DOP4000
series

User's manual

Software: 6.6
Revision: 1

Important notice   The information contained in this manual is subject to change without prior notice.

The2 purpose of this manual is only to explain the use of the velocimeter. Signal Processing cannot be held responsible for any damage which could result from the improper use of the information contained herein.

Signal Processing cannot guarantee the reliability of the velocimeter, nor be held responsible for the consequences, when the velocimeter is being used in conjunction with equipment not supplied or approved by Signal Processing.

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This instrument complies to norms EN50081-1, EN50082-2. Nevertheless the immunity of the velocimeter to external perturbations conducted or radiated can not be guaranteed if their frequencies are in the range of the emitted ultrasonic frequencies and their harmonics.

Medical application   This instrument should not be used on human body.

Guarantee   Signal Processing guarantees that the velocimeter will function according to the specifications given in this manual under normal use. The guarantee is valid for one after the date of delivery. All items not manufactured by Signal Processing are covered only by the warranties which their manufacturers supply. Under this guarantee, Signal Processing will replace or repair (according to its best judgment) the defective part. This guarantee is automatically void if the damage is proven to be the result of improper use.
It is highly recommended that the buyer thoroughly inspects the apparatus immediately after delivery. Any malfunctions must be reported in writing to Signal Processing.
The costs of insurance and delivery for any defective parts are under the responsibility of the buyer. Signal Processing will return the parts postage paid to the address where the parts were originally sent, with the insurance remaining the responsibility of the buyer.

Assistance   All questions pertaining to the installation and use of the apparatus should be directed to:

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Signal Processing S.A. - DOP4000 user's manual

1 Doppler ultrasound velocimetry

Doppler ultrasound velocimetry, was originally applied in the medical field and dates back more than 30 years. The use of pulsed emissions has extended this technique to other fields and has opened the way to new measuring techniques in fluid dynamics. The term "Doppler ultrasound velocimetry" implies that the velocity is measured by finding the Doppler frequency in the received signal, as is the case in Laser Doppler velocimetry. In fact, in ultrasonic pulsed Doppler velocimetry, this is never the case. Velocities are derived from shifts in positions between pulses, and the Doppler effect plays a minor role.

1.1 Doppler effect

The Doppler effect is the change in frequency of an acoustic or electromagnetic wave resulting from the movement of either the emitter or receptor.

Let us consider an ultrasonic transducer which emits waves of frequency f_e and remains constant in a medium where the speed of sound is c. A receptor, or target, in the medium moves with a velocity v. By convention, v is considered negative when the target is moving toward the transducer. If the trajectory of the target forms an angle θ_1 with respect to the direction of propagation of the ultrasonic wave, the frequency of the waves perceived by the target will be:

$$f_t = f_e - \frac{f_e v \cos\theta_1}{c}$$
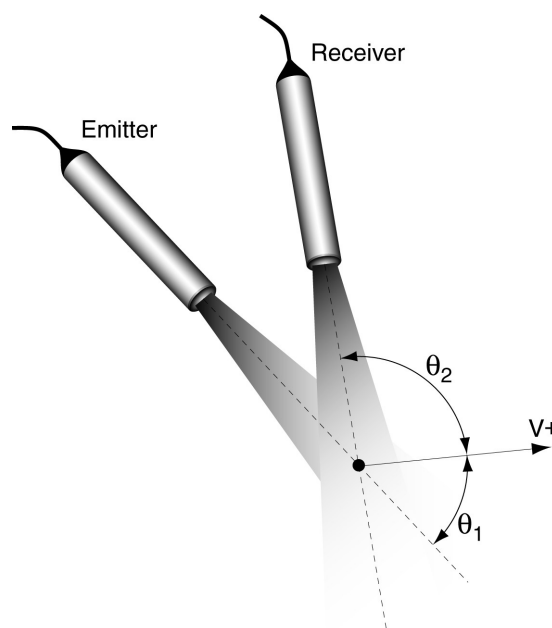
If the acoustic impedance of the target is different from that of the surrounding medium, the waves will be partially reflected. The target acts as a moving source of ultrasonic signals. The frequency of the waves reflected by the target, as measured by a stationary receiver, is:

$$f_r = f_g + \frac{f_g v \cos \Theta_2}{c}$$

As the velocity of the target is much smaller than the speed of sound (v << c) it is reasonable to neglect the second order terms. The difference between the emitted and received signals, which is known as the Doppler frequency shift, is then expressed by:

$$f_d = \frac{f_e v \cdot (\cos \Theta_1 - \cos \Theta_2)}{c}$$

If the same transducer is used for receiving the signals the above equation becomes (Doppler equation):

$$f_d = \frac{2 f_e v \cos \theta_1}{c}$$

1.2 Pulsed Doppler ultrasound

In pulsed Doppler ultrasound, instead of emitting continuous ultrasonic waves, an emitter sends a short ultrasonic burst periodically and a receiver continuously collects echoes issued from targets that may be present in the path of the ultrasonic beam. By sampling the incoming echoes at the same time relative to the emission of the bursts, the shift of positions of scatterers are measured. Let's assume the case illustrated in the figure below, where only one particle is in the ultrasonic beam. From the knowledge of the time delay T_d between an emitted burst and the echo reflected by the particle, the depth p of this particle can be computed by:

