Acoustic Doppler Velocimeter Performance in a Laboratory Flume

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Abstract. This report summarizes laboratory tests of a Nortek Acoustic Doppler Velocimeter, designed to understand its performance depending on how it is setup for data collection. We learn that the Velocimeter is able to collect data at sample rates up to 50 Hz without impairing data quality. With tests using maximum velocity settings of 0.3 and 1.0 m/s, we find that 0.3 m/s produces more spikes but a lower noise level overall, particularly after spikes are removed. With tests using different sample volumes, we learn that the lowest noise comes from the largest volume and that the smallest volume works acceptably only at relatively slow sample rates.

Introduction

This report summarizes results of tests carried out at the National Sediment Laboratory in Oxford Mississippi. Data were collected with a new 10 MHz Nortek Acoustic Doppler Velocimeter. This instrument is an improved version of instruments that have been commercially available since 1994.

Data collection consisted of a series of test runs, each with roughly the same duration (about 2 minutes), but with varying setup parameters. Table 1 lists the parameters that were varied.

Table 1. Parameters varied during the Velocimeter tests.

Parameter	***Settings used***
Sample rate	1, 5, 25, 50 and 100 Hz
Maximum velocity	0.3 and 1.0 m/s
Sample volume	3, 6 and 9 mm.
Flow conditions	Smooth and turbulent

The *sample rate* is the rate at which data are reported. A Velocimeter pings at a rate considerably faster than 100 Hz, and internally averages multiple samples to produce each output sample. The total number of internal samples collected every second is independent of the sample rate.

The *maximum velocity* setting is in fact a nominal value that determines the velocity range within which a Velocimeter can obtain good data. Because of the Velocimeter's beam geometry, the maximum vertical velocity is smaller than the nominal maximum velocity, and the maximum horizontal velocity is larger. In these experiments, the maximum horizontal velocity was always comfortably inside the limits imposed by the velocity range.

Table 2. Maximum horizontal and vertical velocity vs. nominal velocity range.

Nominal velocity range	***Max. horizontal velocity***	***Max. vertical velocity***
0.3 m/s	1.2 m/s	0.3 m/s
1.0 m/s	3.0 m/s	0.75 m/s

The *sample volume* is a setting that controls the vertical extent of the volume within which velocity is measured. The name "sample volume" as used here is actually a bit of a misnomer—it is really just the vertical extent of the sample volume. This actual sample volume can be described roughly as a cylinder with diameter around 6 mm and a height of 3, 6 or 9 mm. Table 3 gives the volume associated with each setting.

Table 3. Actual measurement volume as a function of sample volume setting.

Setting	***Volume***
3 mm	85 mm^3
6 mm	170 mm^3
9 mm	250 mm^3

The different *flow conditions* were obtained by placing the probe in different places in the flume. The level of turbulence can be seen in Figures 5 and 6, later in this report.

Instrumental Uncertainties

Figure 1 presents mean velocities as a function of sample rate. Each mean value was an average of observed velocity over the 120-s duration of the run. The means (blue) and standard deviations (red) plotted in Figure 1 were computed using all available runs and all available sample volumes at each given sample rate.

