

FlowTracker2 Lab ADV: SNR, Sampling Rate and Velocity Range Effects on Data

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I. INTRODUCTION

The FlowTracker2[®] Handheld ADV is an Acoustic Doppler Velocimeter (ADV[®]) that is designed to perform point velocity measurements in water with scientific accuracy. The FlowTracker2 offers ADV performance from a simple handheld interface, allowing rapid data collection without the use of a computer.



Figure 1. The FlowTracker2 Lab ADV probe assembly (left), along with its power and communications cable and power supply.

The FlowTracker2 was launched in 2016 with a number of hardware and software improvements over the original FlowTracker[®], and like its predecessor, it has been widely accepted as a primary tool for wading discharge measurements. In early 2019, SonTek released the FlowTracker2 Lab ADV, enabling a FlowTracker2's probe assembly to be used in environments where a direct connection to a computer is more desirable than using the rugged handheld display, and also providing for faster sampling rates. The hardware components for the FlowTracker2 Lab ADV are shown in Figure 1. The FlowTracker2 probe assembly is capable of sampling at rates of 1, 2, 5, and 10Hz using the FlowTracker2 software (compared to the 2Hz available when using the handheld display). Additionally, options for selecting various velocity ranges are enabled so the user can achieve the best quality data given their experiment conditions. The FlowTracker2 Users' Manual [1] documents in detail the FlowTracker2 principles of operation in both discharge and Lab ADV configurations.

This FlowTracker2 Lab ADV SNR, Sampling Rates and Velocity Ranges Effects on Data Technical Note serves as a primer for pulse-coherent ADV signal processing, explains the importance of choosing the proper sampling rate and velocity range for a given setup, and illustrates how SNR can affect a measurement. Examples of different configurations and the effects on data quality are discussed.

II. FLOWTRACKER2[®] ADV[®]-SPECIFIC SIGNAL PROCESSING

The FlowTracker2 probe is a pulse coherent Acoustic Doppler Velocimeter (ADV[®]). The ADV was invented by SonTek in 1992. An ADV's high single ping accuracy allows for measurements in normally hard-to-measure conditions including turbulence, rapidly changing flows, near boundaries and high shear regimes. Its small physical profile and small sampling volume size allows for a measurement at a specific location that is much more precise than multi-beam single cell or profiling Acoustic Doppler systems. Here, we introduce some background on the pulse coherent method, and the main factors contributing to its data quality. We then discuss the ambiguity velocity and SNR, and how these parameters affect the ADV data.

A. Pulse-coherent Signal Processing Theory

Acoustic Doppler velocity meters can be built to ping using various techniques. Each technique has a range of velocities and conditions over which it works best. The three main techniques include *narrowband* (often called "Incoherent"), *broadband*, and *pulse coherent*. The *narrowband* technique consists of a single monochromatic sound pulse upon which simple signal processing is performed to measure the frequency shift between the sent and reflected pulse. The *broadband* technique pings with multiple repeating sequences of acoustic codes and is able to cover a larger velocity range compared to *narrowband*. The *pulse coherent* technique was first introduced by Lhermitte and Serafin [2] and consists of a sequence of pulse pairs, typically with the time between pulses in a pair much longer than the length of a single pulse. This "coherent" method allows for a high accuracy, low noise velocity calculation based on the phase shift between the two pulses, and works best for resolving fine-scale measurements.

In pulse coherent systems, the phase shift, $\Delta\Phi$, is calculated from the two signals, and is related to Δf , the Doppler Shift, by

$$\Delta f = \Delta\Phi / 2\pi\Delta t,$$

where Δt is the time difference between pings. The actual detection and calculation of $\Delta\Phi$ uses signal processing techniques involving covariance functions. The velocity is then calculated using

$$v = c\Delta f / 2f,$$

where f is the principle frequency of the instrument ($f = 10\text{MHz}$ in the case of the FlowTracker2 ADV probe).

B. Ambiguity Velocity and Wrapping

The phase, Φ , is defined on a 360° (or 0 to 2π) circle for any sinusoidal signal. There is a range of $\Delta\Phi$ where there exists an 'ambiguous' velocity.