$$P = \frac{c \cdot T_d}{2}$$

where c is the sound velocity of the ultrasonic wave in the liquid.
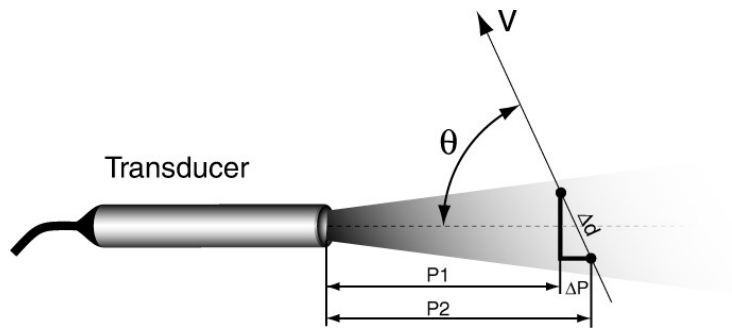
If the particle is moving at an angle θ in relation to the axis of the ultrasonic beam, its velocity can be measured by computing the variation of its depth between two emissions separated in time by T_{prf}:

$$(P_2 - P_1) = v \cdot T_{prf} \cdot \cos\theta = \frac{c}{2} \cdot (T_2 - T_1)$$

The time difference $(T_2 - T_1)$ is always very short, most of the time less than a microsecond. It is advantageous to replace this time measurement by a measurement of the phase shift of the received echo.

$$\delta = 2\pi \cdot f_e \cdot (T_2 - T_1)$$

where f_e is the emitting frequency. With this information the velocity of the target is expressed by:

$$v = \frac{c \cdot \delta}{4\pi \cdot f_e \cdot \cos\Theta \cdot T_{prf}} = \frac{c \cdot f_d}{2 \cdot f_e \cdot \cos\Theta}$$

This last equation gives the same result as the Doppler equation but one should always be aware that the phenomena involved are not the same. Let's assume that the particles are randomly distributed inside the ultrasonic beam. The echoes returned by each particle are then combined together in a random fashion, giving a random echo signal. Hopefully, a high degree of correlation exists between different emissions. This high degree of correlation is highlighted in all digital processing techniques used in Signal Processing's Ultrasonic Doppler velocimeter to extract information, such as the velocity.

1.3 Advantages and limitations

The main advantage of pulsed Doppler ultrasound is its ability to offer spatial information associated with velocity values. Unfortunately, as the information is available only

periodically, this technique suffers from the Nyquist theorem. This means that a maximum velocity   exists for each pulse repetition frequency (PRF):

$$v_{max} = \frac{c}{4 \cdot f_e \cdot \cos\Theta \cdot T_{prf}}$$

If the measured velocity is higher than this maximum velocity, a phenomena named aliasing will appear. In such a situation, all Doppler frequencies above the half of the sampling frequency ($f_{prf} = 1/T_{prf}$), are folded back in the low frequency region or aliased. The figure below illustrates the relationship between the real frequency and the measured frequency.
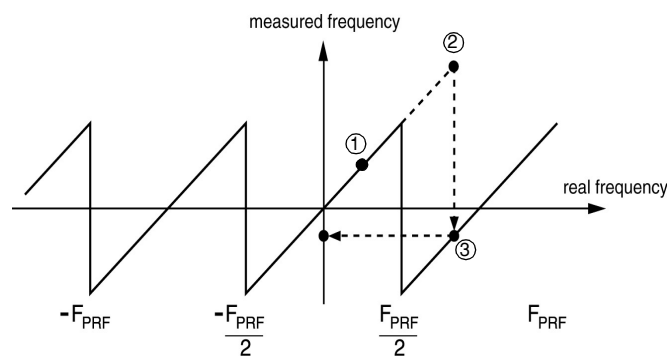
At point ① , the real Doppler frequency is below the Nyquist limit ($F_{prf}/2$), so the measured frequency is equal to the real frequency. At point ② , the real Doppler frequency is much above the Nyquist limit. Point ② is then backfolded to point ③ , which gives a negative velocity. This negative frequency is equal to the real frequency from which the sampling frequency is substracted. For an analog signal it is possible to avoid aliasing by filtering the signal before sampling it in order to remove all the frequencies above the Nyquist limit ($F_{PRF}/2$). Unfortunately for pulsed Doppler ultrasound only samples are available and therefore it is not possible to remove the aliasing. The only solution is to adapt the sampling rate or the pulse repetition frequency to the Doppler signal that has to be measured.

Note: An easy way to check the presence of aliasing is to examine the evolution of the measured Doppler frequency when changing the pulsed repetition frequency.

In addition to the maximum velocity limitation, there is a maximum depth at which a velocity may be measured. This limit is determined by the time needed for the ultrasonic signal to travel from the transducer to the target and back. This time is determined by the

pulse repetition frequency (PRF) of the ultrasonic pulses. This gives a maximum depth equal to:

$$P_{max} = \frac{T_{prf} \cdot c}{2}$$

Reducing the PRF (increasing T_{prf}) will increase the maximum measurable depth, but will also reduce the maximum Doppler frequency which can be measured. The maximum velocity and depth which may be measured are thus related according to the following equation:

$$P_{max} V_{max} = \frac{c^2}{8 f_e}$$

At any given instant, an echo signal can come from many different depths, corresponding to echoes from previously emitted signals. The presence of several acoustic interfaces also causes several reflections which can cause a false determination of the target depth. Nevertheless, if the PRF is sufficiently low (a few kHz), the attenuation of previously emitted pulses will render them indiscernible. The same goes for reflected signals. With a large increase in the PRF, pulsed Doppler ultrasound can approach the properties of continuous wave Doppler, with a loss of axial resolution but no maximum velocity limitation.