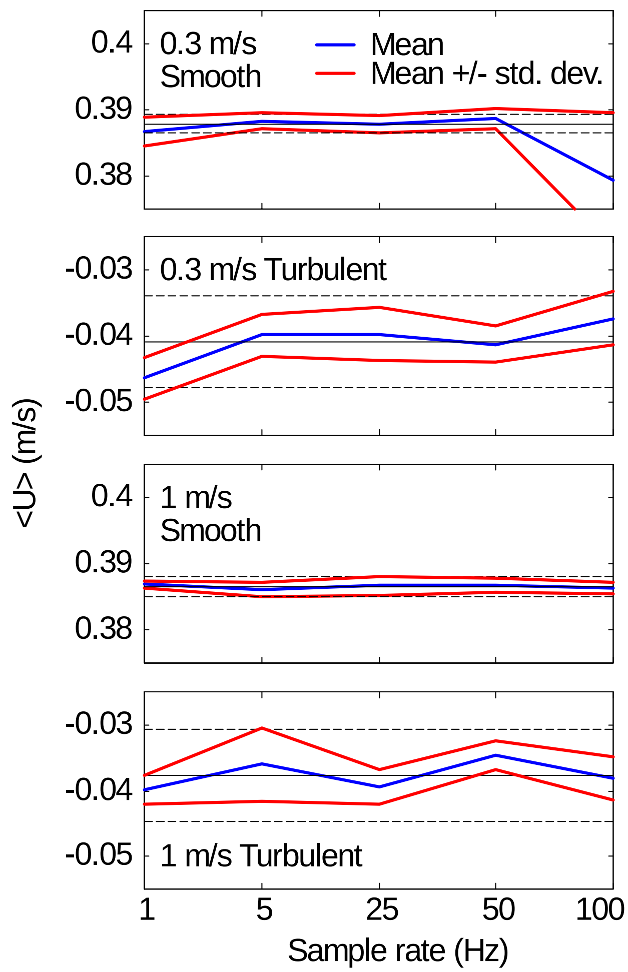

Figure 1. Mean velocity vs. sample rate.

The solid black line was population mean, or the average of all the mean velocities, excluding runs at 100 Hz. The dashed black lines represent error bounds based on the predicted uncertainty of the mean velocities. Because flow fluctuations were larger in the turbulent flow than in the smooth flow, the uncertainty of the mean velocities is larger in the turbulent flow than in the smooth flow. This is reflected in the wider error bounds shown by the dashed lines in Figure 1. Appendix 1 describes how the error bounds were computed.

As long as mean velocities stay within the error bounds, or do not stray too far out of the error bounds, one cannot say with any certainty that they are statistically different from the population mean. The only measurements that were significantly outside the error bounds were the measurements using 0.3 m/s velocity range at 100 Hz. The measurements that were the source of bias were the ones using the 3 mm sample volume.

Figure 2 shows how mean velocity varies with sample volume. The only substantial deviations from the population means occur with 3 mm sample volume at sample rates of 100 Hz.

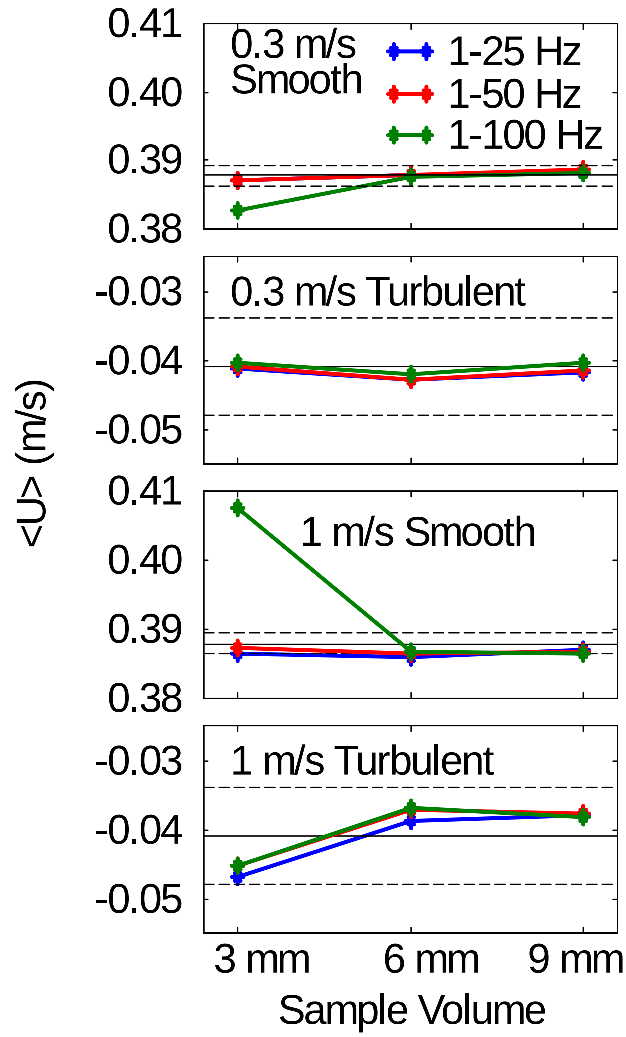

Figure 2. Mean velocity vs. sample volume.