Figure 2 depicts different phase shift examples, including an ambiguous phase shift. A maximum velocity measurable corresponds to when $\Delta\Phi$ enters an ambiguous state and is determined by how the ping timing is configured for a given instrument. This maximum velocity (often called "ambiguity velocity") should guide the user in selecting the velocity range in the FlowTracker2 Lab ADV system. If the probe encounters velocities beyond this maximum ambiguity velocity, a phenomenon called "wrapping" will occur.

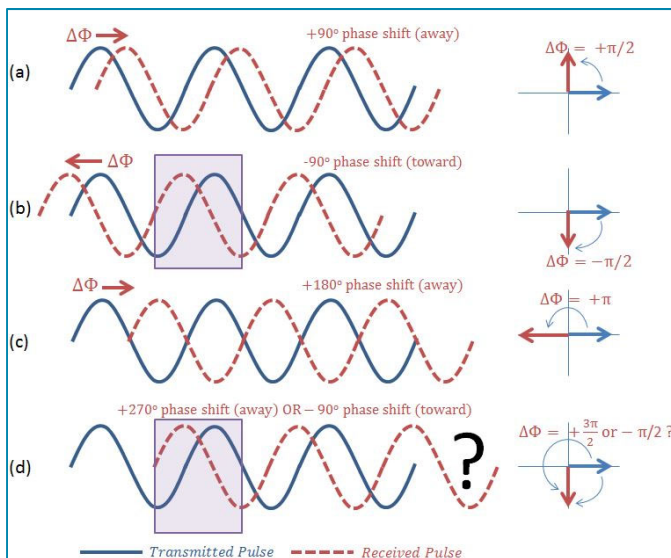


Figure 2. Illustration of phase shift and ambiguity. (a) Phase shift +90 degrees away from original signal. (b) Phase shift -90 degrees toward original signal. (c) Phase shift +180 degrees away from original signal. (d) Phase shift ambiguity showing either a +270 degree shift away or -90 degree shift toward original signal. The grey box outlined in (b) and (d) shows the same perceived phase shift despite a possible reversal in shift direction, resulting in an ambiguity.

The resulting "wrapped" velocity is usually the opposite sign compared to the expected velocity. It is thus critical for a pulse coherent system to be set up to for a certain maximum velocity of the flow in order to get proper velocity measurements.

C. SNR and the Importance of Sufficient Scatterers

All acoustic Doppler systems require a sufficient amount of acoustic scattering material in the water in order to return a proper signal; these systems measure the velocity of the scatterers, and the assumption is made that the scatterers move at the velocity of the water. The variable "SNR," or Signal-to-Noise-Ratio, represents the signal return strength as the acoustic pulses bounce off the scatterers in the water compared to the background noise. As a general guideline, for field applications, the FlowTracker2 will warn users when a low SNR limit of 3dB is reached. Normally at such low values, a

reliable velocity calculation is difficult to achieve. However, with the expanded capabilities of the FT2 Lab ADV, sampling in very low SNR (<3dB) can be possible with the proper settings. Examples of data from extremely low SNR tests in a tow tank are shown in the following sections.

III. FT2 LAB ADV SETUP CHOICES AND IMPACTS ON DATA QUALITY

The FT2 Lab ADV has a variety of different sampling rates and velocity ranges from which to choose, including the unique Auto-Velocity range feature. An explanation of these choices and the impacts on measurement quality is provided in the following sections. All examples of data were obtained in a tow tank at SonTek's facilities. For details on using the FlowTracker2 in a tow tank and its associated terminology, please refer to FlowTracker2 Tow Tank Verification Report [3]. For each tow cart run, the FlowTracker2 probe was pulled by a motorized cart at a fixed speed over a 6m length of the tow tank. Only data in the positive-X direction are used in statistics and analysis to avoid negative velocity biases when the probe moves backwards. In between sets of forward-backward runs, the tank was allowed to settle for 5 minutes for low speed (0.1m/s) runs and 15 minutes for high speed (0.5m/s) runs to allow for the tank water to settle to zero velocities.

A. Choosing a Sampling Rate

In the "Lab ADV" function of the FlowTracker2 Software v1.6 and beyond, the user has a choice to set the Sampling Rate to 1, 2, 5, or 10Hz. Figure 3 shows a screenshot of the choices available in the Sampling Rate drop-down.