2 Architecture of the velocimeter   2 - 1

2.1 Schematic block

The figure below shows the schematic block of the velocimeter. Generally, the same transducer is used to both emit and receive the ultrasonic signals. The signal coming from the emitter provides the trigger for the emitted signal at the PRF.
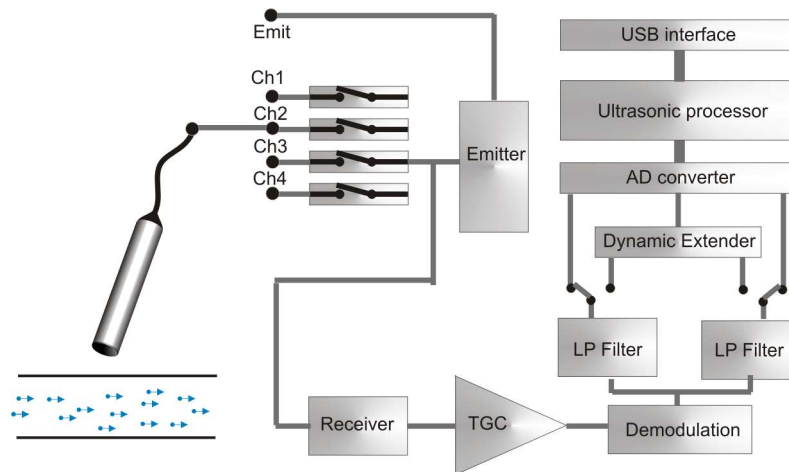
The amplification of the echo signal is increased according to the depth (Time Gain Control or TGC) in order to compensate for the attenuation of the waves. Following the amplification, the echo signal is demodulated, then filtered to isolate the Doppler information. A low pass filter suppresses the added frequencies in the spectrum generated by the demodulation.

The Doppler signals then pass, or not, through the Dynamic Extender circuitry and is sampled and converted into digital values by a fast A/D converter. The time between acquisitions determines the axial spacing between sample volumes, while the delay between the emission of the ultrasonic burst and sampling time of the Doppler signals determines the distance between the transducer and the sample volume. The signals coming from the A/D converter are stored, then filtered by a high pass filter which eliminates the steady and quasi steady components. Finally, the frequencies of the Doppler signals are estimated and sent to an external computer via the USB interface.

2.2 The front panel of the DOP4000

The front panel of the DOP4000 contains the four probes connectors, marked CH1 to CH4, a connector where the emitted pulse can be found, marked EMI, and two user's defined synchronization connectors, marked Sync1 and Sync2. A red LED indicates the state of the power supply of the instrument.

The DOP4000 front panel

Note: the instantaneous voltage that may appear at probe connectors and the EMI connector can be in the order of 100 V_{pp} for few microseconds.

Caution:Never apply a voltage above 5 Volt or under 0 Volt to the Sync1 and Sync2 connectors.

2.3 The rear panel of the instrument

The rear panel contains the USB connector, the power supply connector and a line voltage switch, which allows to select the correct power line voltage.

Caution:Be sure to select the correct power line voltage before applying the power supply.

3 Installing the software

This chapter explains how to install the software UDOP and the USB driver that controls the DOP4000 ultrasonic Doppler velocimeter. The driver installation is realized only once on the connected PC.

You should follow the steps below:

> - get the software from our web site.
> - installing the software driver
> - install the UDOP software
> - connecting the cables
> - switching on the power supply of the velocimeter
> - running the UDOP software

3.1 Getting the software

The software that controls the DOP4000, UDOP, and the associated USB driver is available on our website at the following address:

http://www.signal-processing.com/dop4000_download.html

Download the following zip file "dop4000_update_v_vv_v.zip" where v_vv_v represents the software version and unzip that file to a directory of your choice. This directory will be the directory that will contain UDOP software and must contain the following directories:

> - DRIVER
> - MANUAL
> - UTILITIES
> - US_FIELD_DATA

and the following files:

> - udop4000.chm
> - ftd2xx.dll
> - Udopvvvv.exe (vvvv represent the software version)
> - Udop21488_vvvv.bin

3.2 Installing the software driver

The driver to install is contained in an ".exe" file located in the directory named "driver". After a click on that file the following display appears:

Accept the extraction:
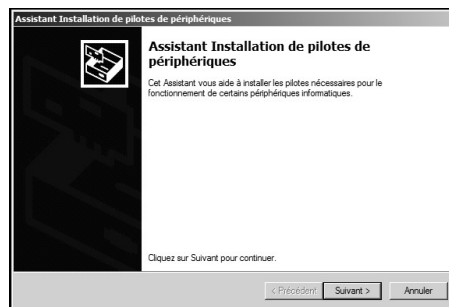
Then accept the installation:
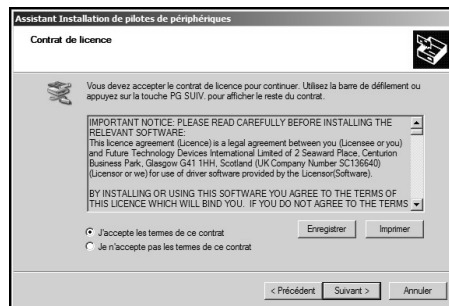
If the installation is successful, the following displays appears:"
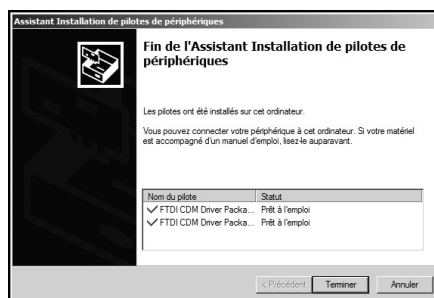
3.3 Connecting the cables

