ACCURACY, RESOLUTION, AND REPEATABILITY OF POWERSIGHT PDPA AND LDV SYSTEMS

TECHNICAL NOTE

Accuracy of the PowerSight PDPA and LDV systems is primarily dependent on the optics and the processor settings used to acquire data. There are many variables which influence accuracy and repeatability. The transmitting and receiving optics within the PowerSight module are precisely aligned, contributing very little to the uncertainty.

The PowerSight LDV system with the FSA signal processor has been used to measure velocities down to <1 mm/sec without significant uncertainty. The main reason is attributed to the design of the FSA processor. The FSA utilizes automatically optimized sampling rate selection and variable downmixing. Practically speaking, the user has the ability to select the narrowest frequency band for the flow of interest, giving the highest possible resolution, while still acquiring data over the full span of velocities present in the flow. Thus, the highest possible accuracy and resolution is achieved.

Doppler Frequency Signal Processing

The FSA 3500 and FSA 4000 are the state-of-the-art digital burst correlators. The FSA employs multiple 8-bit digitizers to continuously and simultaneously sample the incoming signal at three different rates. The FSA's patented DFT-based burst detector is designed to validate bursts based on both amplitude and signal-to-noise ratio (or "coherency"). The corresponding results are unbiased measurements with higher data rates and increased accuracy of flow turbulence levels. A contributing factor to the FSA's fast processing speed is the DFT-based (Discrete Fourier Transform) analysis, in which the FSA's burst detector uses high speed look-up tables to measure the signal-to-noise ratio and approximate the burst frequency in real time. This approximation then allows the FSA to choose the optimal rate for which to perform the final sampling. The Fourier transform technique ensures a high sensitivity to any coherent frequencies in the incoming signal stream. Most importantly, *since the burst detector measures the approximate frequency of every burst, each burst can be sampled at the optimum sampling rate*. This ingenious patented technique uses the burst detectors frequency estimate to select the most appropriate sampling rate of multiple 8 bit A/D converters in the FSA. In this way, the FSA can obtain the maximum accuracy and resolution because the FSA utilizes the maximum number of cycles.

FFT based Sampling by Other Processors

Figure 1 shows an example of a burst being sampled by a typical FFT based signal processor with fixed sampling rate. Notice how the A/D converter samples only a portion of the burst. Each cycle of the Doppler burst carries frequency and phase (velocity and diameter) information. Only about half the cycles are utilized. Thus, excessive samples are wasted, and information is lost.

