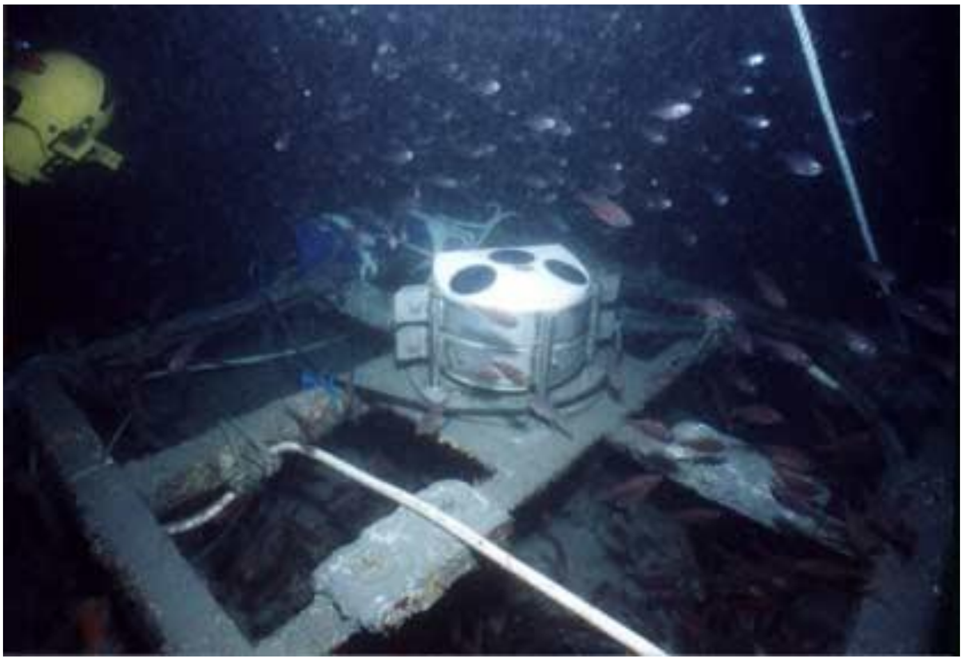

NORTEK AS

PRINCIPLES OF OPERATION

Measuring Currents and Waves

April 2013

CONTENT

INTRODUCTION

Nortek AS is a scientific instrumentation company that develops and distributes water velocity instruments. Our products are based on the acoustic Doppler principle and span from single point turbulence sensors to long range current profilers. Figure 1 show some of the instruments Nortek currently produce.

Figure 1: Some of the instruments Nortek currently produce: (a) Aquadopp Profiler, Aquadopp Current Meter, Vessel Mounted (VM), Continental, Acoustic Wave and Current Meter (AWAC), Vectrino, Vector, and Aquadopp Current Meter Deep Water (here: a 6000 m system).

The instruments can be divided into three main groups; Current Meters, Current Profilers and Velocimeters:

Current Meters: Aquadopp Current Meter and Deep Water Aquadopp Current Meter (DW) measure water currents at one level. The Aquadopp Current Meter, henceforth called Aquadopp, has three acoustic transducers that can be arranged in a variety of head configurations. Current meters are simple to use and appropriate when only one measurement point is required, or when measurements at great depths are of interest. The Aquadopp and Aquadopp DW are available as 2 MHz systems. The DW Aquadopp is designed for deployments down to 3000/6000 m. The Current Meters are equipped with temperature, compass, tilt and pressure sensors, and an internal battery pack that enables autonomous deployments for very long periods of time.

Current Profilers: The Aquadopp Profiler (AquaPro), the Acoustic Wave and Current Profiler (AWAC) and the Continental measure current speed and direction in multiple layers through the water column. Nortek makes current profilers with ranges from a few cm (High Resolution (HR) mode) to several hundred meters, available as: 2, 1, 0.6, or 0.4 MHz (for the AquaPro, the latter three frequencies for the AWAC), 2/1 and 2/0.6 MHz (Z-cell profiler) and 470 or 190 kHz (Continental). The AWAC may also be used as operational Vessel Mounted (VM) systems, but then without bottom tracking. The Aquadopp Z-cell is an extension of the AquaPro; it has the same specifications, but with the added capability of measuring the current at the level of the instrument ("Cell Zero"). The Current Profilers are equipped with temperature, compass, tilt and pressure sensors.

Velocimeters: The Velocimeters belong to a special class of high-resolution 3D instruments used to study rapid velocity fluctuations in the laboratory or in the ocean. These instruments have three or more focused beams to measure with high sampling rates in a small volume (single point). The basic measurement technology is coherent Doppler processing, which is characterized by accurate data at high rates with no appreciable zero offset. The Vector is a field instrument designed for measurements of rapid small scale changes in 3D velocity, used for turbulence, boundary layer measurements, surf zone measurements, and measurements in very low flow areas. The Vectrino is used in hydraulic laboratories to measure turbulence and velocities in flumes and physical models. The Vectrino Profiler is a profiling version of the Vectrino, with a 3 cm profiling zone. The Vector is equipped with temperature, compass, tilt and pressure sensors. The Vectrino has a thermistor embedded in the probe.

Waves: Some of the instruments can, in addition to making current velocity measurement, be used as wave gauges. Wave systems measure both wave height and direction. The AWAC is perhaps the most respected, sophisticated and frequently used acoustic Doppler profiler and directional wave gauge in the world. The AWAC may use a combination of the Acoustic Surface Tracking (AST), velocity data and pressure data to make high quality wave measurements, and may be deployed up to 100 m below the surface.

The AquaPro and Vector are also able to burst sample the pressure sensor and one cell of current velocity. Due to the very small sampling volume that can be precisely positioned, the Vector is an excellent choice for making wave measurements in very shallow water or in the surf zone. Alternatively the Aquadopp may be regarded as a more cost effective directional wave gauge. The AquaPro, Vector, and Aquadopp are PUV wave measurement instruments.

This document is divided into two parts, the first covers the underlying principles for obtaining current measurements. The Doppler Effect is described and the individuality and special features of the instruments are highlighted. Some limitations and special considerations for measurements are presented at the end. The second part focuses on waves and wave processing methods. Special wave properties are described to explain how it is possible to measure and obtain wave parameters, and what limitations that exist. The wave parameters of interest, both directional and non-directional, are described, and the different processing methods for obtaining these parameters are presented.

PART I: CURRENTS

1. BASIC OPERATING PRINCIPLES

1.1 THE DOPPLER EFFECT

The Nortek instruments measure the velocity of water by utilizing a physical principle called the Doppler Effect, illustrated in Figure 2. When a wave source moves with respect to an observer, or when the observer itself moves relative to the wave source, the Doppler Effect can be observed. For example, if a train whistle is heard when standing still, the sound waves will travel with the same speed in every direction, and an observer (not moving) will hear a uniform sound. When the train starts to move towards the observer, each sound wave originates from a position that is one step closer to the observer for every second. The time it takes for the sound wave to reach the observer declines steadily, i.e. the waves arrive with decreasing time intervals, and this can be construed as a frequency shift in the sound wave. Based on this perceived frequency shift, the speed of the train can be measured. When the observer moves and the source of the waves is still, the Doppler frequency shift still appears because the velocity of the sound wave relative to the observer is changed.

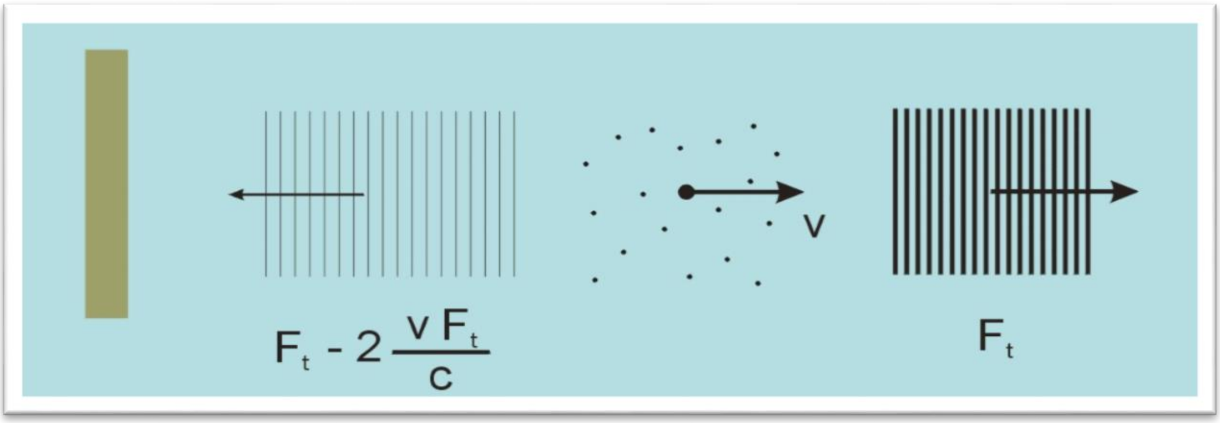

Figure 2: An acoustic echo reflected from moving particles is shifted in frequency (Doppler shifted) in proportion to the particle velocity. F_t is the frequency of the transmitted pulse.

Acoustic Doppler instruments transmit a short pulse of sound ("ping") of constant frequency into the water, listen to its echo and measure the change in pitch or frequency of the echo. The difference in frequency between the transmitted and the 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 zooplankton, sediment or small air bubbles. The scattering material 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. Figure 3 illustrates the Doppler Effect; the pulse is shifted/compressed to a higher frequency upon return (Figure 3 b)). This illustrated shift indicates that the reflecting particle moves toward the instrument. In the opposite case, when the target moves away, the received signal pulse is stretched compared to the transmitted pulse. When the target is stationary, the received signal will have the same frequency as the transmitted pulse. Only the velocity parallel to the beam is measured, since this is the only motion that affects the Doppler Shift. It does not sense the velocity perpendicular to the beam at all. The Doppler Shift is thus used to calculate the velocity of the water along the path of the acoustic pulse. The following equation expresses this:

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

Here, V is the current velocity, $F_{Doppler}$ is the change in received frequency (the Doppler Shift), F_{source} is the frequency of the transmitted wave and C is the speed of sound in water.

The first term on the right hand side of the equation tells us the same as Figure 3 illustrates; if the distance between the transducer and the scattering target increases (decreases), the frequency of the reflected pulse decreases (increases). The rightmost term includes the speed of sound, so that the actual velocity is calculated.

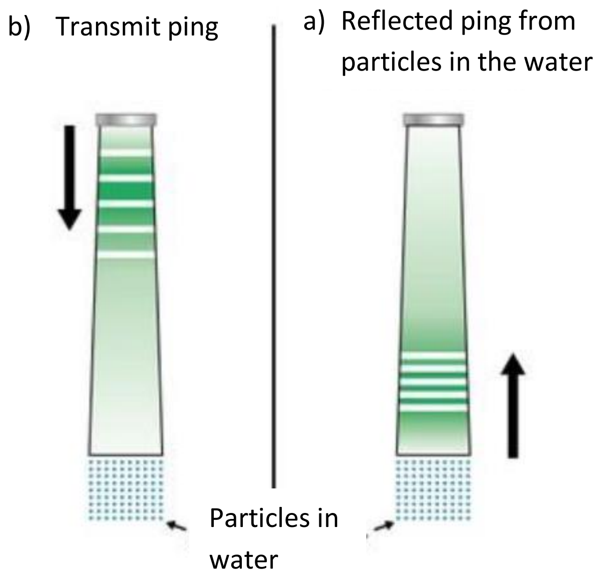

Figure 3: Illustration of a pulse transmitted (a) and reflected by particles in the water (b).

There are many ways to measure the Doppler Effect, each with its own advantages and drawbacks. In most cases Nortek implements a narrowband auto-covariance method because it has been established as robust, reliable and accurate. Auto-covariance is a statistical method similar to the covariance method, which calculates how much two variables change together. The auto-covariance covers the covariance of time series; a variable is compared to the time-shifted version of itself.

PULSE COHERENT PROFILERS

A pulse coherent profiler must transmit at least two pulses in order to obtain a measure of the current velocity, as opposed to the method described above, where a measure of radial speed along its acoustic beams is obtained through the calculated Doppler shift from one emitted pulse. The Aquadopp HR-Profiler, the Vector and the Vectrino are Pulse coherent instruments. The backscattered signal is range-gated (separated into different segments for independent processing) for each pulse. After the second pulse is range-gated, the phase difference between the backscattered signals is calculated for each range cell. The phase difference is a direct measure of the velocity, expressed as

$$V = \frac{\Delta\varphi C}{4\pi F_{source} \Delta t}$$

Here, V is the current velocity, $\Delta\varphi$is the phase difference, F_{source} is the transmitted frequency and Δt is the time difference between two consecutive pulses.

