NORTEK MANUALS

Principles of Operation

55 | 250 | 500 | 1000kHz

NORTEK

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Introduction

This manual is designed to help users of Signature Series product line, also known as broadband instruments, to get familiar with the principles and concepts of the system. Details about how to measure velocity, different sampling modes and data output can be found in the chapters that follow, together with a number of other relevant subjects. If you are interested in how to operate your Signature instrument, the instrument specific Operations manual is a better starting point. These are available at http://www.nortek-as.com/en/support/manuals. For information about how to communicate, control and develop for your instrument, consult our System Integrators Guide, available here: http://www.nortek-as.com/en/support/application-development

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At our website, www.nortek-as.com, you will find technical support, user manuals, and the latest software and firmware. General information, technical notes and user experience can also be found here.

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Your feedback is appreciated
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1 Velocity Estimates

An acoustic Doppler current profiler (ADCP) measures current speed and direction by transmitting high-frequent sound waves into the water column, from below or above the measurement area of interest.

The instrument measures velocities along its individual beams by calculating the Doppler shift (D) of the returned signal. The distance to the measurement volume is defined by the two way travel time of the transmit pulse. The speed of sound (C) is used to convert the Doppler shift to velocity whereas a transformation matrix defined by the orientation of the individual beams transforms the individual beams estimates to Cartesian 3D velocities in a XYZ coordinate system, V = T x C × D. The built-in compass and attitude sensor can further transform the XYZ coordinates to Earth referenced coordinated, ENU.

In this section the concept of 3D velocity estimates is in focus, and in the following each of the components of the equation is described in detail.

1.1 Doppler Effect

The Signature measures the velocity of water by utilizing a physical principle called the Doppler effect. The Doppler effect is the change in frequency of a wave when a wave source moves with respect to an observer, or when the observer itself moves relative to the wave source.

The Signature uses the Doppler effect by transmitting a wave/sound pulse and listens for the return pulse. More specifically, it transmits a frequency modulated pulse, which is referred to as a *chirp*. A chirp is an acoustic sine wave which sweeps frequency from low to high, and the term *bandwidth* is the difference between the highest frequency signal component and the lowest frequency signal component. And in this context it can be mentioned that the Signature instruments are referred to as broadband instruments, and the term broadband is used because the bandwidth is increased compared to the narrowband instruments. A series of chirps are put together to form one transmit pulse, or ping. The length of each transmit pulse segment (chirp) defines the velocity range of the measured velocity. The use of broadband transmit pulses leads to more independent information per ping, which reduces the measurement uncertainty (more about this here: Measurement Uncertainty)
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The pulse does not reflect from the water itself, but from small suspended particles in the water. The scattering material float passively and it is assumed that they move with the same speed as the water - the measured velocity of the particles is the velocity of the water surrounding the particle. This is a key assumption for the Doppler approach to measure water velocity. Another key attribute for velocity measurements in the ocean is the fact that ocean currents usually are mainly horizontal and horizontally homogeneous. Currents may vary rapidly with depth, but they vary slowly over horizontal displacements.

The instrument relates the change in frequency to a relative velocity of the scattering particle compared to the instrument. Only changes in the distance between the instrument and the scattering material (radial motion, along the path of the acoustic pulse) can be measured since this is the only motion that affects the Doppler shift. That means that the instrument does not sense the velocity perpendicular to the beam at all. The instrument then performs onboard signal processing by comparing the transmitted wave with the received wave. The relative velocity can be calculated using this equation:

$$V = \frac{F_{Doppler}}{F_{source}} * \frac{C}{2}$$

Where V is the current velocity, $F_{doppler}$ is the change in received frequency (the Doppler shift), F_{source}

is the frequency of the transmitted sound wave and C is the speed of sound in water.

From the equation above one can see that:

- If the backscattering particle is moving away from the instrument (V is negative), the Doppler shift is negative
- If the distance between the transducer and the scattering target decreases, the frequency of the reflected pulse increases.
- If the scattering particle and the instrument stay at a fixed distance from one another, there is no Doppler shift.

The transmit signal is reflected from a number of particles, with the result of a return echo that is far more complicated (i.e presents different phases of the Doppler shift) than in the equation above. In order to find a repeating pattern in the echo, statistical processing methods are required. The ideal tool to look for repeating patterns is *autocorrelation*. The details about this method are beyond the scope of this manual, but the short explanation is that two identical echoes have high correlation and two dissimilar echoes have low correlation. It is thus finding the similarity with itself at a delayed time, making it possible to detect small changes in the return signal. A sharp correlation peak is highly benefitial, as the position of the autocorrelation peak yields the Doppler shift, which is proportional to the speed of the water.

1.1.1 Noise

Every signal that is received is subject to some amount of noise. The Doppler noise characteristics can be summarized as:

- Random and non-biased. That means if the measurements are averaged for a long enough time, the correct velocity will be obtained.
- The distribution of the velocity is Gaussian, meaning that the velocities measured are symmetric around the true velocity.
- Averaging reduces uncertainty. The more measurements that are averaged, the better is the estimate of the mean velocity.
- Noise Spectrum is white, meaning that the noise spectrum is flat. One way to estimate the noise is to take the time series data and calculate the frequency spectrum. The high frequency part of the spectrum sometimes turn out to be flat and thereby constitutes the upper band for the (white) noise spectrum. By integrating the energy in the box bound by the white noise an estimate of the noise variance will be the result. If there is no flat line near the high frequency range in the spectrum, the noise level is too low to play a part in the data.

The velocity measurement obtained from a single ping is typically too noisy to use by itself, but the average of a number of these pings is less noisy and therefore more useful. The goal is to come up with a bias-free estimate of the velocity profile and at the same time optimize the velocity precision, i.e. minimize the noise variance of the velocity profile. Read more about how noise affects the precision in the measurement uncertainty section.

When is noise of importance

- The noise floor defines the ability of the system to resolve turbulence. More information about how to find the noise level can be found in the Turbulence section.
- The effect on range can be very large and a well-designed, noise-immune current profiler operating in for example 55kHz nominal frequency can easily get 100-200m more range than a system that is subject to external or internal noise. Refer to the section about Range and range criteria for more about this.

Grounding point

To reduce noise generated by the instrument itself, the Signature instruments has a grounding point on the endbell. This grounding point is connected to the instrument ground, and works as a direct electrical connection to seawater.

1.2 Speed of sound

The speed of sound is important when computing velocity from the measured Doppler shift. The instrument also measures distance indirectly by computing the travel time it takes for sound to reach a distance and back. Speed of sound is computed by using a user-defined salinity and the measured temperature. The process works well because sound speed is more sensitive to temperature than it is to salinity. For instance, a rather large 12 psu change in salinity will affect speed of sound by 1%.

Speed of sound corrections
If it is necessary to correct for errors or changes in speed of sound, the correction method is relatively simple. Use the following equation:

$$V_{corrected} = V_{old}\frac{SS_{new}}{SS_{old}}$$

where V is velocity and SS_{new} is the true sound speed and SS_{old} is the original sound speed used. This may be relevant in case the instrument is deployed with incorrect speed of sound entered, as there will be a bias error in the velocity measurements (the magnitude will depend on how big the difference between the actual speed of sound and the fixed speed of sound is).

Read more about the effects of speed of sound variation with depth (thermoclines and haloclines) in the Environmental Properties section.

1.3 Beam Geometry

Each beam measures the frequency shift of the echo of the transmitted signal, and the corresponding velocity is found by using the Doppler shift. Remember that any particle motion perpendicular to the beam will not affect the Doppler shift, so the velocity component from the Doppler shift says something about the radial velocity along one beam path. One beam is required for each velocity component, so for measuring horizontal and vertical components of velocity, data from a minimum of three beams are required. The measurement method assumes horizontal homogeneity (water moves in the same direction with the same speed) in the area that the beams cover, because of the spatial averaging required. This is an accepted requirement, as horizontal flow gradients are not a typical phenomenon in these environments.

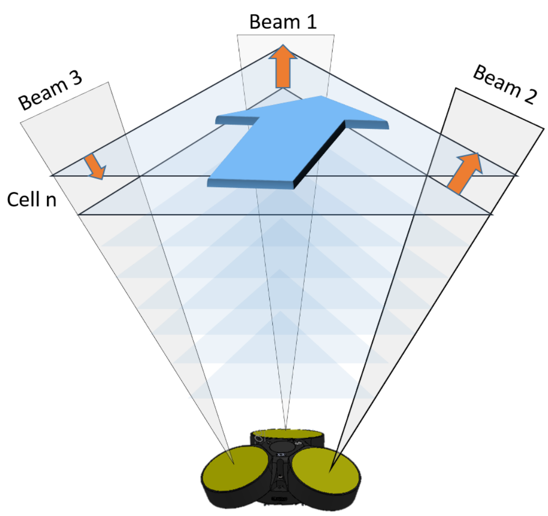

Figure 1: Signature55 has the familiar three beam configuration. The instrument has upward looking orientation in this figure, but it can aslo be used for down- or sidelooking orientation

The beams measure the velocity in three or four different locations due to the divergent design of the instrument (either 20 or 25 degrees - refer to the data sheet for specific instrument details). Each instrument has its own unique transformation matrix, based on the transducer orientation. This matrix is can be found in the data structures, for the interested user. The matrix is used when transforming the along beam velocities to e.g.instrument-referenced coordinates XYZ. It is also worth noting that calibration is not needed because of these matrixes. As long as the sensor heads are not physically deformed, the head matrixes will, consequently, remain the same.

The fourth and fifth beam
The Signature250/500/1000 has four slanted beams and a fifth vertical beam (optional for Signature250).

The four slanted beams are used for measuring the Doppler shift. Each pair of beams (beams number 1&3 and 2&4) measure one horizontal and one vertical velocity component. The 3D velocity is the resultant of the horizontal velocity from beam 1 and 3, horizontal velocity from beam 2 and 4 and one of the vertical velocities. The two independent estimates of the vertical velocity is beneficial when assessing data quality. The estimates can be used to calculate the difference between the two, which will indicate the homogeneity of the velocity in the horizontal layer.

The vertical (5th) beam ensures a well-resolved vertical motion, enhances wave data and enables high resolution distance measurements that is useful for ice thickness or ice drift measurements. It does not provide any information about the horizontal velocity. It is often referred to as altimeter.

For doing science on short-term varying currents or turbulence, five beams provide a significant advantage because all five second-order variables can be estimated directly. Thus, all components of turbulent kinetic energy and even turbulent stress are observed with this 5-beam configuration. Read more about this in the Applications section.

1.4 Measurement Uncertainty

The Doppler velocity uncertainties comprise two types of errors; the short-term error (random) and the long-term error (bias).

Short-term error
One velocity measurement is commonly the average of many velocity estimates (also called pings). The uncertainty of each ping is dominated by the short-term - or random - error. The short-term error depends partly on internal factors such as the size of the transmit pulse, the measurement volume and the beam geometry (which is collectively called Doppler noise) and external factors such as signal strength of the return echo, turbulence, and instrument motion. The random error is uncorrelated from ping to ping, so by averaging together a number of pings, the measurement uncertainty is reduced to acceptable levels according to the formula:

$$\sigma_{mean} = \sigma_{single\ ping} / \sqrt{N}$$

Where σ represents the standard deviation and N is the number of pings averaged together.

The Deployment Software predicts this instrumental error based on the short-term error of a single ping and the number of pings averaged together, and reports it under Horizontal and Vertical Precision.

Precision - a definition
The concept of "precision" is related to idea of "repeatability" as it is being used for acoustic doppler systems. Because of issues that are inherent to the estimation technique that is being used, the velocity estimate will include some random noise. The magnitude of this noise is often described through its standard deviation, which is really the square root of the variance of the noise (see

equation above). If, for example, the true signal was removed from the data, the "precision" would be equal to the standard deviation of the noise time series. Since the signal cannot really be removed (it is unknown), the variance of the noise is calculated using spectral techniques and the square root of this noise is provided in the software as an estimate of the standard deviation.