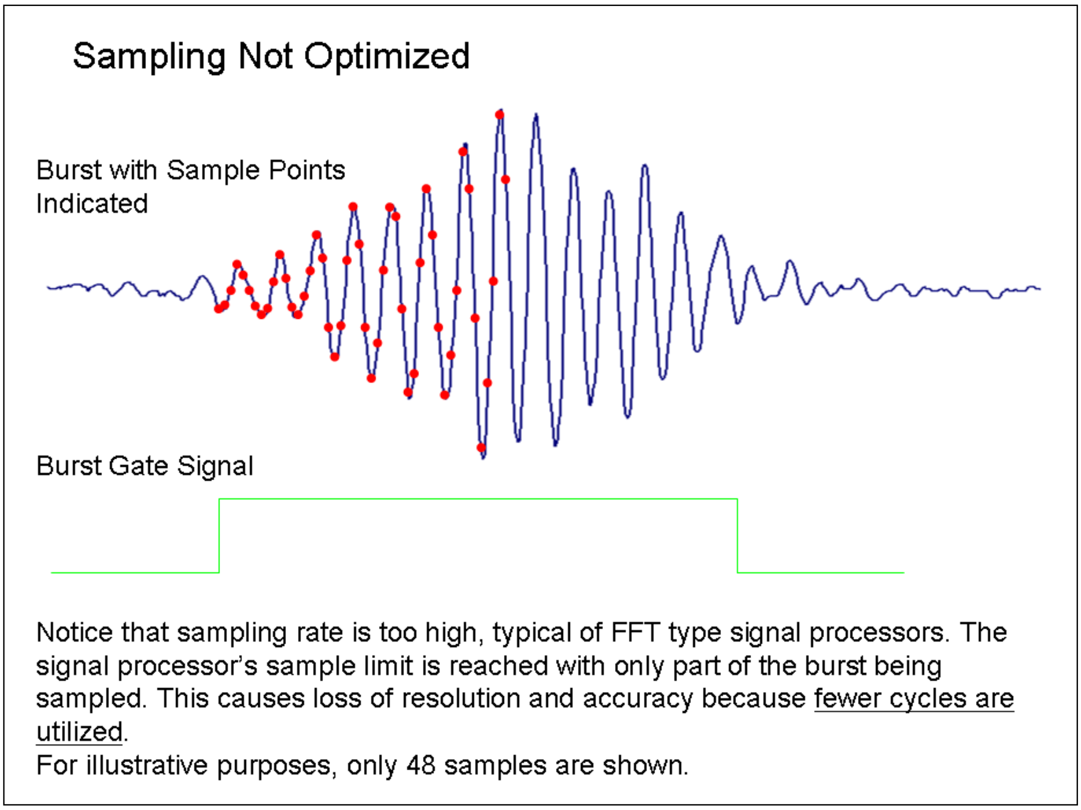

Figure 1. How a burst is sampled with a fixed sampling rate, typical of FFT type signal processor.

Discrete Fourier Transform and Dynamic Optimum Sampling by FSA Processor

Figure 2 shows the case when a burst is sampled by the FSA signal processor with dynamic optimum sampling rate selection. It is shown that the A/D converter samples the entire burst. The frequency and phase (velocity and diameter) information of every valid cycle of the Doppler burst is utilized. Thus, all samples are utilized to the highest extent, and resolution and accuracy are optimized.

The 8 bit sampled data are then passed on to the processor section of the FSA where multiple digital signal processors (DSPs) use an auto-correlation/cross-correlation technique to obtain the burst frequency and phase. Thus, the FSA is the only signal processor available which uses both the Fourier transform and auto-correlation/cross-correlation techniques, giving the best sensitivity, accuracy, and resolution.

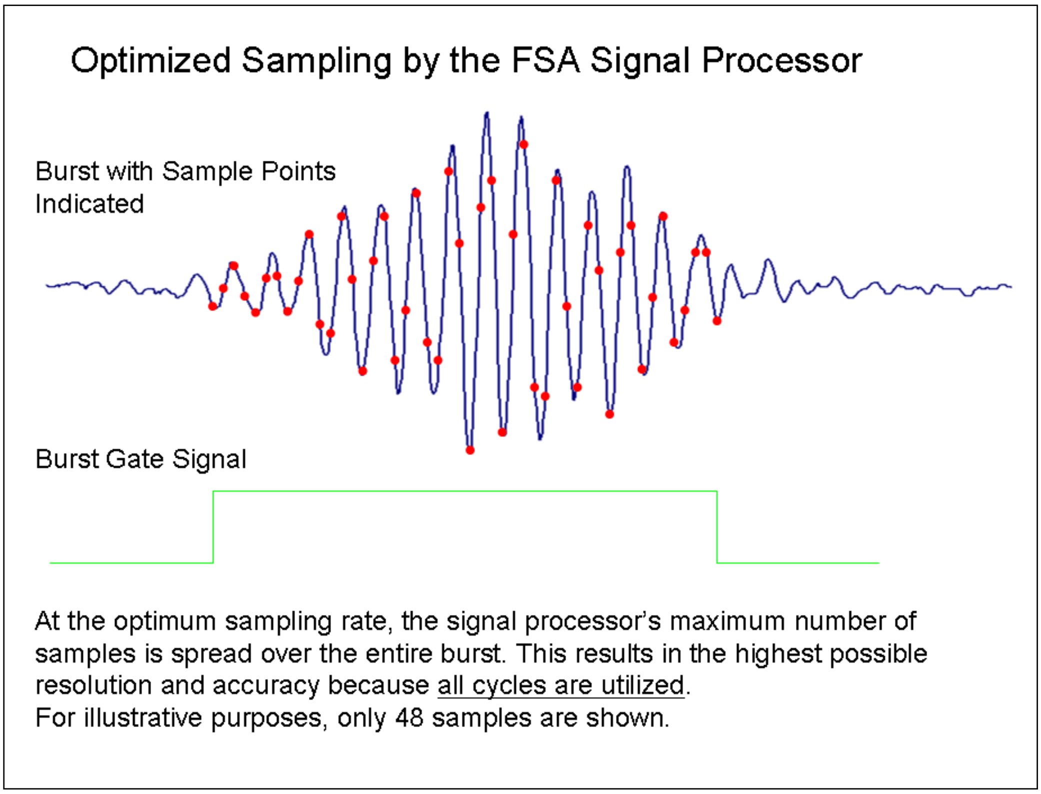

Figure 2. How a burst is sampled with optimized sampling rate scheme used by the FSA signal processor.