The Doppler phase shift is computed using the covariance method. By computing the complex covariance of the two return signals, the Doppler phase shift can be calculated by taking the four quadrant arctangent (atan2 in most programming languages) of the real and imaginary parts of the covariance function. This restricts solving the phase difference within the range of [-π, π]. The calculation of φ is beyond the scope of this manual, but the impacts of using this method is important. It introduces the problem of ambiguous determination of the phase shift; if the phase difference goes outside the range of ±π, the measurement uniqueness is lost, something known as Velocity ambiguity. For example, a sine wave with phase -π looks the same as a sine wave with phase π. Read more about this in Section 4.4.

Pulse coherent systems are typically used for difficult measurement situations such as turbulence measurements, very slow, low energy flows, and rapidly varying flows requiring high single ping accuracy. They can work well in areas with high shear, near boundaries, under breaking waves, and many other situations. Pulse coherent data from single or small ensemble average measurements are useful because of the individual measurement accuracy and low noise. Pulse coherent profilers can measure in far smaller cell sizes (on the order of 1 cm) providing more details of the flow than standard Doppler systems.

The Pulse Coherent Primer document (Technical note no. 027) [1] that discusses the basic theory and operations of the instrument using pulse coherent methods is highly recommended reading for users of pulse coherent profilers. It provides explanations and examples of common issues such as ambiguity velocity, correlation and coordinates transforms.

1.2 DOPPLER BEAMS

Doppler current sensors use large transducers (relative to the wavelength of the sound) to obtain narrow acoustic beams. Narrow beams are essential for obtaining good data. E.g. the beams on the AquaPro have a width of 1.7° (2 MHz), 3.4° (1 MHz), 3.0° (600 kHz) or 3.7° (400 kHz).

One beam is required for each velocity component, so to obtain data for three velocity components (e.g. east, north and up), three beams are required. The beams measure the velocity of particles in three different places. The instrument combines the three along-beam velocities and uses the relative orientation of the transducers to calculate the 3D water velocity.

MONO-STATIC DOPPLERS

Mono-static systems use the same transducer to both transmit and receive signals. The transducer generates a sound pulse at a known frequency, and when the pulse hits the particle, some of the energy is reflected along the same axis as the transmitted pulse, and is registered by the instrument. The three beams measure the velocity in three different locations, due to the convex design of the instrument head. An essential and reasonable assumption for this calculation is that the flow is uniform across layers of constant depth.

BI-STATIC DOPPLERS

Bi-static systems use separate transmit and receive beams. It transmits through a central beam and receives through the beams displaced off to the side (see e.g. Figure 7). The physically separated transmitter and receiver result in motion along two axes, corresponding to each transducer's normal vector, contributing to the motion. Thus, the motion along the angular bisector is what is actually measured. Here the assumption of homogeneous flow, as required for the mono-static systems, is not necessary. Bi-static systems simultaneously sample small volumes or areas, thereby providing full three dimensional measurements of the velocities.

2. MEASUREMENT AREA

The instruments measure the velocity in three dimensions. Each transducer generates a sound pulse and measures the Doppler shift of the returned signal. The Doppler shifts from all the three beams are combined to calculate the 3D velocity in a specified depth layer, a sampling volume or in a profile covering a defined depth. The measurement area varies according to the transducer geometry, the frequency used, blanking distance, deployment method etc. In this section, the difference between the *current meters*, the *current profilers* and the *velocimeters* regarding measurement area is in focus.

2.1 CURRENT METERS

Current meters measure the water current at one defined sampling area. The volume of the body of water covered by the three beams is dependent on the distance from the instrument, the blanking, the cell size and the beam geometry. In Figure 4, you can see the measurement cell location of an Aquadopp DW. The same configuration defines the measurement location for the Aquadopp.

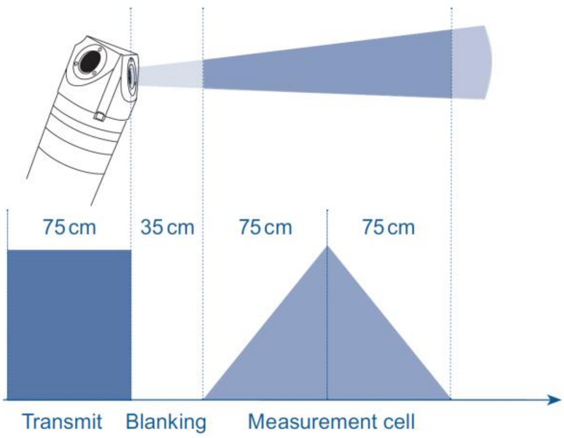

Figure 4: Measurement cell location, here for the Aquadopp DW.

Remember that the transducer works as both a transmitter and receiver. The transducer vibrates to produce a sound wave. It does not stop vibrating immediately after the supplied energy has stopped; the vibrations are damped with time. This is called 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 area is user selectable in the software.

One measurement cell represents the average of the return signal for a given period. The cell size and the transmit pulse are of equal size. The cell is shaped like a triangle, as shown in Figure 4, due to convolution; this is indicative of the weighting of the measurement. Even though the cell extends 150 cm, the nominal cell size is 75 cm because the cell is most sensitive to backscattered echoes in the middle 75 cm. Thus, the maximum extent of the cell is double the length of the transmit pulse.

The beam geometry is determined by the orientation of the acoustic beams. A variety of sensor heads are available for the Aquadopp; a Standard sensor head, a Right angle sensor head, a Symmetric sensor head (as Aquadopp DW in Figure 4), an Asymmetric sensor head, a Hockey-puck-looking sensor head and a 2D side-looking sensor head. The flexible transducer design is the key to the wide range of Aquadopp applications. The Aquadopp beam geometry is one of its innovative features; it gives you more flexibility with mounting options. For example it allows you to design your mooring to minimize disturbance caused by the mooring itself (more on this in the Mounting Guideline available at the Nortek web).

2.2 CURRENT PROFILERS

Current profilers measure current speed and direction in multiple distances from the transducers. Figure 5 shows the profiling range divided into a few regions. The current profilers have three beams oriented at 25° off the vertical axis, and equally spaced at 120° azimuth angles.

Closest to the transducers is a region called the blanking, with the already described purpose of minimizing the interference of ringing in the data. The size of the blanking varies with acoustic frequency; lower frequency instruments typically have longer blanking distance (cf. Table 1, page 15). The software sets a default blanking distance, but you can adjust the range out further. The Aquadopp Z-Cell solves the possible problem of losing near-instrument measurements. This is accomplished by including three horizontally oriented transducers which measure a 2D current velocity at the level of the instrument.

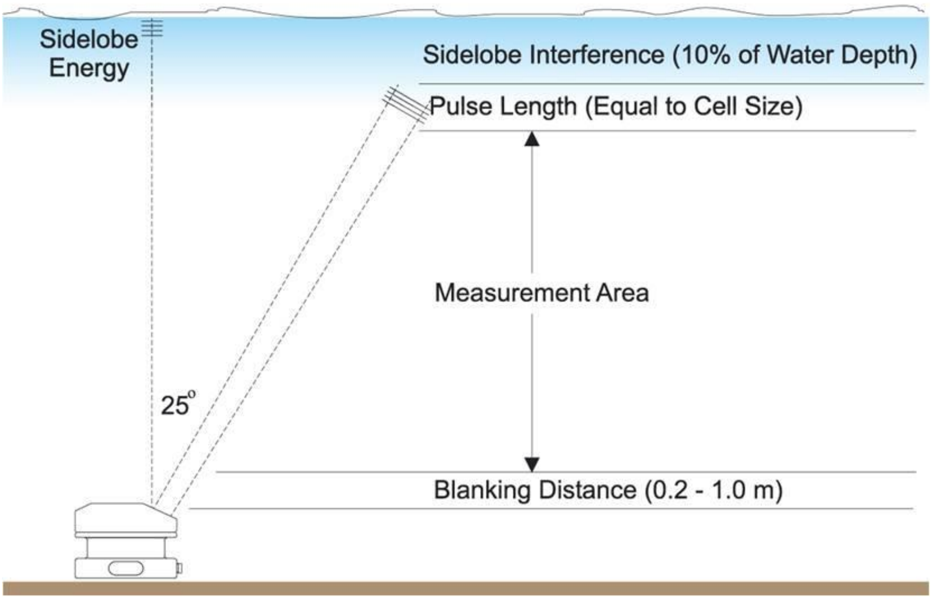

Figure 5: The AWAC profiling range broken down into different regions.

The Current Profiler will make velocity measurements in the *Measurement Area* (cf. Figure 5). The measurement location is a function of the time at which the sound pulse hit a particles and is reflected back to the source. The continuous return signal from the transmitted sound wave is received and amplified before it is sectioned up into smaller segments in the instrument, where each segment corresponds to a depth cell. Each cell represents the average of the return signal for a given period, according to the user-specified cell size. The velocities from the three beams are combined at each cell so that the 3D velocity is calculated, making a velocity profile of the measurement area.

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

- The size and location of the depth cell are determined both by the transmit pulse length and the size of the received echo segment ("The receive windows" – how long the instrument listens).
- Mathematically, the size of the depth cell is the convolution of the transmit pulse length and the receive window.
- The depth cell does not give equal weight to all points within the cell but is weighted towards the middle. When the transmit pulse and the receive pulse are matched, the weighting function has a triangular shape.

Nortek instruments use a transmit pulse that is equal to the user specified cell size, with the consequence that adjacent cells overlap. The centers of the cells are separated by the user specified cell size, as seen in Figure 6.

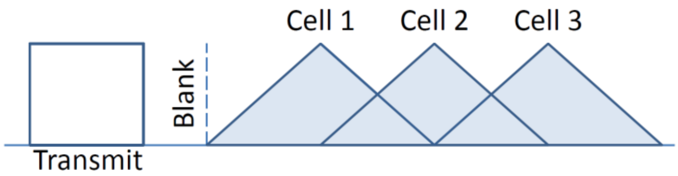

Figure 6: A series of cells where the separation between adjacent cells is equal to the length of the transmit pulse.

The first cell is centered at a distance equal to:

$$Center\ of\ first\ cell = Blanking + n * cell\ size$$

For example, the default AquaPro configuration 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 $\frac{1}{\cos 25}$ due to the transducer geometry.

The total range of the measurement area is determined by the acoustic frequency (see Table 1) and the scattering return from the water. The latter will be reviewed in Section 4.6.

2.3 VELOCIMETERS

All Acoustic Doppler Velocimeters send out short acoustic pulse pairs from the transmitter (center) element. When the pulses travel through the focus point for the receiver beams, the echo is recorded in each of the acoustic receiver elements. The phase shift between two subsequent pulses is then processed to find the actual velocity of the water, based on the Doppler shift. The result is scaled with the measured speed of sound in the liquid, and then the velocity vector is either recorded or transmitted to a PC at a rapid rate.

Note that for mono-static systems, the relative motion along the transducers' normal vector is measured. For bi-static systems, the transmitter and receiver are physically separated. This results in motion along two axes. The Doppler shift observed at each receiver is proportional to the component of the flow velocity along the bisector of transmit and receive beams (see Figure 7a)). Doppler shifts measured at all three receivers provide estimates of flow velocity along three different directions, which are then combined geometrically to obtain the three orthogonal components of the water velocity vector V (illustrated by the blue arrow in Figure 7b)). Thus, by knowing the relative orientation of the bi-static axes, the velocimeters are able to calculate the 3D water velocity in the sampling volume. The receive beams are slanted 30°, thus the angular bisector is 15° away from the transmit beam. The result of measuring the bi-sector is that the instrument is more sensitive to the Z-velocity (the component parallel to the transmit beam) than it is to the X- or Y-velocity. Consequently, the Z-velocity component yields a lower measurement uncertainty.

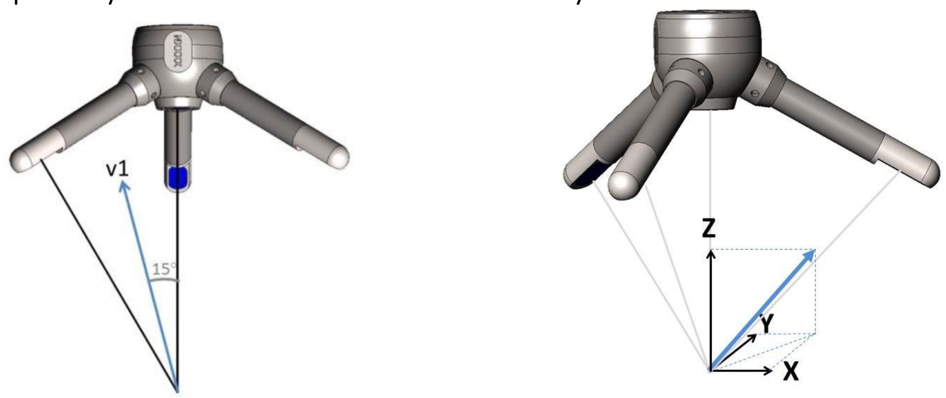

Figure 7: a) The transmit/receive beam pair is sensitive to velocity in the direction of the angular bisector between the beams. **b)** The blue arrow indicates a positive velocity.

