ADCP 101

1. The Doppler principle

1.1. The Doppler effect

Acoustic Doppler Current Profilers measure water velocity using a principle of physics discovered by Christian Johann Doppler (1842). The Doppler effect relates to the change in frequency for an observer moving relative to a source of sound or light. Doppler first stated his principle in the article, “Concerning the coloured light of double stars and some other constellations in the heavens”. In daily life, a common example of the Acoustic Doppler effect or Doppler shift is the siren of an ambulance as it approaches, passes and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by and lower during recession. When the source of the waves is moving towards the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave. Hence, the time between the arrivals of successive wave crests at the observer is reduced, causing an increase in the frequency (compressed sound waves). Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wavefronts is then increased (stretched out sound waves). The total Doppler effect results therefore from the motion of the source and motion of the observer. The relationship between the source frequency, f_S and the Doppler-shifted frequency, f_D, can be given by:

$$f_D = f_S\left(\frac{c + v_O}{c - v_S}\right), \qquad \text{(eq. 1)}$$

where c is the speed of sound, v_O is the velocity of the observer and v_S is the velocity of the source. In terms of the corresponding periods, Eq. 1 becomes:

$$T_D = T_S\left(\frac{c - v_S}{c + v_O}\right) = T_S\,\frac{f_S}{f_D}, \qquad \text{(eq. 2)}$$

where T_S and T_D is the source and Doppler-shifted period, respectively.

1.2. Doppler shifts using acoustic scatterers

A Doppler current profiler applies the Doppler principle by acting both as a source and receiver while bouncing short pulses of acoustic energy off particles/scatterers (e.g. clay, silt, bubbles, phyto- and zooplankton) that are always present in natural waters. The scatterers are floating in the water and are assumed to move with the same horizontal and vertical speed as the water. The scatterers will reflect the transmitted sound energy in all directions and a small amount of the reflected signal is Doppler shifted towards the receiver. Because the instreúment both transmits and receives the sound pulse, the Doppler shift is doubled (once on the way to the scatterers, and a second time on the way back after reflection). Assuming that the velocities of the scatterers (v_O) and the instrument/source (v_S) are much slower than the speed of sound ($v_O << c$, $v_S << c$) the resulting equation for the Doppler shift becomes:

$$\Delta f = 2 f_S \frac{v_O}{c}, \qquad \text{(eq. 3)}$$

where Δf is the Doppler shift.

Example:
With a 600kHz transmitted sound frequency, 1500 ms^{-1} *speed of sound, and scatterers moving at 1 cms*$^{-1}$*, the frequency shift is:*

$$\Delta f = 2 \cdot 6 \cdot 10^5 \, Hz \frac{10^{-2} ms^{-1}}{1.5 \cdot 10^3 ms^{-1}} = 8 \, Hz.$$

(eq. 4)

However, what we have explained so far only applies when sound sources and receivers are moving closer or further away from each other.

1.3. Decomposing the radial motion of Doppler shift

If we come back to the ambulance approaching the observer directly, the pitch would remain constant until the vehicle hit him, and then immediately jump to a lower pitch. Because the vehicle passes by the observer, the radial velocity does not remain constant but instead varies as a function of the angle between his line of sight and the ambulance's velocity.