Accuracy of the PowerSight System

Velocity Measurements

Since the FSA uses intelligent burst detection to both detect incoming bursts and obtain the approximate frequency of the burst, it can be sampled at the optimum rate. This procedure ensures that every burst is measured with the highest possible accuracy. Since there are many parameters involved, a typical velocity accuracy is 0.1% of V_{max}, where V_{max} is the maximum velocity at the current settings. The main optical parameter is fringe parallelism over the entire measurement volume, because the PowerSight detects light from particles passing thru the entire region, not just the center parallel region. This typically results in an error of less than 0.5% of $V_{measured}$.

Assuming a 25 m/s flow being measured in the 2 to 20 MHz band, we have a Vmax of 100 m/s, assuming 5 um fringe spacing. From above, 0.5% of 25 m/s = 0.125 m/s and 0.1% of 100 m/s = 0.1 m/s, which is our maximum expected error in velocity.

Diameter Measurements

Using the intelligent burst detection to both detect incoming bursts and obtain the approximate frequency of the burst, the FSA utilizes the phase information from as many cycles as possible. Using all the cycles ensures that every droplet is measured with the highest possible accuracy. There are many other parameters involved, such as the accuracy in measuring phase, accuracy in fluid refractive index value, the linearity of phase-to-diameter plot, and the phase Doppler Slope value. For refractive fluids at typical velocities, the accuracy of the arithmetic mean diameter (D_{10}) of a large number of samples has been found to be:

$$< [1\% \text{ x } D_{max} + 1\% \text{ x } D_{measured}],$$

where D_{max} is the maximum diameter at the current settings and $D_{measured}$ is the measured droplet diameter. Here, fringe parallelism is not a factor since the receiver slit allows signal from only the centermost portion of the measurement region.

For example, assuming a 125 µm D_{max} (as determined from the current lens focal lengths, beam expansion, receiver angle, etc.), a large number of samples are taken of 20 µm droplets. From above, 1% of 125 µm = 1.25 µm and 1% of 20 µm = 0.2 um, so 1.25 + 0.2 = 1.45 µm, which is our maximum expected error in diameter for a 20 µm droplet.

Resolution of the PowerSight System

Velocity Measurements

The FSA 3500/4000 Series of Signal Processors use a 16-bit digital output. This results in a frequency resolution of up to 0.0015%. The FSA 3500 has a frequency range of 300 Hz to 100 MHz (with frequency shift). The resolution of the processors is 0.015% of reading, or better, which corresponds to ~15 Hz or ~0.07 mm/s in the range of frequencies (~100 kHz or ~0.5 m/s) encountered in water channel flows, assuming a 5um fringe spacing. This resolution also corresponds to ~0.002% of operating bandwidth. The resolution at frequencies (~10 MHz or ~50 m/s) encountered in typical air flows would not be expected to exceed 1.5 kHz or 0.007 m/s.

Diameter Measurements

As for Phase, the FSA Signal Processors use a 12-bit digital output. This results in a phase resolution of up to 0.024%. The use of three detectors in the receiver used by the TSI system, results in a ~3x improvement in resolution over a single detector pair. Thus, assuming a 125 µm D_{max} at current lens focal lengths, beam expansion, receiver angle, etc., we can expect a resolution of about 0.3 x 125 µm x 0.00024 = 0.009 µm or 9 nm. Measurements typically exceed this value by a factor of about 2.

Repeatability of the Measurements by PowerSight Systems

All real-world measurements show some degree of variation in measurements of a constant parameter. Repeatability is a measure of the ability of the LDV or PDPA system to produce the same reading of a control velocity or diameter time after time. A large number of measurements are typically acquired in LDV and PDPA (e.g. ~50,000) which improves accuracy. The repeatability of individual velocity measurements has been shown to be better than 0.05% while the repeatability of diameter measurements is better than 0.3% at low and moderate velocities, and under 0.8% at high velocities.

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