Figure 3 shows how standard deviation varies with sample rate. Standard deviation should increase with sample rate. The amount of increase depends on the spectrum. If the spectrum is flat, doubling the sample rate will increase the standard deviation by about 40% (see equation 2 in Appendix B). If the spectrum is red (as in the inertial subrange—see Appendix B), the increase will be less than 40%. It is clear in Figure 3 that the standard deviation increases by substantially more than 40% between 50 and 100 Hz. This tells us that 100 Hz sampling increases the instrumental measurement uncertainty relative to slower sample rates.

Figure 4 shows how standard deviations vary with sample volume. The standard deviation is relatively constant for all sample volumes and sample rates except the smallest sample volume (3 mm) and the fastest sample rate (100 Hz). This is consistent with what we learned from Figure 3, but it tells us that 100 Hz sampling introduces little additional noise as long as the sample volume is 6 or 9 mm. The fact that the standard deviation varies little with sample rate (other than the effects of the small sample volume) is consistent with the fact that the spectra are all red—most of the measurement variance is at lower frequencies.

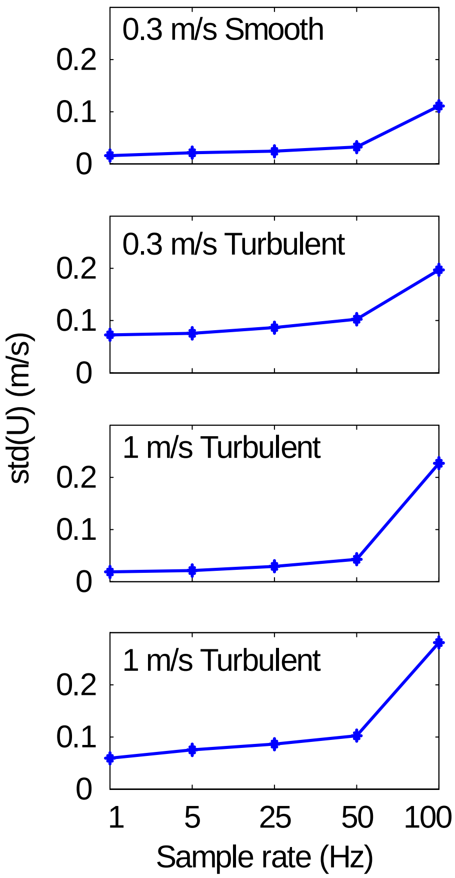

Figure 3. Standard deviation vs. sample rate.

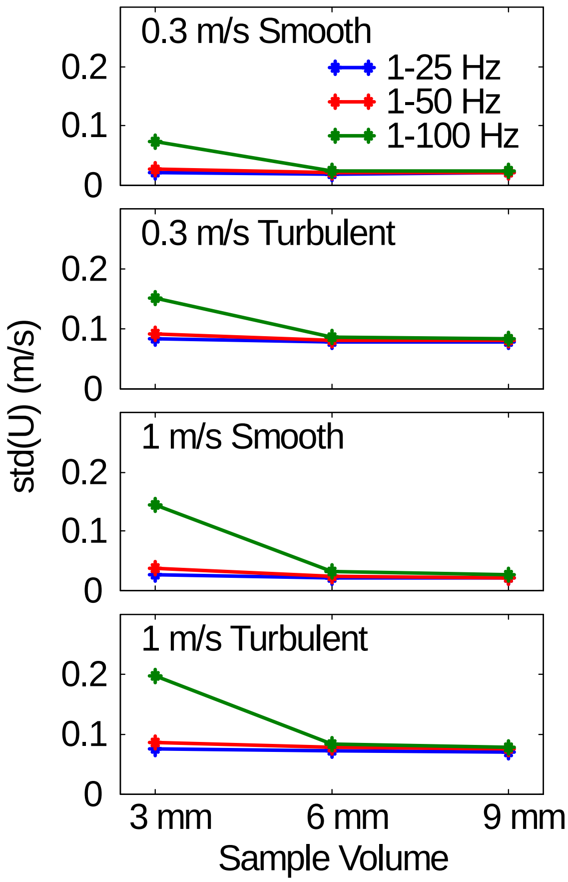

Figure 4. Standard deviations vs. sample volume.