Figure 8 shows how the Vector beams intersect each other 157 mm from the transmitter. The measurement volume is defined by this intersection and by range gating in time. The transmit transducer sends a short pulse that covers only about 4 mm vertically, and the receivers listen to an echo that corresponds to about 14 mm vertically. Since the Vector use three receivers, all focused on the same volume, it obtains three simultaneous velocity components from that very volume.

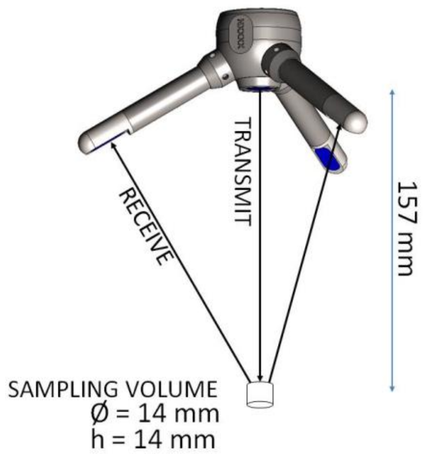

Figure 8: The Vector beams intersect each other at a known distance from the center transducer, defining the measurement volume.

The Vectrino measurement volume is also defined where the beams intersect each other and range gating in time. For this instrument, they intersect each other 50 mm from the transmitter. The transmit transducer sends a short pulse that covers 3-15 mm vertically (user adjustable), and the receivers listen to an echo that corresponds to this volume (see Figure 9). The diameter of the volume is 6 mm. The Vectrino Side-looking probe (Figure 9, to the right) has two horizontal beams and two slanted 65° from the vertical. The two horizontal beams measure the U and V velocity. This means that the two slanted beams are not needed to measure the horizontal velocity, thus the side-looking probe can act as a 2D system. Side-looking probes do not have the problem of weak spots (cf. Section 4.3), so they are a little more robust to operate, especially in high flow environments. Due to the design, the side-looking probe has higher instrument noise in the vertical than in the horizontal.

The Vectrino and Vectrino Profiler have four receiver arms as opposed to the more traditional three. Because of the arrangement of the receiver arms, each pair (composed of two opposing receivers) can measure a horizontal component and the vertical velocity. Z1 and Z2 are the vertical velocity estimates associated with receivers 1 & 3 (X) and 2 & 4 (Y) (cf. Figure 11, upper part). Z1 and Z2 are independent measurements of the vertical velocity for the standard downward looking probe. Note that the side-looking probe does not have a secondary measurement of the vertical velocity. Z1 will be the correct vertical velocity and Z2 should be output as zero.

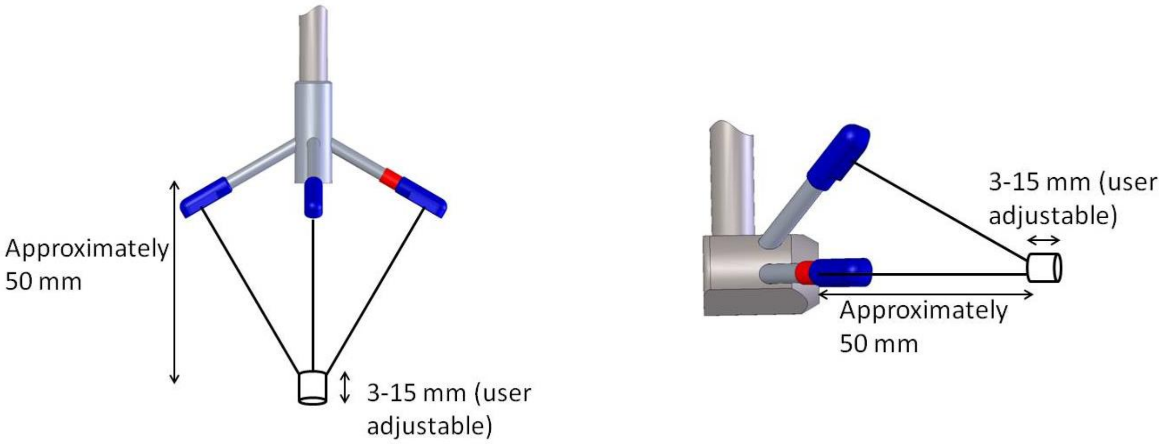

Figure 9: The Vectrino beams intersect each other at a user adjustable distance from the transducer, defining the measurement volume. The Vectrino to the right has a side-looking probe.

The mechanical and acoustic characteristics of the Vectrino and the Vectrino Profiler are identical; both employ the same probe assembly and transducers. However, the Vectrino Profiler provides for profiling over a 30 mm range interval thereby allowing measurement of the spatial structure of the flow (see Figure 10). The Vectrino Profiler pulse intervals are longer than the Vectrino because of the need to sample data from farther away when forming velocity profile. Four passive transducers, angled at 30° towards the center surround the central active transducer, allowing 3D velocity measurements. With a profiling range up to 30 mm, a usable profiling region approximately 45-75 mm in height from the central transducer is provided. A description of the Vectrino Profiler hardware and software capabilities, some of the novel features and the algorithms used by the instrument can be found in [2].

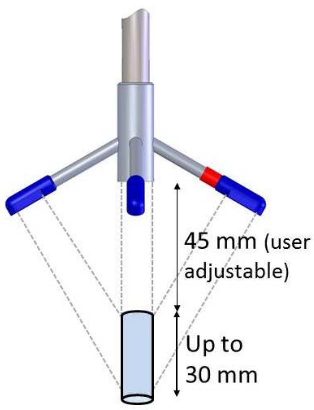

Figure 10: Vectrino Profiler sampling area.

2.4 SUMMARY

Table 1: Overview of the instrument's default blanking distances, maximum number of cells, cell sizes and ranges.

Instrument	Frequency	Min. Blanking	Max. # cells	Cell size	Profiling range
Aquadopp	2 MHz	0.35 m	1	0.75 m	-
Aquadopp DW	2 MHz	0.5 m	1	0.75 m	-
AquaPro	400 kHz	1 m	128	2-8 m	60-90 m
	600 kHz	0.5 m	128	1-4 m	30-40 m
	1 MHz	0.20 m	128	0.3-4 m	12-20 m
	2 MHz	0.05 m	128	0.1-2 m	4-10 m
AWAC	400 kHz	1 m	128	1-8 m	100 m
	600 kHz	0.5 m	128	0.5-8 m	50 m
	1 MHz	0.4 m	128	0.25-4 m	30 m
Continental	190 kHz	2 m	128	2-20 m	200 m
	470 kHz	1 m	128	1-10 m	100 m
Vector	6 MHz	-	1	5-20 mm	0.15 m
Vectrino	10 MHz	-	1	3-15 mm	0.05 m / 0.1 m (field probe)
Vectrino Profiler	10 MHz	-	30	1-4 mm (user selectable)	40-74 mm (calibrated)

3. ORIENTATION

3.1 COORDINATE SYSTEM

You may specify the preferred coordinate system in the Deployment Planning menu. The velocity measurement is a vector in the direction of the transducer beam, which we refer 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) if the instrument is equipped with a compass and tilt sensor. 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.

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. On the Vector and the Vectrino, Beam 1 is defined as the arm with the black / red marking (placed opposite of the engraved head ID on the Vector).
- 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 first (index) finger to point in the direction of positive X-axis and the second (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.

COORDINATE TRANSFORMS

The transform of the coordinate system from beam to XYZ or ENU coordinates is an important step when examining Doppler velocity data. Understanding coordinate transforms is important in interpreting velocity data, fixing problems in a data set, and ultimately, obtaining the highest quality data.

The information needed to convert from Beam to XYZ coordinates is a set of beam velocity measurements and the instrument's 3 x 3 (or 4 x 4 for the Vectrino's) transformation matrix. Each instrument has its own unique matrix, reported in the *.hdr file, when performing a binary data conversion in the software. Each row of the matrix represents a component in the instrument's XYZ coordinate system, starting with X at the top row. Each column represents a beam. The third and fourth rows of the Vectrino transformation matrix represent the two estimates of vertical velocity (Z1 and Z2) produced by the instrument.

Recall the basics of matrix multiplication:

$$\begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

Where T_{ij} represents the elements in the Transformation matrix, b_i are the beam velocities and u_i are the transformed velocities. When writing out the matrix multiplication above, the following system of equations is obtained:

$$T_{11}b_1 + T_{12}b_2 + T_{13}b_3 = u_1$$

$$T_{21}b_1 + T_{22}b_2 + T_{23}b_3 = u_2$$

$$T_{31}b_1 + T_{32}b_2 + T_{33}b_3 = u_3$$

Here we can see how each orthogonal velocity component is a combination of the various beam velocities. The figure below shows an assortment of velocimeters probes and instrument heads. For the Vector probe (see rightmost illustration of Figure 11, upper part), one may notice that the X component is predominantly measured by $b_1$with nearly equal contributions from b_2 and b_3. This makes sense since the XYZ coordinate system is aligned with X pointing along one beam / receiver arm. Beams 2 and 3 are at some angle α to the X axis and measure a component of X proportional to $\cos\alpha$. For the Y-component, b_1 contributes to zero (or very near zero) because the Y-component is perpendicular to beam 1. Finally, the Z component is an equal combination of all three beams since the Z-axis is aligned with the central transducer and each beam is at the same angle to the Z-axis. Note that this applies to other head configurations as well.

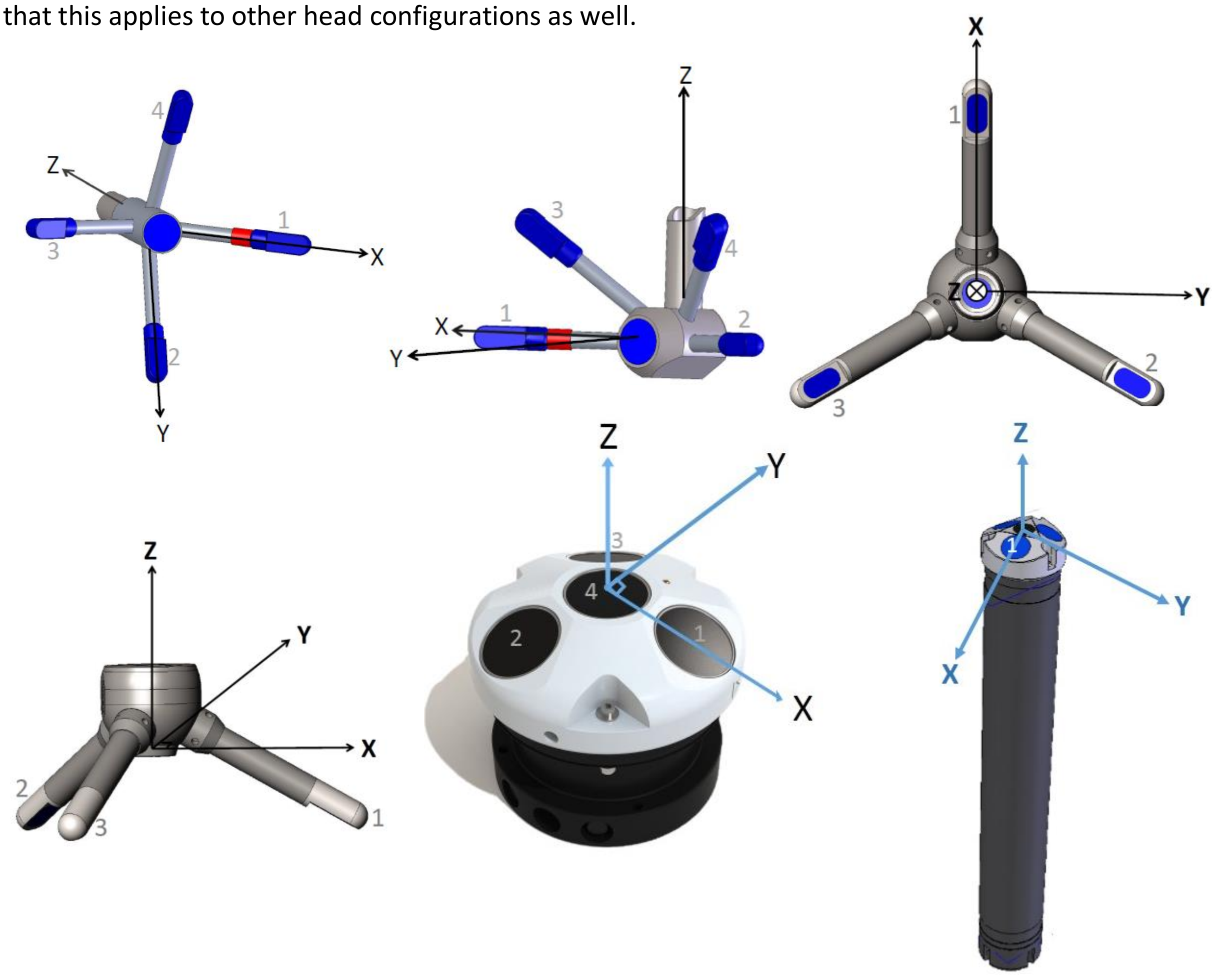

Figure 11: The Vectrino, Vector, AWAC and Aquadopp (symmetric head) XYZ coordinate systems and beam numbering as defined relative to the probes/beams. The Vectrino in the upper middle is the side-looking version. Beam 1 of the Vectrino has a red marking, a black marking defines beam 1 for the Vector (not shown here). For the Vector, beam 1 is also the arm opposite of the engraved head ID. Beam 1 point in the direction of positive X-axis; the Z-direction is towards the electronics of the instruments. The Y direction can be found in accordance with the right-hand rule. Beam 1 of the AWAC and Aquadopp is marked with an X engraved on the housing, barely visible in the AWAC in the lower middle.