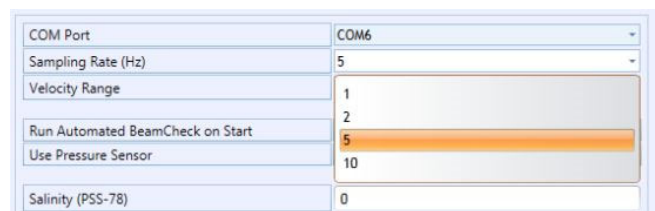


Figure 3. The FlowTracker2 Software Lab ADV dialog showing the sampling rates available.

Generally speaking, faster sampling allows for the resolution of phenomena occurring at smaller time scales at the cost of possibly increasing measurement noise. Figure 4 shows the impact of selecting different sampling rates.

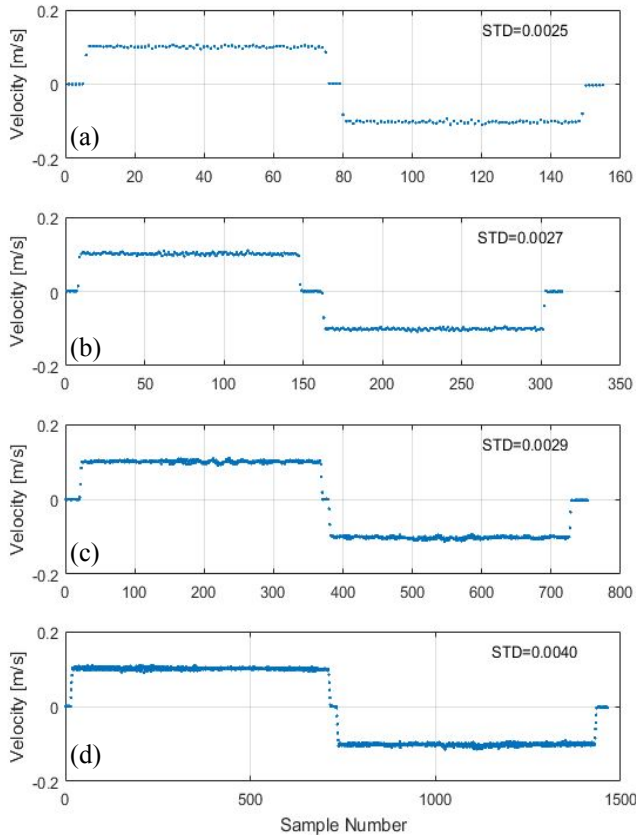


Figure 4. Tow tank runs for various sampling rates. From top to bottom, sampling rates were set at (a) 1Hz, (b) 2Hz, (c) 5Hz, and (d) 10Hz. All runs were performed at a tow cart speed of 0.1m/s with a velocity range set to 10cm/s. The standard deviations [in m/s] of the positive X-direction portion is displayed in the top right of each plot.

All tow tank runs in Figure 4 show forward-backward tow tank run pairs at 0.1m/s with a velocity range selection at the '±10cm/s' range. The average SNR for these runs was 22dB, which provides enough scatterers to give a very reliable signal. The standard deviation (STD) of the positive-X velocity segments only is displayed on the upper right of each figure. Although there is minimal difference in standard deviation among the first three slowest sampling rates, the fastest 10Hz run shows an increased STD, suggesting higher variability in the measurement. In the first three slowest sampling rates, the signal is sufficient to give similar results, and only begins deteriorating at the highest sampling rate.

B. Choosing a Velocity Range

Another critical parameter to set is the velocity range. The different velocity range choices are shown in Table 1 and Table 15-2 of the FlowTracker2 Users' Manual [1]. The velocity range naming convention corresponds to the average expected maximum velocity during the sampling. There is a buffer in the range to accommodate fluctuations of the velocity about that average expected maximum value. For example, for the range of '±10cm/s,' the absolute maximum velocity in the X direction

that can be accommodated is ±40cm/s. Beyond ±40cm/s, the individual velocity samples will begin to wrap and an incorrect velocity value will be reported.

