NORTEK MANUALS

Principles of Operation
CURRENTS

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1 Introduction

This manual is designed to give an overview of the principles of operation when using a Nortek instrument to measure currents. Most information found here is general and relevant for all different types of current meters and profilers. For instrument specific details related to operation and configuration, please refer to the deployment software. For information about wave measurements, please refer to the Principles of Operation - Waves.

Nortek online
At our website, www.nortekgroup.com, you will find technical support, user manuals, FAQs, and the latest software and firmware. General information, technical notes, and user experience can also be found here. On our products page you can find technical specifications and software and firmware relevant for your specific instrument.

Your feedback is appreciated
If you find errors, omissions or sections insufficiently explained, please do not hesitate to contact us. We appreciate your comments and your fellow users will as well.

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2 Measurement principles

Nortek instruments use the acoustic Doppler principle and measure current speed and direction by transmitting high-frequency sound waves into the water column, from below or above the measurement area of interest. The instrument can either measure at one level (Current Meters) or at several levels through the water column (Acoustic Doppler Current Profilers, ADCPs).

The Doppler current sensors estimates the water velocity indirectly by measuring the velocity of the particles that are moving with the water. The instrument measures velocities along its individual beams by calculating the Doppler shift (D) of the returned sound signal that is reflected from the moving particles in the water. 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, and a transformation matrix (T) defined by the orientation of the individual beams transforms the beam velocity estimates to Cartesian 3D velocities in a XYZ coordinate system relative to the instrument head.

$$V = D \times C \times T \tag{1}$$

The built-in compass and attitude sensor can further transform the XYZ coordinates to Earth referenced coordinates, East-North-Up (ENU). In the following sections each of the components in equation 1 is described in detail.

2.1 Doppler Effect

The Doppler effect is the apparent 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 Nortek instruments use the Doppler effect by transmitting a short pulse of sound ("ping") of known frequency into the water, listening to the return signal and measure the change in frequency of the signal. The difference in frequency between the transmitted and received pulses is proportional to the velocity of the water. The emitted sound pulse does not reflect from the water itself, but from small suspended particles. These particles are typically phyto- or zooplankton, suspended sediment, or small air bubbles. The scattering materials float passively in the water 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. The sound pulse scatters in all directions when it hits the particles. Most of the sound continues forward, but a small amount is reflected back to the source. 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 consider 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 equation 2.

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

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 equation 2 one can see that:

- If the backscattering particle is moving away from the instrument so that the frequency of the reflected pulse decreases, the Doppler shift and hence the velocity of the particle V is negative.
- If the distance between the transducer and the scattering target decreases, i.e. the particle is moving towards the instrument, the frequency of the reflected pulse increases and the Doppler shift and the velocity is positive.
- If the scattering particle and the instrument stay at a fixed distance from one another, there is no Doppler shift.

In order for the instrument to be able to calculate the Doppler shift the emitted sound needs a known transmit frequency. Nortek instruments range from the so-called narrowband instruments, which transmit a pulse of near-constant frequency, to more advanced broadband instruments which sweep frequencies from low to high in its emitted signal. The signal that is emitted from a so-called broadband instrument is referred to as a chirp and a series of chirps are put together to form one transmit pulse, or ping. The difference between the highest and lowest frequency signal component is referred to as the instrument's bandwidth.

2.2 Speed of sound

The speed of sound is important when computing velocity from the measured Doppler shift as seen in equation 2 in the Doppler Effect section. The instrument also uses the speed of sound and the time lag between the transmitted and received pulse to indirectly measure distance and determine how far the pulse traveled before it was reflected.

Speed of sound increases with increased temperature, salinity and pressure. The instruments compute the speed of sound based on the measured temperature. A constant salinity is assumed, and set by the user during the configuration of the instrument before deployment. This assumption works relatively well because the speed of sound is more sensitive to temperature variation than it is to salinity variation.

- A variation of 1°C 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 speed of sound 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 atm, i.e. approximately 100 meters of water depth (derived by the hydrostatic equation). This is not compensated for by the instrument.

The estimates of the horizontal velocities will not be affected by vertical variations of speed of sound through the water column. Such vertical variations can occur as a consequence of thermoclines (changes in temperature with depth) or haloclines (changes in salinity with depth). 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 how the sound speed changes over the profile. That means that the position of the measurement cells in the water column will change if the speed of sound profile changes. 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 the sound velocity profile through the water column.

Speed of sound corrections

Sound speed errors are typically small, but if it is necessary to correct for errors or changes in speed of sound, the correction method is relatively simple. This can for example be necessary if you have entered a salinity value that is far off from the actual salinity at the deployment site in your configuration or if the temperature sensor has malfunctioned. To correct the velocity estimates, use the following equation:

$$V_{corrected} = V_{old} \frac{SS_{new}}{SS_{old}} \tag{3}$$

where V is velocity, SS_{new} is the true sound speed, calculated post deployment based on known temperature and salinity at the site and SS_{old} is the original, incorrect sound speed used.

2.3 Beam geometry and coordinate systems

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. Nortek current meters have three or four slanted beams that measures one velocity component each. The beams are tilted either 20 or 25 degrees from the vertical (refer to the data sheet for specific instrument details), and depending on the instrument type the beams will be measuring velocity at three or four different locations due to this divergent design (see Figure 1). To achieve horizontal or vertical velocity components, we rely on measurements from all three or four beams, and therefore measurements from three or four separate locations. We therefore have to assume that water moved in the same direction and with the same speed at each of the individual locations covered by each beam. This horizontal homogeneity is one of the key assumptions we do when measuring ocean currents with Nortek instruments. This is an accepted requirement, as currents vary little in the horizontal plane in most areas.

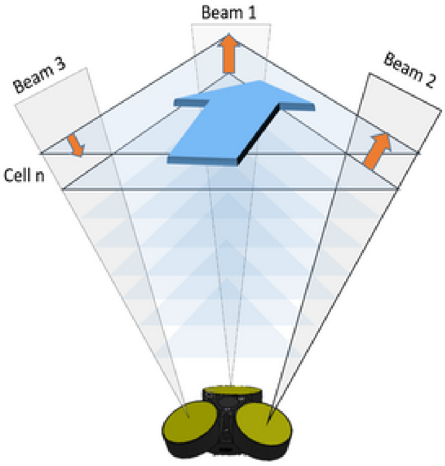

Figure 1: The beam geometry of a Signature 55. Each beam measures the current velocity at separate locations. By assuming horizontal homogeneity these individual measurements can be used to calculate the horizontal velocity component (shown by the blure arrow).

