noise reduced the amount of useful HWA data from this experiment. Furthermore, most flights were performed at cloud tops of continental clouds with high LWC and high droplet concentrations. According to the discussion at the end of section 2a, these conditions are more difficult for the despiking analysis. A short sample of 35-s duration...
from a flight conducted on 24 April 2005 was chosen to investigate the capabilities of an HWA in atmospheric clouds. The sample was taken at a height of around 1700 m with a mean static temperature of 7°C and a mean TAS of 16 m s⁻¹. The time series of the LWC as cloud indicator, the horizontal wind velocity measured with an ultrasonic anemometer (Gill Solent HS; see Siebert and Muschinski 2001), and the horizontal wind velocity measured with the HWA are shown in Fig. 11. For this experiment the sampling frequency of the HWA was 2 kHz. The HWA was calibrated against the sonic measurements (here a polynomial of second order was used). The 17-s-long cloud penetration is characterized by a low but variable LWC with a maximum of 0.2 g m⁻³. The wind velocity data from the sonic anemometer and hot wire were not corrected for attitude or motion of the ACTOS payload since in this study only small-scale features are of interest. In Fig. 11 the time series of the velocity data are shifted relative to each other by ±1 m s⁻¹. In the upper curve the spikes due to droplets can be clearly seen. A few spikes in the despiked data (lower panel) result from coincidences; that is, the time between two droplets was shorter than the time of a typical droplet spike. For this case the interpolation creates a new spike even if both droplets have been correctly detected. However, this problem occurred much more often in real clouds than in the wind tunnel, even with similar droplet number concentrations and LWC, indicating that droplet clustering is more pronounced in natural clouds.

In Fig. 12 the spectra of the horizontal velocity measured with the sonic anemometer (sampling frequency \( f_s = 100 \) Hz) and the hot wire are shown. The temporal resolution of the hot-wire data was reduced from 2 kHz to 400 Hz by calculating nonoverlapping block averages to reduce high-frequency noise (after applying the despiking algorithm). The spectra were calculated over the complete 35-s-long record, including the cloud data. For frequencies below 10 Hz, all 3 spectra agree well but have a slope slightly below \(-5/3\). For higher frequencies, the raw hot-wire spectrum begins to flatten whereas the sonic and despiked data show a similar behavior. Between 10 and 40 Hz both spectra begin to flatten but the despiked hot-wire spectrum decreases again with a nearly constant slope.

4. Discussion and summary

We have described HWA measurements made in a small wind tunnel at maximum flow speeds ranging from 4.2 to 13.3 m s⁻¹ and \( 0.47 \leq \text{LWC} \leq 2.50 \) g m⁻³. The resolution was close to the Kolmogorov dissipation scale. At these flow speeds, an HWA with a wire diameter of 5 μm was not destroyed by the impacting
droplets. For LWC < 1 g m$^{-3}$, the fraction of the hot-wire signal influenced by spikes due to droplet impacts was small ($\phi < 0.01$). The power spectrum of a 10-s-long record including the spikes compared well with the spectrum of a drop-free record with the same flow characteristics. Removing the spikes did not change the spectral behavior significantly. At lower flow speed and therefore increased droplet number concentration (and

![Graph 1](image1.png)

**Fig. 11.** (top) Time series of LWC and (bottom) velocity fluctuations measured with the sonic and hot wire. The sonic measurements are used as a reference; the raw and despiked hot-wire measurements are shifted vertically ±1 m s$^{-1}$ for better presentation.

![Graph 2](image2.png)

**Fig. 12.** Power spectra of sonic and hot-wire data as presented in Fig. 11. Nonoverlapping block averages were used to reduce the frequency of the hot-wire data from 2 kHz to 400 Hz. A $-5/3$ slope is included as a reference for inertial subrange behavior.
increased LWC), the power spectrum begins to flatten at wavelengths about 10 times the Kolmogorov scale. This flattening could be reduced after despiking. At high LWC of about 2.5 g m\(^{-3}\), the despiking algorithm becomes less effective since coincidence becomes more pronounced. Furthermore, the ratio of the time that is affected by spikes and the total integration time increases to \(\phi \approx 0.2\) (the “010” case). However, even under these conditions, the despiking algorithm is effective and the flattening of the spectrum could be reduced significantly.

Initial validation of the technique was accomplished by flying an HWA on the helicopter-borne ACTOS in cumulus clouds. The despiked spectra compare reasonably well with the lower-resolution data from the sonic anemometer. Future measurements can be improved by sampling at a higher rate and by improving the noise shielding in the data acquisition system.

The experiments confirm that hot-wire anemometry is most useful when the fraction \(\phi\) of signal contaminated by droplets is minimized. This fraction varies approximately as \(\phi \propto \text{LWC} \times \varpi\), making it clear that the true airspeed of the measurement platform is an important consideration. We have confirmed that speeds typical for a helicopter system (<20 m s\(^{-1}\)) are acceptable, given realistic cloud liquid water contents. It seems unlikely, however, that the technique would work reliably on a high-speed aircraft platform.

Besides the density of droplet spikes, it is also necessary to consider the amplitude of the spikes so as to determine whether they can be distinguished from the turbulence itself. For the velocity derivative method described here it is necessary to compare the “acceleration” due to a droplet impact to the typical acceleration (velocity increment) measured by the hot wire. Empirically, we found the droplet acceleration spikes to be on the order of 10\(^4\) m s\(^{-2}\); presumably, this depends on the exact configuration of the chosen hot-wire system.

Within the inertial subrange, the second-order structure function \(D(t') = [(u(t + t') - u(t'))^2]\) with a given time increment \(t'\) is related to the energy dissipation rate as (Kaimal and Finnigan 1994)

\[
\epsilon \equiv \frac{1}{2} \frac{[D(t')]^{3/2}}{t' \varpi} \approx \frac{a_t^3 \Delta t^2}{\varpi} \approx 10^2 \text{ m}^2 \text{ s}^{-3}
\]

With calculating a critical \(D_s(t')\) at the time increment \(\Delta t = 1/f_s = 10^{-3}\) s, we get \(D_s(t') \sim (a_t \Delta t)^2\), where \(a_t \approx 10^7\) m s\(^{-3}\) is the critical acceleration for the case with high flow velocity (\(\varpi = 16.5\) m s\(^{-1}\)). Therefore, we may estimate that for

\[
\epsilon \approx \frac{\left(\frac{1}{2}\right)^{3/2} a_t^3 \Delta t^2}{\varpi} \approx 10^2 \text{ m}^2 \text{ s}^{-3}
\]

droplet spikes would no longer be distinguishable from turbulent accelerations, making the despiking algorithm unusable. This high critical value for \(\epsilon\) is quite unrealistic even for local areas of deep convective cumulus clouds. In this case, however, we would speculate that the droplet spikes have little influence on the turbulence statistics and energy spectra.

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