Velocity Range	Absolute max velocity in arbitrary direction in ideal conditions	Absolute max velocity in X direction in ideal conditions	Recommended max velocity in arbitrary direction in ideal conditions	Recommended max velocity in X direction in ideal conditions
Auto	± 112 cm/s	± 448 cm/s	± 60 cm/s	± 200 cm/s
± 10 cm/s	± 10 cm/s	± 40 cm/s	± 3 cm/s	± 10 cm/s
± 20 cm/s	± 14 cm/s	± 52 cm/s	± 7 cm/s	± 20 cm/s
± 50 cm/s	± 27 cm/s	± 108 cm/s	± 15 cm/s	± 50 cm/s
± 100 cm/s	± 55 cm/s	± 220 cm/s	± 30 cm/s	± 100 cm/s
± 200 cm/s	± 112 cm/s	± 448 cm/s	± 60 cm/s	± 200 cm/s

Ideal conditions consist of:

- ideal signal conditions (high SNR, low noise)
- Ideal boundary conditions (no boundaries nearby)
- Ideal temperature and sound speed (18°C and 1475 m/s)
- For X direction velocity – uniform flow in X direction

2D/3D FT2 probe would use the same recommendation with Z velocity maximum same as the arbitrary direction.

Table 1. Velocity range choices available in the FlowTracker2 Lab ADV and their specific maximum velocity specifications.

Care should be taken to select an appropriate velocity range suitable for a specific study such that the average expected maximum value is near the 'Velocity Range' value, and that no individual velocity sample exceeds the absolute maximum velocity in the X-direction for the given range. There may be a temptation to select the largest velocity range setting to cover all possibilities; the problem with this approach is that selecting a larger velocity range will, in general, increase sample noise due to decreasing the resolution of possible values over the given range. Thus, a value should be selected that uses the lowest velocity range possible without exceeding the maximum to give the highest quality data. Figure 5 shows the data time series for tow tank trials performed at the same 0.1m/s spanning all velocity range options, and Table 1 summarizes the effect on the standard deviation. The results from these tow tank runs show the deterioration of the signal due to decreasing the resolution as the velocity range is increased.

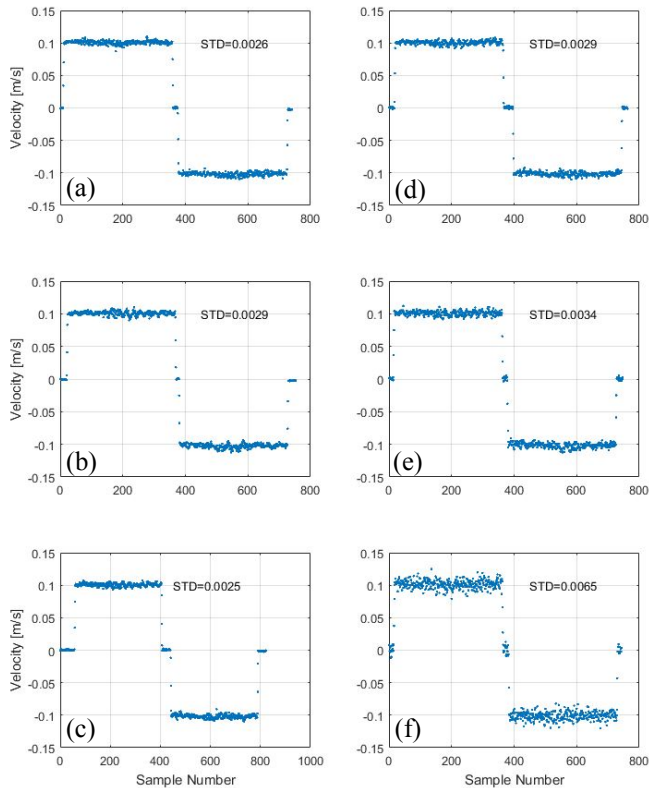


Figure 5. Varying velocity ranges. All runs were performed at 0.1m/s using a sampling rate of 5Hz. Velocity ranges are as follows: (a) Auto, (b) ± 10 cm/s, (c) ± 20 cm/s, (d) ± 50 cm/s, (e) ± 100 cm/s, and (f) ± 200 cm/s. The standard deviations [in m/s] of the positive X-direction portion is displayed in the top right of each plot.

All runs from Figure 5 and Table 2 were performed at a sampling rate of 5Hz. It is evident that as the velocity range is increased, the noisiness or variability of the data increases. In the lower velocity ranges, there is little to no difference among standard deviations due to the high SNR signal overcoming noise and also due to the smaller differences between the actual velocity range cutoffs. Once the highest velocity range is selected (± 200 cm/s), the resolution of the time series is lessened such that the standard deviation increases two-fold from the previous velocity range. It should be noted that this is just one data example, and the actual amount of signal quality loss (in terms of resolution/noise) is variable and depends on many factors, including SNR, sampling rate, and tank noise conditions.