As briefly mentioned; in many situations, external factors such as the environment itself dominate the short-term error. This is true near an energetic surface and in turbulent flow such as boundary layers and rivers. In situations like this, the data collection strategy should take into account the nature and the time scales of the environmental fluctuations. Here are two examples:

- Waves. When measuring mean velocities in the presence of waves sample velocity at roughly ¼ the interval of the dominant wave period, and measure through 6-10 wave cycles.
- Turbulent flow. In boundary layers, a rough rule of thumb is that the root mean square (RMS) turbulent velocity is 10% of the mean velocity. If, for example, the mean velocity is 1 m/s, it is possible to estimate turbulent fluctuations to be 10 cm/s. Obtaining 1 cm/s RMS uncertainty would require at least 100 pings.

Long-term error
Random errors can be reduced, but never eliminated. When averaging several pings to reduce the error, there will be a difference between the resulting “mean current” and the actual current. This deviation from the actual current measurement is called bias, and is often also referred to as *Accuracy*. Bias are not random and cannot be reduced by averaging, it has a fixed magnitude and direction that is either proportional or constant to the measured velocity. The bias is often much smaller than the random errors removed by averaging, and it represents the limit to how much it is possible to reduce the short-term error. The long-term bias depends on internal signal processing, especially filters. The bias for the Signature series can be found in the instrument specific brochures.

2 Measurement Area

The instrument is able to measure velocities at different distances from the transducers by time gating the received acoustic signal. The sound wave travels with the speed of sound through the water column and as the signal hits particles part of the acoustic energy is reflected back to the transducer, while the rest of the energy continues further into the water column and is reflected at a later point in time. By measuring the time it takes for the energy to travel two ways one can know the location of the reflection point. With scaling by the speed of sound in water, the duration can be expressed as a distance (meters) corresponding to the size of the depth cell.

The profiling range and resolution is primarily a function of the frequency of the instrument; low frequency instruments are able to profile longer distances, while instruments that transmit higher frequency sound waves do have shorter profiling ranges but are able to achieve higher resolution. Environmental properties and boundaries also come into play when considering measurement area.

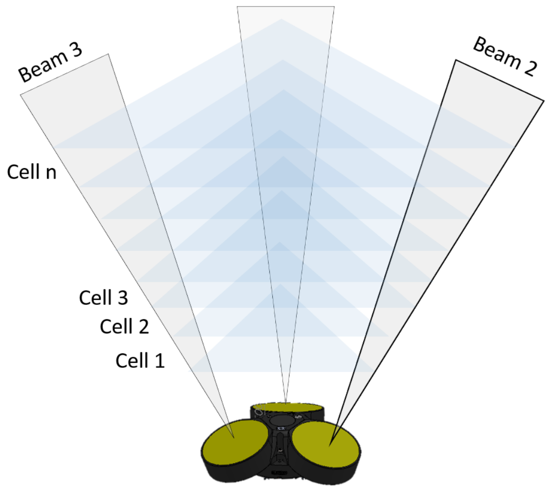

Figure 2: The measurement profile, sectioned into cells.

2.1 Cells

A velocity profile is a set of velocity measurements in a sequence of depth cells. The cell size specifies the *vertical* length of each depth cell in the profile, thus the cell size defines the depth resolution. More and smaller cells give more details about the variation of currents throughout depth. Each cell represents the average of the return signal for a given period of time corresponding to that cell size.

Selecting a proper cell size depends on what the objective with the deployment is. If the instrument is deployed in shallow water then it is usually of interest to get as much details in the data set as possible and therefore select a small cell size. In deeper waters, where optimal range may be the goal, increasing the cell size to the max may be a good approach. A larger cell size will have more scattering particles to reflect more of the transmitted signal, thus more information to calculate average velocities from. This leads to the important fact that the standard deviation (precision) of the velocity measurement is inversely proportional to the depth cell size. See Noise for more info.

2.2 Cell Position

When trying to determine the exact position of the depth cells, consider the following:

- The cell size selected when configuring the instrument for deployment. The instrument applies approximate triangular weighting to each measurement cell (see example below).
- **Blanking Distance:** The transducer works as both a transmitter and receiver. Sound waves are generated by supplying energy to the transducers so that they vibrate. After the energy has

stopped, the vibrations are damped with time, something that is known as transducer ringing. The distance the sound travels during the attenuation of the ringing is the minimum blanking distance. Thus, blanking is the time during which no measurements take place, essentially to give the transducers time to settle before the echo returns to the receiver. The size of the blanking varies with acoustic frequency; lower frequency instruments typically have longer blanking distance. The software sets a default blanking distance, but it is possible to adjust the range out further. The minimum blanking distance depends on strength of the echo coming back: In very clear water, the echo is weak and blanking should maybe be longer. In water laden with particles, the blanking can be smaller.

- The n-th cell is centered at a vertical distance from the transducer equal to: ***Center of n'th cell = Blanking + n*cell size***

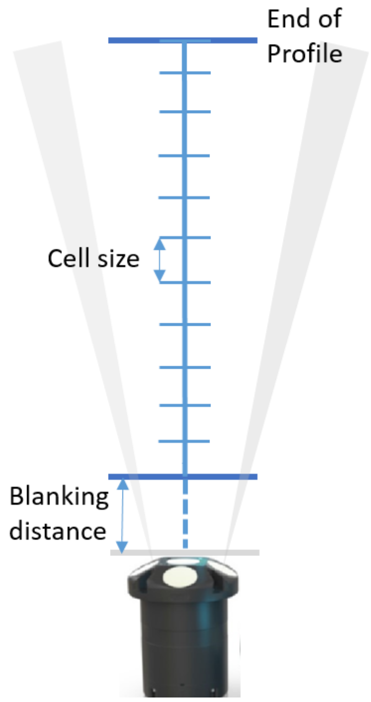

Figure 3: Definition of velocity profile is shown. Maximum range is determined by the scattering environment.

➲ Example: If one uses a blanking distance of 0.2 m and a cell size of 0.5 m. The center of the first cell (n=1) is thus located at 0.2 m + 1 * 0.5 m = 0.7 m from the instrument. The full extent of the first cell is from 0.2 to 1.2 m. Correspondingly, the center of the second cell is 0.2 m + 2 * 0.5 m = 1.2 m and the full extent of the cell is from 0.7 to 1.7 m. Note that these numbers are projections along the vertical axis, the numbers along the beam axis are larger by a factor of 1/cos(theta) due to the transducer geometry. Both the blanking distances and cell size is adjusted for a nominal slant angle of theta = 20 or 25 degrees.

Wave cell position

There is more information about the wave application in the Waves section, in this part the specific subject of position of the wave cell is covered. The four beams slanted off to the side measure wave generated orbital velocities. From the velocity profile one may select a level below the surface where the measurements form an array projected from the Signature to just below the surface. Managing the fact that orbital velocities attenuate exponentially with depth means that the data used for wave processing are the ones that are measured close to the surface, while ensuring that there is no contamination from the surface either directly from the cells touching the surface or indirectly from sidelobe energy leaking off the main beam. This can be managed by adaptively positioning the cells just below the surface by a fraction of the measured depth; 10% of the depth has proven to provide a good signal response without contamination. Wave processing will select a suitable wave cell per wave burst, so it will change depending on the tidal conditions. The cell position will be indicated in

Nortek's post-processing software for waves (SignatureWaves).

2.3 Range and range criteria

The range of the instrument is dictated by both fixed and variable parameters. Fixed parameters are constant over time and do not change with a particular configuration or instrument setup. These include beam directivity and output power, and in practice, the most important of which is the acoustic frequency. The higher the frequency of the instrument, the shorter is the range. For the Signature series, there is an option of having the instrument's long range mode = OFF (broadband) or long range mode = ON (see Average for more info). Apart from this the acoustic frequency cannot be changed. The impact that frequency, beam directivity, and power have on the instrument’s profiling range is well understood and can be fairly well defined and modeled.

In simple terms, the velocity profiling range is the product of the number of cells and the cell size (plus the blanking distance), but variable parameters also include the reflective characteristics of the particles in the water, where range is a strong function of scattering conditions. A small amount of scattering particles can be seen as low Signal-to-Noise Ratio (SNR - see definition below), and this is one of the key parameters when looking at measurement range. Velocity data cannot be measured when sound scatterers do not exist in the water column. Too many scattering particles, on the other hand, may result in that the returned amplitudes can be reduced because of absorption, beam spreading and attenuation. The acoustic backscattering cross section varies with the presence of scattering material in the water column. The amount and type of material changes with location, depth and time of year because biological activity in the ocean is patchy. There is usually more biological activity close to the surface, so generally an upward looking current profiler is likely to get more range than an instrument pointing downward. Even in a well-designed instrument the unknown scattering conditions have a large effect on the profiling range. As a consequence, it is hard to specify an exact profiling range without knowing something about the local environmental conditions in advance.

Signal-to-noise ratio - a definition

The Signal-to-noise ratio (SNR) is defined as follows: $SNR = 20 \times \log_{10}(Amplitude_{signal}/Amplitude_{noise})$ [dB], and it is a measure of the strength of the acoustic signal relative to the background noise level. Strictly speaking, it is impossible to measure the signal without the noise present, so $Amplitude_{signal}$ should read $Amplitude_{signal+noise}$.

There are two parameters that can be used as a criteria for determining the actual range of the instrument, in addition to the limit when the pulse hits a physical boundary or the surface/bottom:

- SNR: The signal strength data gives information about what range the instrument can accurately measure velocity data. Near the instrument, the SNR is typically high. As the distance from the instrument increases, the signal strength decreases due to geometric spreading and absorption, as can be seen in the two next figures. At a certain distance from the instrument, the acoustic SNR falls to the point where the velocity data is too noisy to use. The instrument is able to compute and record velocity from beyond this range, but the data are not useful. The limit to look for is where the signal is about 3 dB higher than the noise floor. In the example below the data from a range test outside Toulon in France is presented. Note the drop in SNR and Correlation, and how this is used to define the maximum range for this deployment.

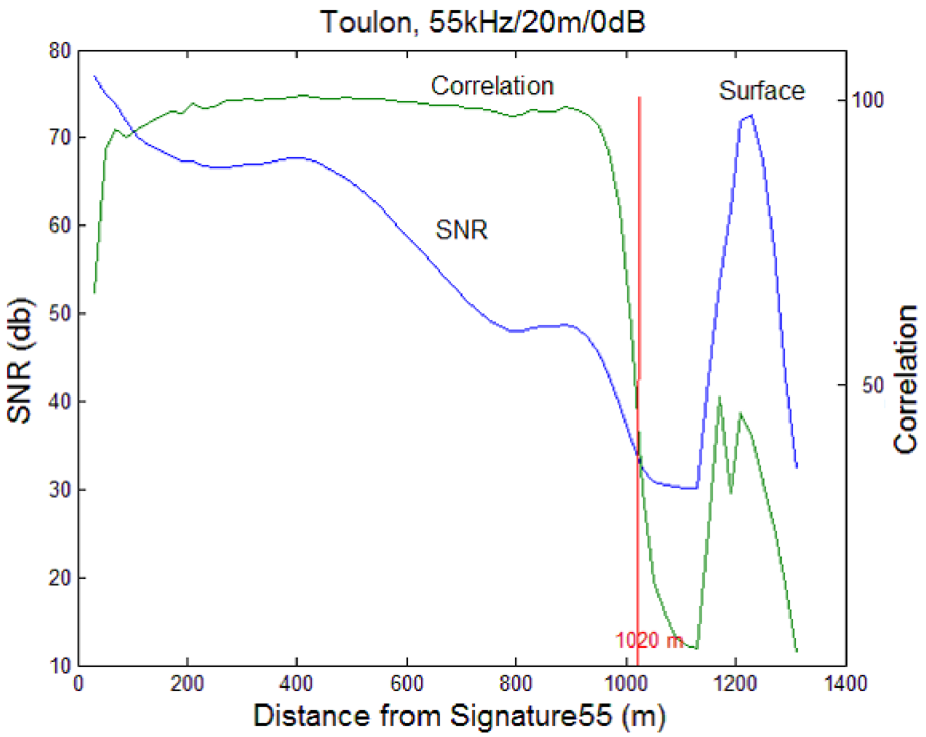

Figure 4: Range testing in Toulon, France. 1200m depth, measured with 55kHz/20 m cells/ full power.