Some of our instruments also have a center transducer with a vertical beam. This can have several applications, depending on the instrument type. Please refer to the instrument data sheet for further information:

1. Since the beam is vertical it can not give any information about horizontal velocity, but it can be used to obtain a direct measure of the vertical motion. This is only available on the Signature instruments, and requires the Burst license.
2. The vertical beam is most often used as an altimeter to measure the distance to either the air-water interface or ice. For AWACs this is the only use for the centered fourth beam. For Signature instruments this requires the Wave measurement license.

The raw data collected from the instrument is the mentioned radial velocities measured by each beam. By assuming horizontal homogeneity these velocities can be converted to more applicable coordinate systems using information about the geometry of the instrument head and sensor data gathered by the instrument. Each instrument has its own unique transformation matrix, based on the transducer orientation. This matrix can be found in the data structures for the interested user. The matrix is used when transforming the along beam velocities to instrument-referenced coordinates XYZ. In the following sections each of the three available coordinate systems are explained.

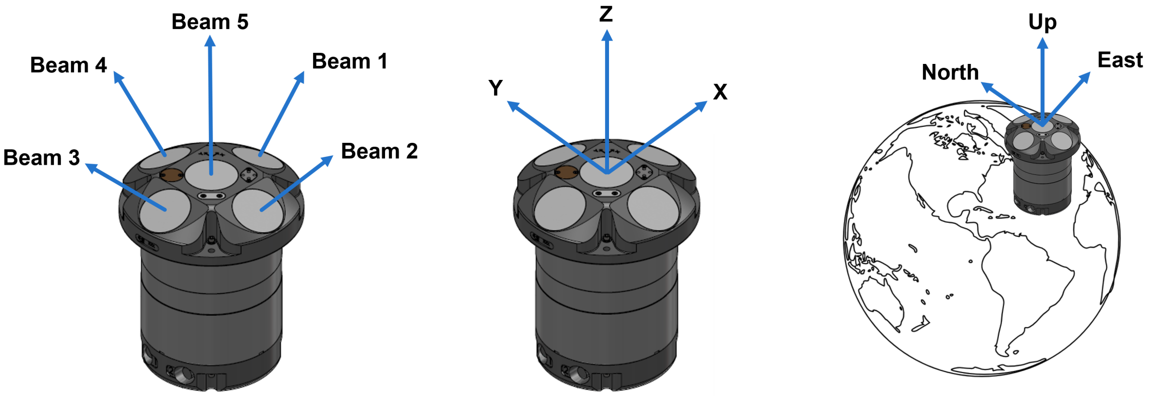

Figure 2: The three different coordinate systems shown on a Signature 500. Left to right: Beam, XYZ, and ENU.

Beam coordinate system

In beam coordinates, each beam makes up one axis and velocities are measured as vectors in the direction of the transducer beams. A positive velocity measurement is directed in the same direction as the beam points. The transducers/beams are numbered, and the axes are named according to the numbering (as shown in Figure 2). All raw velocity measurements are initially taken in beam coordinate system initially, and then converted to either XYZ or ENU. Since the transducers are fixed, the beam directions and hence the direction of the beam axes depend on the orientation of the instrument head.

Cartesian coordinate system (XYZ)

The Cartesian coordinate system is defined by an origin point and three perpendicular axes X, Y, and Z. On most Nortek instruments, the X-axis is in the same direction as beam 1. However, the X-axis does not have the same angle as the Beam 1-axis, rather it points orthogonal to the instruments with positive direction defined outwards. The Y-axis follows the same convention. The XY-plane is also orthogonal to the instrument, which means that the Z-axis points straight upwards when the instrument is looking up and straight downwards when the instrument is looking down. Two independent vertical estimates (Z1 and Z2) are provided from instruments with four slanted beams, where Z1 and Z2 are associated with beam 1 & 3 and beam 2 & 4 respectively. The axis directions can be found using the right-hand-rule with the first (index) finger pointing in the positive X-direction, the second (middle) finger in positive Y-direction and the thumb in the positive Z-direction. It is important to note that the XYZ coordinates are in reference to the instrument head so the measured velocity directions are dependent on the instrument orientation. In the XY-plane, currents flowing in the Y-direction is reported as a direction of 0° and the X-direction is reported as the direction of 90°. These current directions should not be confused with the reported heading, which will give the orientation of the instrument itself. To make use of the XYZ coordinate system knowledge about the instrument orientation, either from the heading value or from external sensors is necessary.

East-North-Up coordinate system (ENU)

ENU stands for "East", "North" and "Up" and similarly to the Cartesian coordinate system is also defined by three perpendicular axes. The first axis points towards magnetic East, the second axis points towards magnetic North and the last points vertically upwards orthogonal to the East-North plane. As with the XYZ coordinates, the right-hand-rule can be used to find the axis directions, with the index finger indicating East, the middle finger as North, and the thumb representing Up-direction. This coordinate system is relative to the earth's magnetic field and not the instrument head like the others, meaning that measured velocity directions do not depend on instrument orientation. The directions East and North will always be towards magnetic East and magnetic North, while Up will always points towards the sea surface (for a submerged upward facing instrument). Instruments with four slanted beams will provide two independent Up estimates, where Up1 is associated with beam 1 & 3 and Up2 is associated with beam 2 & 4. Just like a compass, currents flowing towards North is reported as 0° and towards East as 90°. It is important to note that only the slanted beams can be represented in ENU coordinates. If collecting current data from the vertical center beam, this will always be given in BEAM coordinates.

Built-in compass and tilt sensors make the determination of this coordinate system possible. Although tilt corrections are made during the ENU velocity conversion, these corrections are separate from the optional corrections made when remapping cells using the "remove tilt effects" or "bin mapping" feature in Nortek software. For more information about how a tilted instrument can affect your data, please refer to the tilt correction chapter.

2.4 Precision and measurement uncertainty

Every signal received by the instrument is subject to some amount of noise. The velocity measurement obtained from a single ping is typically too noisy to be used alone, but the average of a number of these pings is less noisy and therefore more useful. The Doppler noise characteristics can be summarized as:

- Random and non-biased. That means if the measurements are averaged over a long enough time period, 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.