Before connecting the DOP4000 to the power supply line, be sure that the voltage selection switch is set for the correct line voltage. Connect the USB port of the DOP4000 to any available USB 2 compatible port on the PC. The DOP4000 do not request power from the USB port. Then turn on the power switch. Windows will then detect the DOP4000.

3.4 What to do in case of troubles during the installation of the driver?

If a wrong answer is given during the installation procedure, the installation may failed. In such a case you have to re-install again the driver.

More information on the driver can be found on the website:

> http://www.ftdichip.com/Drivers/D2XX.htm

3.5 What to do if the application do not start?

The application UDOP uses a configuration file, named:

- UDOP4000_nnn_vvvv_CFG.BIN
  where nnn is a 3 digits that identifies the instrument and vvvv identifies the software version

  or

- UDOPCFG_vvvv.BIN if in simulation

that contains the working parameters. If the file is corrupted or contains incorrect parameters, UDOP can not be executed. In such a case you must delete the configuration file. If no configuration file is detected at start-up, UDOP will create a new one, containing the default parameters.

3.6 Connecting more then one DOP to the same PC?

UDOP can recognize up to 4 different DOP3000 or DOP4000 velocimeters. This means that you can connect to the same PC up to four instruments. For each velocimeter you must launch the UDOP application. UDOP identifies the instrument by its serial number, which is displayed in the title bar of the application. Each instrument keeps in a file its own functioning parameters.

Note: The size of the UDOP window can be resized as desired, following the same procedure as for any windows applications.
If the acquisition time is very fast, it may appear that the PC can't follow the acquisition rate for all the instruments.

4 Using the velocimeter

This chapter is intended to explain how to use DOP ultrasonic Doppler velocimeter. Before using the instrument be sure that the USB software driver is already installed. If the driver is not installed properly, UDOP will not detect any instrument and will start in simulation mode.

4.1 Installation of the ultrasonic probe

The DOP emits and receives the ultrasonic echoes on the same BNC connector. Probes can be connected or removed without turning off the power line of the velocimeter.

Caution:Ultrasonic probes are fragile. They must be handled with care and they must not receive any shocks. The probe support must not induce mechanical stress especially to the front surface of the probe.

Whenever possible it is always better to put the probe directly in contact with the liquid. Crossing interfaces or walls induces reflections which reduce the amount of ultrasonic power injected in the liquid and may disturb the ultrasonic field (see the chapter «Influences of interfaces»).

The probe should be mounted on a rigid support which should have some degrees of freedom in order to select an appropriate position, but it may be useful to start by handling the probe by hand in order to find a good position.

When positioning the probe the points below should be taken into account:

- a good position is a position which generates the minimum stationary echoes;
- when crossing interfaces, the angle between the probe axis and the surface of the interface must take into account the maximum refraction angle. This angle is defined by the ultrasonic properties of the different medium in presence;
- vibrations of the probe support should be avoided;
- it is absolutely necessary to remove of any gas layers or bubbles when coupling the probe; the attenuation of ultrasonic waves in gas at the working frequencies is so high that most of the emitted energy is dissipated in the gas.
- be sure that the front face of the probe is always in contact with the liquid or the coupling medium.

- always try to avoid to be perpendicular to an interface. Being just only a few degrees away from the perpendicular reduces stationary echoes that may appear between the transducer and proximate walls.

When the ultrasonic probe is directly in contact with the liquid it is not necessary to use any coupling medium. If the ultrasonic waves have to cross a solid interface it is absolutely necessary to use a coupling medium, like the ultrasonic gel delivered with the instrument. It is not necessary to put the probe in contact with the interface. The coupling medium, which can be an ultrasonic gel, will guarantee a path for the ultrasonic waves. The coupling medium should be put in enough quantity. It should completely cover the extremity of the probe.

Small gas bubbles may appears after a certain time on the surface of the probe especially when the liquid contains a lot of gas dissolved in it. These bubbles should be removed.

4.2 Defining the operating parameters

The quality of the measurements depends on the choice of the parameters values. Unfortunately in ultrasonic Doppler velocimetry the most important parameters are linked together, like the maximum measurable depth and the maximum velocity.

UDOP allows to define the operating parameters by two methods. The first one, which is named "the assisted mode" allows to bypass the introduction of the ultrasonic parameters and allows to enter directly the application parameters which are the velocity range and the depth range. A quality factor parameters is used to realize a kind of compromise between the acquisition rate and the standard deviation of the measured values.

Most of the value are entered by means of input button such the one illustrated in the figure below:

If the edit zone is used to enter a new value, the new number must be validated by the pressing the carriage return on the keyboard. The sliding bar also allows to change the value. The big one covers all the possible range, the small one only a portion around the current value.