Figures 5 and 6 show velocity spectra. These spectra tell us how the instrument's noise level varies with setup. Turbulent flow appears to increase the noise level—it also causes a corresponding drop in signal correlation (not shown here). Sampling at 100 Hz increases the instrumental noise for all conditions, although the noise has the least effect in turbulent flow in which the flow fluctuations remain largely above the instrumental noise. Sampling with a 3 mm measurement volume substantially increases noise level. A 6 mm sample volume appears to increase the noise level by about a factor of 2, which means that the corresponding noise standard deviation increases by about 40%. The spectral peaks at 12 and 20 Hz are not instrumental, but rather are associated with the flume itself.

The fact that the noise floor is nearly the same for 25 and 50 Hz sampling tells us that 50 Hz sampling does not add instrumental noise. Another way to say this is that sampling at 50 Hz, then averaging the data down to 25 Hz will produce data of equal quality to data that were originally sampled at 25 Hz.

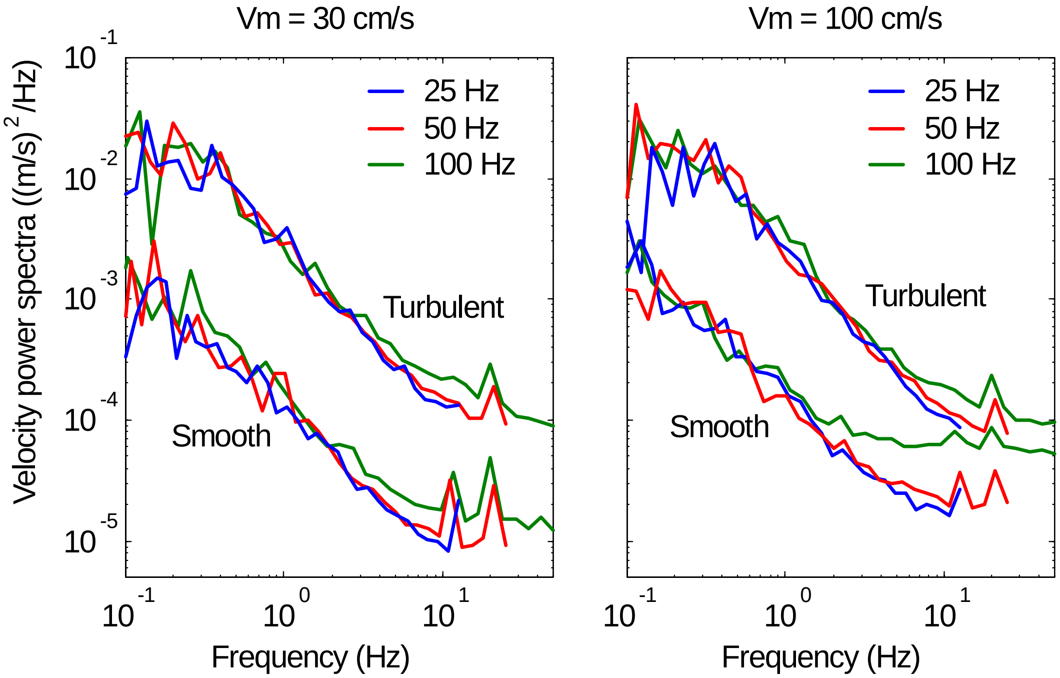

Figure 5. Velocity spectra using different sample rates. All spectra use a sample volume of 9 mm.