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 estimate is commonly the average of many velocity measurements (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:

$$\sigma_{mean} = \frac{\sigma_{singleping}}{\sqrt{N}} \tag{4}$$

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

As seen from equation 4, the standard deviation of a velocity estimate decreases with increasing number of data points included in the average. The number of pings that your velocity estimate is based on depends on how you configure your instrument, and the Nortek Deployment software therefore predicts the instrument 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. The concept of "precision" is related to idea of "repeatability" as it is being used for acoustic Doppler systems. The precision value given is a theoretical estimate of the standard deviation of the velocity measurements based on how the instrument is set up. The velocity precision is always calculated along beam first and is a function of frequency, bandwidth, cell size and velocity range. From there the horizontal and vertical precision are calculated based on number of beams and the geometry of the head.

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 these, 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 is 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. This bias for each individual instrument can be found it its respective technical documentation.

3 Measurement area

The profiling instruments are 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 the scattering 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) from the instrument and each measurement can be assigned to different cells. How the position of each cell is defined is described in the next sections.

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 have shorter profiling ranges but are able to achieve higher resolution. Environmental properties and boundaries also come into play when considering measurement area. How different parameters affect your measurements and how to determine the valid range are also described in the following sections.

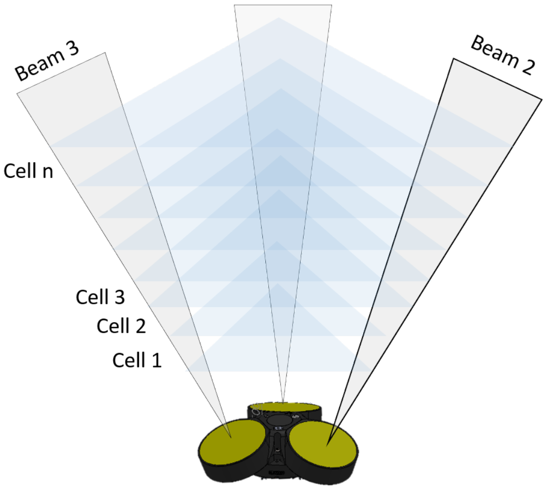

Figure 3: The measurement profile, illustrated by a Signature 55, sectioned into cells.

3.1 Range and range criteria

The profiling range and spatial resolution is primarily a function of the acoustic frequency. Lower frequency instruments have longer range than instruments using higher frequency; on the other hand, the latter has better spatial resolution. The maximum ranges for specific instruments can be found in the respective technical specifications. Be aware that these are nominal values. In addition to the instrument frequency, the profiling range is also dependent on the scattering conditions and the cell size. As described in the Doppler Effect section we depend on particles to scatter the sound signal to be able to measure velocities with the Doppler Principle. The concentration of scattering materials and the strength of the scattering return from the water will influence the profiling range; more particles reflect more sound and hence give a better range. 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.

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, amplitude and correlation.

3.1.1 Amplitude

In general, amplitude is a typical variable used to describe the characteristics of a wave. It says something about the amount of energy transferred by the wave and can be seen as a measure of how strong or big the wave is. Regarding acoustics, a greater amplitude means a greater intensity and the wave sounds louder (in the audible frequency range). The amplitude, or signal strength, for current measurements, can be defined as "a measure of the magnitude of the acoustic reflection from water". As the amplitude is a measure of the echoes, it is a function of the scattering conditions. The amplitude is given in the dimensionless units decibel (dB) or counts. The relation between the two units may vary slightly between instruments, but a conversion of 0.5 dB/counts is a good estimate.

ADCP instruments emit longitudinal sound waves into the water and measure the echoes. To receive an echo signal it is crucial to have enough scattering material in the water that can reflect the transmitted signal. When we talk about amplitude for current measurements, we usually refer to the amplitude of the echo signal, which is what the instrument registers. However, the transmitted sound pulse also has an amplitude, telling us something about how much energy is emitted from the instrument. The echo signals reflected from scattering materials usually contain far less energy, i.e. lower amplitude, than the transmitted signal, due to reflection, scattering and absorption of the signal as it travels through the profile. This also implies that the strength of the echo signal decreases with distance from the instrument because there is less energy to reflect. This decrease follows the Sonar equation and will look similar to the left amplitude profile in Figure 4. After a gradual decrease in signal strength, the amplitude reaches a constant limit known as the noise floor. At this point, the instrument only measures noise, and the standard deviation becomes large. All instruments have an individual noise floor due to internal electronic noise inside the instrument. The point where the signal strength profile reaches the noise floor value therefore determine the profiling range. Beyond this point, noise is dominating the signal and the data should be discarded.

How far the instrument can measure before the signal strength reaches the noise floor depends on several factors. The type and amount of scattering material play a decisive role. The upper layer of the water column normally contains more scattering materials, which implies that an upside-looking instrument might have a longer range than an instrument measuring from the surface and down. The range is also affected by the instrument frequency, where lower frequencies generally enable longer ranges. Cell size is also a factor when it comes to the maximum profiling range, as the cell size determines the length of the transmit pulse. Bigger cell size means longer transmit pulses and more data points within each cell. A drawback is that increasing the cell size reduces the spatial resolution. Increasing the power level means more energy is emitted, which is useful when a longer range is desired. A consequence of this is higher power consumption and possible shorter deployment. The configured profiling range also depends on chosen blanking distance (start of profile) and the number of cells. A maximum profiling range is given in the technical specifications of every current profiling instrument. Keep in mind that this is a nominal value, with the possibility that the actual values obtained could be longer or shorter.