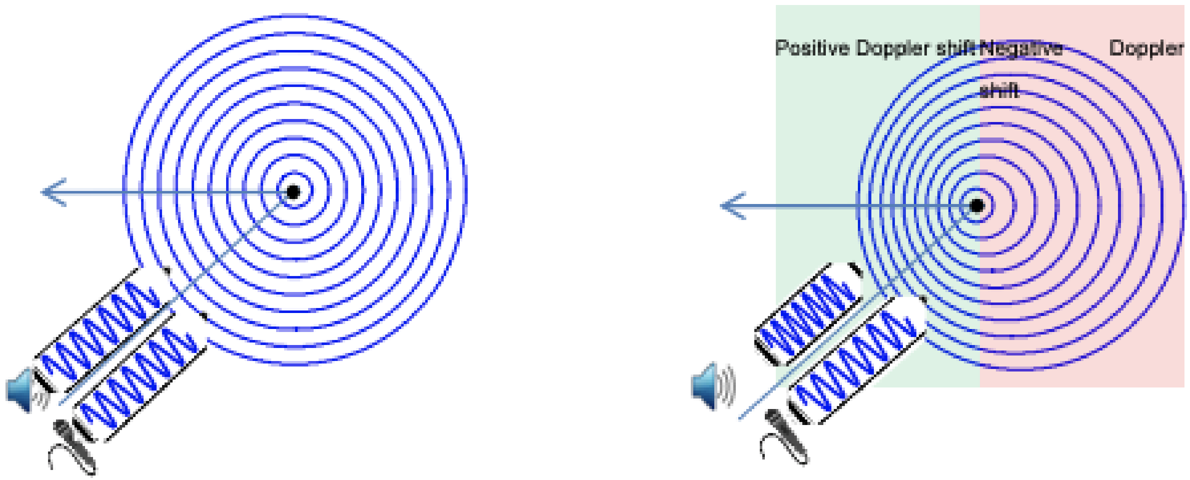

Figure 1. Doppler shifts from a stationary (left) and moving (right) target.

In Fig. 1, a transmitter transmits a signal towards two reflectors (scatterer). In the left figure, the reflector is stationary, while in the right figure the reflector is moving with a constant speed towards the left (relative in the figure). The circles in both plots indicate the wavelengths of the returned signal in all directions. For a stationary reflector, the wavelength of the reflected signal will be the same in all directions, and it will have the same frequency as transmitted, i.e. no Doppler shift, regardless of the position of the transmitter/receiver. For a moving reflector as in the right figure, the wavelength and frequency of the reflected signal will differ depending on the position of the receiver. The Doppler shift will depend on both the target speed and the angle θ between the direction of the moving target and the direction from the target to the receiver. We assume that the source is stationary. For a moving glider, this would not be the case, unless the sensor corrects for the movement. For angles θ < 90° (i.e. from straight on, to just before directly to the left or right) the Doppler shift is positive, and for angles θ > 90° the Doppler shift will be negative. At θ = 90° there is no Doppler shift. The angular motion changes the direction between the source and the receiver but not the distance separating them. The derived Doppler shift as a function of both speed and direction can be expressed as:

$$f_D = f_S\left(\frac{c + v_O}{c - v_S}\right) \cdot cos(\theta). \qquad \text{(eq. 5)}$$

2. Principles of operation

2.1. Geometry and features of the Aanderaa DCPS

The Aanderaa Doppler Current Profiling Sensor (DCPS) has four transducers acting both as transmitters and receivers. All four transducers transmit acoustic pulses simultaneously at approximately 600 kHz. The transducers are oriented in 90° azimuth from each other and with a 25° angle to the vertical (Figure 3).