Velocity Range	Mean Velocity	Standard Deviation
Auto	0.1009	0.0026
± 10 cm/s	0.1007	0.0029
± 20 cm/s	0.1007	0.0025
± 50 cm/s	0.1006	0.0029
± 100 cm/s	0.1009	0.0034
± 200 cm/s	0.1018	0.0065

Table 2. Summary of standard deviations for experiments performed in Figure 5.

Users will notice the option for an 'Auto' velocity range setting for all sampling rates except for 10Hz. 'Auto' is the setting that the FlowTracker2 uses when taking a measurement using the

handheld display. When 'Auto' velocity range is selected, the FlowTracker2 probe will dedicate a certain number of pings at the beginning of each sample to estimate the actual velocity and automatically select the appropriate velocity range for that sample. In the example provided in this section (and in most scenarios with favorable water conditions), the 'Auto' range setting will produce data that will be comparable in quality to manually selecting the proper range setting. In the example given in Figure 5 and Table 2, the 'Auto' setting results in a standard deviation comparable to the ± 10 cm/s manual velocity range (and also similar to the ± 20 and ± 50 cm/s ranges). There are certain situations where the manual setting is more desirable, such as low SNR conditions, as shown in the example in the next section. The sampling rate of 10Hz does not have an 'Auto' range choice because at such fast sampling rates, the signal is too severely degraded when some pings are used for the auto range detection rather than for the actual velocity measurement.

As mentioned earlier, if an incorrect velocity range is selected for a given measurement situation, "wrapping" of the velocities will occur, and incorrect velocities will be reported by the probe. Usually, the "wrapped" velocities will be the opposite sign compared to what is expected. Figure 6 shows an example of velocity wrapping, where the tow cart was run at 0.5m/s, and data are recorded using a ± 10 cm/s (top) and ± 20 cm/s (bottom) velocity range setting.

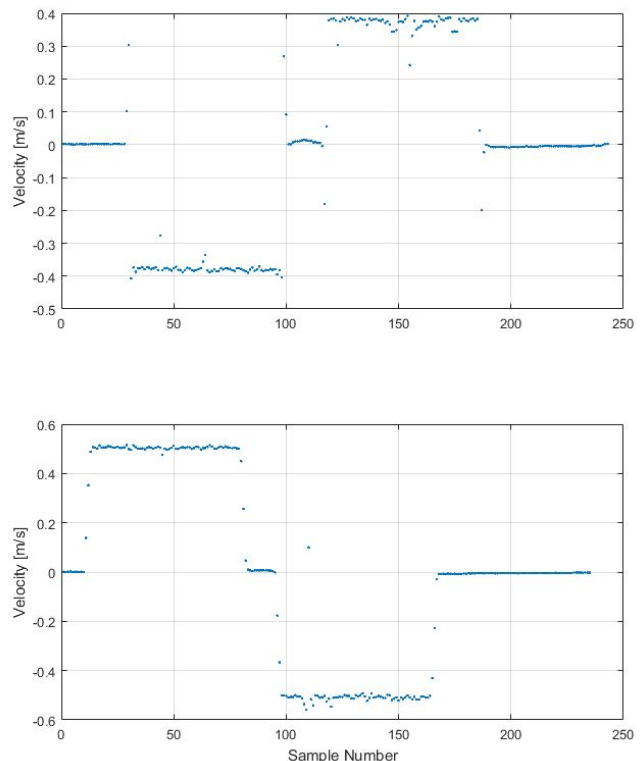


Figure 6. Example of velocity wrapping. Top: An example of velocity wrapping. This experiment consists of a forward-backward run at 0.5m/s at 5Hz sampling using the ± 10 cm/s velocity range setting. Bottom: A forward-backward run at 0.5m/s at 5Hz sampling using the ± 20 cm/s velocity range which eliminates the wrapping seen in the top figure.

All data are recorded at a 5Hz sampling rate. Note that for the case of the $\pm 10\text{cm/s}$ velocity range setting, the absolute maximum velocity of 40cm/s (according to Table 2) is exceeded, so wrapping is expected at the low cart speed of 50cm/s . All velocities appear to have the opposite sign for this forward-backwards run, and the absolute values are also incorrect. Bumping the velocity range to the next available ($\pm 20\text{cm/s}$) fixes this issue and velocity data are reported correctly at the expected positive, then negative, 50cm/s . This example highlights how critical it is to choose the proper velocity range for a given experiment to avoid velocity wrapping and to optimize the data quality.