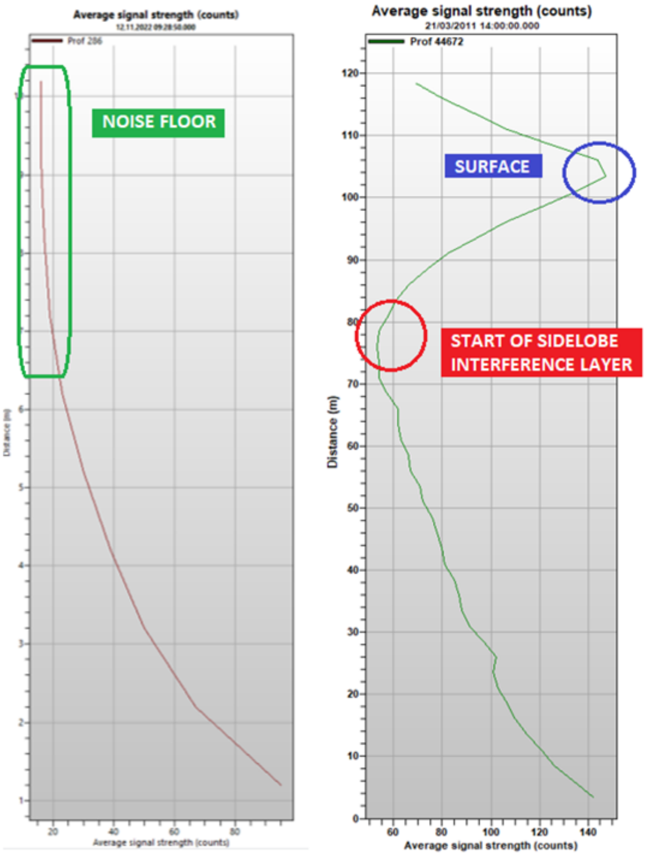

Figure 4: Typical amplitude behavior along a profiling range for two upward looking instruments. The y-axis is distance from the instrument head while the x-axis is the signal strength in counts. Left: The amplitude gradually decreases according to the Sonar equation and reaches the noise floor when the values level off. This applies in situations when the instrument does not detect blockages or boundaries. Right: After a gradual decrease in amplitude the signal strength increases as the signal approaches the surface. This increase in amplitude can also be seen when measuring the seabed or other blockages. The area in which the amplitude increases is affected by side lobe interference (see next sections).

Amplitude data can show both spatial (profiler) and temporal (profiler and current meter) variations. Figure 5 shows amplitude data from a Signature 500 data set opened in the post processing software Ocean Contour. Figure 5-a presents the amplitude readings for Beam 2 in space and time. The amplitude along the horizontal dotted line is illustrated in Figure 5-b and shows how the amplitude changes with time within that specific cell. Figure 5-c shows the amplitude along the vertical dotted line in Figure 5-a and tells how the amplitude changes along the profiling range at that specific time. The amplitude values always refer to the along-beam signal strength and are independent of the chosen velocity coordinate system.

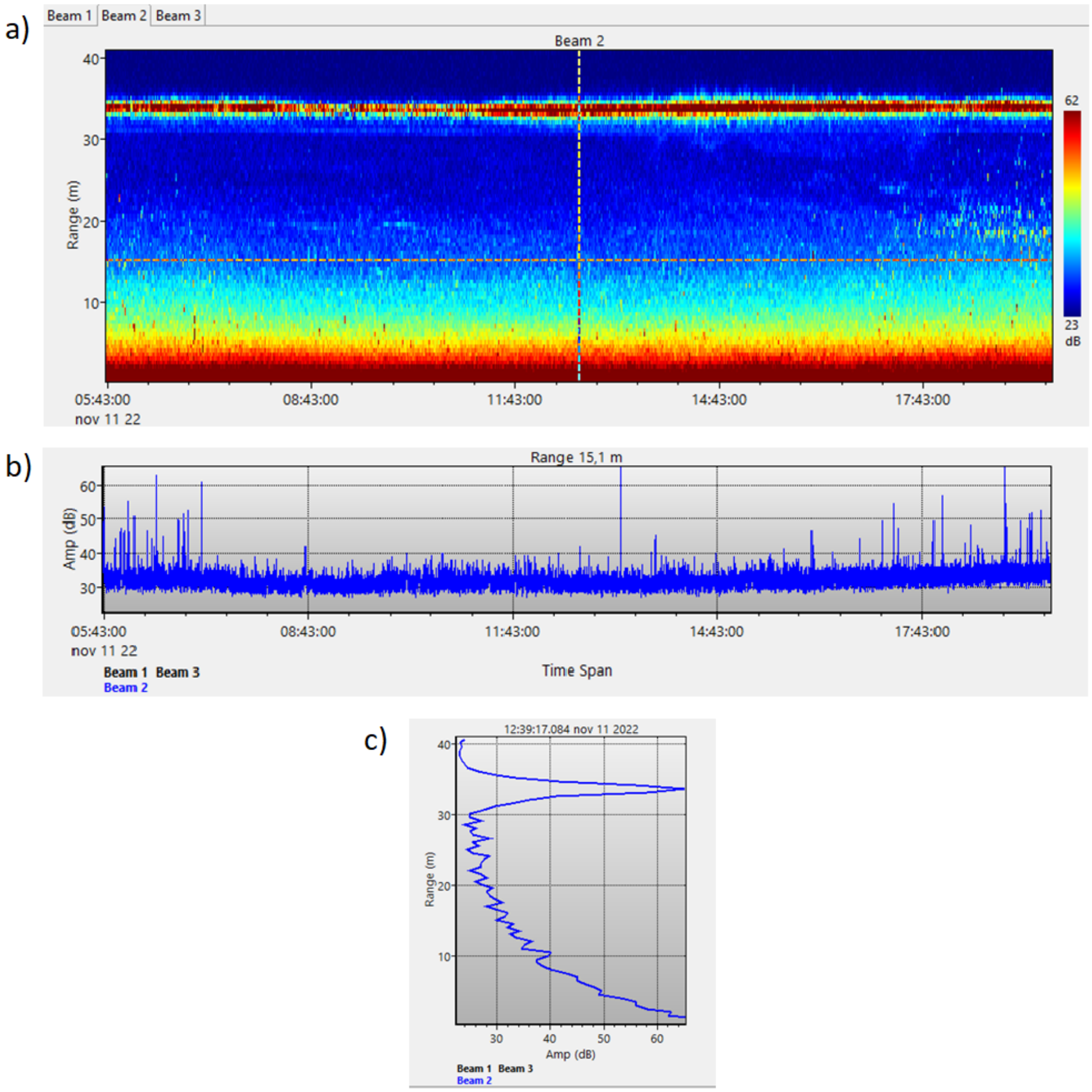

Figure 5: Amplitude can show both temporal and spatial resolution for current profilers. (a) shows both temporal (x-axis) and spatial (y-axis) variation from an example deployment, (b) shows the temporal variation in one cell, and (c) gives spatial resolution through the profile at a given time.