Figure 2. *The Doppler Current Profiling Sensor 5400.*

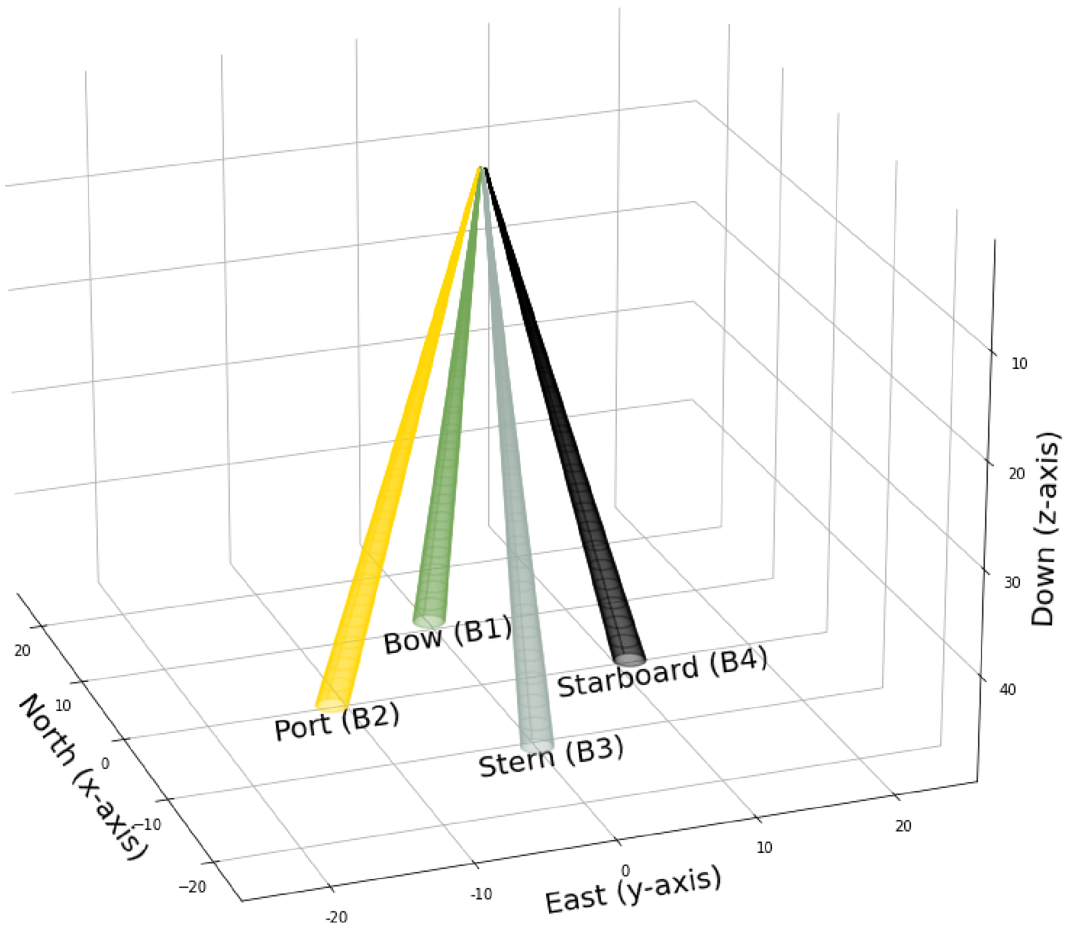

Figure 3. *The configuration of the four beams on a downward-looking DCPS.*

They are incorporated into a cylindrical shaped housing that contains all the necessary electronics offering an independently working sensor. It includes a three-axis solid-state compass able to obtain the current direction independently of sensor orientation and to constantly measure and compensate the measurements for tilt.

The configuration of transducers on the DCPS is the so-called "Janus" configuration, named after the Roman God who could simultaneously look forward and backwards. The configuration is particularly good for rejecting errors in horizontal velocity caused by instrument tilting since the two opposing beams allow vertical velocity components to cancel out when computing horizontal velocity. Also, instrument tilting, pitch, and roll cause velocity error proportional to the sine of the pitch and roll. The four beams allow for the calculation of two horizontal velocities with positive Doppler shift (moving towards the instrument), and two with negative (moving away), and four beams with vertical velocities. The direction of the vertical current is defined as positive when moving upwards.

Horizontal current speed and direction can be calculated with just three beams. The fourth beam is redundant but in the DCPS it allows for an evaluation of whether the assumption of horizontal homogeneity is reasonable, comparing the four vertical velocity estimates.

Utilizing four beams also makes it possible to calculate four different three-beam solutions by omitting one of the transducers. This can be useful in the case when for example one of the beams are receiving erroneous data caused by objects like mooring lines and floats that are not moving with the water flow. The DCPS has this ability built-in. It gives enhanced possibilities to understand the prevailing conditions and obtain high-quality data.

2.2. Narrowband Doppler Processing

The narrowband processing consists of measuring the frequency Doppler shift to calculate current velocity and direction at different distances from the sensor. So far, we have described the Doppler effect observed by one scatterer. In reality, the transmitted signal is reflected from several scatterers distributed in the water column, each of the scatterers will return an exact copy of the transmitted signal, with modified amplitude and phase (Figure 4). The phase of the signal will vary with the distance between the scatterer and the instrument and the amplitude of the reflected signal depends on the acoustic impedance of the scatterer, the size of the scatterer, and the distance. Due to the random distribution of scatterers both amplitude and phase will be more or less random. At the receiver, all contributions of the distributed scatterers will be summed into a single signal which will reflect the average Doppler shifted signal for this cell.