- Correlation: The correlation data presents a statistical measure of similar behaviour between the received signals with respect to time. The magnitude of the correlation is a measure of the quality of the velocity data. A commonly accepted threshold for range when considering correlation data is where a drop to about 50% can be found.

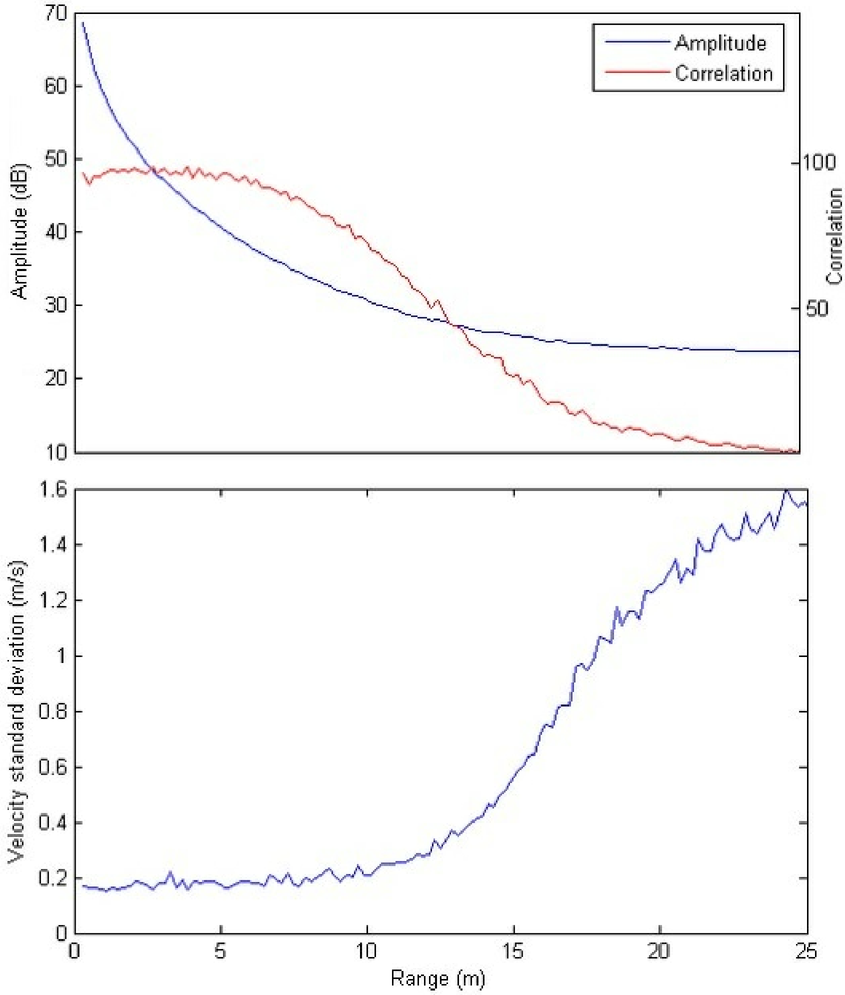

Figure 5: Upper: Amplitude and Correlation. Lower: Standard Deviation. Note how the standard deviation inceases as the correlation drops. Correlation rule of thumb: 50%. Can be justified by this plot

The instruments outputs data irrespective of the SNR, so the data should be screened for both SNR and correlation to identify events where the signal strength is too low to allow collection of good data.

Noise level and range

As the distance from the instrument increases, the acoustic SNR falls to the point where the velocity data becomes too noisy to use. Noise is a limiting factor in all measurement techniques.

- If measuring turbulence it is possible to measure until the signal reaches the noise floor.
- If measuring average velocities (steady flow) averaging more will lead to reduced noise - and the more noise, the longer the averaging period.

Boundary Interference

If the surface, bottom or another physical boundary is within the range of the profiler, the maximum range is defined by where the boundary reflections can be detected by the instrument. One can see this in the signal strength data as a strong peak. In the example from Toulon, the surface signature is clearly seen at about 1200 m from the instrument. Read more about sidelobe interference in the next section.

2.4 Sidelobe Interference

Measuring velocities close to a boundary is difficult due to sidelobe interference. The acoustic beams focus most of the energy in the center, but a small amount leaks out in other directions. Sidelobe interference is caused when the leaked energy strikes a boundary (surface/bottom/physical object) before the main lobe is finished traversing the measurement range and back, see illustration below. Low energy signals that travel straight to the surface can produce sufficient echo to contaminate the desired signal from the water because sound reflects much stronger from the surface-air boundary than from the typical particles in water. These sidelobe echoes start occurring just before the boundary reaches it and thus, they dominate the returned signal in these range cells.

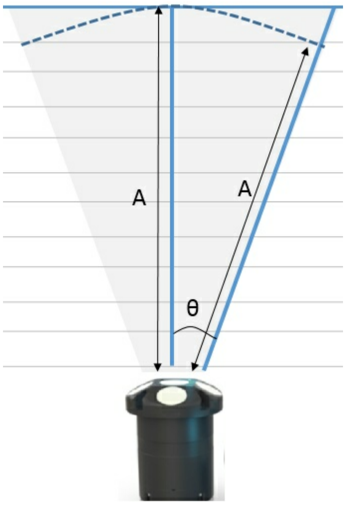

Figure 6: A schematic showing where to expect effects of Sidelobe interference. Distance to surface is A and theta is the angle of the beam relative to vertical. The cell size is idicated by the horizontal lines

With reference to the figure above; if the distance to the surface is A, then contaminations of the current measurements begin at the same distance A along the slanted beams. That means that the top cell (furthest from the instrument) in the figure above should be discarded.

The following is an approximate equation illustrating the constraint of near-surface contamination:

$$R_{max} = A \times \cos(\theta) - \text{Cell Size}$$

where R_{max} is the range for valid data, A is as defined above, and θ is the angle of the beam relative to vertical. For a 25º beam angle for a Signature deployed upward looking, the echoes from the sidelobe reflecting off the water surface are received by the transducers at the same time as the echoes from the main lobe sound reflected by the particles in the water at 90% of the ADCP distance to the surface. The velocity data are contaminated from this distance onwards to the water surface.

Note that sidelobe interference can occur when sound waves hit any interface which has strong sound reflections. The extent to which it will contaminate the velocity measurements is a function of the boundary conditions, the scattering return strength from the water and the acoustic properties of the transducers. Strong reflections occur when there are large differences in the speed of sound in the medium, one of them being water. Because the instrument's beams are narrow, sidelobe interference is not always a factor in the measurements. It may be unimportant in water with strong backscatter (i.e. sediment-laden estuary), but may contaminate when the backscatter is weak.

The sidelobe interference will typically result in a bias towards the velocity of the interfering boundary. For the bottom this is a bias towards zero (unless there is a moving bottom) and at the surface it will depend on the sea state or surface wind conditions. A tip when analyzing data is to check the vertical velocity (Z) extra carefully in this area. It should typically read close to zero. If not, it might be an effect of interference. For Signature500/1000: The vertical beam does not experience sidelobe interference since it is pointed directly to the surface.

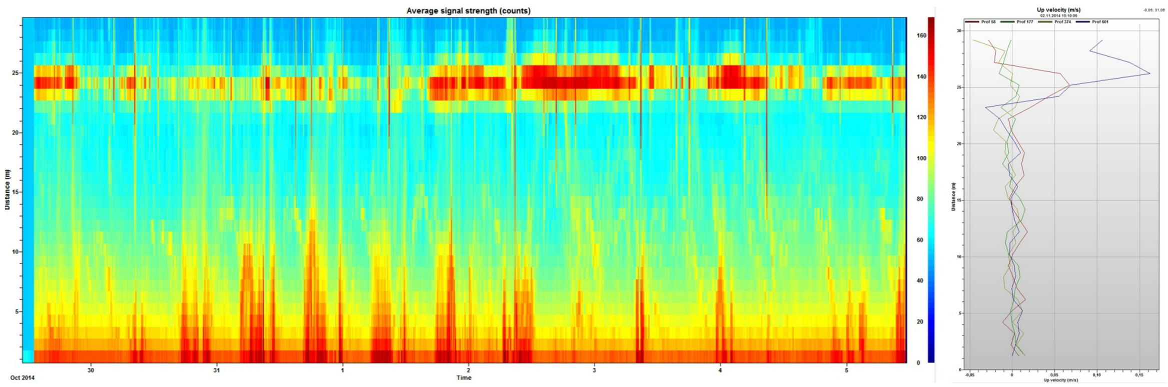

Figure 7: Contour plot of signal strength of a Signature1000 deployed at 24.5 meters depth in the Oslo fjord. Left: Signs of sidelobe interference from the surface can be seen at 21.6 m from the instrument. Right: Profiles of vertical velocity, showing the bias near the surface.

Transducer clearance

When mounting an instrument it is not always easy to consider interference from physical structures/objects that can occur in either the main beam or the sidelobe area of one or more transducers. The figure below is meant as guidance by showing the main beam and the "keepout area", indicating where to make sure there are no objects. Objects in the path of the sound waves may affect the entire water profile (depending on size and acoustic properties), and bias the data beyond recovery.

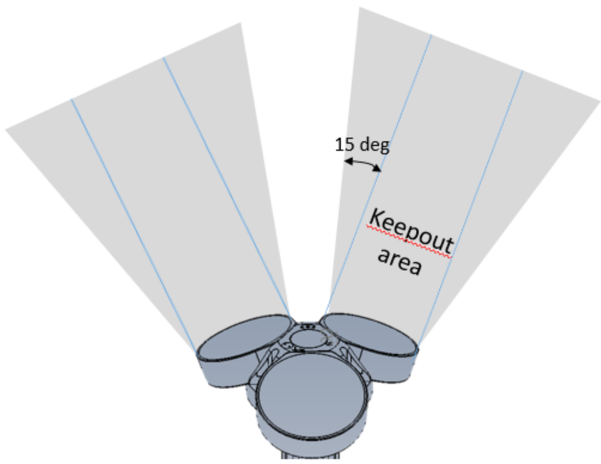

Figure 8: Recommended keepout area is presented in grey (showing only two beams, for the sake of overview), to avoid interference from physical objects

2.5 Environmental properties

Acoustic backscattering

The acoustic backscattering cross section varies with the presence of scattering material in the water column. This scattering material is typically zooplankton, sediment or miniscule air bubbles. The concentration of scattering material affect the measurement range of the instrument, simply because more scattering material reflect more of the acoustic signal.

When identifying the variability in scattering material over the profiling range, compare the actual data with the range variable elements in the sonar equation:

$$EL = SL - 2\alpha R - 20 * \log_{10} R$$

where EL is the receive level, SL is an arbitrary source level, α is the frequency dependent water absorption and R is the along-beam range.

The acoustic backscattering can be used to measure the concentration of scattering particles or suspended sediments. The Signature series has not been designed with absolute calibration in mind, but can very well be used for measuring relative concentration. See the document on Sediment Concentration Estimation for more information about this.