C. The Importance of Sufficient Scatterers (high SNR)

Previous sections have summarized the different choices available to users in the FlowTracker2 Lab ADV application and how these choices impact the data quality. This section will discuss how the SNR can add additional complexity to your resulting data quality. In general, SonTek recommends taking measurements with SNR values greater than 3dB to get a reliable velocity calculation. Figure 7 shows tow tank runs performed at 0.1m/s using a $\pm 20\text{cm/s}$ velocity range setting at 2Hz sampling before and after seeding material (hollow borosilicate glass microspheres) was added to the tank. The average SNR in the low SNR run (top) was 0.5dB , whereas for the high SNR run (bottom), it was 22dB .

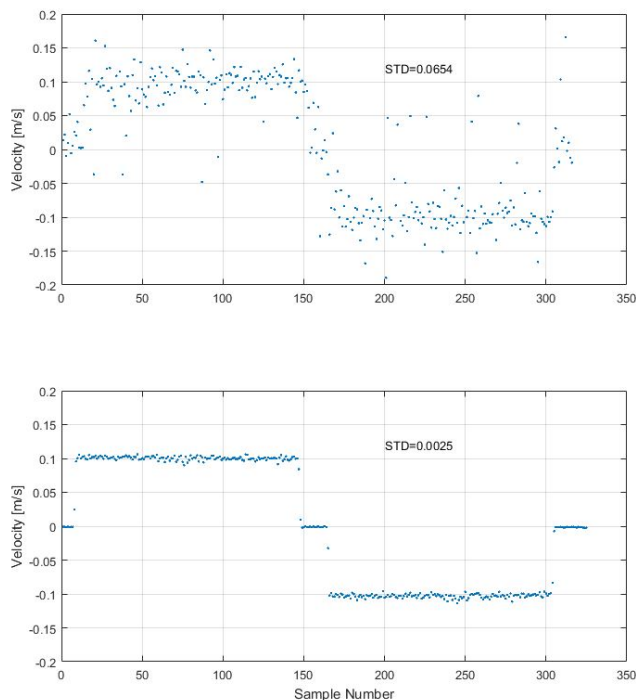


Figure 7. Top: Low SNR (mean $\sim 0.5\text{dB}$) tow tank run. Bottom: High SNR (mean $\sim 22\text{dB}$) tow tank run. Both runs were performed at 0.1m/s using a 2Hz sampling rate and $\pm 20\text{cm/s}$ velocity range. The standard deviations [in m/s] of the positive X-direction portion is displayed in the top right of each plot.

It is obvious from Figure 7 that only changing the amount of scatterers in the water while keeping all over variables constant has a direct effect on the noisiness and accuracy of the velocity measurement. With sufficient SNR, in this example, the SonTek - a xylem brand +1 858 546 8327

standard deviation of the positive-direction run was more than 25 times less than the low SNR run. That being said, despite the extremely low SNR in the top run, averaging the velocity over the positive run results in a value of 0.0975m/s , which differs by only 0.0025m/s from the tow cart expected velocity of 0.1m/s , and is still within the velocity error specification for the FlowTracker2 probe. This example shows that even in extremely low SNR conditions, when enough samples are collected, an accurate average velocity can still be achieved with the proper settings.

As shown in the previous section's example, increasing the velocity range without changing the actual velocity results in an increasing standard deviation of the velocity signal and noisier data. This deterioration of the signal is amplified in low SNR environments. Figure 8 shows the effect of the velocity range choice on the resulting data in low SNR conditions for sampling rates at 5Hz and forward-backwards run sets at 0.1m/s .