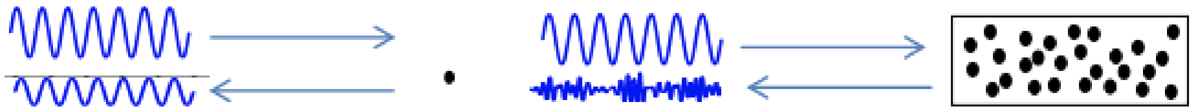

Figure 4. Reflection from a single reflector (left) and a cell containing a large number of scatterers.

The DCPS working in the narrowband mode transmits pulses, which are sinusoidal signals with a fixed frequency of 600 kHz. Depending on if the particles are moving away or towards the instrument the Doppler-shifted signal will be a compressed or stretched version of the transmitted signal.

2.3. Broadband mode

Broadband mode is available on the sensor, however, its use is discouraged by the manufacturer following a paper by Tengberg et al. (2018). In the paper, they analyse DCPS data from surface platforms (buoys) and determine that measuring currents in broadband mode from a moving platform would result in noisy and ultimately unusable data, even if this was not the main result and aim with the paper.

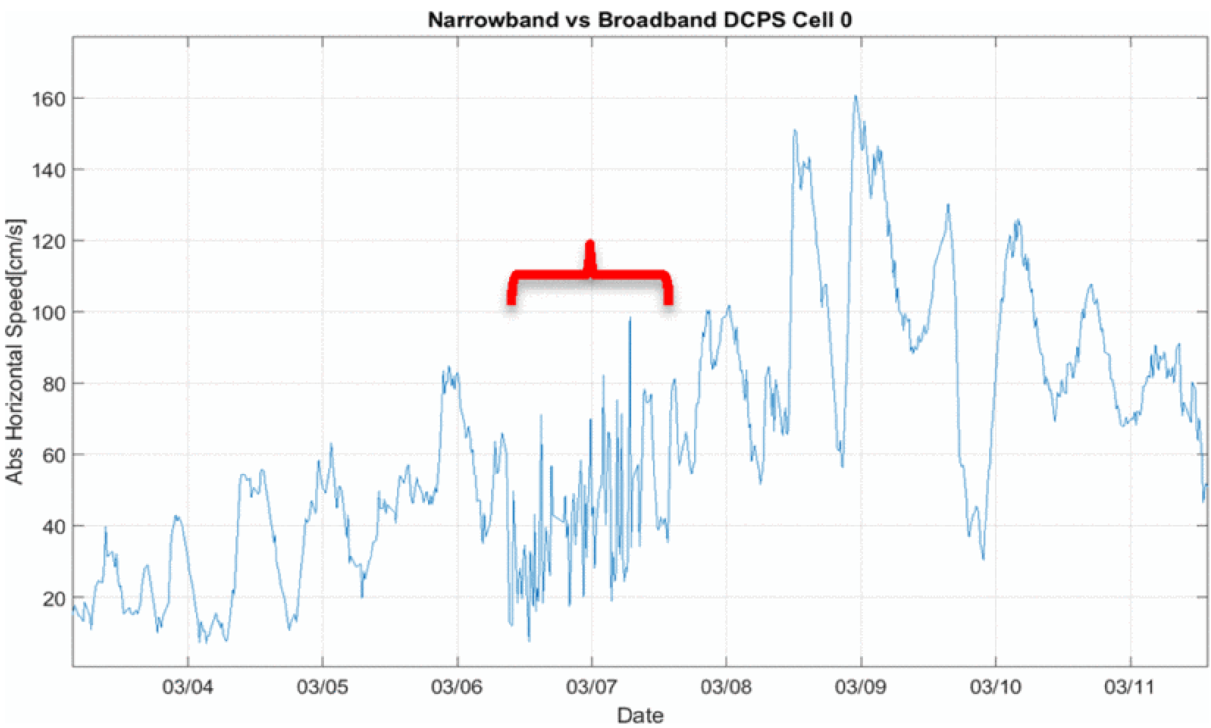

Figure 5. Broadband and narrowband measurements of horizontal current speed (cm/s) from a DCPS (first cell) on an EMM 2.0 buoy moving due to wave action. The DCPS was set to broadband mid-measurement period; while in narrowband otherwise. In narrowband mode, the noise levels are low and tidal variations can be distinguished. However, in broadband mode, the output was noisy and ultimately unusable. (Figure 14, Tengberg et al., 2018)

2.4. From signal transmission to reception

Whether the instrument is configured in broad- or narrowband, the user needs to configure the number of cells and the size of each cell (0.5-5m). These cells could be defined as the volume of water in which the instrument is performing the measurement. By defining cell size and the number of cells, and knowing the speed of sound, the instrument determines the time frame when the reflected signal from the corresponding cell will be received.