The transformation between the beam and XYZ coordinates can be accomplished with no loss of information, due to the fact that the transformation matrix is used. When converting to ENU coordinates, the instrument compass update rate sets the limit to which coordinate transforms can be performed. When converting to ENU coordinates, the instruments' compass reading is used. The magnetometer measures the magnitude of three components of the earth's magnetic field at a user-specified rate. All Nortek products (with compass) combine this information to compute the instrument's heading, and then use this to correct the measured velocities to earth coordinates. This is typically sampled at 1 Hz, meaning the transformation matrix is updated with pitch, roll and heading information every second. If the current measurement data rate is 4 Hz, it means the four samples in each second share the same heading and attitude and there the same transformation. If onboard averaging is performed and the instrument is moving during the average interval, it is not possible to recover valid XYZ data from an ENU average velocity. With the Vector, it is therefore not recommended to collect internally averaged beam or XYZ velocity data because of bias due to a moving instrument.

The Vector, Vectrino and Vectrino Profiler measure velocity components parallel to their three bi-static beams, or in beam components. They can report data in beam or XYZ coordinate systems, the Vector can in addition report data in ENU. The XYZ coordinates are relative to the probe and independent of whether the instruments point up or down. Figure 11 defines the XYZ coordinates.

The assumption of horizontally homogenous flow is a requirement for the mono-static profilers (with diverging beams) to avoid measurement bias when using XYZ or ENU coordinate systems. This assumption is required since the beams diverge and the horizontal distance between the beams increases with increasing distance from the instrument. If the flow is not homogenous, then the velocity reported will not be representative of the actual flow and generally biased towards zero because XYZ and ENU velocities are a spatial average of the three beams.

Detailed information about the coordinate transformation equations used can be found on the Nortek Forum (http://nortek-as.com/en/knowledge-center/forum).

3.2 PITCH, ROLL AND HEADING

In their raw format, currents are measured along each of the three beams. 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 pitch, roll and compass heading (if equipped) are therefore used to aid in the transformation needed to correct for the instrument's attitude and motion.

When the instrument is tilted during deployment, the measurement cell from e.g. beam 1 does not correspond to the same measurement cell of e.g. beam 2, as sketched in the right part of Figure 12. In this example, depth cell 6 from the first beam corresponds to depth cell 7 of the second beam when the instrument is tilted 15°. In all current profilers, the velocity is measured in fixed cells along each acoustic beam. 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. But since the beam axis is not vertical (but 25°), the size of the cell will not be the same in beam 1 as beam 2.

Note that the transforms from beam to XYZ or ENU (cf. next section) corrects for tilt (and compass) in the sense that the final coordinate system is aligned with the gravitational axis (and the magnetic north pole). However, the data are not automatically corrected for the vertical mapping of the cells (use cells at the same level) and for this reason there will be residual errors in the 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. This is not done in the instruments for the simple reason that the mapping is non-linear. Remapping is included as processing options in the Storm and Surge software. Depth cell mapping matches 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. The best solution, however, 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 surface sidelobe layer and in some case reducing the effective range of your instrument.

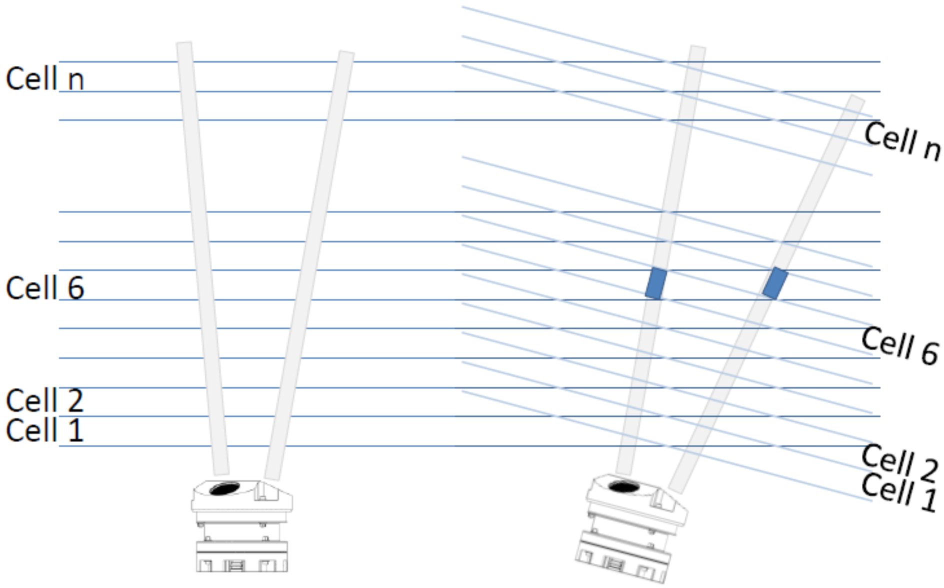

Figure 12: Tilting of the instrument (here 15°) result in measurements from different cells at the same depth.

Sometimes deployment frames tilt excessively or even fall over. If the instrument's tilt reading is 20° or less, your data should be within the specifications. Tilt readings between 20° and 30° affect the data accuracy in a way that is likely to make the data fail to meet the specifications. Data acquired during tilts exceeding 30° are in general not reliable and should be discarded. Using an AWAC with the AST option, a maximum tilt of 5° within the vertical should be targeted.

4. OPERATIONAL CONCERNS

4.1 SPEED OF SOUND

As already elucidated in the equations in Section 1.1, the speed of sound in water influences the calculation of the velocity data. The time lag between the transmitted and received pulse determines how far the pulse travelled before it was reflected.

The instruments compute the speed of sound based on the measured temperature (accuracy of 0.1° C). A nominal salinity is assumed, an assumption that works relatively well because the sound speed is more sensitive to temperature variation than it is to salinity variation.

Sound speed errors are typically small, but if you must correct velocity data for errors, use the following equation:

$$V_{corrected} = V_{old}\left(\frac{C_{new}}{C_{old}}\right)$$

Here, *V* is the velocity and *C* is the speed of sound.

4.2 SIDELOBE INTERFERENCE

As Figure 5 illustrates, the water column can be divided into different regions. A current profiler has a couple of un-measurable areas in its profile; it cannot measure velocities in the area close to the sensor head, due to the described ringing and the required blanking distance (if you do not use a Z-cell instrument). In addition, it cannot measure the velocities close to the remote boundary whether it is the seabed or the surface (depending on mounting location) due to an interference phenomenon known as sidelobe interference. Data collected by an Aquadopp can also be restricted by this interference.

Data from the upper region of the water column may be influenced by sidelobe Interference. The acoustic beams focus most of the energy in the center of the beams, but a small amount leaks out in other directions. Because sound reflects much stronger from the surface / air boundary than from the water, low energy signals that travel straight to the surface can produce sufficient echo to contaminate the desired signal from the water. This type of interference may affect 5-10% of the velocity profile. As sketched in Figure 13, the Sidelobe energy will reflect from the boundary while the main beam is still in the region near the boundary. If the distance to the surface is *A* (Figure 13 a), then contaminations of the current measurements begin at the same distance *A* along the slanted beams. In the figure, the top two cells might be contaminated. The following is an approximate equation illustrating the constraint of near-surface contamination:

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

Here, R_{max} is the range for valid data and θ is the angle of the beam relative to vertical. The take home is to be cautious in the upper part of the water column. A tip when analyzing data is to check the vertical velocity (Z) extra carefully in this area. It should read ≈ 0. If not, it might be an effect of interference.

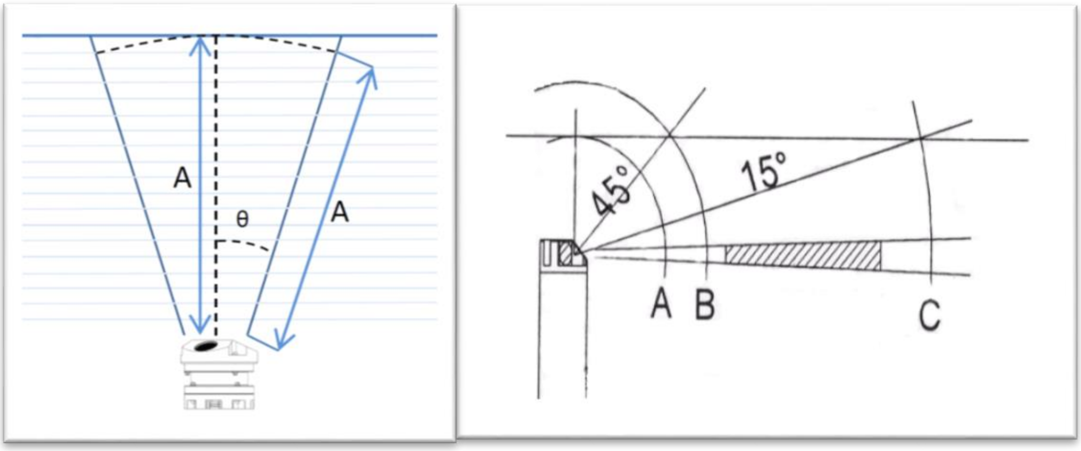

Figure 13: The geometry of sidelobe interference**. a)** a profiler; here an AWAC. The upper two cells are contaminated by interference. **A** is the vertical distance to the surface, θ is the angle of the beam. **b)** Aquadopp with definitions of three positions along the beam; **A** is where the distance along the beam equals the distance straight up to the surface, **B** is the distance along the beam equal to the distance to the surface along a 45° angle, **C** is the distance along the beam equal to the distance to the surface along a 15° angle. The shaded area is the proposed measurement area.

The extent to which the sidelobe interference 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. 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.

If you are concerned with sidelobe interference, Figure 13 b) illustrates how to minimize the possibility of contamination in your data, when you are near the water surface using an Aquadopp with the sketched head configuration. Sidelobe returning vertically from a smooth water surface (Area *A* in Figure 13 b)) pose the most likely source of contamination. Even though Sidelobe interference from this direction is very weak, a smooth water surface is the strongest reflector you will encounter – it behaves like a mirror. As the angle increases (toward position *B*), the strength of the surface echo weakens substantially. From position *C* and beyond, the angle between the surface and beam become disadvantageous again, the sidelobe interference begins to increase and your beam may begin to be affected by surface velocities. This may not be such a problem because the surface velocity is typically close to the velocity just below the surface.

The situation changes if you place the Aquadopp near the bottom (if you turn Figure 13 b) upside down). Echoes vertically from the bottom are typically much weaker than the mirror reflection from the surface, so contamination at Position *A* will be less serious. However, contamination at Position *C* could be more serious; the bottom does not move, and the backscatter from hard reflectors, like rocks, can be large.

4.3 WEAK SPOTS

The Vector, Vectrino and Vectrino Profiler are pulse coherent systems, and as such, they are susceptible to pulse interference when measuring near boundaries. This especially applies to Vectrino Profiler, as this is a profiling instrument. Pulse interference for acoustic Velocimeters is called a "weak spot" and will show in data as low SNR (Signal-to-Noise Ratio – see definition in Section 4.5) and correlation values, as well as noisy velocity traces.

A weak spots is related to the spatial separation between the pulse pairs transmitted by the Velocimeter. A weak spot occurs when the first pulse hits the bottom and the reflected signal of the first pulse reaches the sampling volume at the same time as the second pulse goes through the sampling volume. The two pulses passing through the same volume at the same time creates interference, reducing data quality and generally leading to unusable data.

Table 2 summarizes the distances where weak spots occur for the Vector and Vectrino indexed to the Nominal Velocity Range setting. Changing to the next higher or lower velocity range as appropriate will eliminate the problem. Alternatively, moving the instrument (measurement volume) up or down away from the boundary by just a few centimeters can reduce the weak spot effects. Note that the distances to boundaries specified are approximate and will depend on the speed of sound and the boundary surface.