It is not possible to give a general rule which guarantee the best choice in any cases. Nevertheless the following advises will help the user to find appropriate settings.

We recommend to always start a new measurement with the default parameters. The default parameters can be selected by a click in parameters menu on "Default parameters". The default parameters select the assisted mode. Then open the "Assisted mode parameters" panel from the menu bar (Parameter -> Assisted mode parameters). In this panel:

- select the emitting frequency that corresponds to the ultrasonic probe connected to it. The velocimeter can emit a very short ultrasonic pulse. This means that at high ultrasonic frequency, it is some time not possible to exactly select the frequency for which the probe is designed. This is not an issue as the bandwidth of the probe (around 50%) allows to use a frequency around its nominal value.

- verify that the sound velocity corresponds to the liquid you are using.

- select the starting depth by entering a value in the field named "From".

- select a velocity scale much higher that the one you expect. This will insure that the measured profile will not contains aliased velocities. You will adapt after the velocity scale step by step

- enter a temporary maximum depth in the field named "To", around few centimeters away from the starting depth.

- select an acquisition time by moving the cursor on the sliding bar in order to have a blue or a yellow cursor.

Accept the settings and look at the resulting velocity profile. You will certainly have to improve the quality of the measured profile (see next chapter)

- You can then increase step by step the investigated depth until the whole range of interest is covered and only after adapt the velocity scale to let the velocity profile cover the widest range of the velocity scale as possible.

Note: By clicking on the velocity scale you can move the origin by dragging the mouse and leaving therefore more space for a positive or negative velocity.

4.3 Searching for artifacts

In many situations, interfaces and walls close to the measuring area generate artificial echoes which are named artifacts. These echoes appear on the screen as if they were real echoes. They are in fact images of real echoes (or duplicate echoes) that come after the PRF time. These artifacts disturb the measurement if they are strong and should be removed if possible. Unfortunately the only way to remove these artifacts consist to:

- move the probe away from the walls
- change the PRF value.

UDOP software let the user to easily change the PRF value in order to investigate its influence. The PRF can be changed in a floating panel, which is visible if the user has marked in the "option" panel the corresponding check box. Any changes in depth of an echo due to a change in the PRF value means that this echo is an artifact.

4.4 Adjusting the scales

Not all types of flows are bidirectional and even if they are, the range of positive and negative velocities can be different from each other. UDOP allows to move the origin of the velocity scale along the velocity axis in order to provide a part from its positive range to its negative range or vice-versa. This possibility allows to increase the maximum measurable velocity without changing other parameters and can be used whenever aliasing can disturb the measurement.

The modification of the velocity offset is realized by clicking on the velocity axis and moving the mouse up or down. A double click on the velocity axis cancel any applied offset.

If the selected measured data is an echo or an energy profile the scale can be changed by a mouse click on the arrows located beside the legend of the axis. Any change in the scale affects the recorded data.

The modification of the depth scale can also be realized the same way as the velocity scale. If the assisted mode is active, a change in the measured depth range may induce also a change the measurable velocity range.

Note: The two arrows, placed beside the legend, indicate that the scale can be changed.

4.5 Improvement of the quality of the measured profile

All the suggestions below refer to the assisted mode.

I see a profile with most of the values close to the zero line, but not zero.

> Adapted the velocity scale to the measured data. If the maximum velocity scale is still lower then the maximum desired velocity, you must reduce the maximum depth.

I do not see any profiles or the profile contains a lot of zero.

> If you have follow the recommendations mentioned in the previous chapters, the problem may comes from a really to much higher velocity scale or a lack of ultrasonic energy. Try to decrease step by step the velocity scale. If this does not improve the measurement, you should check the following points:

- are the coupling of the probe correct (no gas or bubble at the interface.
- if crossing wall, verify that the angle between the probe axis and the surface of the wall is not to big (take care for a complete reflection).
- verify that the echo profile is not saturated by visualizing this profile.

After checking the above points you can do the following:

- leave the assisted mode by unchecking the assisted mode enable field in the "Preference" menu.
- Enter in the "Operating parameters" panel from the "Parameter" menu.
- increase the sensitivity and see the result. If a "High" or "Very High" sensitivity value improves the result, the level of the received echoes are at the limit of the detection capability of the instrument.
- Try to increase the emitting power

> If none of these modifications improve the profile, you must add particles to the liquid in order to receive stronger echoes.

My profile looks like noise

> This can be the case if the velocity scale is far to low, and the measured profile is a totally aliased profile. Increase step by step the velocity scale and looks on the result. If this does not improve the profile, you are certainly measuring in a noisy environment. Try to use a power line as far away as possible from any potential noisy source (switching power supply, heating system). Try to shield the probe cable with some metallic foils (alu foils used for food). If this last point improves the profile a special shielded probe can be used (available on request).

The beginning of the profile is not measured (zero values)

> This may appears if the amplification level is to high and saturates the input stage. The TGC should be adapted. Please note that close to the transducer, the ringing effect of the piezo ceramic avoid any measurement. This is normal.

The end of the profile is not measured (zero values)

> This may appear if the amplification level is to low or the liquid attenuates to much the ultrasonic waves. Try to improve the TGC, the level of the emission and the sensitivity.