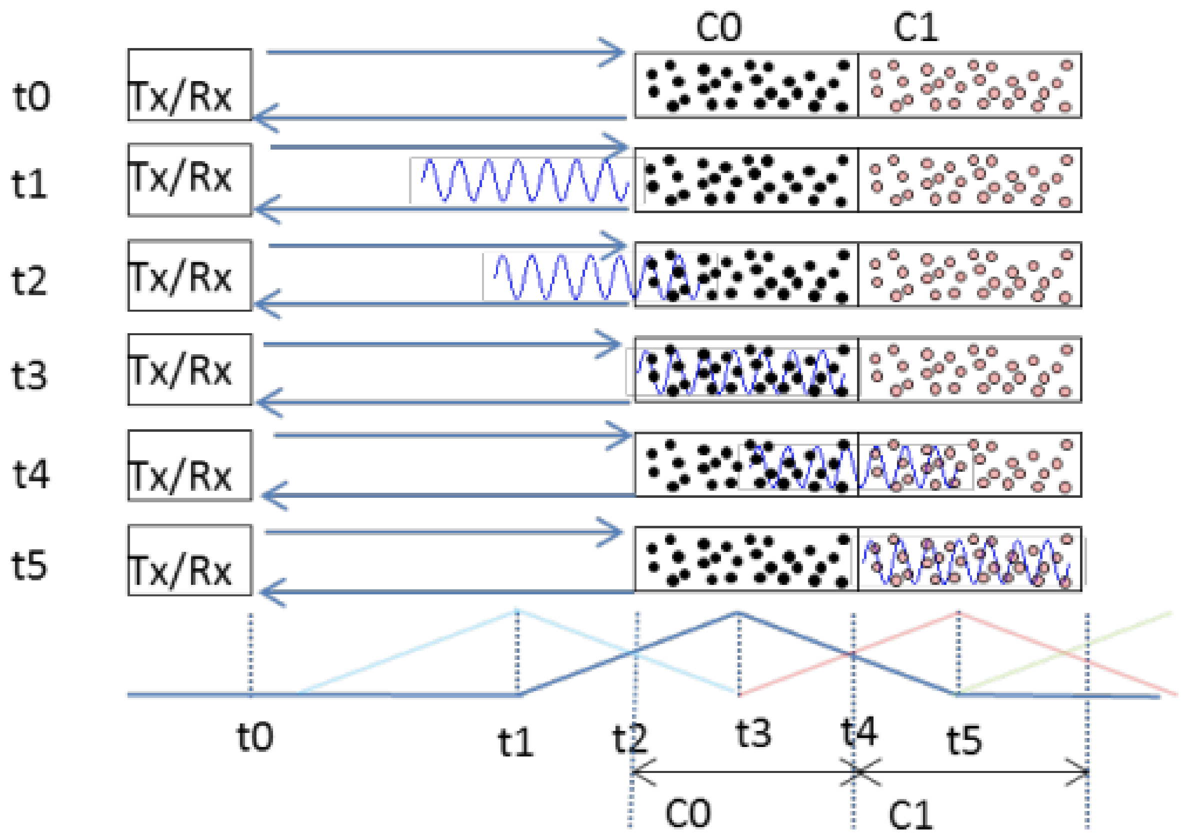

Figure 6. *Schematic for transmission and reception of the reflected signal. At t_0, the sensors transmit the acoustic pulse. At the receiver, the recording for the first cell (C0) starts when the center of the transmitted pulse reaches the beginning of C0 at t_2 and stops when the center of the pulse leaves C0 at t_4. In other words, the receiver collects samples for the same duration as the transmitted pulse. In Narrowband, the extent of the pulse in water also matches the cell size.*

When configuring the instrument, it is possible to define cell spacing. When cell spacing is shorter than cell size, there will be an overlap between cells. The size of the cell is not changed, but the spacing between them is reduced as the next cell will “overlap” the previous cell.