Depth variations of speed of sound
Speed of sound increases with increased temperature, salinity and pressure.

- A variation of one degree Celsius translates to approximately 4.5 m/s in speed of sound variation
- The average salinity of sea water is around 35 PSU. The rate of variation of sound velocity is approximately 1.2 m/s for a 1 PSU alteration in salinity.
- Pressure is a function of depth and the rate of change of sound velocity is approximately 1.6 m/s for every alteration of 10 atmospheres, i.e. approximately 100 meters of water depth (derived by the hydrostatic equation). Not compensated for by the instrument.

The estimates of the horizontal velocities will not be affected by variations of speed of sound. The interested reader can check out the theory behind Snell's law, but the concept is that the acoustic energy travels the same path from the transducer to the particles and back again, and is therefore negated. Because the instrument measures the change in frequency (and not time or distance), the instrument only needs to know the sound speed at the location of the instrument.

On the other hand, the range accuracy is dependent on the sound speed profile. That means that the position of the measurement cells in the water column will change if the speed of sound profile changes. See Orientation for more information. The only way to know for sure the vertical position of the measurement cells is then to use a Sound Velocity Profiler or a CTD to measure sound velocity profile through the water column.

When estimating the distance to the surface using the vertical altimeter (for wave and ice measurements) the two-way travel time of the short pulse transmitted towards the surface is used together with an estimate of the speed of sound. Deviations between the true speed of sound profile and the estimated profile (here assumed to be uniform with depth) will directly lead to errors in the distance to the surface. The estimated profile is based on a fixed salinity and the temperature measured. These deviations can lead to absolute distance errors of up to 3%, but are typically much less. This presents more of an error for absolute distances than relative distances (such as wave height). The same error applies to surface displacements, where 3% is an acceptable error for wave height.

Salinity
Salinity affects the molecular acoustic losses, which are lower in fresh water than in salt water. As a result, the profiling range is often longer in lakes. Within the ocean, the salinity variations are small and it does not really represent a variable environmental parameter.

Air bubbles
From an underwater acoustics standpoint, air-water interfaces are more or less impassable. Clouds of air bubbles can largely inhibit acoustic transmission. This is usually a greater problem at the surface where breaking waves create clouds of air bubbles. Bubbles may reduce the profiling range, or even block the signal completely. Bubble clouds can have a relatively broad footprint and persist for as long as 60 seconds.

When measuring waves, the performance of the altimeter is affected in two ways. The first is that the pulse will lose energy through scattering as it passes through the bubble clouds, which means that the surface reflection will be weaker. The second point is that it elevates the acoustic noise floor in the vicinity of the returned pulse, making it sometimes difficult to distinguish and pinpoint the surface reflection from the bubble clouds.

3 Sampling

The Signature Series is built with flexibility in mind and employ a timing scheme allowing the user to fit different measurement modes into one measurement period. The various different types of sampling modes mainly differ in power consumption, sampling rate, type and amount of data stored. These different sampling modes can be used as a single plan, concurrent plan or alternating plan, see the Deployment software for interactive examples of this.

Before going into the details of the each selection, a short recap of the background regarding sampling of Average and Burst is made. The biggest difference between the two modes is the sampling frequency, the second is the bandwidth.

Sampling Frequency
The idea behind Average is to measure the mean current profile, that is, the current flow that is typically measured every 10 minute. Due to the amount of information available in a single ping (as an effect of using broadband processing) there is no need for a high number of pings, so that there can be several seconds between each ping. When Average is selected, data are output at a maximum of 1 Hz.

For Burst data will be output at 1 Hz or faster. As opposed to a Average measurement, it is crucial to sample fast enough to “capture” or represent the turbulence energy spectra. Turbulence is, as waves, a statistical parameter which means that one needs to measure a certain period of time or samples to have enough data to calculate the relevant parameters.

Long Range Mode
The instrument will always prioritize to use broadband transmit pulses if possible. However, it is possible to decrease the bandwidth to increase the range, this is called Long Range mode in the Deployment software. This implies more pings are needed to get an equally low standard deviation, by averaging. This is not possible for Burst and is not relevant either since the objective for turbulence measurements is to get a precise velocity as fast as possible.

3.1 Data types

Average data are sampled at equally spaced intervals, while Burst means that data are sampled rapidly for a set period of time. The Average and Burst configurations are set independently, but their limits may be dependent on each other. The Deployment software is designed to intelligently inform the user about these along with which types are available for each instrument and licenses. Below are all the various types of individual sampling schemes which may configured in alternate or concurrent plans.

Sampling plan

Average allows for the following types of data (depending on instrument and licenses):
- Average - current profiles using the slanted beams. Fine and coarse profiles available for Signature55.
- Ice drift - tracking of ice velocity and direction.
- Ice draft (keel) - measures the distance to bottom of the ice and pressure.

Burst has settings for the following types of data (depending on instrument and licenses):
- Burst using 4 beams - rapid, broadband turbulence measurements using the slanted beams
- Burst using vertical beam - rapid, broadband turbulence measurements using the vertical beam.
- Bursting using 5 beams - rapid, broadband turbulence measurements on all five beams. The vertical beam must be sampled separately from the four slanted beams due to the small angle between them and risk of cross-talk.
- Waves/altimeter - measures wave height and direction, as well as necessary data to post-process for wave parameters, see Waves for more info. For wave height and direction both a slot for

altimeter and burst using 4 beams is necessary.
- Ice drift - tracking of ice velocity and direction
- Ice draft (keel) - measures the distance to bottom of the ice and pressure. Finding the difference between the two will give ice thickness.
- HR using vertical beam - high resolution pulse coherent measurement along the vertical beam.
- Echo sounder - small pulses transmitted along the vertical beam resulting in high resolution (mm cells) amplitude measurements. Useful for biomass evaluation.

3.2 Multi-functionality

All instruments, except the Signature55, can operate with two separate configurations; Average and Burst. These are set to operate concurrently, i.e. within the same second, and have slightly different measurement modes available.

All instruments can also set an Alternate plan; a second, separately configurable set of Average and Burst. When enabled, the Alternate plan can be scheduled to measure at a set interval or ratio compared to the original plan.

3.2.1 Single or Concurrent Sampling - Specifics for Signature250/500/1000

Each of the sampling plans can be selected as a single plan, or two plans can be chosen to sample Concurrently. In addition, it is possible to Alternate between two plans for the Signature500/1000. The user selects a Single or Concurrent sampling plan which sets one of the possible operations in each slot. Available measurement modes depend on the licenses of the instrument, but most basic types are Average, Burst and Altimeter. Within each of the sampling modes a vast array of parameters can be set but this can be seen in the Deployment software. Concurrent sampling will effectively reduce that particular mode's sampling rate by a factor of 2 or 4 depending on the mode, see Data types for more info.

Single and Concurrent
In the figure below there are two examples of setups, the upper panel shows a single Average current profile and the lower panel shows current profiles and Burst are measured concurrently. The Average profile measurement interval is set to 600 seconds, and the average interval to 300 seconds. That means that in a single sampling mode, data is collected for 5 minutes every 10 minutes. In the lower panel, an example of a Concurrent plan is shown. The Average profile is configured the same way as the first example. In addition, Burst mode is configured to make a measurement of 2048 samples at 2 Hz every 30 minutes. In the periods where no measurements are made, the instrument goes to sleep.

The Average data and the Burst data will be separated into two different files when exporting data using the Deployment software.

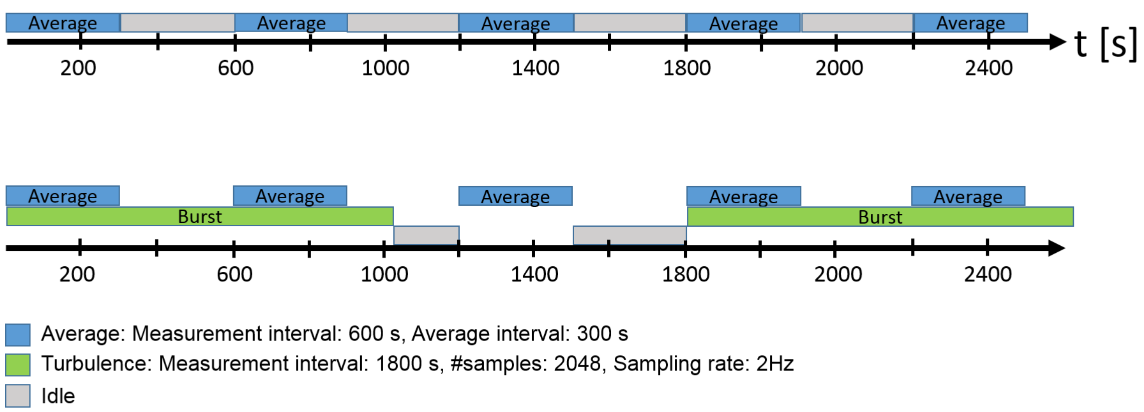

Figure 9: Example of a single plan (upper) and concurrent plan (lower).

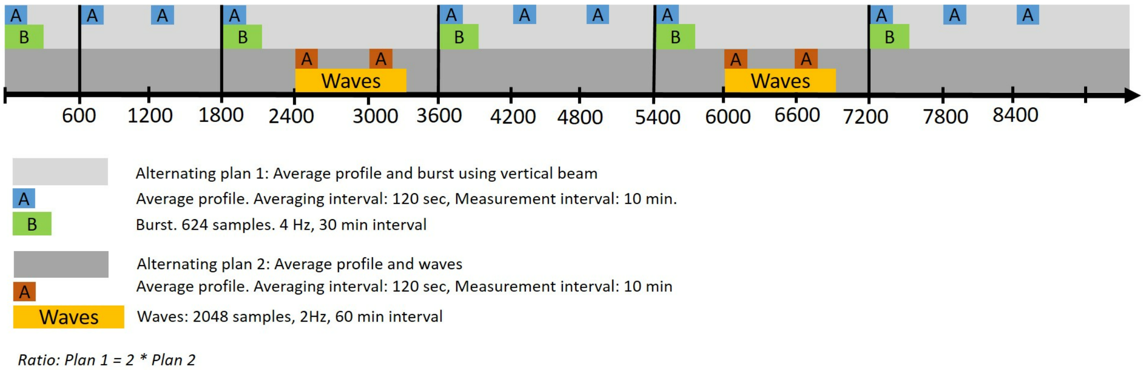

Figure 10: Example of a setup where the instrument alternates between measuring Average & Burst, and Average & Waves at a ratio of 2:1.

3.2.2 Alternating Sampling - Specifics for Signature55

Low frequency sound propagates further than high frequency sound, so the lowest frequencies are used for the greatest profiling ranges. On the other hand, higher frequency sound produces velocity measurements with lower velocity uncertainty, and it enables measurement with smaller depth cells. By alternating two frequencies in the Signature55 it is possible to get long range measurements and high-resolution data. In the software, the long-range is named "Coarse" and the shorter-range is called "Fine", so these designations will continue to be used. See Average for more info.

The alternating plans will be split into two separate data files in the Deployment software.

In the sketch below the Average interval and Measurement interval for the Fine and Coarse profiles, and the corresponding sampling sequence can be seen.