The Velocity range specifies the separation in time for the two pulses. This parameter can be adjusted in the Configuration dialog. The rule of thumb is to set the velocity range as low as possible without the potential for water velocities to exceed the horizontal or vertical velocity ranges.

The Vectrino Profiler can make use of adaptive ping intervals to reduce weak spot interference. This allows the ping intervals to be adjusted dynamically during data collection to account for changing conditions within the environment. Options range from *Once* (perform adaptive check only during the configuration phase at the start of acquisition) or *1/sec* (dynamic checking) [2]. Using the Max Interval algorithm (also accessible in the Configuration dialog) allows the time interval to be adjusted manually. After setting the velocity range as low as possible, the range can be adjusted to a slightly higher range, to move the weak spots out of the sampling window.

Table 2: Weak spots listed as the distance from Sample Volume to boundary for the Vector and Vectrino. Note that the weak spot location is dependent on the speed of sound and the boundary surface, so the values given are only estimates and weak spots may be encountered a centimeter or more away from these values.

Velocity Range (m/s)	Vector (m)	Vectrino (m)
0.01	3.12	
0.03		0.38, 0.75
0.10	0.46	0.23, 0.45
0.30	0.20	0.10, 0.23
1.00	0.08, 0.20	0.05, 0.12
2.00	0.05, 0.09	
2.50		0.03, 0.10
4.00	0.03, 0.06	0.02, 0.05
7.00	0.02, 0.04	

The vertical extent of the weak spots is a function of the bottom composition. If the bottom is well defined (e.g. sand) the extent is no bigger than the transmit pulse or about 1 cm. If the bottom is rough, the vertical extent can be larger. It is also a matter of the relative strength between the water scattering and the bottom echo - if the water scattering is high the whole issue goes away.

4.4 VELOCITY AMBIGUITY AND PHASE WRAP

An inherent problem with coherent Doppler processing is that of the velocity ambiguity (cf. Section 1.1). This arises as a result of the fact that the phase difference can only be determined to within $\pm\pi$ radians. The ambiguity velocity can be estimated:

$$V = \frac{C}{4F_{source}\Delta t}$$

Here, F_{source} is the frequency of the transmitted wave and C is the speed of sound in water. The choice of Δt is crucial for correct operation of the instrument; the size of the separation between pulses determines the maximum unambiguous velocity that can be measured. Longer lags have lower maximum velocities, while shorter lags have higher maximum velocities. Conversely, longer lags will typically have lower noise levels than shorter lags.

If the absolute value of φ is greater than π, phase wrapping occurs and the measured phase shift has a value $\varphi_{measured} = \varphi_{actual} - 2\pi$. We see this phase wrapping in a velocity trace as an abrupt, unrealistic change in magnitude and almost always with a change in sign. While it is possible for phase wrapping to occur without a sign change, this would be the result of an extremely large wrap where the phase shift exceeds 2π.

The simplest way to avoid phase wrapping is to have a little prior knowledge of flow conditions and to set up the instrument appropriately for the environment. The latter is done in the Deployment Planning, where you can set the Nominal Velocity Range. It is the maximum velocity you expect to measure during the deployment or experiment. Note that since the transmitter and receiver are physically separated, the measured velocity is along the bi-static axis (cf. Figure 7 a). By decomposing the velocity along the bi-static axis onto the vertical and horizontal axes you get the corresponding maximum vertical and horizontal velocity ranges. These ranges are presented in the deployment planning dialog (right part). Measurement uncertainty is roughly proportional to the Nominal Velocity Range – smaller velocity ranges give you better measurements regarding uncertainty. An example of the problem with phase wrapping is discussed in Technical note no. 027; "A Practical Primer for Pulse Coherent Instruments" [1].

For the AquaPro HR, Extended Velocity Range (EVR) may be an option to increase the ambiguity velocity. It is an extremely useful feature for the HR profiler, allowing its use in much higher energy environments than pulse coherent profilers typically operate. This is achieved without compromising the low noise and single ping accuracy pulse coherent profilers are known for. EVR utilizes an additional pulse pair to create a set of pulses with two different lags and velocity ranges. The longer lag is the standard pulse coherent lag set by the user, while the EVR lag is shorter and has three times the velocity range. The standard phase shift is compared to the EVR phase shift and corrected so it matches the EVR data if needed. EVR does not eliminate the possibility of ambiguity problems if velocities exceed the specified velocity range in the Deployment Planning dialog. Technical note no. 028, named "Extended Velocity Range Mode" [3] is recommended reading for users of the HR profiler.

4.5 MAXIMUM RANGE AND SIGNAL STRENGTH

The profiling range and spatial resolution is primarily a function of the acoustic frequency. Instruments using a low frequency have longer range than instruments using higher frequency; on the other hand, the latter has better spatial resolution. The profiling range is also dependent on the scattering conditions and the cell size. The latter due to the fact that the amount of energy transmitted into the water is set according to the cell size. 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. The amount of particles in the water varies with depth, a subject that is covered in the next section.

Signal strength (amplitude) is a measure of the magnitude of the acoustic reflection from the water, and is a function of type and amount of particles in the water. Due to spreading and absorption, the signal strength decreases with range. The signal strength is accessed as raw signal amplitude (using dimensionless unit called Counts) or as a Signal-to-Noise ratio, SNR (in dB- see definition below). The determination of the range over which the instrument can measure velocity accurately is the primary use of the signal strength. It may also be used to retrieve information about the suspended sediment or the concentration of the scattering materials. Note that this is usually not recommended due to the fact that different types of scattering elements produce different echoes, and it is difficult to distinguish between conditions with few, relatively big scattering elements or lots of small elements.

When the signal strength reaches the noise level, the maximum range is reached. The Doppler Shift is not accurately measured beyond this point. The noise floor is typically found at around 25 counts (as displayed in Figure 14). Because of the way we compute the signal strength however, you can actually obtain good data at signal strengths a few dB below the noise floor. This means the noise floor gives you a conservative "cutoff" for good data.

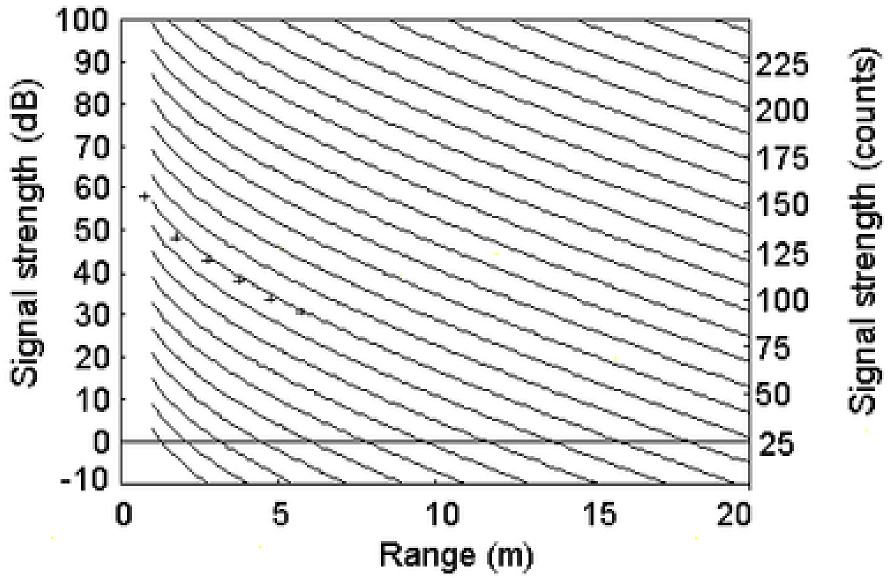

Figure 14: Measurement range vs. signal strength at 2 MHz. The "+" symbol shows actual data from a river at power level 2.

Figure 14 shows how signal strength varies with range, based on the Sonar Equation. The family of curves represent different source levels. The Sonar Equation accounts for the frequency of the transducers, sound spreading and reduction in signal strength as the sound pulse travels and reaches the particle, the amount of sound reflected back to the transducer and sound spreading and reduction in signal strength as the reflected pulse travels back.

In Figure 14, it is evident that there is a loss in signal strength with increasing range, as described earlier. If you know the signal strength at a given power level and a given range, you can use the figure to predict the signal strength you would have at a different power level and range. If you keep the same power level and change the range, follow the curve closest to the value you started with. If you change the power level, move up or down one curve for each power level (the curves are 6 dB apart).

Signal-to-Noise Ratio – a definition

The Signal-to-Noise ratio (SNR) is defined as $SNR = 20log_{10}\frac{Amplitude_{signal}}{Amplitude_{noise}}$

Strictly speaking, we are unable to measure the signal without the noise present, so $Amplitude_{signal}$ *should read* $Amplitude_{signal+noise}$*. However, for SNR values in the magnitude applicable to typical Vectrino situations, the difference is negligible.*

4.6 OCEAN SCATTERING

The instruments rely on acoustic backscattering to operate. The amount of energy that comes back from the water depends on the number of particles that are suspended in the water column. Very clean water means few particles and it is thus a poor scattering environment. Velocity estimates have greater uncertainty when the received acoustic signal is very weak. To overcome weak acoustic echo an increase in the transmit power may be the solution, but this also increases the power consumption. Some background knowledge about the scattering conditions at the area of measurements is helpful. The water column in the open ocean can be divided into four zones when discussing acoustic scattering:

- **The upper 100 m.** Light penetrates and this zone is characterized by high biological activity. The acoustic scattering is strong and getting adequate SNR is normally not an issue. In this zone, the instruments can be operated with reduced transmit power to save power.
- **The bottom 100 m**. Fine sediments are lifted into suspension by turbulence generated as the water flows over the bottom. In this zone, the SNR is adequate and a profiling instrument has a useful range. In terms of instrument design, this is an “easy” part of the water column, even if the bottom is located 6000 m below the surface.
- **From the surface to 1000 m.** In this zone, there is a gradual decrease in the SNR as you move downwards. There is still biological activity and the SNR is generally adequate. There is a chance that the SNR may change with the seasons, so we generally recommend that instruments deployed in this zone are configured for maximum output power.
- **From 1000 m below the surface to 100 m above the bottom.** This is the most challenging area, characterized by minimal biological activity and very weak acoustic scattering. The Aquadopp DW should always be configured for maximum power output when deployed in this part of the water column.

There are also certain regions in the world where scattering conditions are less than optimal. These can vary with season.

- **Extreme latitudes.** These cold regions tend to be less supportive of biological activity (i.e., plankton) and therefore there is less scattering in the water.
- **Tropical regions.** Regions where there is clear visibility from the surface, such as the tropics has reduced scattering.

5. VELOCITY UNCERTAINTY

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

The velocity measurements are the average of many velocity estimates (called pings). The uncertainty of each ping is dominated by the short-term error. This error is uncorrelated from ping to ping, so by averaging together many pings, the measurement uncertainty is reduced. The short-term error depends partly on internal factors, such as the size of the transmit pulse, the measurement volume and the beam geometry. Beams parallel to the dominant flow will have smaller short-term errors than beams at a steep angle relative to the flow.

The instrument's software predicts errors based on the short-term error of a single ping and the number of pings averaged together. Averaging multiple pings reduces errors according to the formula:

$$\sigma_{V,mean} = \frac{\sigma_{V,ping}}{\sqrt{N}}$$

Where σ represents the standard deviation and N is the number of pings you average together. Note that the software predicts only the instrumental error.

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, your 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 you should sample velocity at roughly ¼ the interval of the dominant wave period, and you should sample through 6-10 wave cycles.
- Turbulent flow. In boundary layers, a rough rule of thumb is that the RMS turbulent velocity is 10% of the mean velocity. If, for example, your mean velocity is 1 m/s, you could estimate turbulent fluctuations to be 10 cm/s. Obtaining 1 cm/s RMS uncertainty would require at least 100 pings.

When averaging several pings to reduce the error, there is a difference between the resulting "mean current" and the measured current. This deviation from the actual current measurement is called bias. The bias is often much smaller than the random errors you remove by averaging, and it represents the limit to how much you can reduce your short-term error. The long-term bias depends on internal signal processing, especially filters, and by the beam geometry. The long-term bias for the Aquadopp is typically less than 1 cm/s.

PART II: WAVES

6. BACKGROUND

6.1 WHAT ARE WAVES?

All bodies of water experience waves. These may range from long waves, such as tidal waves (caused by the gravitational forcing of the sun and the moon) to short waves generated by the wind's drag on the water surface. If you were to look at the distribution of energy for waves you would see considerable variability ranging 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 (see Figure 15). These are the waves that engineers and scientists are primarily interested. To accurately measure these waves it often comes down to how well this band is represented by the measurement method.