4.6 Influences of interfaces

The interfaces reflect and modify the acoustic field. The intensity of the acoustic field received in a point depends on the material, on the shape and on the number of interfaces crossed by the ultrasonic waves. This means that it is often very difficult to have a good knowledge of the ultrasonic intensity. This lack of knowledge does not allow a precise determination of the size of the measuring volume. The interfaces may generate, in certain situations, artifacts and induce modifications in the velocity profiles as presented in the figures 1 and 2 below.

The ultrasonic beam BC reflected by the far interface of the figure 1 transforms this interface in a transmitter. The same particles contained in the liquid will backscatter a second time energy in the direction to the transducer.

.
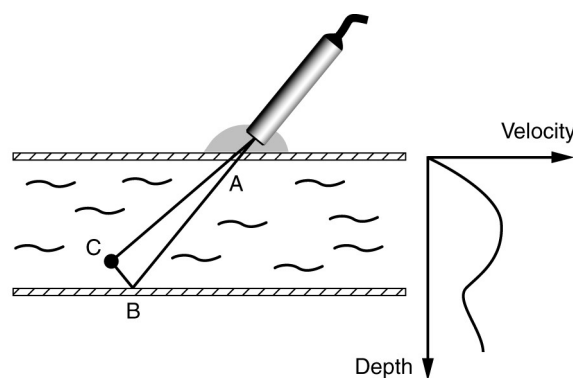
Figure 1

The depth associated to the path ABC is located outside the flowing liquid. Imaginary velocity components are added to the real velocity profile. The measurement of velocities near the far interface is affected by this phenomenon. The size of the ultrasonic beam

determines mainly the level of this artifact. The effect mentioned above explains why it is impossible to obtain a zero velocity value at the far wall.

Reflected waves

Refracted waves
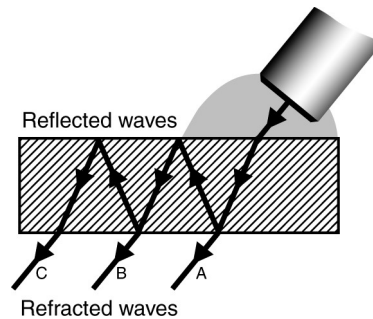
Figure 2

The figure 2 displays another situation some times encountered. The reflected ultrasonic waves inside a wall enlarge the ultrasonic beam and complicates the determination of the depth of the gates. This phenomena appears if the difference in the acoustic impedance between the liquid and the interface is high, as for instance in steel. In such a case, a lot of acoustic energy remains in the steel, which induces longer saturation of the receiver and a lost in depth resolution.

These reflections disturb the determination of the size and the shape of the measuring volume. The thickness, the acoustical impedance and the attenuation coefficient of the interface determine the level of this phenomenon.

4.7 Moving interfaces

Interfaces often give strong reflections. Despite of the many reflections which are necessary to reach the transducer, the energy reflected by these interfaces is often stronger than the energy coming from the particles flowing with the liquid. When some interfaces are in movement the correct estimation of all the velocity field is more difficult. The echoes generated by such interfaces may affect the velocity profile in some places due to the combination of many reflections. The Doppler frequency induced by these movable interfaces can not be removed if their values have the same values as the flowing particles.

4.8 Intensity of the ultrasonic field after crossing a wall

When an ultrasonic beam encounters a wall, a part of its energy is reflected and an other part is refracted. The intensity of both beams, the reflected and the refracted beams, can be computed when the two following parameters are known:

- the acoustic impedance of the medium;
- the angle of incidence.

The simple equations below assume a plane infinite wall or interface. This is of course never the case. Nevertheless, these three equations can really help because:

- they give an approximation of the total reflection angle;
- they predict the amount of ultrasonic energy that will penetrate in the liquid;
- they predict the amount of energy that tends to remain in the wall.
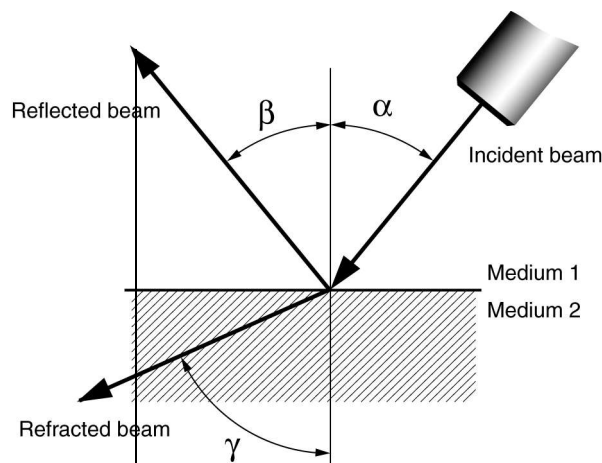
$$D = \frac{4Z_1 Z_2 \cos^2(\alpha)}{(Z_2 \cos(\alpha) + Z_1 \cos(\gamma))^2}$$

$$\gamma = \mathrm{asin}\left(\frac{C_2 \sin\alpha}{C_1}\right)$$

$$R = \left[\frac{Z_2 \cos(\alpha) - Z_1 \cos(\gamma)}{Z_2 \cos(\alpha) + Z_1 \cos(\gamma)}\right]^2$$

where:

- R is the reflection coefficient, which is equal to the ratio of the reflected intensity to the incident intensity;

- D is the refraction coefficient, which is equal to the ratio of the refracted intensity to the incident intensity;

- γ the refraction angle

- Zi is the acoustic impedance of the medium i, which is equal to the product of the sound speed by the density of the medium i.