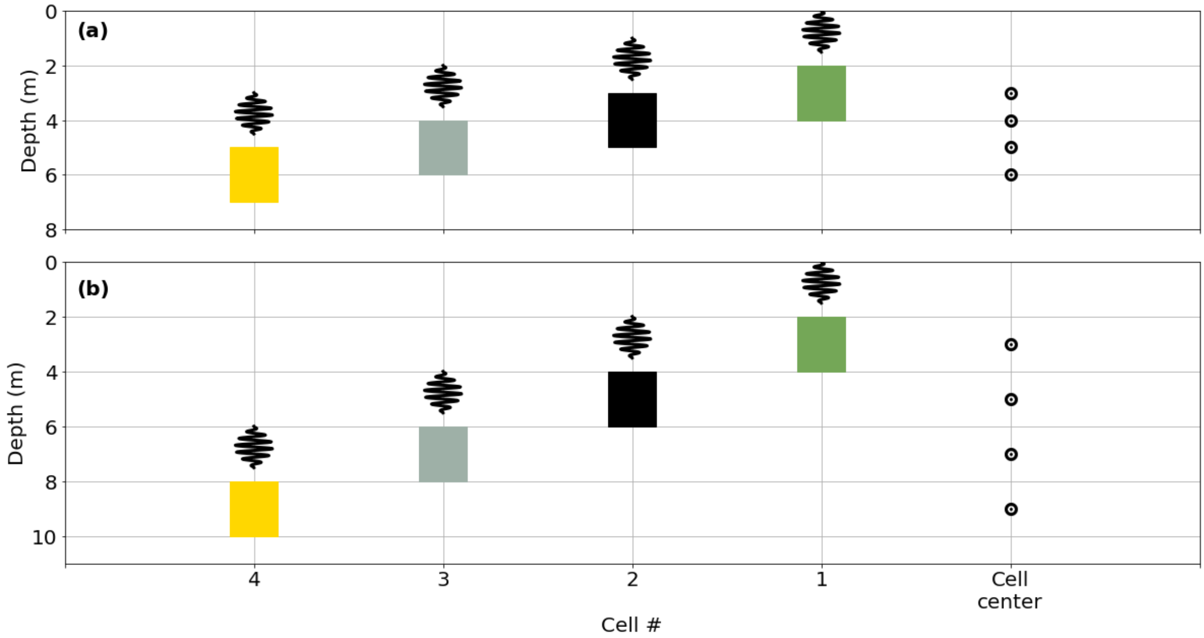

Figure 7. Comparison between two different cell spacings with the same cell size. (a) Cell spacing = 1 m, (b) cell spacing = 2 m. In (a), the cells overlap and can be correlated with each other. In (b) the cells do not overlap. In the case of (a), the horizontal range is limited, since we are sacrificing depth for overlap.

The advantage of using overlap is that one can correlate the cells with each other and therefore validate each beam. It can also be used when measuring the current as close to the boundary as possible (surface or bottom). Cells that contain samples from the boundary are contaminated by strong boundary reflections and are not used for measuring the current. By having a small spacing between cells the last good uncontaminated cell can easily be picked out. It will also improve the vertical resolution without reducing the cell size.

2.5. Compensation for tilt and rotation

With the built-in 3-axis compass (heading) and an accelerometer (tilt), every single measurement is compensated for tilt and rotation of the sensor.