This 0.5 – 30 second band that defines wind waves has a variability that makes characterizing waves non-trivial. 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 the wave can grow. 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.

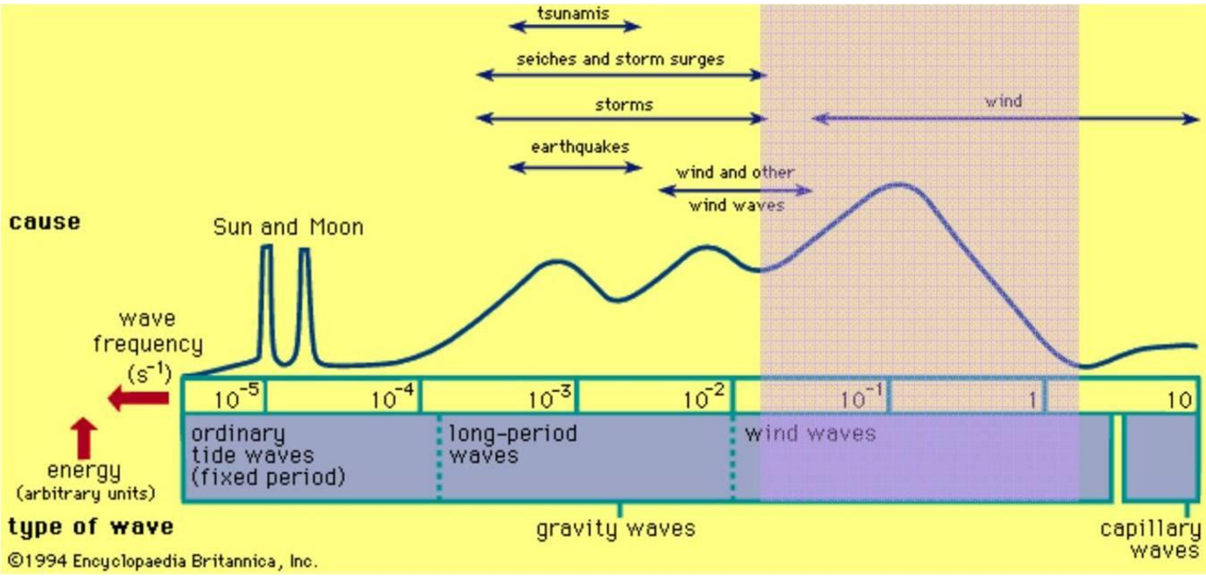

Figure 15: Distribution of energy. The region with periods from 0.5-30 seconds represents the wind wave band portion of the spectrum. Remember that $\boldsymbol{Period} = \frac{\mathbf{1}}{\boldsymbol{Frequency}}$.

6.2 MODES OF OPERATION

The Aquadopp can use the "diagnostic" mode to configure the instrument to burst sample velocity and pressure at 1 Hz, in order to make directional wave measurements. Note that the first sample in the burst mode is the noise floor measurement (no signal transmitted) and is therefore not used in the wave measurements.

The AWAC, Vector and AquaPro have two modes of operation; current profiling and wave bursts. The two modes are sequential, i.e. the system first collets a current profile, then wave data for a period of time determined by the number of samples and the sampling rate. The system averages the full current profile over the prescribed averaging interval (illustrated in Figure 16, in this example: 120 s). The whole sequence will start over again each measurement interval. The instrument will not do profiling and wave burst measurements at the same time, the wave measurements are given priority. The skipped current profile can be interpolated in the ASCII conversion software afterwards. Note that when specifying the number of samples and measurement interval in the deployment planning, there must be enough time to make a wave and current measurements for each interval.

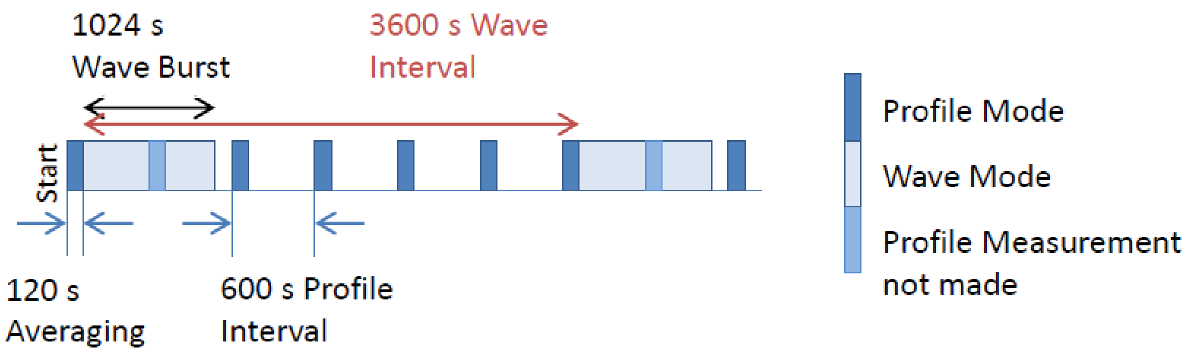

Figure 16: The AWAC, AquaPro and Vector measures profile and waves sequentially. In case of conflict, wave measurements are given priority over profile measurements. Note that the intervals are user selectable in the software; this is just an example.

SAMPLING

Waves are random and therefore measuring waves requires sampling over a period of time that will best "capture" or represent the complete sea state statistically. As a rough rule of thumb we try to get 100 cycles of the longest wave we would expect; this means if we expect the longest wave period to be 10 seconds for a particular body of water, then 1000 seconds is the preferred sampling length.

7. STATISTICAL APPROACH

Since the sea surface is composed of different types of waves and in general is irregular in both time and space, the sea state is characterized by statistics (wave height, period, direction etc.). A couple of assumptions are necessary when trying to approximate the wave field; the first is that the wave field can be described as a summation of many different sine waves with different frequencies, amplitudes and directions. This makes it possible to use Fourier analysis to reduce a time series of waves to a certain number of sine waves. Fourier analysis is a mathematical method used to break down and transform a periodic function into a set of simpler functions (e.g. sine and cosine) thereby providing a simpler, general solution. For more information, see a textbook covering signal processing, for example *Data Analysis Methods in Physical Oceanography*. The second assumption is that the wave field is statistically stable, meaning that the same statistical result would be obtained if the same wave measurements were made just a moment later (a so-called short term description).

7.1 ESTIMATING WAVE PARAMETERS

TIME SERIES

The simplest method for estimating wave parameters is to evaluate the time series of sea surface displacement from a single measurement point. The resulting time series analysis determines how far the water surface extends above and below the mean water level. Individual waves can then be determined by where the trace crosses the mean level; this is commonly referred to as the *zero crossing method* (see Figure 17). The individual waves in the record can be characterized by period (defined by where it crosses the mean water level) and height (defined by the distance from trough to crest between crossings). The result of this exercise is a wave record composed of many waves with a variety of heights and periods. If these waves are ranked by their height and/or period then the resulting rankings can be used to calculate common estimates of height and period.

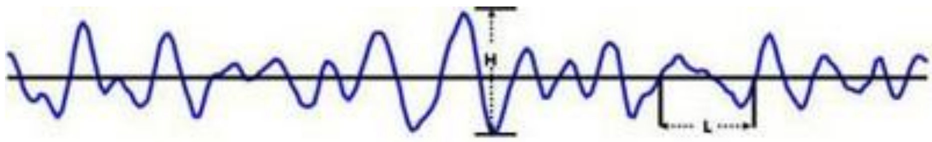

Figure 17: Example of a time series of the surface displacement. Here the zero-crossing technique is used to determine individual wave heights (H) and wave periods (L).

SPECTRAL ANALYSIS

The time series analysis may seem like the appropriate manner to approach wave measurements. However, two common restrictions keep many from succeeding. The first restriction is that time series analysis can be a little daunting; the second that many wave measuring devices do not have the technology to directly measure the surface displacement and, therefore, do not allow for the possibility of time series analysis. Instead they measure a wave related property such as pressure or orbital velocity (cf. next section) and infer the sea state from the spectra of the time series.

A different approach is the spectral analysis, made possible by application of Fourier transforms. A given trace of the waves can be analyzed by using Fast Fourier Transform (FFT) to produce energy density spectra (e.g. Figure 18). The spectrum shows how the energy density is related to different frequencies. Having obtained a spectrum, the frequency domain wave parameters may be found. Both the ease of interpretation and large number of non-direct measuring instruments has left spectral analysis as the primary method for processing wave results. It provides an enriched collection of wave parameters and also permits directional wave analysis.

The most complete solution is both a time series analysis and spectral analysis; however, this is often not possible with the majority of instrumentation available today.

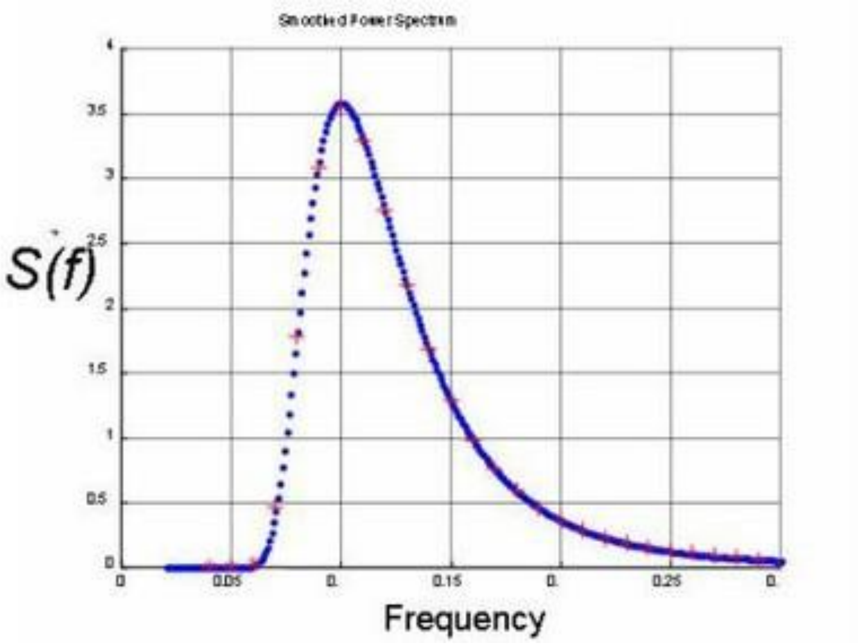

Figure 18: Energy density spectrum for a time series. This is ultimately used for estimating wave parameters of height and period.

8. BASIC PRINCIPLES

8.1 WAVE INDUCED SUBSURFACE PROPERTIES

ORBITAL VELOCITY

The orbital velocity produced when a wave passes is the basic mechanism for obtaining information about the waves on the surface. When a wave propagates past a point it creates local currents below the surface. These currents are special in the sense that they are changing direction, whereby the crest of a wave will have the affected water below it moving in the direction of propagation, and the affected water below the trough moving in the opposite direction of the propagation, as illustrated in Figure 19. This cyclical motion constructs a circular path in deep water and is often referred to as a wave's *orbital velocity*.

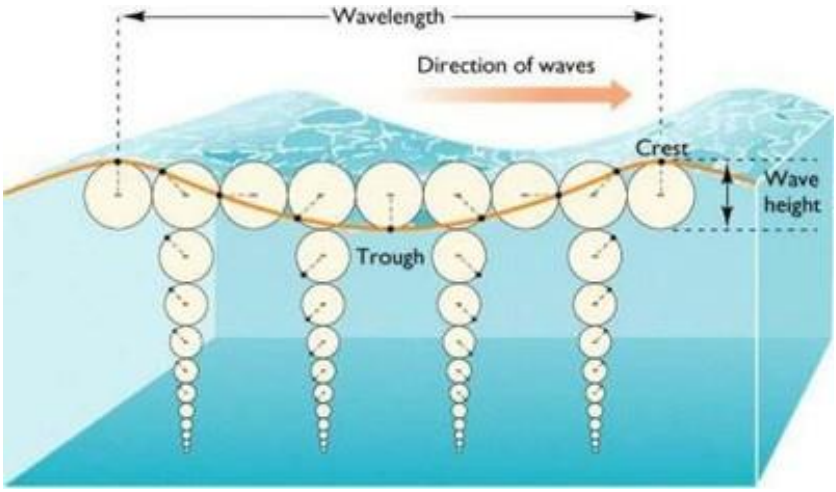

Figure 19: Description of the orbital velocities beneath a wave as it propagates. Note that the orbital velocity attenuates with depth.

The ability to measure the orbital dynamics from below allows us to interpret the waves on the surface, by use of linear wave theory. This provides the means to estimate many of the wave parameters that are commonly used to describe a sea state. An important detail to understand about orbital velocities is that they attenuate exponentially with increased depth and shorter wavelength. The wave energy will only propagate to a certain depth; the energy cannot be seen or measured below this depth. This means that short waves in deep water do not have an orbital velocity signal that penetrates to the bottom. Higher frequency waves attenuate more quickly with depth. Thus there exists a tradeoff between the depth of the measurement location and the ability to measure the higher frequency waves. This is exactly why we are both depth *and* frequency limited when measuring waves.