From these equations, it is possible to compute the value of the angle for which all the ultrasonic waves will be reflected. By setting a value of 90 degrees to the refracted angle, we can compute the value of the total reflection angle. For instance:

- for aluminium, its value is 14 degrees;

- for steel, its values is 15 degrees;

- for plexiglas, its value is 33 degrees

We can also see the very strong influence of the wall material when the angle of incidence is different from the perpendicular. The two examples below show this influence very well:

Table 1:

Material	α	γ	R	D
Plexiglas	30	66	0.42	0.58
	27	56	0.30	0.69
	25	50	0.26	0.74
	20	38	0.20	0.80
	15	18	0.15	0.85
Steel	14	69	0.95	0.047
	12	53	0.92	0.077
	10	42	0.90	0.094
	8	32	0.89	0.11
	4	15	0.88	0.12

5 Computation and display of data profiles

The velocimeter does not only computes and displays velocity profiles. It also allows to collect much more information in real time. These additional information are:

-the profile of the echo modulus
-the velocity profile and the profile of the echo modulus
-the profile of the Doppler energy
-the profile and the corresponding histogram
-the power spectrum of a selected gate
-the velocity profile and the profile of the Doppler energy
-the velocity profile and velocity versus time of many selected gates
-the velocity profile and its evolution versus time
-the velocity profile and the evolution of the flow rate

5.1 Velocity profile

The velocity profile is the main display. The velocity profile is the result of the computation of Doppler frequency shifts coming from many gates placed along the ultrasonic beam. UDOP displays the velocity values along its Y axis or the vertical axis. The measured velocity component is always the projection of the real velocity vector along the ultrasonic beam axis. All velocities values are in mm/s.

If the Doppler angle is used (value different from 0), the velocimeter assumes that the user knows the real direction of the velocity vector and UDOP gives the modulus of the velocity vector, assuming that the measured component (along the ultrasonic beam axis) is the projection of the real vector over the ultrasonic beam axis.

The depths are the distances measured along the ultrasonic beam axis from the surface of the transducer to the beginning of the measuring volume. All depths are given in millimeters.

In order to allow more space to the positive or negative values, the origin of the velocity scale can be moved by clicking the left mouse button when it the mouse is over the velocity scale and moving it (drag mode). A double click put the origin in the middle.

5.2 Echo modulus profile

The echo modulus profile gives the evolution of the echo envelope of the ultrasonic signal received by the transducer. This display informs the user on the presence of high reflective structures and on a possible saturation of the receiver stage of the velocimeter.

As the saturation of the receiver stage is a key point for reliable measurements, this display is highly recommended for each new measurement. The echo modulus profile is the only display that allows the user to verify that a correct emission level and TGC amplification are selected.

UDOP displays the echo modulus values along its Y axis or vertical axis. The numbers displayed on that axis do not have any unit. They are relative numbers and covers a range from 1 to 2048. As the available data are given in a byte format, a zoom capability is given by changing the scale of the Y axis. This is realized by clicking on the arrow above and below the Y axis legend.

5.3 Doppler energy profile

The Doppler energy display is a display that enables to collect information on moving particles. This display shows the amount of ultrasonic energy reflected by moving structures. It computes the level of the high-pass filtered echo signal. Only the echo modulus envelope of moving structures is then displayed.

UDOP displays the Doppler energy values along its Y axis or vertical axis. The numbers displayed on that axis do not have any unit. They are relative numbers and covers a range from 1 to 2048. As the available data are given in a byte format, a zoom capability is given by changing the scale of the Y axis. This is realized by clicking on the arrow above and below the Y axis legend.

5.4 Histogram

The histogram of the velocity profile, the echo profile or the energy profile can be computed and displayed in real time.

This histogram displays its information in a color coded mode. The whole measured Y scale is divided in a user's defined number of classes. After the computation of a profile, for each gate that makes the profile, a class number is computed from the value found in the gate (velocity, echo, energy) and the corresponding class is then incremented . The value of each class is then converted to a color in a linear way. A zero value gives the background color and the color of the curve is attached to the maximum value found in all the classes. All the classes are then displayed.

5.5 Velocity versus time of a gate

This display shows the velocity profile and the evolution of the velocity versus time for a particular gate. The position of the gate is selected on the graph that shows the velocity

profile by placing a cursor on the velocity profile. The time scale of the graph that shows the velocity versus time can be changed in the windows named "V(t) parameters".

Note: To move the position of the selected gate it is not necessary to place the mouse over the cursor. A click inside the graph will place the cursor at the mouse depth.

5.6 Power spectrum of a selected gate

In pulsed ultrasound Doppler velocimetry the sampling volume contains not a unique particle but a lot of small particles having most of the time different shapes, different sizes and different acoustic impedances. As all of these particles contribute to generate a unique value of the amplitude of the echo for each emission, the evolution of the echo amplitude will fluctuate. The reason comes from the fact that some particles enter in the sampling volume and others leave it. This fluctuation in amplitude will remain after the demodulation process and will be present on the demodulated Doppler signal, often called I and Q signals. The level of this fluctuation is greatly influence by the shape of the ultrasonic beam, which defines the geometry and sizes of the sampling volumes.