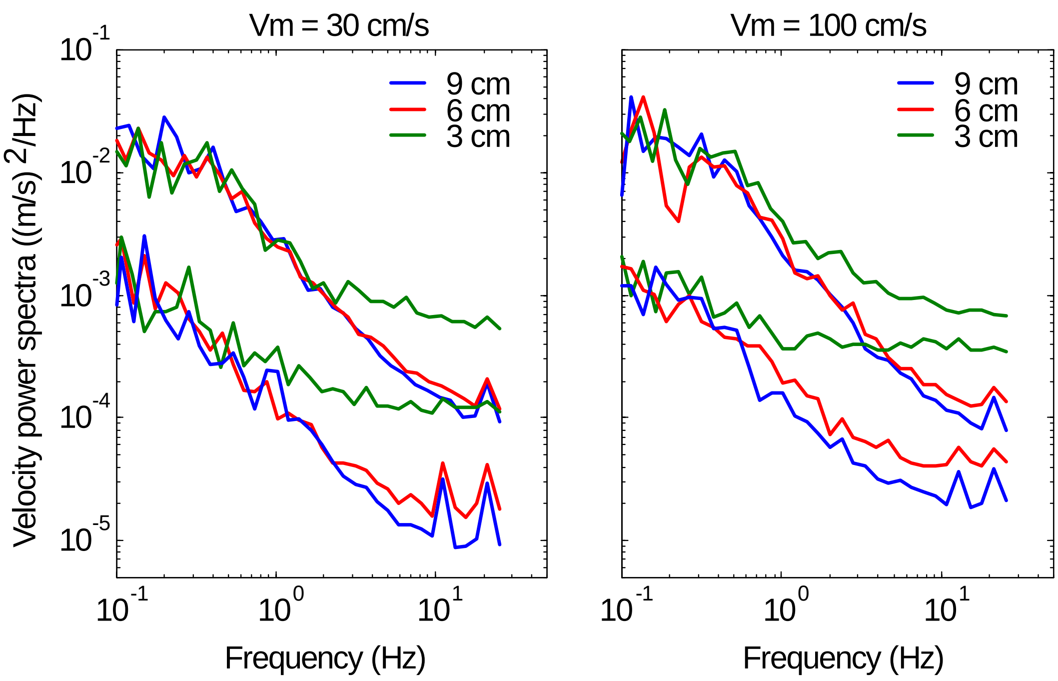

Figure 6. Velocity spectra for different sample volumes. All spectra use a sample rate of 50 Hz.

Velocity Spikes

Velocimeters all produce data with spikes. Spikes are easily identified by eye, and can be identified automatically by evaluation of the first differences (the differences between adjacent samples, which is the discrete equivalent of the first derivative). Spikes were identified in this

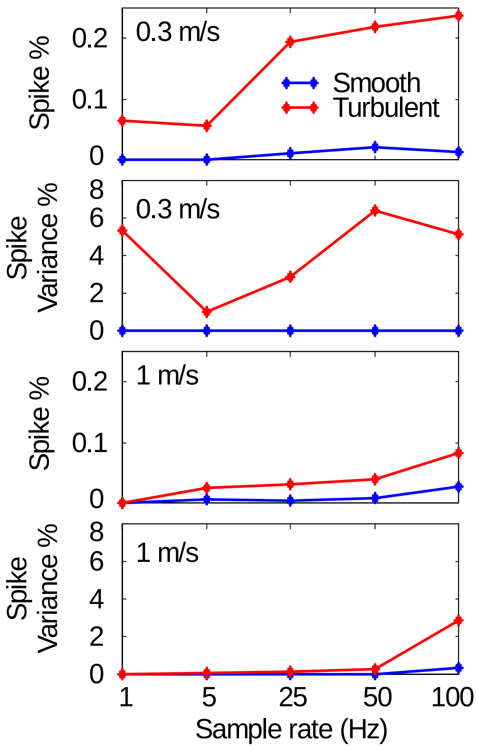

Figure 7. Spike statistics vs. sample rate.

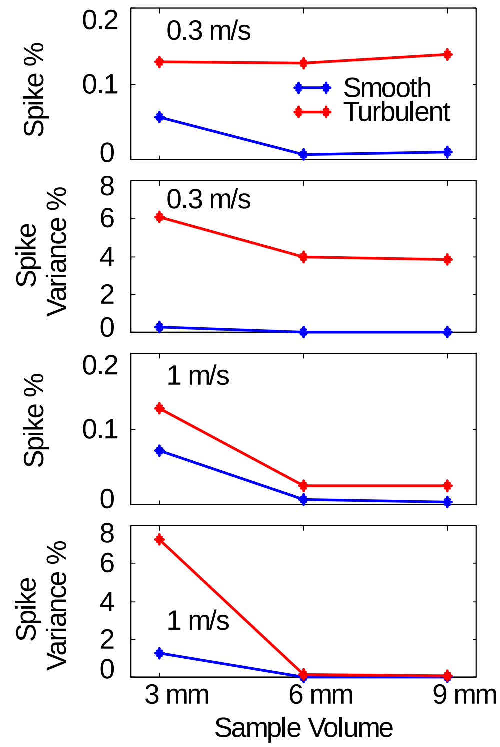

Figure 8. Spike statistics vs. sample volume.

data by finding first differences that departed from mean first differences by more than 5 standard deviations (this follows a procedure used by Alex Hay, personal communication).