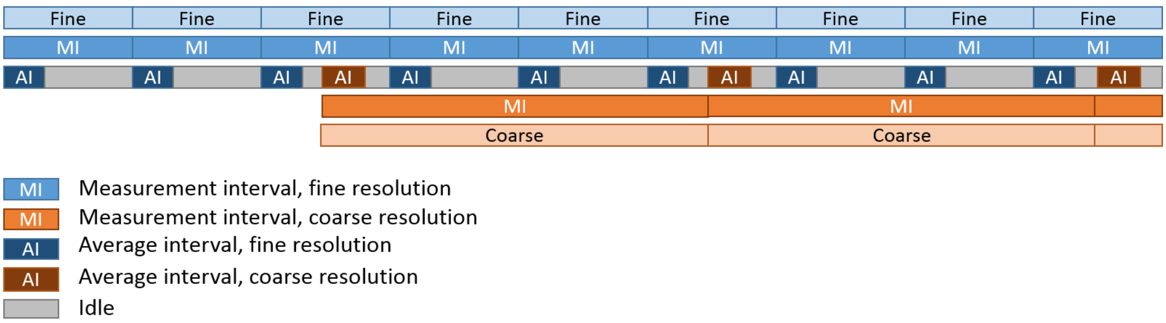

Figure 11: Fine and Coarse alternating plans on arbitrary timescale showing the active and inactive periods of sampling.

3.3 Sampling rate

The available sampling rates will vary depending on the instrument's transmit frequency and configuration. In general, higher frequency means quicker sampling rates and shorter range.

Average mode

The Signature is configured to sample uniformly across the Average Interval meaning the pings are spread evenly throughout that period of time. Data will be stored at maximum 1 Hz additionally to the averaged ensemble. The Effects tab of the Deployment Wizard specifies the total number of pings in the Average Interval. See Noise for more info. Measurement load, a parameter which is set in the Deployment software, determines the relative time which the instrument is actively measuring or pinging.

➲ For example a Signature1000 measuring an average current profile with an Average Interval of 60 s. The measurement load has been manually configured to 50% meaning the number of pings is 120. In this case the data would be stored at 1 Hz consisting of two pings.

Burst - Signature1000/500
Signature1000 has a maximum sampling rate of 16Hz. The Signature500 has a maximum sampling rate of 8Hz. These two instruments are designed to allow for rapid measurements suitable for turbulence studies, and also wave or ice measurements. A general rule to figure out the maximum sampling rate for a certain configuration is to consider adding each additional type of measurement halving the original maximum sampling rate. The bullet points in the Data types chapter are considered separate measurement types and thus each need their own time slot.

➲ For example, a Signature1000 configured with a single plan using "Waves and burst using 5 beams" will have a maximum sampling rate of 4Hz. From the data types earlier select "Burst using 4 beams", "Burst using vertical beam" and "Waves/altimeter" which takes sampling rate from 16Hz to 8Hz to 4Hz, respectively. Essentially the instrument will be able to collect those three data types at 4Hz each. The directional information for the waves measurements are taken from the burst using 4 beams in this case, see Waves for more info.

Signature55/250
The Signature250 and Signature55 do not operate with the same concept of time slots as above, instead both have a maximum sampling rate of 1Hz. A different concept is introduced which determines the maximum sampling rate, multiplexing. In addition when the Signature55 is set to profile further an extra second must be added due to travel time of the signal, depending on end of profile and cell size.

Multiplexing
A threshold value to be aware of on the Signature 250 and Signature55 is power level -6dB. The power required above this threshold cannot be stored for all beams in the capacitor bank. Therefore the instruments will ping one or two transducers and a 3D velocity estimate is made when a full cycle of all beams has been completed. The Signature55 pings one beam at a time and therefore it is not recommended to multiplex (without AHRS) on a moving platform such as a surface buoy since it may lead to velocity bias. The Signature250 pings the beams in pairs, so the effect of a velocity bias is lessened.

➲ For example, a Signature55 configured to profile 1100m with max power level it will take a total of 6 seconds, 2 seconds per beam, to complete a full profile.

3.3.1 Advanced - sampling ping sequence

A set number of time slots make up what operations are possible within a one second timeframe. The number of time slots defines the maximum sampling rate of the instrument and depends ultimately on the frequency of the instrument. The tables below shows the concept of data collection schemes. These time slots can be filled by different measurement types like described in the previous sections. When these time slots are filled, data is collected rapidly. It is also possible to use more of these slots to let the instrument sleep, if the plan is to deploy for a long time and save power.

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Data																

Slot	1	2	3	4	5	6	7	8
Data								

Figure 12: Time slot table for Signature1000 (upper panel) and Signature500 (lower panel) each corresponding to one second.

Constraints
Most measurement types are configured to share the number of time slots evenly between all other configured measurements. For example if average, burst using four beams and altimeter are

selected, the maximum sampling rate for each type would be 4Hz on a Signature1000.
The measurement is configured to alternate bursts symmetrically, for example it is not possible to ping the slanted beams once and the vertical beam five times.

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Data				Alt		AP4		AP4		AP4						
Data	BP4		BP5		BP4		BP5		BP4		BP5		BP4		BP5	

Figure 13: Alternating and concurrent plan. Upper Data: Average Profile. 1 min Average current profile. Lower Data: Turbulence with 4 Hz Burst using 5 beams.

4 Applications

Concurrent and/or alternating sampling modes allows for observation of different processes each on their own scale, including time scales, length scales and/or velocity scales. More information about this can be found in the Sampling chapter. The Signature series is capable of measuring turbulence profiles, ice measurements and waves in addition to current profiles. The following sections describe different measurement types which are available depending on the licenses.

There are a number of useful tips that can be found in the Mounting Guidelines and Operations manual when it comes to pre-deployment procedures and deployment considerations.

4.1 Average Current Profiles

The average current profile gives measurements of current speed and direction in multiple layers throughout the water column. Different bodies of water will have different phenomena governing the majority of water movement, but the most typical force is the tidal cycle. In most areas the currents vary little in the horizontal plane, but may differ more in vertical layers hence the idea of cells. Depending on the weather conditions, currents may have greater velocities near the surface due to wind drag. Due to strong density gradients there is little vertical mixing and therefore vertical velocities near zero.

An average current profile will have a certain number of pings over the course of the average interval, after which both the individual ping data (max 1Hz) and the average will be stored to recorder. This cycle is repeated every measurement interval.

Long Range Mode
It is possible to operate in both narrowband and broadband in the same deployment when using concurrent or alternating plans. The modes are referred to as broadband and long range mode. To remove any confusion long range mode is used instead of narrowband since single ping standard deviation is still lower than classic narrowband instruments (f.ex AquaPro or AWAC).
The Signature55 is slightly different since it can operate in Coarse (Long range mode) or Fine profile (full bandwidth). In Coarse mode it will use a narrower bandwidth with center frequency of 55kHz which gives the longest range, sacrificing some resolution. In the Fine profile a broadband ping centered around 75kHz will be used which gives high resolution, but sacrificing some range. It is also possible to alternate between the two modes during deployment, see Alternating for more info.

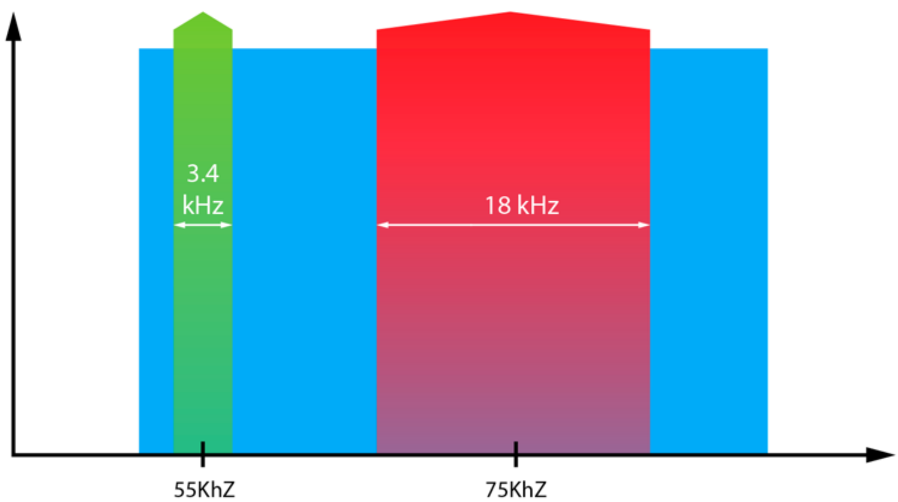

Figure 14: Illustration showing the long range and full broadband options for Signature55.

Setup considerations

1. Choose a measurement interval that captures the expected variations corresponding to the desired time resolution. For example a typical tidal cycle is well resolved with a profile measured once every 5, 10, 20, or even 30 minutes.
2. The end of profile should be selected so that it extends a few cells beyond the bottom or surface boundary. This helps with quality controlling the data in the processing. Remember the effects from Sidelobe Interference.
3. The Average Interval is the period over which the instrument measures and averages before it reports. The default value is adequate for almost all applications. Changing this to a longer or shorter period of time is a trade off between improved precision and power consumption. Rule of thumb: Try to get the precision to be less than 10% of the expected mean velocities in the deployment area.

Below are some suggestions based on which of three main parameters are most important and the relevant trade-offs.

To improve the precision:
- Increase the average interval.
- Increase the number of pings within the average interval by increasing measurement load
- When the random error is reduced to a value below the bias error, there is no point doing more averaging. See Measurement Uncertainty for more info.
- Increase the cell size. Standard deviation (precision) of the velocity measurements is inversely proportional to the cell size (larger cells give smaller standard deviations).

To increase profiling range:
- Increase power level.
- Increase the cell size.
- Deploy the instrument upward facing.
- Ensure sufficient scattering material. See Environmental Properties for more info.

To decrease power usage:
- Tune the power level down to suit the desired profiling range.
- Reduce the cell size.
- Lower the number of pings by reducing measurement load.
- Increase the measurement interval.

For mounting on surface buoys it is important to sample twice the rate of the buoys own response, so that means burst sampling at 2 or 4 Hz.

4.2 Waves

All bodies of water experience waves. These may range from long waves, such as tides to tiny wavelets generated by the wind's drag on the water surface. There is considerable variability in the distribution of energy for waves with periods from 12 hours to 0.5 seconds. A significant contribution of this energy is found in the band from 0.5 to 30 seconds and is commonly referred to as wind waves. These are the waves engineers and scientists are primarily interested in when they discuss wave measurements. Measuring these waves accurately often comes down to how complete the measurement method covers this band.

Wind waves are random and may vary in both time and space, and this variability makes characterizing waves non-trivial. To point out the obvious, waves begin both small in height and short in length, created by local winds, and grow as a function of wind strength, duration of wind, and distance. As a result, the wave environment at a particular location may be composed of a combination of local wind waves from a sea breeze and long waves (swell) generated by storm events hundreds or thousands of kilometers away. What this means to someone trying to measure waves is that they need to appreciate the fact that the local sea state is composed of waves with different amplitudes, periods, and directions. Understanding this is the first step towards making accurate wave measurements. For more information about waves and wave processing, check out our Principles of Operation, Part II.

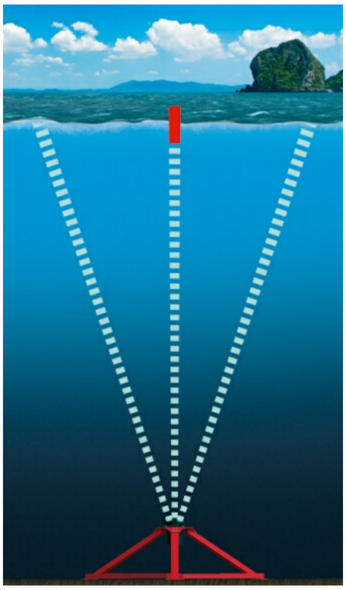

Figure 15: The figure shows the sampling area of the Signature while measuring waves.