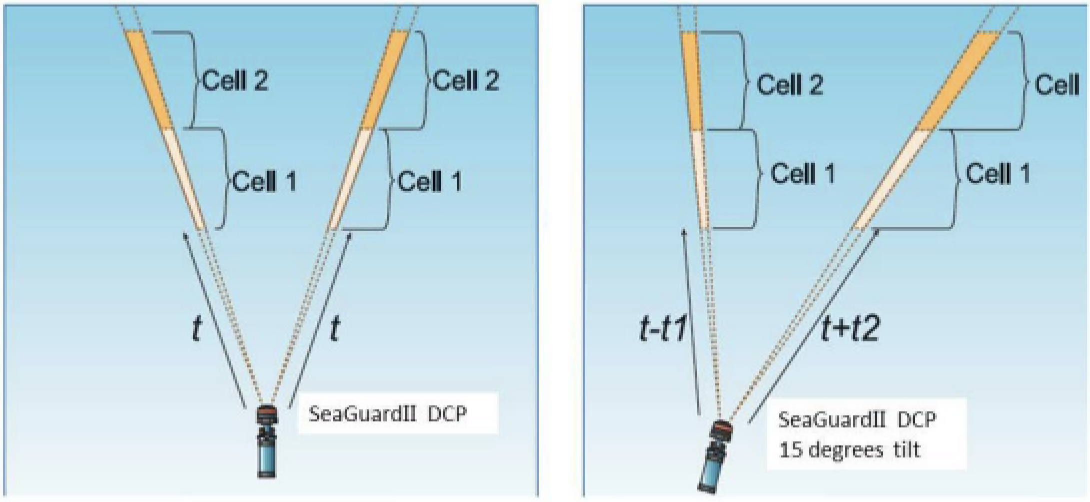

Figure 8. *Illustration of the beam repositioning when the instrument is tilted, for example with 15° tilt.*

When the sensor is tilting in one direction two of the beams will become more horizontally oriented and two beams become more vertically oriented. The more vertically oriented beams will have a shorter travelling distance than the more horizontally oriented beams to reach the depth level/cell at which the current will be measured. The DCPS will automatically tilt/time compensate the individual beams for each measurement so that the Doppler shift for all the four beams will be from the same depth level to obtain the true horizontal layer. The tilt compensation algorithm is updated for each ping and works with tilt up to ±50°. However, above ±35° the tilt sensor is outside the calibrated range, meaning that the profiling range and accuracy will decrease. For indication, at 50° tilt, the effective range is 25 m.

2.5.1. Decomposition of current Doppler vector along beams

A positive Doppler shift is measured when the current is going towards the transducer. Any current direction can be decomposed into the sensor's x-, y-, and z-axis. In the case of a current parallel to the x-axis only beam 1 and 3 (Figure 3) will be able to measure the current, and similarly for a current parallel to the y-axis, where only beam 2 and 4 will be able to measure the current. In these two special cases, the current will be orthogonal to the two remaining beams, hence no current will be measured from these beams. For each of the current directions (x, y, and z) the contribution from each of the sensors will be reduced due to the angle between each of the beams and the x-, y-, and z-axis.

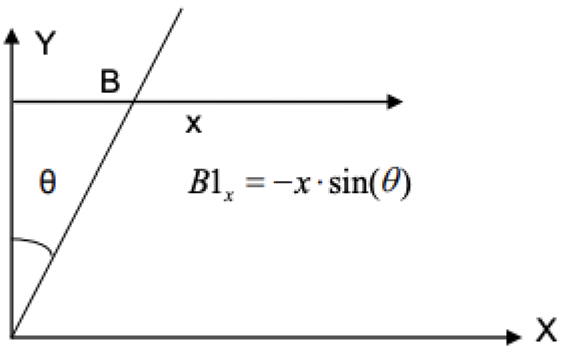

Figure 9. Decomposition of beam currents

Correspondingly, if the current is described in the sensor's reference frame, then x, y, and z each of the beam currents can be described. The following equations give the relationship between the decomposed current field (x, y, and z) and the contribution of each of the beams:

$$B1_x = -x \cdot \sin\theta \quad B2_x = 0 \quad B3_x = x \cdot \sin\theta \quad B4_x = 0$$

$$B1_y = 0 \quad B2_y = y \cdot \sin\theta \quad B3_y = 0 \quad B4_y = -y \cdot \sin\theta$$

$$B1_z = -z \cdot \cos\theta \quad B1_z = -z \cdot \cos\theta \quad B1_z = -z \cdot \cos\theta \quad B1_z = -z \cdot \cos\theta$$

By summing the contribution from each beam for the axes the following equations can be derived:

$$B3_x - B1_x = 2x \cdot \sin\theta \quad \Rightarrow \quad x = \frac{1}{2\sin\theta}(S3_x - S1_x)$$

(eq.6)

$$B2_y - B4_y = 2y \cdot \sin\theta \quad \Rightarrow \quad y = \frac{1}{2\sin\theta}(S2_y - S4_y)$$
(eq.7)

$$B1_z + B2_z + B3_z + B4_z = -4z \cdot \Rightarrow \quad z = -\frac{1}{4\cos\theta}(B1_z + B2_z + B3_z + B4_z)$$
(eq.8)

Equations 6-8 give the relationship between the beam current and the decomposed current x, y, and z.