The transformation from along beam velocity measurements to U- and V velocity components assumes that currents are uniform within the plane created by the three beams. This assumption is clearly not valid when measuring waves, since the beam cells are spatially separated and therefore the orbital velocities will not be equal at different cells. However, the directional analysis does not need the exact magnitudes of U and V. From the definition of the directional Fourier coefficients, the factors multiplying U and V will drop out from the definitions of the Fourier coefficients relations as long as the factors are functions only of frequency equal both for U and V [4].

DYNAMIC PRESSURE

Another important property when measuring waves is the dynamic pressure. It is largely dependent on the presence of orbital velocities and this means it also experiences attenuation as a function of depth and wavelength (see Figure 20). The dynamic pressure is at maximum under the wave crest. The rate of decrease with depth is well understood and modeled by linear wave theory. This allows us to measure the pressure near the bottom, and to rescale the measurement to obtain the wave elevation spectrum at the surface, by use of transfer functions. Note that the dynamic pressure is sensitive to errors in the wavenumber ($k = \frac{2\pi}{\lambda}$), as is evident from the equation below.

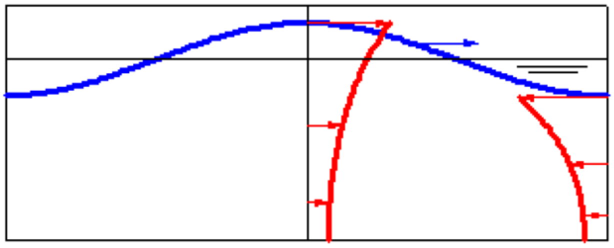

Figure 20: A wave moving in the direction of the blue arrow. The pressure profile is shown in red. Pressure and velocity (red arrows) under the crest are in phase with each other (Reprinted from [5]).

8.2 TRANSFER FUNCTIONS

Both the dynamic pressure and the orbital velocities are driven by the surface waves. The signals associated with these properties are complicated by the fact that they attenuate exponentially with depth. The exact behavior of the attenuation has to do largely with the water depth and the wavelength. In a nutshell the behavior is as follows, (1) as we move down in the water column the signal is increasingly attenuated, (2) as the wave length decreases (shorter period or higher frequency) the signal again experiences increasing attenuation. We use linear wave theory to convert pressure and velocity spectra to surface elevation spectra. The pressure attenuation factor is given by

$$T_p = \frac{\cosh k(h+z)}{\cosh kh},$$

and for the velocity as

$$T_v = \frac{\omega \sinh k(h+z)}{\cosh kh}.$$

Here, h is the water depth; z is the position in the water column, ω is the circular frequency, and k is the wavenumber [6]. This attenuation is exactly why the instrument is restricted to measure longer waves at deeper instrument locations. It is difficult, if not impossible, to measure high frequency waves of low amplitudes from instruments deployed at large depths.

8.3 CUTOFF AND EXTRAPOLATION

A matter that must be taken into consideration when using spectral analysis to estimate wave statistics is that as we move up in frequency there will be a point where there is no response in the signal yet the attenuation continues to become more significant. This weakening, or attenuation, increases with frequency. At some cutoff frequency, the velocity and pressure signal becomes so weak that the waves can no longer be detected.

The problem arises when the perturbation is less than the sensitivity of the sensor. This leads to a false growth with the spectral level as we increase frequency (as illustrated in Figure 21). The end result is that the calculated surface spectrum "blows up" into infinity. The reason for this false growth is that as we move up in frequency, the signal drops into the noise floor while the transfer function decays exponentially. Therefore, at some frequency in the spectrum a minimum must be chosen before it grows without bound.

This behavior at high frequencies necessitates the need for defining a cutoff frequency and an extrapolation from this frequency onward. Since we will ultimately integrate the spectra for the momentum calculations, we require spectra that are unambiguous and bounded. We assume that the spectrum follows a Pierson-Moskowitz or JONSWAP type spectrum. This is an empirical spectral shape, where the tail rolls off at a rate of $f^{-4.5}$.

The frequency at which the cutoff is selected is determined by finding the last local minimum above a maximum amplification factor in the spectrum as we sweep up in frequency. The problem with a sensors cutoff leaves the possibility of not detecting wave energy about the cutoff, and this lead to errors in some wave estimates (H_{m0}, T_{m02}) if no extrapolation is done. The AST has no extrapolation applied to it because it does not have a cutoff frequency limitation like the pressure or velocity based estimates. This is because AST is a direct measurement of the surface, and transfer functions are not used.

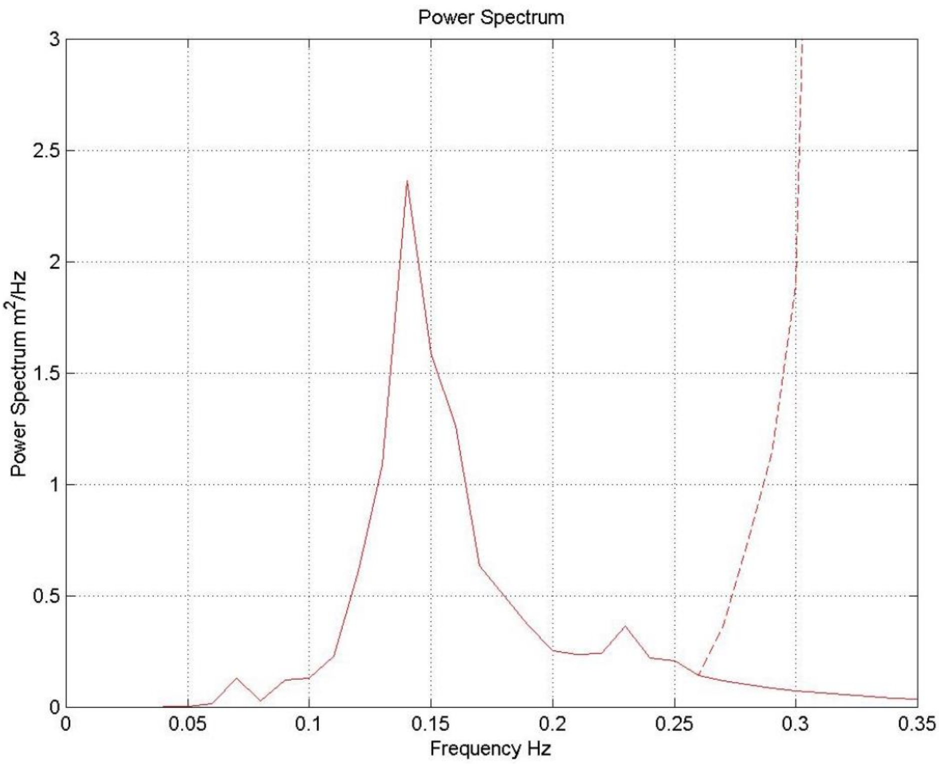

Figure 21: Example of high frequency extrapolation. Note that the original signal is represented by the dashed line. The figure is reprinted from [6].

8.4 CORRECTION FOR BACKGROUND CURRENTS

In case of strong background currents, the measured waves may be affected by a Doppler shift. That is, when currents are directed against the waves, the waves are compressed. When the currents travel in the same direction, the waves are elongated. The resulting spectra will see the peak energy shift slightly to lower or higher frequencies. It is not just the magnitude of the currents that is essential but also the direction. Currents flowing in a direction perpendicular to the wave direction will have no effect on the waves.

The degree to which the Doppler shift modifies the surface waves depends on the current speed relative to the wave propagation speed. This means that slow propagating (short period) waves are the most affected by currents.

Measurements that infer the surface waves from either orbital velocity or pressure measurements require special attention regarding background currents. This is because the transfer function used for inferring the surface waves is wavenumber dependent, and it is the wavenumber that is modified by the background currents. The wavenumber solution must take into account the mean current and direction relative to the wave direction. The post-processing method that relies on the wavenumber solution is the PUV method (see section 10.1), and it is the one which is most sensitive to the effects of currents. The correction for background currents is done in post-processing software when necessary. The AWAC with AST is a direct measure of the surface waves and therefore its response is unaffected by background currents.

9. WAVE PARAMETERS

9.1 NON-DIRECTIONAL

The most common non-directional wave parameters describe height and period of the wave field and are single values representative of the time series. The instruments collect raw wave data that must go through a processing step before it can be used to interpret the waves on the surface. The processing will lead to classic wave estimates for the following wave parameters:

Period (T) is defined as the time interval between two successive peaks (or troughs) passing a fixed point, measured in seconds. The Peak Period (T_p) is the period associated with maximum peak in the spectrum. It is found using the spectral analysis method, and it tells the characteristic frequency of the arriving wave energy (remember that frequency is the inverse of the period). The only parameter needed to find the peak period is one that varies with the wave frequency, which may be the water level, the pressure or the orbital velocity. To find the peak period, the spectral analysis is used on the time series of the parameter used to point out the frequency with the most energy. The Mean Period (T_z) is the mean of all the periods in the record.

Wave height (H) is the vertical change in height between the crest and the trough. The wave height is twice the amplitude (a). The parameter most used by oceanographers to characterize a particular sea state is the significant wave height (H_s or H_{m0}) defined as the mean of the highest 1/3 of all waves in the record's ranking. Classically, this estimate is performed by sorting all waves in a time record according to height (referred to as H_s). However in our approach, we utilize the spectrum of the sea surface to approximate this value. A generally accepted approximation is $H_{m0} = 4.0\sqrt{m0}$. The *m0* represents the first momentum of the power spectrum. The k^{th} momentum is defined by $m_k = \int f^k C(f)df$, where *C* is the power spectrum, and *f* is the frequency [6].

Other wave height parameters of interest are the maximum wave height ($\mathrm{H_{max}}$), which is simply the largest measured wave in the record, and the mean of the largest 10% of all waves in the record ($\mathrm{H_{10}}$). These two parameters are commonly used for coastal design and assessment and are only possible when we have a direct measure of the surface displacement (e.g. AST). Indirect measurements of waves cannot produce these parameters.

9.2 DIRECTIONAL

Calculated wave directions are based on the first pair of Fourier coefficients and describe the mean direction at a given frequency. The directional wave spectrum is commonly expressed as a composition of the frequency spectrum and the directional spreading:

$$E(f,\theta) = S(f) * D(f,\theta)$$

Here, f is the frequency and θ is the direction. *E* is the full directional spectra, *S* is the energy density spectra (frequency spectrum) and *D* is the normalized energy spectra (directional spreading). The energy density spectrum is retrieved by spectral analysis for the time series of surface elevation (pressure, AST, orbital velocities), while the estimation of the directional spreading use a combination of the measurements taken; dynamic pressure + orbital velocities or AST + orbital velocities. The directional distribution can be approximated by a Fourier expansion according to $D(f,\theta) = \frac{1}{\pi}[\frac{1}{2} + \sum_n\{a_n cos\, n\theta + b_n \sin n\theta\}]$.

The **cross-spectrum** is a measure of the similarity of two different measured parameters, clarifying if they are varying together. If they vary at the same frequency, then it is likely they are related. The full cross-spectrum is presented as $C_{xy} = S_x S_y^*$, where the * indicates the complex conjugate [6]. The cross-spectrum is calculated between every sensor, and the directional spectrum is assumed to be linearly related to the cross-spectrum [7]. It has been shown that the first two pairs of Fourier Coefficients can be expressed in terms of the cross-spectrum [6]

$$a_1(f) = \frac{C_{*u}}{[C_{**}(C_{uu} + C_{vv})]^{1/2}}$$

$$b_1(f) = \frac{C_{*v}}{[C_{**}(C_{uu} + C_{vv})]^{\frac{1}{2}}}$$

$$a_2(f) = \frac{C_{uu} - C_{vv}}{C_{uu} + C_{vv}}$$

$$b_2(f) = \frac{2C_{uv}}{C_{uu} + C_{vv}}$$

Here, C_{uv} represent the cross-spectra of the u and v velocity components. C_{uu} and C_{vv} are the velocity component power spectra, and C_{**} is the pressure (C_{pp}) or the surface elevation spectra (C_{ss}) (depending on the method used).

Generally, the two parameters defining the directional distribution is the mean wave direction (θ_1) and the directional spreading (σ). The mean direction is expressed as: $\theta_1 = \arctan 2(b_1, a_1)$. The directional spreading is calculated as $\sigma = \sqrt{2(1 - r_1)}$, where $r_1 = \sqrt{a_1^2 + b_1^2}$.

Note that wave directions are always reported as the direction where the waves are coming *from*.