The level of spiking is quantified below in terms of the number of points, and as a fraction of the total measurement variance. If spikes are small, they may not change the variance noticeably, but large spikes can change the variance a lot. Spikes have a white spectrum, so spikes just increase the noise level.

Figures 7 and 8 show how different setups influence the level of spiking. The worst spiking occurred at 100 Hz and 3 mm sample volume. The 3 mm sample volume data were excluded from the Figure 7 and 100 Hz data were excluded from Figure 8. Data using 6 or 9 mm sample volumes, and data using sample rates of 50 Hz or slower never had more than 0.23% data spikes. As long as the level of spiking remained a small fraction of 1%, the large spikes that contributed the most variance were easily identified and removed.

Turbulent flow increases spiking at all sample rates and sample volumes. Spiking increases with fast sample rates and with small sample volumes, and the combination of fast sampling (100 Hz) and small sample volume (3 mm) appears to make the data nearly unusable.

These results tell us that increasing the velocity range can reduce spiking. While a larger velocity range is normally associated with a lower noise level, spikes appear to raise the noise level. Figure 9 compares data taken at 25 Hz sample rate in smooth and turbulent flow with 0.3 and 1.0 m/s velocity ranges. In smooth flow, the 0.3 m/s velocity range data has a lower noise level than the 1.0 m/s velocity range data. In turbulent flow, spikes account for 0.2% of the 0.3 m/s velocity range data and only 0.01% of the 1.0 m/s velocity range data. even after spike removal, the noise level of the 0.3 m/s velocity range data is higher.

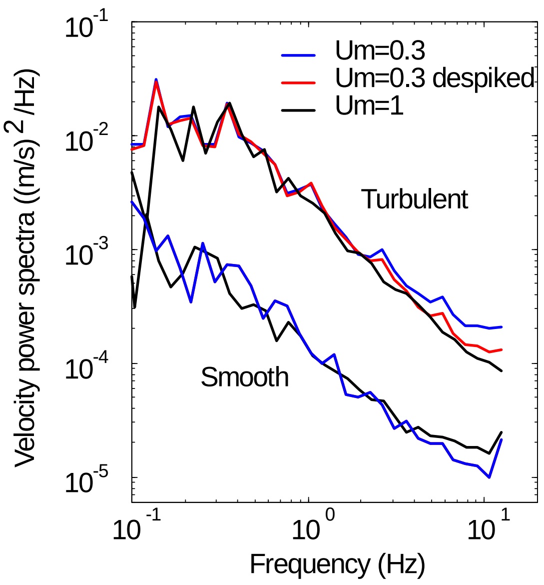

Figure 9. The effects of spiking on noise level. The bottom spectra are in smooth flow, and spiking is not a factor. In smooth flow, the smaller velocity range also produces the lower noise level.

The upper spectra are in turbulent flow, and here spiking is a factor. The 1.0 m/s velocity range is nearly free of spikes (0.01% of the data have spikes). The 0.3 m/s velocity range is about 0.2% spikes. After removal of the spikes, the noise level of the 0.3 m/s velocity range data still has a slightly higher noise level.

Conclusions

1) 25 and 50 Hz sampling produce the same noise level. 100 Hz sampling appears to increase noise substantially, but can produce noise levels that fall below the turbulent spectra in energetic turbulence.
2) 6 mm sample volume roughly doubles the noise level obtained with 9 mm sample volume
3) 3 mm sample volume produces a substantially higher noise level, but the added noise is insignificant at sample rates of 1 and 5 Hz. The higher noise level may also fall below the turbulent spectra when sampled at 25 Hz.
4) 3 mm sample volume appears not to bias the mean velocity unless sampling is rapid (100 Hz).
5) 1.0 m/s max velocity roughly doubles the instrumental noise level compared with 0.3 m/s max velocity.
6) 1.0 m/s max velocity produces far less spiking than 0.3 m/s sampling. When spiking is a factor, increasing the velocity range can reduce spiking and reduce the noise level as well.
7) Spiking does not appear to be related to the current speed, but it is strongly related to the turbulence level.
8) Increasing the sample rate increases spiking. Increasing turbulence increases spiking. Reducing the sample volume increases spiking. Reducing the maximum velocity increases spiking. The biggest factors influencing spiking appear to be turbulence followed by maximum velocity.