The instrument will be configured to sample a number of samples at a certain sample rate every measurement interval (Check Deployment software help file for details on this). One may view the Signature's measurements as two separate operations which permits the ability to estimate Directional and Non-Directional wave parameters:

1. The four beams slanted off to the side measure wave generated orbital velocities. Each beam measures a truncated profile - or one sufficiently capturing the orbital velocities. From the recorded profile one may select a level below the surface where the measurements form an array projected from the Signature to just below the surface. Managing the fact that orbital velocities attenuate exponentially with depth means that the data used for wave processing are the ones that are measured close to the surface, while ensuring that there is no contamination from the surface either directly from the cells touching the surface or indirectly from sidelobes. This can be managed by adaptively positioning the cells just below the surface by a fraction of the measured depth; 10% of the depth has proven to provide a good signal response without contamination.
2. The fifth, vertical beam works as an altimeter and measure the distance to the surface directly. It thus traces the surface wave profile as it passes through its field of view. The Signature series instruments have a relatively large, fixed altimeter window, which is defined in processing depending on the pressure sensor (calculated per ping). Wave processing will select a suitable wave cell per wave burst, so it will change depending on the tidal conditions. The data are processed by using the Nortek AST routine (see definition below)

Acoustic Surface Tracking - a definition

The Acoustic Surface Tracking (AST) is basically echo-ranging to the surface with the vertically oriented transducer (altimeter). The approach used to detect the surface is relatively simple. It can be broken down into the following sequence of steps. 1) Transmit a relatively short pulse; 2) Specify a receive window covering the range of all possible wave heights; 3) Discretise the receive window into multiple cells (~5 cm); 4) Apply a match filter over series of cells to locate the maximum peak, which is the surface; 5) Use quadratic interpolation to precisely estimate surface location.

A cleanup step is iteratively performed on the raw time series and if the cumulative number of false and no detects exceeds 10% of the total number of samples in the ensemble, the ensemble is considered corrupt and discarded.

The resulting time series of the raw measurements is not particularly useful from a practical standpoint, and therefore needs to be processed to yield parameters that can broadly, yet accurately, characterize the sea state. The Signature does not process wave data internally, but post-processing software does exist.

The resulting wave parameters into the two categories introduced above; Non-Directional Parameters (Wave Height) and Directional Parameters (Wave Direction).

- Non-Directional parameters covers parameters that do not depend on the direction of the waves, and comprise: Peak period (Tp)Mean period (Tm02), Mean zerocrossing period (Tz), Mean 1/3 Period (T3), Mean 1/10 Period (T10) and Maximum Period (Tmax), Significant wave height (Hm0), Mean 1/3 and 1/10 height (H3 and H10), Maximum height (Hmax), Mean height (Hmean),
- Directional parameters covers Peak direction (DirTp), Directional spread (SprTp) and Mean direction (Mdir). Note that wave directions are always reported as the direction where the waves are coming from.

There are some limitations to resolving short waves. The following describe the limitations for non-directional and directional waves.

Non-Directional - or footprint limitation

The wave resolution from the altimeter measurements is dependent on deployment depth. The diameter, or the "footprint" of the area ensonified by the altimeter increases as the distance from the surface increases. When the diameter of this footprint becomes similar in size to a wavelength, then the structure of the waveform (crest and trough) cannot be well resolved. There is an average of the distance over the waveform and thus a "smearing" of the true features. A "cut off" frequency is assumed when the footprint diameter is equivalent to half a wavelength. The relationship is plotted in the figures below.

➲ Example: The Signature250 is to be deployed with a distance to the surface of 80 m, and the footprint on the surface from the altimeter beam will be 80*tan(2.2). The minimum wavelength needs to be the twice of this footprint, that means ~6.15 m. One can then use simple wave theory to find an equation that relates wave length (L) to wave period (T); L = gT^2/2π. Using this equation the minimum wave period measurable at 80 m depth is ~2 m.

Directional limitation

The directional limitation lies within the relationship of the wavelength and separation distance of the measurement cells.

- The shortest period wave is limited by the rule that one can only unambiguously estimate direction for waves that have a wavelength that is two times the separation between the closest cells.
- The spatial separation of the cells will depend on the depth of the instrument, as the distance between the measurement cells will increase with distance from the instrument.

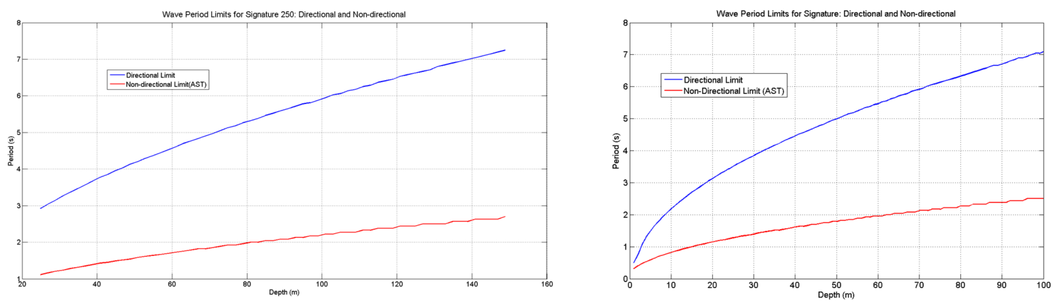

Figure 16: Shows the directional and non-directional limitations for different instrument depths and different wave periods. To the right: Signature250. Left: Signature1000 and Signature500.

One perceived solution is to position the measurement cells closer to the instrument such that the spatial separation is reduced and consequently the frequency at which this ambiguity occurs is higher. Unfortunately, moving the measurement cell further down in the water column means that the orbital velocity signal may disappear. The result is that there is no performance gain by drawing the cells in closer to the instrument.

Setup considerations

- Waves are random and therefore measuring waves requires sampling over a period of time that will best “capture” or represent the complete sea state. For long waves, it may be necessary to increase the overall sampling period in order to ensure a proper statistical presentation. As a rough rule of thumb try to get 100 cycles of the longest wave we would expect; this means if the longest expected wave period is 10 seconds for a particular body of water, then 1000 seconds is the preferred sampling length.
- Specific recommendations cannot be provided other than the sampling rate needs to be at least twice as fast as the signal of interest in order to resolve it unambiguously (i.e. the Nyquist sampling criteria).
- Mounting depth: Orbital velocities attenuate exponentially with depth and this behavior is more severe for higher frequency waves (short waves). This means that the further down in the water column that the orbital velocities are measured, the less high frequency information is available. This is the classic problem faced by bottom mounted instruments, and note that even the ADCP class of instruments suffers from this challenge if it is not managed effectively.
- Mounting angle: Since the vertical acoustic pulse is reflecting from the surface the best response occurs when the pulse path is orthogonal to the surface from which it is reflecting. The return response deteriorates as the beam deviates from the vertical. Performance is notably reduced when the tilt exceeds 5 degrees.
- Mounting method: If the instrument is to be deployed on a subsurface buoy, make sure that the natural frequency of the buoy itself is not the same of the wave frequencies being measured. More about this in our Mounting Guideline. More information about general tips and tricks can also be found Mounting Guidelines.

4.3 Ice

The Signature instrument can use the upward looking altimeter to measure the range to the ice-water boundary and thus get information about ice draft. In addition it uses the measured Doppler shift from the velocity of the ice sheet or ice bergs to get information about the ice drift. Note that a specific firmware needs to be used to enable ice measurements.

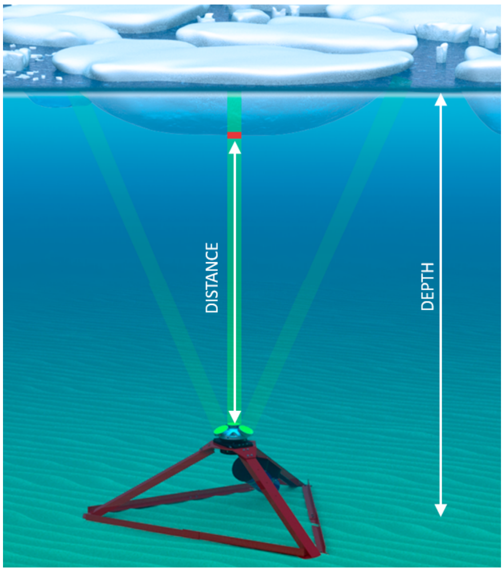

Figure 17: The distance to the boundary between ice and water is measured by the center beam.

Ice draft (keel)
The instrument measures the distance to the submerged part of the ice sheet directly. The measurement of the thickness of the ice draft is made by subtracting the location of the leading edge of the altimeter peak from the mean depth determined from the high accuracy, temperature compensated pressure sensor. Ice draft (keel) = Water depth - Distance to ice. In post-processing it is necessary to convert the pressure measurements to an equivalent height of the free water surface, and to apply various corrections (see below) to both types of data.

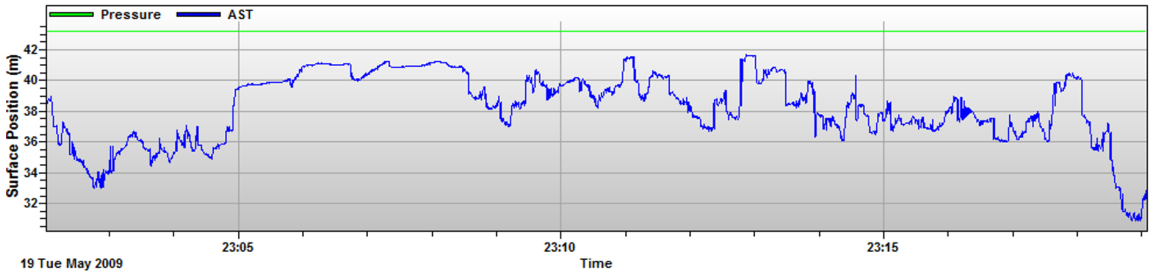

Figure 18: Distance and Pressure estimates. From this one can find the ice thickness.

Leading Edge - a definition
The altimeter is basically echo-ranging to the surface. The approach used to detect the surface is relatively simple. It can be broken down into the following sequence of steps: 1) Transmit a short pulse; 2) Specify a receive window; 3) Apply a match filter process which use a leading edge detector over the profile to locate surface; 4) Use quadratic interpolation to precisely estimate interface location.

Ice drift (tracking)
For this type of measurement the four slanted beams transmit long pulses, compared to normal current profile pings, to completely ensonify the ice surface area. A long transmit pulse means the ice is ensonified for the full beam width. This generates a strong, sharp and accurate echo back to the instrument which is Doppler shifted proportional to the velocity of the ice. A Nortek proprietary algorithm is used for estimating the ice tracking.

Figure of Merit (FOM) is a quality parameter that estimates the white noise (or Doppler noise) for each ping, and gives a snapshot of the quality of the measurement. In general, a lower FOM is better, and if the number is high it should be considered removing the velocity estimate from the series. FOM is scaled to be proportional to the standard deviation.

Correcting for error sources in ice measurements

Atmospheric variations: In addition to the instruments pressure measurements there needs to be a correction for the atmospheric variations. The pressure sensor measures absolute pressure, but the data are presented relative to a nominal value of atmospheric pressure at the time that pressure offset was taken (i.e., a constant mean value of atmospheric pressure is already subtracted from the absolute pressure measurements). The data have to be corrected for fluctuations of the actual atmospheric pressure relative to the assigned mean pressure. These fluctuations, which are associated with the passage of high and low pressure zones in the atmosphere, occur on daily to weekly time scales and can have an amplitude equivalent to +/- 0.5 m of water height, if not corrected. A time series record of barometric pressure is required to make this important correction.

Since atmospheric pressure variations are associated with large-scale synoptic weather systems, the barometric pressure measurement does not have to be made right at the location of the instrument. Atmospheric pressure measurements obtained within a few tens of kilometers from the deployment site typically result in residual errors after correction of less than +/- 0.05m [http://www.nortek-as.com/lib/bibliography/waves-in-the-summer-ice-in-the-winter]. It should also be mentioned that care should be taken when estimating the density, which is used to convert pressure to depth.