As a quality check an amplitude test should be applied to each beam and to each cell in your data. Whenever the amplitude profile deviates from the Sonar equation you should look closer at the data. If the amplitude increases with distance in one or more beams it may indicate a solid boundary such as the surface, bottom, or an obstruction. The right amplitude profile in Figure 4 is taken from an instrument measuring the sea surface. Here you can see that the amplitude at first decreases, but before it reaches the noise floor the amplitude then increases until the surface is detected at the peak value. This is called sidelobe interference. A single data point with unusual high amplitude may indicate a passing object that reflects stronger than water, like a fish.

3.1.2 Correlation

Correlation

Correlation is a statistical measure of similar behavior between two observables, which in our case is how similar the transmitted signal is to itself at a delayed time (when the signal is received after reflection). 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. Correlation decreases with distance from the instrument and establishes the maximum usable profiling range. A commonly accepted threshold for range when considering correlation data is 50%. Figure 6 shows how a threshold of 50% can be justified, by how the standard deviation increases as the correlation drops.

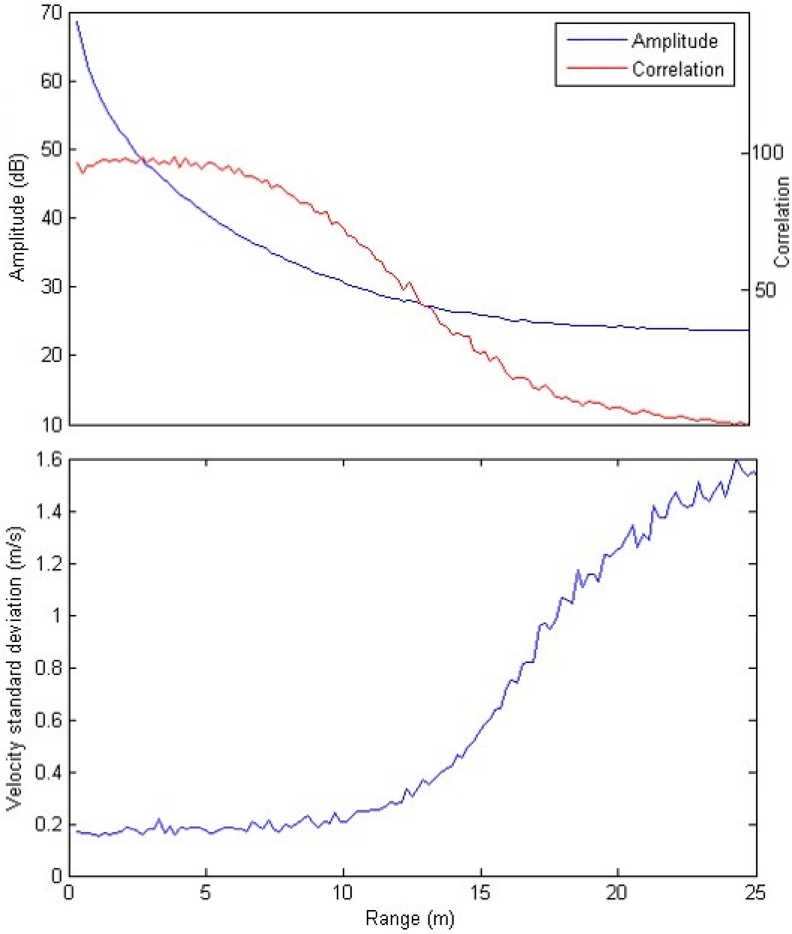

Figure 6: Upper: Amplitude and correlation. Lower: Standard deviation. Note how the standard deviation increases as the correlation drops.

Amplitude vs. correlation

Both amplitude and correlation are used as quality parameters of velocity data, and both can be used to establish the maximum range. Since they are based on different things, they are also sensitive to different abnormalities. The correlation should drop to 50% approximately where the signal to noise ratio (SNR) reached the 3 dB threshold. When this is not the case, take it as a sign that the data need more careful analysis. Note that not all instruments measure correlation, for these the focus has to be on the amplitude.

3.2 Blanking distance

In order for the transducers to transmit sound waves into the water they are applied with energy to make them vibrate. After a certain signal has been emitted, the power supply is turned off to make the transducers stop vibrating and prepare them to listen for echoes. However, the acoustic activity around the transducers won't stop immediately, but are damped with time instead. This is called ringing and will affect the measurements from the area closest to the instrument head.

To minimize the interference from ringing, the instruments are programmed to wait a short time before they start to listen for returned signals. The purpose of this is to give the transducers time to settle down first. As echoes nearby reach the instrument first, this means that there is a region right above the transducers where echoes are ignored. This period when no measurements are made is called blanking, and blanking distance is the vertical distance this constitutes to (see Figure 7). When configuring the instrument, the blanking distance is the vertical distance from the instrument head, so the blanking area along each beam is adjusted based on the transducer angle.

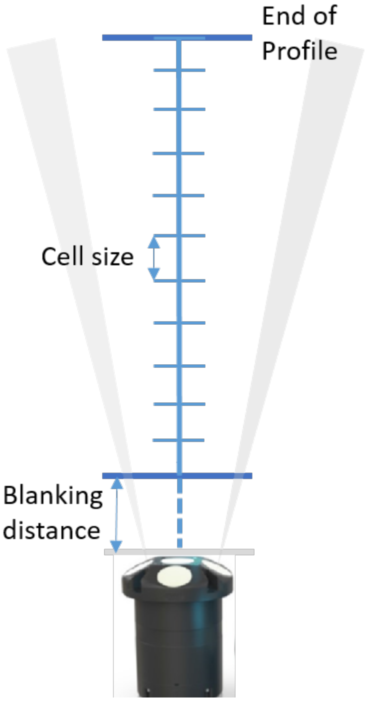

Figure 7: The structure of a velocity profile shown with a Signature 500.

The minimum blanking distance is based on the distance of which the sound travels during attenuation of ringing. The transducers of the different frequency instruments require different time to stop vibrating and the blanking distance will thus vary with acoustic frequency. In general, lower frequencies require longer blanking distances. The minimum blanking distance also depends on the strength of the returned signals. With strong echoes, as in water laden with particles, the blanking distance can be smaller than when the echoes are weak, such as in very clear water.