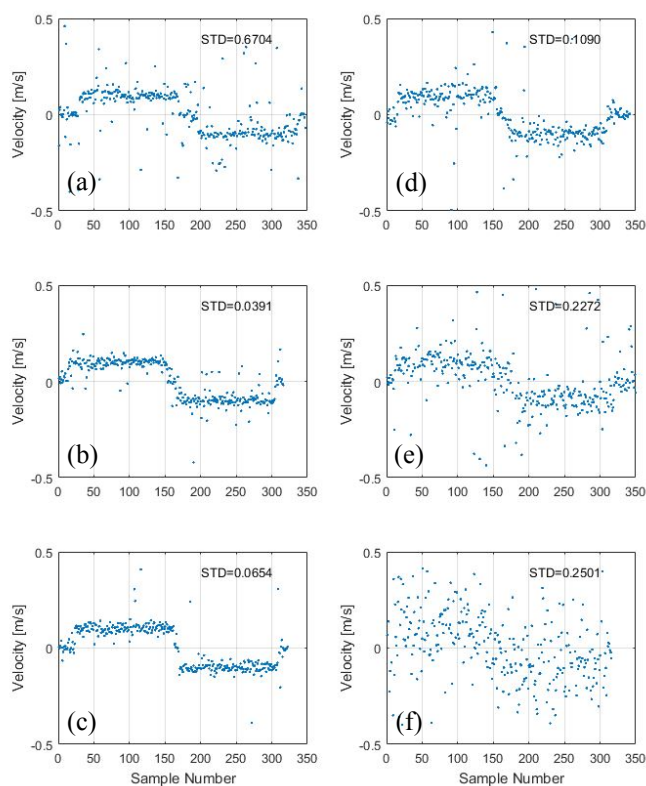


Figure 8. Varying velocity ranges in low SNR conditions. All runs were performed at 0.1m/s using a sampling rate of 5Hz . Velocity ranges are as follows: (a) Auto, (b) $\pm 10\text{cm/s}$, (c) $\pm 20\text{cm/s}$, (d) $\pm 50\text{cm/s}$, (e) $\pm 100\text{cm/s}$, and (f) $\pm 200\text{cm/s}$. The standard deviations [in m/s] of the positive X-direction portion is displayed in the top right of each plot.

In this case, the top left figure representing the 'Auto' range selection appears to perform worse than the first velocity range of $\pm 10\text{cm/s}$. The standard deviation of this 'Auto' range velocity run is 0.67m/s , whereas it is much smaller at 0.04m/s for the manual $\pm 10\text{cm/s}$ range setting. In this case, the low SNR in the tank has the added impact of harming the auto-velocity range ping algorithm. Because some pings are allocated for the auto-range detection, there are not enough pings to achieve an accurate velocity signal with the remaining pings in each inquiry@sontek.com www.sontek.com

sample given the very low SNR. In these cases of extremely low SNR, the user will achieve a better velocity signal by manually selecting the proper velocity range and avoiding the use of the 'Auto' range setting.

As the velocity range is increased, a marked increase in the data variability is shown in Figure 8 to the point where the final velocity range ($\pm 200\text{cm/s}$ in the bottom right figure) creates a time series where the forward and backwards runs are barely distinguishable. Compared to Figure 5 for high SNR conditions, it is obvious that in low SNR conditions, an incorrect velocity range setting (one that is too high for velocity conditions) leads to a much faster deterioration of the velocity signal. The user is advised to experiment with the proper velocity range setting given their velocity and SNR conditions to achieve the best results with their FlowTracker2 Lab ADV probe. In the case where the user does not know *a priori* what velocities to expect in an experiment, the 'Auto' range feature can be used to get a first estimate.

IV. SUMMARY

In this technical note, we have explained in general terms how the FlowTracker2 probe uses pulse-coherent acoustic pulses to calculate velocity as well as the implications this has for user settings and resulting velocity measurements. Various experiments were performed in both low and high SNR tow tank conditions spanning all possible choices of sampling rates and velocity ranges available in the FlowTracker2 Lab ADV. Table 3 summarizes the results for tow tank runs performed in high SNR (average 22dB). In general, standard deviation increases as the velocity range increases (when the velocity is held constant and does not exceed any velocity range maxima). The 'Auto' range setting generally performs similarly, if not better than the manual setting at 10cm/s (the appropriate choice for these experiments).