The built-in accelerometer and magnetometer are used to establish the orientation of the instrument relative to the Earth reference system. The output from the "orientation sensor" is described as a rotation of the sensor along each of the axes. For a non-rotated, upward-facing sensor, the x-axis will be aligned with the north, the y-axis will be aligned with the west, and the z-axis is aligned with up. A positive rotation around the x-axis corresponds with a positive roll value, while a positive rotation around the y-axis represents a negative pitch. A positive rotation around the z-axis equals a counter-clockwise rotation of the sensor.

Each of these rotations can be described by a rotation matrix:

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{vmatrix} \cdot \begin{vmatrix} x \\ y \\ z \end{vmatrix} \quad u_x = A_x \cdot u \quad \theta: x - axis\ rotation$$

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{vmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{vmatrix} \cdot \begin{vmatrix} x \\ y \\ z \end{vmatrix} \quad u_y = B_y \cdot u \quad \phi: y - axis\ rotation$$

$$\begin{vmatrix} x' \\ y' \\ z' \end{vmatrix} = \begin{vmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} x \\ y \\ z \end{vmatrix} \quad u_z = C_z \cdot u \quad \varphi: z - axis\ rotation$$

By multiplying the rotation matrices together, the total rotational matrix can be found:

$$u_{Earth} = C_z \cdot B_y \cdot A_x \cdot u = D_{xyz} \cdot u$$

When u is related to the current in the sensor's reference frame, the u_{Earth} will be related to the current in the Earth's reference frame. The product $D_{xyz} = C_z \cdot B_y \cdot A_x$ can be expressed by:

$$D_{xyz} = \left| \begin{array}{c:c:c} \cos\varphi \cos\phi & \cos\varphi \sin\phi \sin\theta - \sin\varphi \cos\theta & \cos\varphi \sin\phi \cos\theta + \sin\varphi \sin\theta \\ \sin\varphi \cos\phi & \sin\varphi \sin\phi \sin\theta + \cos\varphi \cos\theta & \sin\varphi \sin\phi \cos\theta - \cos\varphi \sin\theta \\ -\sin\phi & \cos\phi \sin\theta & \cos\phi \cos\theta \end{array} \right|$$

This gives the relationship between the current in the sensor's reference frame, and the current in the Earth's reference frame:

$$north = x \cos\varphi \cos\phi + y\,(\cos\varphi \sin\phi \sin\theta - \sin\varphi \cos\theta) + z\,(\cos\varphi \sin\phi \cos\theta + \sin\varphi \sin\theta)$$
(eq.9)

$$west = x \sin\varphi \cos\phi + y\,(\sin\varphi \sin\phi \sin\theta + \cos\varphi \cos\theta) + z\,(\sin\varphi \sin\phi \cos\theta - \cos\varphi \sin\theta)$$
(eq.10)

$$up = x \sin\theta + y\,(\cos\phi \sin\theta) + z\,(\cos\phi \cos\theta)$$
(eq.11)

The combination of equations 6-8 and 9-11 gives the necessary equations to convert Doppler current measurements from the four beams into the current referenced to the Earth's reference system, for a given orientation of the sensor. This orientation is measured for every single ping. Within the measuring period, the currents are averaged in the Earth's frame of reference while utilizing the orientation measurement individually on a ping-to-ping basis. At each depth level and for each of the four beams, the total Doppler shift is obtained. Both horizontal and vertical currents contribute, but the latter is usually of the order of one magnitude less.

Equations 9-11 deal with an upward-facing DCPS, yet they are true for a downward-facing as well, with the change that the positive y-direction is east, and the positive z-direction is down.

2.6. Blanking distance

After transmitting an acoustic pulse, the transducers and electronics must rest for a short time for the transducers to stop vibrating (ringing) before it is able to act as a microphone and receive the very weak (compared to the transmitted pulse) reflected acoustic signals. The ringing of the transducers depends on the transducer size, frequency, and the material embedding the transducers. About 0.5 ms of ringing corresponds to a 1 m blanking distance assuming a sound speed in water of 1500 m s^{-1}.