When planning a deployment, the instrument software sets a default blanking distance. This can nevertheless be changed within a given range, depending on the instrument frequency. The position of measurement cells is shifted when changing the blanking distance, and blanking distance (along with number of cells, cell size and scattering condition) affects the total profiling range.

3.3 Sidelobe interference

Your measurement area will be limited by sidelobe interference when measuring close to boundaries. Even though most of the acoustic energy transmitted from the beams is focused in the center of each beam, a small amount of energy will leak out in other directions - this is sidelobes. When these low-energy signals strike a boundary before the main lobe, the echoes from the leaked energy can be so strong that they dominate and contaminate the received signals - this is when you have sidelobe interference. There is no way in post-processing to filter out the effects of sidelobe interference. All cells affected should be discarded.

Sidelobes are always present when measuring with ADCPs.However, as their energy is much less than that of the main lobe, they only become significant when approaching a boundary that reflects much more strongly than the suspended particles in the water. Strong reflections occur when there are large differences in the speed of sound between two mediums, one being the water. The sea bed is a strong reflector, and the sea surface provides an almost perfect reflection. Other boundaries that can cause sidelobe interference are physical objects, such as underwater structures, buoys, and so on. Boundary conditions thus play a crucial role in determining the impact on velocity measurements. So does the scattering strength from the water and the acoustic properties of the transducers. Sidelobe interference may be unimportant with strong backscatter. It all comes down to how strong the signals from the sidelobes are compared to those from the main lobes.

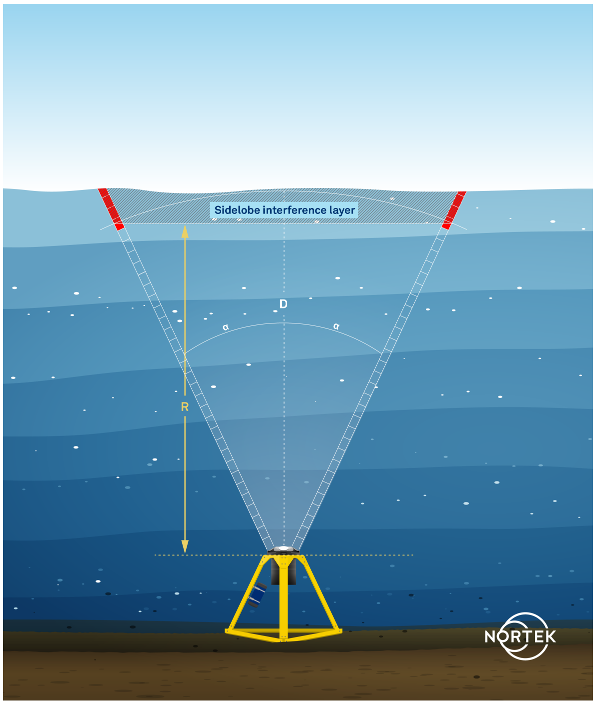

Figure 8: Sidelobe interference for a leveled instrument. The sidelobe interference layer starts at the same distance along the beam as the distance from the instrument to the boundary.

Figure 8 shows an instrument measuring towards the surface and illustrates how much of the profile can be affected by the interference. If the vertical (and shortest) distance to the surface is D, then the contamination of the current measurement begins at the same distance D along the slanted beams. The velocity data are contaminated from this distance and onwards to the water surface. The same principle applies to other boundaries. If sidelobe interference extends partly into one cell, the whole cell should be discarded, because one cannot distinguish where in the cell it applies to. The relation between the effective range R (area unaffected by sidelobe interference), the distance from the instrument to the boundary D, and the transducer angle α can be described by the following trigonometric identity:

$$R = D \times \cos(\alpha)$$

Roughly speaking, we often say that sidelobe interference can affect up to approximately 10% of the velocity profile between the instrument and the boundary for slanted beams. Vertical beams (Signature 500/1000) will not experience sidelobe interference since they point directly to the surface so that α=0° and hence R=D. However, this applies to instruments that are leveled. The impact of sidelobes increases with tilt, as illustrated in Figure 9. In such situations, the effective range decreases according to the tilt θ with the following formula:

$$R = D \times \cos(\alpha + \theta)$$

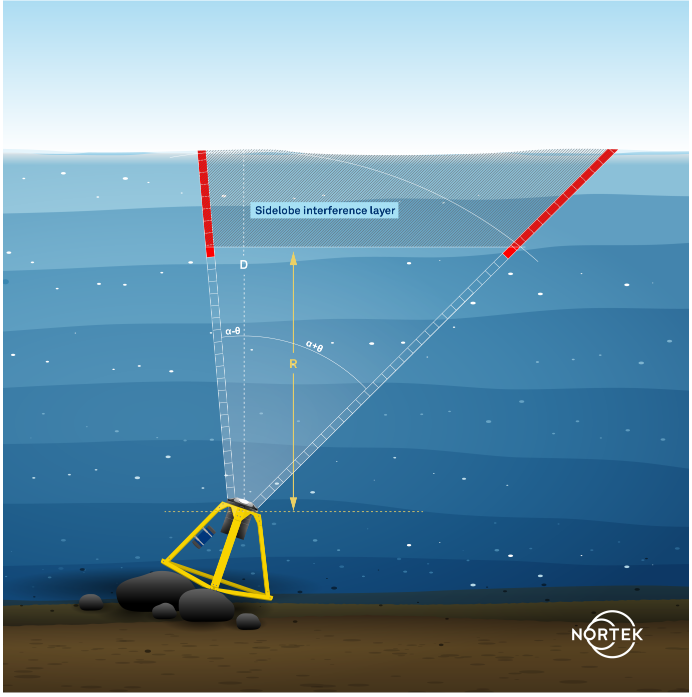

Figure 9: Sidelobe interference for a tilted instrument. The sidelobe interference layer starts at the same distance along the beam as the distance from the instrument to a boundary.

Regarding the velocity data, sidelobe interference will typically appear as a bias toward the velocity of the interfering boundary. This is a bias towards zero for the sea bed (unless there is a moving bottom). For the surface, the bias will depend on the sea state or surface wind conditions. Sidelobe interference has in many cases been noticed by high velocities in the upper layer. This comes from the sidelobes detecting movement of the surface. A recommendation when analyzing data is to check the vertical velocity (Up or Z) extra carefully in these areas. It should typically read close to zero. If not, it might be an effect of interference.