Speed of sound: The Signature's acoustic range measurement technique uses an estimate of the vertically-averaged speed of sound to convert acoustic travel-time measurements into distance estimates. Salinity plays a relatively minor role in sound velocity (about 1.34 m/s per psu at 0 degrees C), so the uncertainty in salinity is not expected to contribute significantly to errors in the acoustic range data. For example, uncorrected salinity variations over the range of 30-35 psu would contribute errors in calculated water depth of only about 0.05 m.

Temperature is important for sound velocity so an uncorrected temperature change of -2.5 degrees C to +2.5 degrees C would result in a depth error of 0.15m. By using the measured temperature to correct the speed of sound, combined with an estimate of salinity based on the assumption that the water column is near the freezing point, it is possible to reduce the residual error due to density uncertainty to less than +/- 0.05 m. It is reasonable to assume that the water column is not highly stratified during ice conditions.

Density: Salinity affects density more than temperature in freezing conditions. Because seawater freezes as a function of temperature and salinity, and the temperature is measured, it is possible to infer salinity. Again, it is reasonable to assume that the water column is not highly stratified during ice conditions.

4.4 Turbulence

Turbulence, as used here, refers to short-term variations in the current velocity. There are a few aspects of the Signature Series that make it particularly suitable for measuring these variations:

- Fast sampling - detecting variations is simplified if the instrument collects many independent current profiles in quick succession.
- Spatial distribution - measure the velocity profiles along 4 or 5 beams simultaneously and thus represent an increase in the spatial distribution of the data.
- To measure turbulent kinetic energy and even turbulent stress, five beams provide a significant advantage because all five second-order variables can be estimated directly. This is in contrast to the mean current, which only requires three, or even just two beams to estimate all relevant velocity components.
- Vertical, fifth beam - Measuring the vertical velocities directly concurrently with the four divergent beam means that it is possible to eliminate signal ambiguity by measuring on the same spatial scale.
- The Signature1000 has true High Resolution (HR) measurement capabilities, meaning that it is capable of vertical velocity measurements with much higher resolution than the standard measurement schemes.

To measure turbulence and get appropriate turbulence statistics require accurate velocity time series that are measured fast enough and at a spatial scale that is appropriate to the flow.

The sampling method is referred to as Burst, meaning that it samples rapidly for a short period of time. There are several options when it comes to burst measurements for turbulence data, depending on instrument and license. See Data types for information.

The instrument will conduct a number of samples at a certain sample rate every measurement interval, which is customizable. Check the Deployment software help file for details on these parameters. As when measuring average current profiles there are tradeoffs when configuring the instrument for turbulence measurements:

- Range: The beam spread increases with distance from the instrument. That means that the distance from the instrument represent a limit to the resolvable length scale. If the application is to sample horizontal fluctuations, the distance from the instrument to the sampling volume needs to be considered.
- Vertical resolution. The cell size is tied to the length of the pulses. Smaller cell sizes means

shorter pulses, and thus higher Doppler noise. Larger cell sizes means longer transmit pulse and lower Doppler noise. It is recommended to use the largest cell size possible (to reduce noise).
- Sampling rate: The sampling rate determines the number of raw pings, **N** that are averaged per velocity value, and the noise is reduced by a factor of v(**N**). Note the difference between number of pings when sampling at for example 8Hz and 4Hz. As for wave measurements, it is important that the sampling rate is higher than the Nyquist frequency of the flow. It can also be recommended to sample a bit faster that what is possible to resolve, in order to find the Doppler noise level when doing the spectral analysis.
- Time averaging: Time averaging will reduce Doppler noise, but at the expense of temporal resolution. However, for turbulence calculations, averaging obscures the velocity variance. Instead, the raw pings must be retained, and Doppler noise must be removed from the velocity variance statistically. Averaging pings not only results in slow measurement rates but also can bias velocity fluctuations towards the mean.
- Noise level: It is recommended to choose a configuration that reports a noise level (standard deviation) that is lower than the expected turbulent fluctuations. That means that prior knowledge of the local conditions is beneficial. In boundary layers, a rough rule of thumb is that the root mean square (RMS) turbulent velocity is 10% of the mean velocity. If, for example, the mean velocity is 1 m/s, it is possible to estimate turbulent fluctuations to be 10 cm/s. Obtaining 1 cm/s RMS uncertainty would require at least 100 pings.
- Remember that random Doppler-shift measurement errors are related to a single beam, therefore it makes sense to collect turbulence data in beam coordinates.

To find the noise level

The velocity spectrum is a combination of the noise spectrum and the velocity spectrum for each velocity component. To find just the noise spectrum, the first step is to calculate the frequency spectrum for each velocity component. The high frequency part of the spectrum sometimes turn out to be flat and thereby constitutes the upper band for the (white) noise spectrum. Then integrate the energy in the box bound by the white noise and it will give an estimate of the noise variance. If the flat line near the high frequency range in the spectrum cannot be found, the noise level is too low to play a part in the data.

The webinar about "Introduction to AD2CP Turbulence Measurements" (available under Speaker Series) is recommended for anyone interested in turbulence and data analysis.

5 Data

The Signature instruments produces a large amount of data, and the following sections describe the different types. Information about data retrieval and conversion of the raw .ad2cp file can be found in the instrument specific Operations Manual, and the format of the raw data files are described in the AD2CP System Integrator's Guide.

As mentioned, the Signature Series enable direct observation of more than one physical process at the same time. With Alternating or Concurrent sampling enabled, the recorded results use exactly the same time base from the same master clock. Because of this, the recorded results are precisely synchronized relative to one another. When converting from binary to ASCII, the data will be separated in to subfiles.

➲ Example: If measuring with Current Profile and Burst, expect to get files with A0 and B0 in the file names, respectively. In addition, measuring with alternating modes will give files with the suffix A0, A1, B0, B1. A0 and B0 contain Current Profiles and Burst data from the content of Alternating plan number one, and A1 and B1 is the Current Profile and Burst data from Alternating plan number 2. Read more about this in the Operations Manual.

With the high sampling rate together with the possibility to store raw data, the stored files can grow large and be a challenge to process. To make life easier and allow the user to quickly be able to investigate the results, an additional data file will be stored containing the averaged current data. Only data where the correlation is above 50% will be included in the averaging, and the data will also include a percent-good value. This averaging is only applicable to average mode, burst data will not be processed in this manner.

5.1 Velocity data

Velocity data is output in m/s. The preferred coordinate system may be specified to use for velocity data. The raw velocity measurement is a vector in the direction along each of the beams, which is referred to as beam coordinates. Beam coordinates can be converted to a Cartesian coordinate system (XYZ) by knowing the beam orientation. Furthermore, the flow can be presented in Earth normal coordinates (ENU- East, North and Up). In order to get the information referenced to earth coordinates (ENU) it is therefore necessary to detect the instrument's orientation in space. Attitude sensors, such as magnetometer and accelerometer are therefore used to aid in the transformation needed to correct for the instrument's attitude and motion. Note that the Deployment Software is able to calculate the remaining two coordinate systems in the "Include coordinate transformations" functionality.

The coordinate systems are defined as follows:

- In Beam coordinates, a positive velocity is directed in the same direction as the beam points. Beam 1 is marked with an "X" on the head.
- In XYZ coordinates, a positive velocity in the X-direction goes in the direction of the X-axis arrow. The X-axis points in the same direction as beam 1. Use the right-hand-rule to remember the notation conventions for vectors. Use the index finger to point in the direction of positive X-axis and the middle finger to point in the direction of positive Y. The positive Z-axis will then be in the direction that the thumb points.
- In ENU coordinates, a positive east velocity goes toward east. This is also a right-handed orthogonal system. The magnetometer is oriented parallel to beam 1 and X-direction.

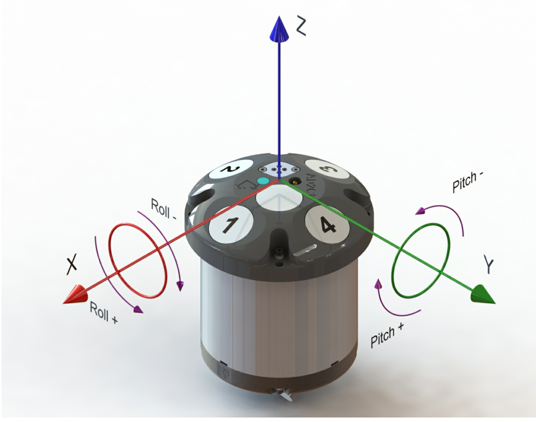

Figure 19: Instrument specific coordinates, XYZ, and definitions for pitch and roll.

ENU and XYZ coordinates are the most practical when handling data. Beam coordinates are primarily useful for higher-level turbulence calculations and for dealing with phase wrapping issues.

5.1.1 HR - High Resolution

The Signature1000 has true High Resolution (HR) measurement capabilities. By using a pulse coherent measurement method on the center transducer, the instrument is capable of vertical velocity measurements with much higher resolution than the standard measurement schemes. Note that a fundamental limitation of pulse coherent measurements is that the achievable velocity range will depend on the profiling range. The pulse coherent processing in the Signature1000 uses a novel technique for ambiguity resolution to achieve a higher velocity range than what has previously been possible for a given profiling range.

Note that the HR mode is applicable to the fifth/center beam only.

5.2 Correlation

Correlation is a statistical measure of similar behaviour between two observables, which in our case are the received signals with respect to time. Correlation is output in %, where 100% means perfect correlation and 0% means no similarity. The magnitude of the correlation is thus a quality measure of the velocity data, and as the correlation decreases so does the data accuracy. The correlation can providea a means for cleaning up data in QA/QC.

The Signature records correlation data for each cell for every ping, for each beam. Correlation correction selects velocity data having correlations below a threshold, and replaces the data with interpolated data. Read more here: QA and QC

Correlation decreases with distance from the instrument and establishes the maximum useable range of the Signatures profiling range.

5.3 Amplitude

The instrument works by measuring the reflection of an acoustic signal from particulate matter in water. Amplitude, or signal strength, is the strength of the return signal for each beam and is output in dB. Just as for correlation, amplitude decreases with distance from the instrument and also establishes the maximum useable range. That is, when the amplitude reaches the noise level of the instrument, accurate velocity estimates can no longer be made. Read more about amplitude and SNR limits in the Range and range criteria section.

Amplitude data may indicate spatial- and temporal variation. An amplitude quality test should be applied to each beam, and to each cell. If the amplitude increases with distance in one or more beams it may indicate a solid boundary such as the bottom or an obstruction. A single, unusual high return may indicate a fish. Natural temporal variation can be explained by the diurnal vertical migration of plankton. If a bottom mounted instrument is completely covered by sediments then the amplitude data will reveal this indicating a rapid amplitude decrease with distance.

5.4 Altimeter

Altimeter data provides the user with a high-resolution distance measurement to the surface or the bottom mainly used for wave and/or ice measurements. Altimeter is output in meters.

The altimeter data can be stored at a user specified interval. Check out the Signature Deployment software for more details.

The altimeter data is processed in different ways, depending on application. Find more information in the AST and the Leading Edge sections.

5.5 Sensor Data

Because of the large recorders that are now available, all raw sensor data are stored on the recorder.

5.5.1 Orientation

It is important to know the attitude and motion of the instrument during data collection since velocity is measured relative to the instrument. The orientation sensor in the Signature series consist of a three axis-linear accelerometer and a three-axis magnetometer. The accelerometer is used to derive the tilt, i.e. the pitch and roll, and the three-axis magnetometer and (along with the two tilt measurements) to derive compass readings. Orientation data is stored as degrees of pitch/roll, 3-axis acceleration vector, 3-axis magnetometer and compass heading.