Sampling Rate	Vel Range	Mean Vel	Abs ERR	STD
1Hz	Auto	0.1011	0.0011	0.0031
	10	0.1010	0.0010	0.0026
	20	0.1016	0.0016	0.0029
	50	0.1015	0.0015	0.0033
	100	0.1006	0.0006	0.0032
	200	0.1007	0.0007	0.0051
2Hz	Auto	0.1012	0.0012	0.0029
	10	0.1014	0.0014	0.0027
	20	0.1006	0.0006	0.0029
	50	0.1010	0.0010	0.0032
	100	0.1007	0.0007	0.0030
	200	0.0999	0.0001	0.0052
5Hz	Auto	0.1009	0.0009	0.0026
	10	0.1007	0.0007	0.0029
	20	0.1007	0.0007	0.0025
	50	0.1006	0.0006	0.0029
	100	0.1009	0.0009	0.0034
	200	0.1018	0.0018	0.0065
10Hz	10	0.1011	0.0011	0.0030
	20	0.1008	0.0008	0.0040
	50	0.1011	0.0011	0.0032
	100	0.1009	0.0009	0.0041
	200	0.1014	0.0014	0.0089

Table 3. Summary of results for high SNR (~22dB) tow tank runs. Columns from left to right: Sampling Rate,

Velocity Range ($\pm\text{cm/s}$), Mean Velocity (m/s), Absolute Error (m/s), Standard Deviation (m/s).

Sampling Rate	Vel Range	Mean Vel	Abs ERR	STD
1Hz	Auto	0.1326	0.0326	0.1397
	10	0.0603	0.0397	0.3374
	20	0.1058	0.0058	0.0285
	50	0.1083	0.0083	0.0490
	100	0.0641	0.0359	0.1793
	200	0.0883	0.0117	0.1291
2Hz	Auto	0.0697	0.0303	0.3003
	10	0.0965	0.0035	0.0342
	20	0.1062	0.0062	0.0400
	50	0.1023	0.0023	0.1606
	100	0.0931	0.0069	0.1719
	200	0.1513	0.0513	0.3846
5Hz	Auto	0.1327	0.0327	0.6704
	10	0.1014	0.0014	0.0391
	20	0.0975	0.0025	0.0654
	50	0.1167	0.0167	0.1090
	100	0.1319	0.0319	0.2272
	200	0.0980	0.0020	0.2501
10Hz	10	0.0913	0.0087	0.0706
	20	0.0885	0.0115	0.1290
	50	0.0833	0.0167	0.2305
	100	0.1080	0.0080	0.3781
	200	0.0131	0.0869	0.8804

Table 4. Summary of results for low SNR (~0.5dB) tow tank runs. Columns from left to right: Sampling Rate, Velocity Range ($\pm\text{cm/s}$), Mean Velocity (m/s), Absolute Error (m/s), Standard Deviation (m/s).

By contrast, Table 4 shows the same tow tank runs but at low SNR (average 0.5dB). Here, the low SNR has a drastic impact on the standard deviations for every run compared to those of the higher SNR runs. The 'Auto' range setting often performs worse than the manual velocity setting due to its taking away from pings required to resolve an accurate velocity in such low SNR conditions. However, it should be noted that the mean velocity over the positive runs even in the situations of highest standard deviation tend to give a reasonable velocity estimate.

Thus, even in extremely unfavorable SNR conditions, increasing the measuring time (and thus more samples to average) can help to achieve an accurate velocity measurement. It should be noted that the data examples shown in this technical note are for illustration purposes only. Actual changes in performance, standard deviation of velocity, and average measured velocities achieved by the FlowTracker2 Lab ADV will depend on the individual tank conditions and measurement settings of each experiment.

REFERENCES

1. FlowTracker2 User's Manual 1.6 (2019). SonTek, A Xylem Brand.
2. Lhermitte, R., & Serafin, R. (1984). Pulse-to-pulse coherent Doppler sonar signal processing techniques. Journal Of Atmospheric And Oceanic Technology, 1(4), 293–208.
3. Wagenaar, D., & Fan, X. (2016). Technical Paper: Tow Tank Verification Report. SonTek, a Xylem Brand.

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While you may already know her from SonTek's stellar Technical Support group, Xue has since joined the Product Management team as an Application Engineer. She has a Doctorate in Physical Oceanography from Scripps Institution of Oceanography, and Bachelors in Physics and Atmospheric/Oceanic Sciences from McGill University (Canada), She speaks English, Chinese and French.

SonTek, founded in 1992 and advancing environmental science in over 100 countries, manufactures reliable acoustic Doppler instrumentation for water velocity measurement in oceans, rivers, lakes, harbors, estuaries, and laboratories. SonTek is headquartered in San Diego, California, and is a brand of Xylem Inc. www.sontek.com

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