10. PROCESSING METHODS

The resulting time series of the raw measurements is not particularly useful from a practical standpoint. The wave data therefore needs to be processed to yield the parameters presented in the previous section that can broadly, yet accurately, characterize the sea state. The following methods are used by Nortek:

10.1 PUV

This method was perhaps the first approach used for measuring directional and non-directional wave properties from below the surface. It dates back to the 1970's and because of its modest requirements for instrumentation and processing, it is still in use to this day. Nortek offers three instruments using PUV measurements; the Vector, the Aquadopp and the AquaPro.

The name itself is a description of the method as it is an abbreviation of the three quantities measured: **P**ressure and the two horizontal components of the wave's orbital velocity, **U** and **V**. These measurements are made at the instrument's deployment depth and because they are co-located at the same point this is referred to as a "triplet" measurement.

The PUV analysis must provide an accurate estimate of the wave elevation spectra in addition to the direction and the directional spreading. The dynamic pressure measurement provides a means of estimating all the non-directional wave parameters, while the combined P, U, and V measurements allow for estimating the directional wave parameters.

Since these estimates are based on the wave energy distribution, and not a direct measure of the free surface, they are considered inferred estimates. Fourier transforms are used to separate the signals into different frequency bands so that it can determine the direction separately for each band. This means that if you have a long-period swell coming from one direction, and a shorter period coming from another, you can tell the direction for each of them separately. The main assumption for standard PUV wave measurements is that waves at a given frequency come from one primary direction.

The most important thing to understand about the PUV method is that it is limited to (a) deployment depths that are shallow (less than 10 meters) and (b) waves that are long (approximately periods of 4 seconds or longer). The limitations are a result of the fact that the orbital velocity attenuates with depth. The limitation of only measuring long waves (swell) is the one that should raise a warning flag for those who are interested in the complete description of the wave environment. As an example, the PUV may be successfully used if one wants to investigate a structure's response only to swell in shallow water. The accuracy of the solution requires measurements over the entire wind wave band (waves with periods of 0.5-30 seconds). Incomplete coverage of the wind wave band can result in underestimation of wave height and missing peaks in the spectrum. The only way to improve the coverage of the wind wave band is to deploy the instrument in relatively shallow water (i.e. 3 meters depth).

To learn more about the PUV method, two papers are recommended. Reference [5] describes the principles of how the PUV method obtains wave direction spectra, illustrated with results obtained with a Vector. Reference [8] explains the limitations of the method, including techniques for handling some of these.

10.2 ARRAY METHOD

The shortcomings of the PUV method prompted the development of a new technique for measuring waves. This new technique involves employing current profilers to measure orbital velocities closer to the surface where the velocities are less attenuated by depth. As a result, the shorter waves could be measured at greater depths. A more complex processing method is required since the measurements are no longer co-located (triplet measurements), but are in the formation of an array of measurement cells ("Projected Array"). The most common array processing method is the Maximum Likelihood Method (MLM), a method that has demonstrated very favorable results. There is an effective doubling of performance; the deployment depth can be doubled or the cutoff period is reduced by half. The MLM makes it possible to resolve the wave field in every direction.

The directional estimates of short waves are limited by the size, or the horizontal separation distance between the cells, of this projected array - which again is dependent upon the deployment depth. As the deployment depth increases, so does the horizontal separation between individual measurement cells. Increased separation distance will lead to a larger minimum wavelength that can be resolved for directional estimates. A rough rule of thumb is that directional estimates for waves that have a wavelength that is two times the separation distance or greater can be resolved unambiguously. This aliasing presents a spatial Nyquist limit and leads to a cutoff frequency where wave directions cannot be resolved. For example, a gauge deployed 40 m below the surface has a directional cutoff frequency of about 0.22 Hz (4.5 seconds). This means the gauge will not be able to resolve directions from waves shorter than 4.5 seconds. The cut-off frequencies for the AWAC can be seen in Figure 22.

An important detail about the array solution is that the complete wind wave band (0.5-30 seconds) is still not covered and underestimation is possible if the instrument is deployed in typical coastal depths (e.g. greater than 15 meters).

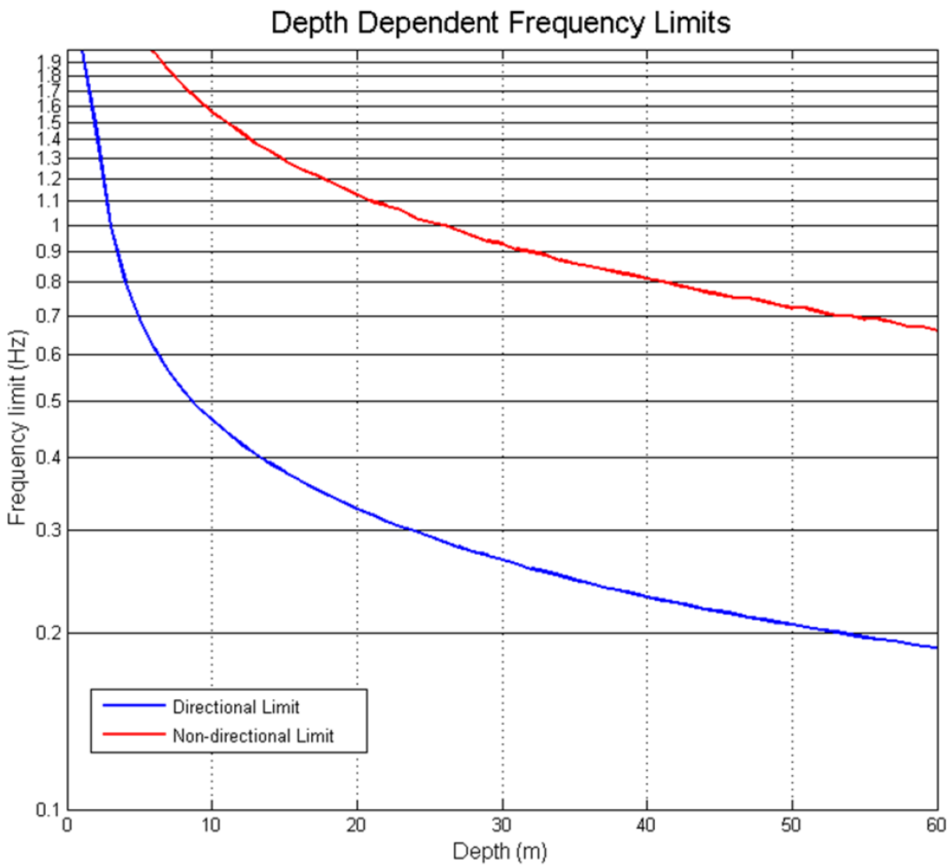

Figure 22: The cutoff frequencies for the AWAC - both for direction and non-directional estimates. This limitation is a result of the horizontal spacing of the velocity cells that construct the array near the surface.

10.3 MLMST AND SUV UTILIZING ACOUSTIC SURFACE TRACKING

ACOUSTIC SURFACE TRACKING (AST)

In 2002, the AWAC was first released with the AST option. The vertically oriented transducer in the center of the AWAC use the echo sounder principle, the travel time from the instrument to the surface and back allows us to estimate the distance to the surface for each ping. The strong impedance mismatch at the water – air interface provides a near perfect reflection, and thus provides a strong return. Although the transmit pulse is rather short, we have a large receive window so that we ensure a surface detection. High resolution of the surface is ensured by finely discretizing the receive window into smaller bins. Each one of the return bins is 2.4 cm. Even greater resolution of the exact surface is achieved through quadratic interpolation of the peak point and its neighbors. The final resolution of the distance to the surface is 1mm.

The record of the distance to the sea surface gives the user the possibility to see the exact wave profile. The direct measure has many advantages; the first, and most profound, is that there is effectively no depth limit for coastal waters and that the largest possible portion of the wind wave band is covered. The AST measurement also allows for both time series and spectral analysis. This means design parameters such as H_{10} and H_{max} can be measured directly.

The ability to measure the wave parameters by use of AST is limited by the size of the area that is ensonified by the AST beam, called the AST footprint. The size of the footprint is determined by a) the beam width and b) the instrument distance from the sea surface. The beam width is fortunately quite narrow, both the 1 MHz, 600 and 400 kHz AWACs has a beam width of 1.7 degrees. The size of the footprint will increase with wider beam width or with greater distance from the surface.

The cutoff frequency (limit of shortest measureable wave) is affected by the size of the footprint. As a general rule, we follow a Nyquist like reasoning; the frequency limit associated with the footprint is when half the wavelength is on the order of the diameter of the footprint. This clearly is the absolute shortest measurable wave. Below you will find a table that shows deployment depth, footprint size, and the resulting shortest measureable wave.

Since the inception of the AST, it has remained the cornerstone of the success of the AWAC. Numerous comparisons have been made with independent and trusted references; the data return has always been near 100% and the estimates of the wave parameters very favorable. In short, the AST circumvented all the shortcomings associated with subsurface wave measurement instruments and allows for the best possible coverage of the wind wave band.

Table 3: Depth dependent AST limits.

Depth [m]	Footprint diameter [m]	Wavelength [m]	Wave period [s]
6	0.20	0.40	0.5
12	0.38	0.75	0.7
24	0.74	1.47	1.0
36	1.08	2.16	1.2
48	1.42	2.85	1.4
60	1.79	3.58	1.5

MLMST

The MLMST is a version of the array method, adapted for surface tracking measurements instead of pressure measurements. The AST is included in the MLM solution to improve upon the accuracy of the directional estimates. Wave orbital velocity measurements are still made close to the surface like the array solution, but instead of the dynamic pressure, the AST option is utilized to estimate the non-directional spectrum (Figure 23 a)). This is an adequate solution for a bottom mounted instrument. The directional estimates are limited by the horizontal separation of the wave measurement cells and AST (Figure 23 b)), and the non-directional estimates are limited by the AST footprint, as described in the previous section.

SUV

If the position of the measurements in the surface array are not stationary (if the instrument is mounted in a subsurface buoy there will always be some motion), then array processing (MLM and MLMST) become mathematically impossible to solve and cannot be used. Nortek developed the SUV method to solve the problem of directional wave measurements from a moving subsurface buoy. This means that when wave measurements are desired in waters where it is not possible to use an array solution (60-100 meters deep) the AWAC may be placed in a subsurface buoy and positioned closer to the surface (e.g. 30 meters below the surface). The result is that the AWAC measures directional wave characteristics as if it was mounted on a seabed at 30 meters, yet it has the flexibility to be mounted at depths determined by the subsurface buoy's mooring system. Wave orbital velocity measurements are still made close to the surface like the array solution, but instead of an array the velocities are converted to the co-located velocity components of U and V (see Figure 23 c)). The other difference is that the dynamic pressure is replaced by the AST option.

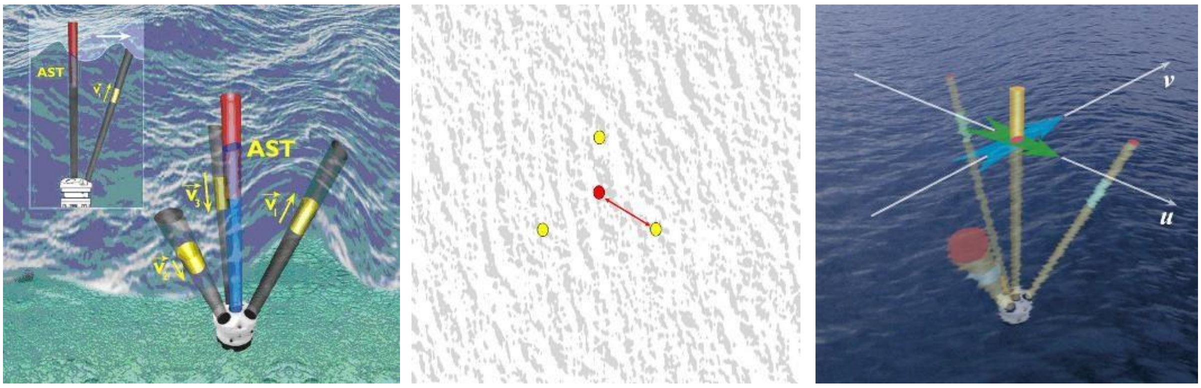

Figure 23: (a) AWAC and the array of measurements cells for orbital velocity measurements (yellow) and the Acoustic Surface Track option (red), **(b)** looking down from above at the array of measurements from the AWAC, **(c)** Axial velocity components of U and V.

The method may also be used for bottom mounted deployments even if data was collected without the SUV mode turned on in the AWAC's deployment configurations. The method is also better suited (than MLM) for deployments where the waves are exposed to large mean currents. Mean currents can present a Doppler shift on the wave field and introduce error in the directional and non-directional estimates if not corrected (as described in Section 8.4); The SUV method does not require this correction. For more on the SUV method, please read "Wave Measurement from a Subsurface Platform" [4].

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