The Signature series have full 3D compass and tilt readings; pitch, roll and heading will be given correctly in full 3D orientation. Note that this is only true as long as the main horizontal axis (X by default) is not pointing vertically up. The explanation for this comes from Euler angles and the phenomenon of gimbal lock. Gimbal lock occurs when the main horizontal axis (i.e. where we define heading, X by default) and vertical (i.e. where we define tilt = 0, Z by default) align. It is in this case where heading is no longer readable. For a profiling instrument this really is not a drawback since we almost always want to measure either consistently pointing vertically or sideways and not rotating in 3D.

Raw magnetometer data is collected every time the compass direction is being read (at 1Hz), and is stored on the recorder.

Compass calibration
Electromagnetic interference from magnets, metals, etc in the vicinity can interfere with the magnetometer measurements which in turn affects the compass. For a description on how to calibrate the compass in the Deployment software, check out the Signature Operations Manual. If it is difficult to accurately calibrate the compass in advance of deployment, it is possible to use the in-situ data to calibrate the compass and correct measured velocities in post-processing. The raw compass and tilt data allows the user to remove the influence of magnetic materials on the compass as long as the instrument rotates at least 180 degrees during deployment. The resulting hard iron correction improves the estimate of current direction, see the chapter on Compass Calibration Post-Deployment.

Tilted instrument
If the instrument has been tilted during deployment corrections for pitch and roll must include velocity corrections and depth corrections. Check out the sections covering Beam Geometry for some background knowledge about the corrections that needs to be done. One aspect with tilt is that the velocity measured along the three or four beams are not made at the same depth. For simplicity, imagine a 2D system with two 25-degree beams oriented 180 degrees apart. If the system is tilted

by 10 degrees, one beam will have an angle of 15 degrees relative to the vertical and the other will have an angle of 35 degrees. If the profiler is tilted severely, then cells that are at a great range can have quite different vertical positions. Note that the transforms from beam or XYZ to ENU corrects for tilt (and compass) in the sense that the final coordinate system is aligned with the gravitational axis (and the magnetic north pole).

The length of each cell (“cell size”) is defined as a time interval multiplied by the speed of sound, which is then projected onto the vertical axis. However, since the beam axis is not vertical (but 20-25°, depending on instrument version), the size of the cell will not be the same in beam 1 as beam 2 when tilted. The instrument do not apply depth corrections on the data automatically for the simple reason that the mapping is non-linear. When there is tilt, there may be residual errors in a current profile. The residual error can be characterized by:

- Smearing of shear. The shear layer will look thicker than it really is, since the measurements are retrieved at different depths.
- Apparent vertical velocities. In areas of shear, there will appear to be a vertical velocity that is in fact an artifact of the processing.

It is possible to remap the velocity cells for each beam and thereby minimize the residual error. Depth cell mapping will match the cells at equal depth by using the information from the tilt sensor when computing the velocity, to maintain the assumption of horizontal homogeneity of the current velocity. Reprocessing with the software will also ensure that the shear data are as accurate as possible.

For small angles of pitch and roll (<10 degrees), the corrections are not significant unless velocity profiles in all three orthogonal coordinates are desired. Values of horizontal water velocity are a function of the cosine of the pitch and roll, which is insignificant for small angels. However, if accurate vertical velocities are desired, even small amounts of pitch and roll can significantly affect accuracies. The best solution is to make sure the instrument is level during deployment. Tilt degrades data in ways that are not always recoverable, such as increasing the thickness of the sidelobe interference layer and in some case reducing the effective range of the instrument.

Instrument movement
The standard, built-in accelerometer and magnetometer approach works well for a fixed or slow moving instrument. However, for an instrument on a moving platform, for instance on a surface buoy, the tilt data derived from the accelerometer will be disturbed by the acceleration due to motion, and consequently the heading measurements will suffer. To overcome this, the optional AHRS (Attitude and Heading Reference System) also contains a gyroscope measuring rotation. Through advanced algorithms, the information from the gyroscope is combined with the accelerometer and magnetometer sensors to provide real tilt and heading information, even when the instrument is moving. The AHRS takes the place of the standard tilt/compass sensor and the instrument will need to be returned to the factory if an hardware upgrade is of interest. The AHRS samples every Average ping (max 1Hz) and also at the rate of the Burst measurements. Note that the buoys own response should be taken into account when configuring a system for a buoy mount. Our general recommendation is to sample at twice the buoys response frequency, normally 2 or 4 Hz.

In contrast to the standard compass; a full 3D compass and tilt reading is the result when there is an AHRS installed.

5.5.2 Pressure

The pressure sensor measures the hydrostatic pressure and reports in units of dBar. Information about the pressure is also of particular importance when measuring waves, ice drift and ice thickness (keel). All Signature instruments use the same piezoresistive pressure sensor, but may differ in its calibrated measurement range (specified upon ordering). The instruments sample pressure every Average ping (max 1Hz) and also at the rate of the Burst measurements.

The instrument do not set the pressure offset automatically, so this must be done using the Deployment software right before deployment to corrects for local atmospheric pressure. For more about this, check out the instrument specific Operation Manual.

5.5.3 Temperature

The temperature is measured by a thermistor embedded in the head, clearly visible from the outside and reported in degrees Celsius. The instruments sample temperature every Average ping (max 1Hz) and also at the rate of the Burst measurements. The time response is two minutes. It uses the speed of sound to convert time to distance, and since speed of sound depends on temperature, this information is of vital importance.

5.6 QA and QC

The Signature stores every current profile as it is being collected, before it is averaged to form an ensemble current profile. QA/QC can therefore be conducted on individual data (“single pings”) for each transducer in post processing to remove interference that has only affected one or more current profiles. This is especially relevant for removing interference from fish, which often are not sufficiently persistent to be seen in amplitude or correlation parameters but still can bias the velocity profile in either direction.

Internal processing
With the high sampling rate offered by the Signature instrument series together with the possibility to store raw data, the stored files can grow large and be a challenge to process. To make life easier and allow the user to quickly be able to investigate the results, an additional data file will be stored containing the averaged current data. Only data where the correlation is above 50% will be included in the averaging, and the data will also include a percent-good value. This averaging is only applicable to average mode, burst data will not be processed in this manner.

Post-Processing considerations
The purpose of the following bullet points is to guide the user into making routines for collecting high quality data and recognizing questionable or erroneous data. It is vital to recognize that these routines combine the use of automation, whether it be Nortek software or Matlab scripts, and careful examination and decision making.

- The first step is to make sure that the instrument was oriented as intended. This is checked by inspecting the time series of the tilt (roll and pitch) and heading sensor data.
  a. If the tilt is large (greater than 10 degrees) then a post processing option such as “map to vertical” is encouraged.
  b. If the tilt is excessive (greater than 30 degrees) it may indicate current profiles are suspect to error. This is because at least one of the transducers will in practice be oriented horizontally, making the relevant velocity component impossible to detect.

If the tilt or heading measurements change greatly from profile to profile (buoy mounted) it is wise to ensure the instrument was configured as a buoy mount.

- Check that the pressure sensor is reasonable. Any shallower than expected depth can explain and void current profiles in the same period. These events usually occur during the deployment, retrieval, and the occasional curious mariner.
- Perhaps the most important parameter to check for is the signal level for each of the individual beams for the full measurement range. The typical behavior of the signal strength profile is that it starts high and exponentially decreases with range. At some point it either dramatically increase because the transmit pulse has met a boundary (surface or bottom), or the signal no longer decreases and become constant. The cells where the signal begins to increase are likely to be corrupted by interference with a boundary. The constant signal level indicates the “noise floor”; as long as the signal level is above the noise floor the measurement in the associated cell is valid. Cells in a beam that have signal level near the noise floor are not valid; usually any current measurements beyond this range are erroneous and invalid.
- It does occur that a single beam is bad (signal near the noise floor in all cells). This can be resolved by performing a post-processing step on the three remaining beams only. For a 3-beam system; this makes one important assumption however, that the vertical currents are zero. This is

a reasonable assumption in the vast majority of current flow.

- If there are spikes or large local increases in the signal strength along a beam it is quite possible that a target found its way in the path of the beam. This may be part of the deployment frame, a mooring, or even a passing fish (or school). These cells should be flagged and removed from the profile. An algorithm that detects a threshold level is often preferred.
- Current profiles that show large current variations vertically or vertical structures should be flagged suspicious. The ones that are most doubtful are those that are physically unrealistic (e.g. 1 m/s changes over a few meters). The measurements in a profile that are far from the mean are best removed.
- One quick test to see where data is valid is to check that the vertical velocity is zero. The cells that show stronger than believable vertical velocities should be discarded.

A great, in-depth, comprehensive resource on this subject is the QARTOD (Quality Assurance of Real-Time Oceanographic Data) manual on Current Observations which is freely available online.

5.7 Compass Calibration Post-Deployment

Influence from local magnetic field can ruin the compass direction and therefore compromise the quality in the directional information. Typical sources are deployment frames, cable, alkaline batteries, shackles, vessels, etc. While the current profilers do have a compass calibration routine integrated in the software, it is not always possible to calibrate compasses in mooring frames, or from a boat. While bottom mounted instruments do not rotate, one option is to devise frames that rotate on the trip to and from the bottom while measuring.

The Signatures measure and record all three components of the earth's magnetic field, **M**, along with the single-ping beam data. As long as the instrument rotates at least 180 degrees in its mooring, it is possible to use the in-situ data to calibrate the compass and correct measured velocities in post processing. If there are no magnetic materials around, the instrument measures the same field **M** independently of its orientation. The components of M vary, but |**M**| is always the same.

If the pitch and roll are small, the vertical component of **M** can be ignored and rather focus on the horizontal components. The easiest way to see the compass offset is to plot the horizontal components as a circle and compare it to a circle centered on the origin. If an offset as in the below picture (blue dots) is seen, then the offset is caused by a nearby "Hard Iron" that rotates with the Signature. Nearby "Soft Iron" squeezes the circle into an ellipse instead.

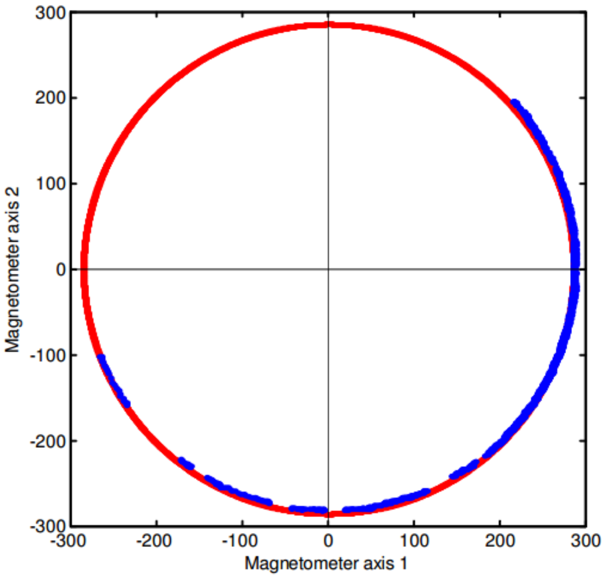

Figure 20: Magnetometer horizontal vector. Data from a perfect magnetometer will fall on a circle centered on the origin. The magnetometer data (blue dots) are offset slightly from the red, indicating some hard iron influence.

The data can be corrected by using **M**c = **M** + **M**o, where **M**c are the corrected data, and **M**o is the offset vector. The largest heading error can be found by

$$sin^{-1}\left(\frac{|M_o|}{<|M|>}\right)$$

The correction will be improved by including the vertical component of the magnetic field and/or the pitch and roll, particularly when instruments tilt, or in near-surface deployments where instruments move about more. For an example on how to correct for compass offset, check out the Technical Note called Signature 55 - Gulf of Mexico that is available on our web site.