Sidelobe interference can also be spotted in amplitude profiles, as shown in Figure 4. The profile to the left is not affected by sidelobe interference, and the amplitude just decreases until it reaches the noise floor. But the profile to the right shows an example of sidelobe interference. After a gradual decrease in amplitude, the signal strength increases as the signal approaches a boundary (here the sea surface), which is represented by the peak. Sidelobes interfere in the area of increase.

Even though there is no way in post-processing to separate the bias effect from the sidelobes, there are some measures that can be taken in advance of a deployment to reduce its impact. One action is to move the instrument closer to the boundary (10% of a short profile is less than 10% for a long profile). Reduction in cell size can also be positive, as this increases the spatial resolution. Keep all objects on the rig out of the measurement area. Also, make sure to keep the instrument as leveled as possible.

3.4 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. A greater number of smaller cells give more details about the vertical variation of currents throughout the water column. Each cell represents the average of the return signal for a given period of time corresponding to that cell size. The current meters measure the water current in one defined sampling area.

Selecting a proper cell size depends on what the objective with the deployment is. If the instrument is deployed in shallow water it is usually of interest to get as much detail in the profile as possible, and therefore selecting a small cell size is key. In deeper waters, where optimal range may be the goal, increasing the cell size to the maximum may be a good approach. The length of the transmitted sound pulse is equal to the configured cell size and a larger cell size will therefore lead to more energy sent out by the instrument which again will result in a better signal strength and longer range. A larger cell size will also have a larger volume of 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 the precision and measurement uncertainty chapter for more info.

3.4.1 Cell position

The depth cell does not give equal weight to all points within the cell, but is weighted towards the middle. As shown in figure 10 the instrument applies approximate triangular weighting to each measurement cell. To find the exact location of the depth cell, relative to the instrument, you have to take both blanking distance and cell size into account and the the nth cell is centered at a vertical distance from the transducer given by the following formula:

$$centher\ of\ n^{th}\ cell = BD + n \times CS$$

where BD is the configured blanking distance and CS is the cell size. As an example, if the blanking distance is set to 1 m and the cell size is 0.5 m, the center of the first cell (n=1) is located at $1m + 1 \times 0.5m = 1.5m$ from the instrument. The full extent of the measurement area for the cell is between 1 m and 2 m. Correspondingly, the center of the second cell will be at 2 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(α) due to the transducer geometry, where α is the angle of the beam relative to the vertical. The principle of triangular weighting is the same for a single point current meter as for a profiling instrument.

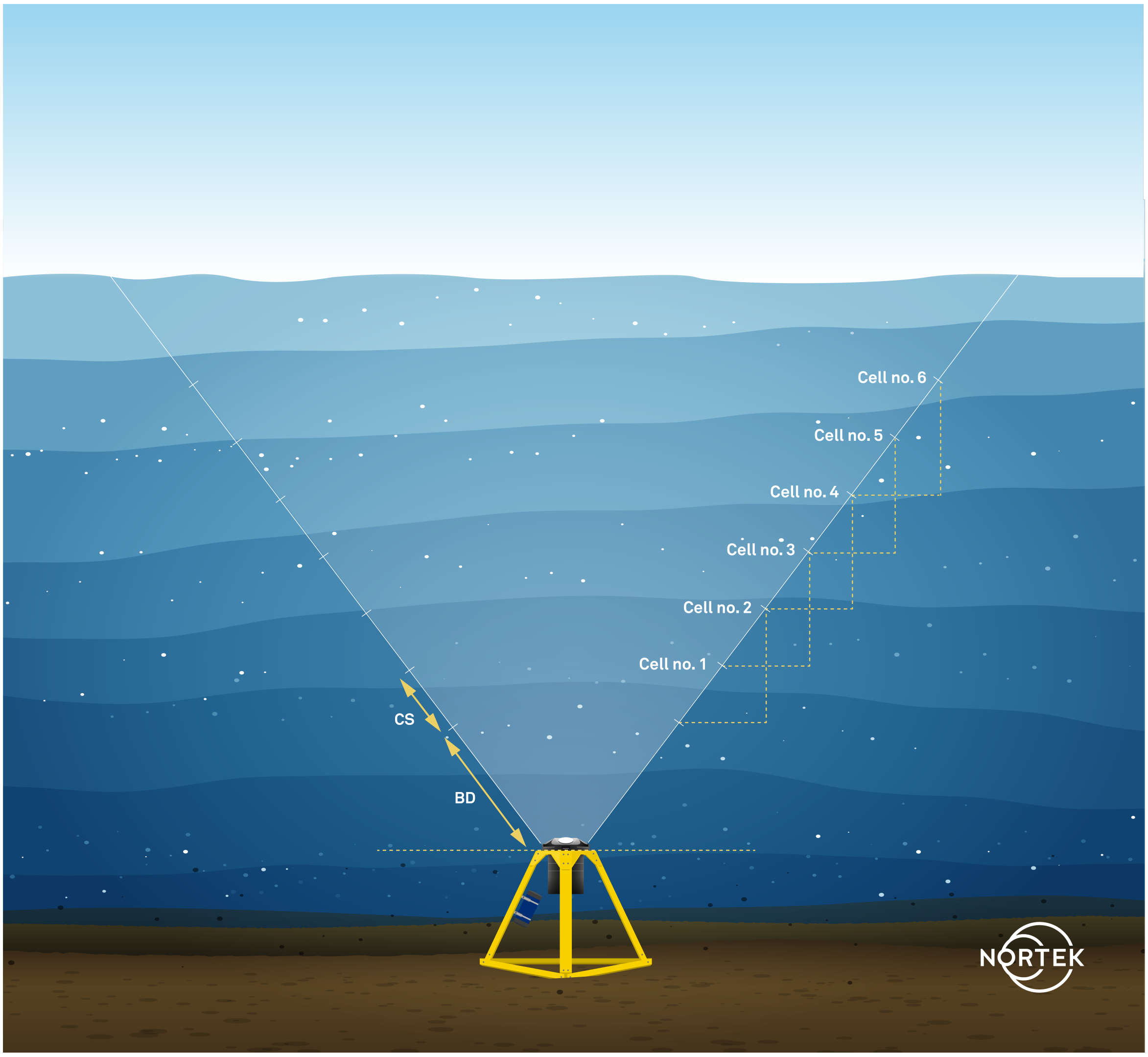

Figure 10: The position of each cell in the profile with blanking distance = BD and cell size = CS. The dashed lines indicates the triangular weighting given to measurements within each cell, and how these measurement areas overlap due to the transmit pulse length.