Appendix A. Predicted standard deviation of mean velocity.

The mean value of a fluctuating velocity will vary with each realization. The size of this variation can be estimated as a function of the amplitude and the spectrum of the fluctuations and the duration over which the average is taken. If each individual estimate is independent and unbiased, then the standard deviation of the mean velocity is related to standard deviation of the individual estimates according to:

$$\sigma(|U|) = \sigma(U)/n^{1/2} \tag{1}$$

where $\sigma(|U|)$ is the standard deviation of the estimates of mean velocity $|U|$, $\sigma(U)$ is the standard deviation of individual velocity estimates and n is the number of individual estimates used to obtain the mean. Figures 5 and 6 show that the spectra are generally flat at frequencies a bit below around 1 Hz, and that they fall off rapidly at higher frequencies. This means that it takes around 1 s to obtain an independent estimate of velocity, because the dominant fluctuations that produce velocity standard deviation occur on time scales of 1 s or longer. This gives us n=120 independent estimates in a 2-minute time series. Table 4 gives us estimated standard deviations for mean velocities in smooth and turbulent flows.

Table 4. Predicted standard deviation of 2-minute averages of fluctuating velocities, assuming that a new independent estimate can be obtained every 1 s. $\sigma(U)$ is the standard deviation of the individual velocity measurements, and $\sigma(|U|)$is the standard deviation of a set of 2-minute mean velocities.

Flow	***σ(U)***	***σ(|U|)***
Smooth	15 mm/s	1.3 mm/s
Turbulent	80 mm/s	7 mm/s

Appendix B. Turbulent velocity spectra and noise level

Figure 10 shows an example spectrum taken from this data set. The run was chosen for its particularly high noise level to illustrate the parts of the spectrum. The spectrum is a log-log plot, created by log averaging. Log averaging uses more averaging at higher frequencies than at lower, with the intent to keep the number of data points plotted per decade roughly constant. One consequence is that the spectrum tends to be smoother at high frequencies than at low frequencies because the higher frequencies are averages of more data points.

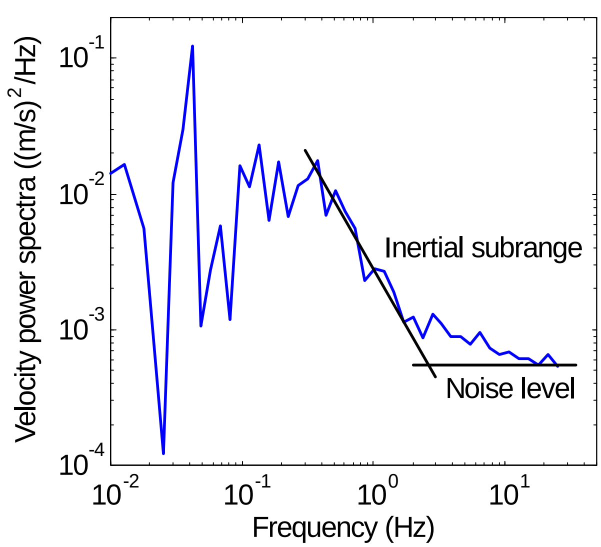

Figure 10. The different parts of a typical velocity spectrum.

Turbulent spectra can be identified by an inertial subrange, which falls with a -5/3 slope (in log-log graphs). The inertial subrange is visible when it rises above the Velocimeter's noise floor. Instrumental noise in Velocimeters is white—it has a constant level independent of frequency. Given the noise level and the sample rate, one can compute the short-term uncertainty using the equation

$$\sigma(U) = (F_s S_n/2)^{1/2} \qquad (2)$$

Where F_s is the sample rate or frequency, S_n is the noise spectrum. Given the noise level in Figure 10 (5×10^{-4} $m^2/s^2/Hz$) and a sample rate of 50 Hz, equation (2) would predict a short-term uncertainty of 40 mm/s. Equation (2) is a close relative of equation (1).