3.4.2 Tilt correction

During current measurements the water column is, as discussed in the previous sections, divided into several segments referred to as cells. This division allows velocities to be measured at various depths. For the best data quality, instruments should be kept stable looking straight upward or downward without any tilt. This is often difficult and sometimes impossible to achieve. The effect of a tilted instrument can be seen Figure 11. When the instrument is tilted, the pointing angle of the instrument beams will be shifted so that the same cell from different beams are not located at the same depth level. Keep in mind that one of the key assumptions when measuring current velocities with an ADCP is that the flow is horizontally homogeneous so that several beams at different angles can be used to resolve different velocity components at individual depth levels. When the instrument is tilted the same cell from different beams will be located at different depths, and when data from these cells are combined residual error in the profile may occur. These errors are typically characterized by:

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

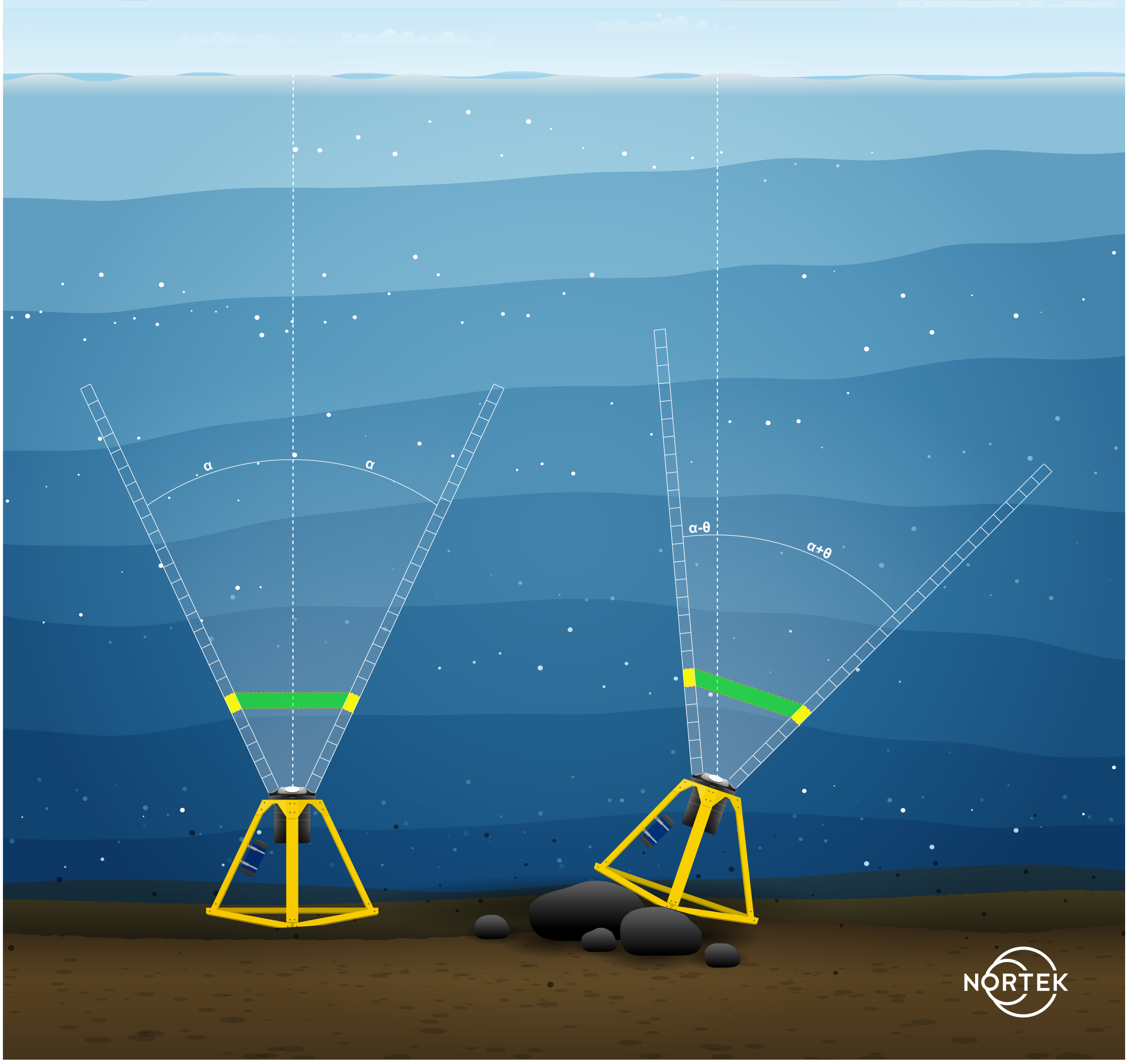

Figure 11: The dispacement of cells in different beams when the instrument is tilted shown with a Siganture 500. α is the beam angle constant with the isntrument head, while θ is the tilt of the instrument.

To avoid these errors in your data, it is possible to remap the cells for each beam so that cells at equal depth are matched and velocities will be computed at that level. This process is called bin mapping and uses the pitch and roll information from the instrument tilt sensor. For the latest Aquadopp range of products (with serial numbers on the form S2SP 123456) bin mapping is done automatically within the instrument on each individual ping, and data outputted is corrected for potential tilt. For the previous generation of Aquadopp Profilers, this correction has to be done in the post-processing. Since the Aquadopp Profiler does not save each individual ping, the tilt correction can only be applied to the averaged product from each average interval. The Signature family of products does save each individual ping so even though also here the correction has to be done in post-processing it can be applied prior to the averaging.

There is no set limit of tilt for when you should or should not apply the bin mapping to your data, as the effect of tilt will depend on the conditions at site. We highly recommend that you carry out thorough quality control of your data, and if the tilt is over 5 degrees you should consider bin mapping. When the instrument tilt exceeds 20 degrees the effective range of the instrument is reduced drastically, since at least one of the beams will be pointing more horizontally than vertically. As described in the sidelobe interference chapter an increase in tilt is also associated with increased sidelobe interference which also affect your range.

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