Moreover, all the Doppler frequency shifts induced by the movement of the particles are combined together. As all the particles do not have exactly the same velocity (in amplitude and in direction), and the Doppler angle changes during their journey across the sampling volume, the demodulated signals contain many Doppler frequencies.

The resulting demodulated signals I and Q contain therefore the combination of these phenomena. In order to have an idea of the aspect of a real demodulated Doppler signal issue from one gate, the figure below illustrates its evolution.

The best way to analyze the frequency content of the demodulated echo signal issued from one gate is to compute its power spectrum. The power spectrum gives information on the distribution of the Doppler frequencies and their relative influences on the computed mean Doppler frequency, which is computed when the velocimeter displays the velocity profile.

Why using the power spectrum of one gate

When once looks at the velocity profile, each gate give a single value of velocity. These values are the result of a computation of the mean Doppler frequency, which is the mean value of the power spectrum. This means that no information is given about the

distribution of the Doppler energy. The same value of velocity can result from many different frequency distributions. The display of the complete power spectrum is a good method to increase the knowledge on the measured velocity values.

How to use the information contained in the power spectrum

The following examples will display different situations where the power spectrum can increase the knowledge in the measured velocity values.
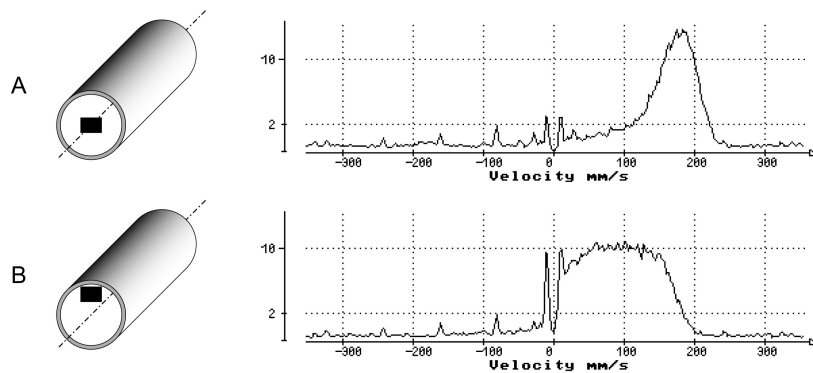
The example A in the figure above shows the computed power spectrum from a gate placed in the middle of a tube where a liquid is flowing. As shown in the power spectrum the sampling volume does not contain a single Doppler frequency. The width of the peak is related to the number of Doppler frequencies present in the sampling volume.

In situation B, the sampling volume has been moved closer to the wall of the tube. The width of the Doppler peak is now much larger which means that much more different velocities are present in the sampling volume. The power spectrum reveals also a small influence of the movements of the walls. As the power spectrum is computed from the high-passed filtered data, the amplitude of the power spectrum at the origin is always zero.

The example C considers a rotating cylinder filled of liquid. The ultrasonic beam crosses the cylinder perpendicularly to the axis of the cylinder. The sampling volume is placed inside the cylinder in a position near the wall.

The power spectrum reveals a very strong influence of the movements of the walls of the cylinder despite the sampling volume does not touch a wall. This situation may appear if some of the multiple ultrasonic reflections may coincide with the sampling time of the echo. In such a case the velocity value is corrupted by the Doppler effect induced by the movement of the walls. The display of the power spectrum indicates clearly that the mean Doppler frequency computed is in fact the result of the mean value of two different

velocity components, one coming from the movements of the walls and the other coming from the movements of the particles contained in the liquid.
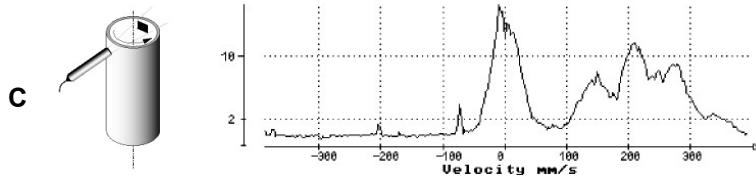
How to visualize use the power spectrum

UDOP can compute this power spectrum by means of an FFT algorithm. The data series is formed by samples taken on the demodulated I and Q signals for a selected depth which corresponds to the gate position. Before the computation of the power spectrum, the data series is filtered by a high pass filter which removes all the stationary components contained in the demodulated signals.

The display of the power spectrum of a gate is available in the compute menu. After its selection a panel named "FFT parameters" appears and enables the selection of the number of emissions used to compute the power spectrum. A hamming window can also be applied if desired.

The cursor available in the velocity profile graph enables to define the position of the gate.

UDOP records both, the velocity profile and the power spectrum. Therefore both data will be available for further analysis.

In order to make the reading of the frequency scale more easy the frequency scale is converted in velocity by using the standard Doppler formula. The FFT velocity (or frequency) resolution can be improved by using the velocity scale factor, available in the manual parameters menu. The available velocity scale factor are 1, 0.5 and 0.25.

The ordinate gives the amplitude of the power spectrum in dBm. This amplitude is the amplitude find at the BNC input. A mouse click on the arrow located above and below the legend of the vertical axis can adapt the level of the scale.

5.7 The velocity profile and its evolution versus time

This display shows the velocity profile and its evolution versus time by showing in a color coded fashion the velocity values in an additional graph. The time scale is defined by the acquisition time of a profile and the dimension of the graph. It can not be adapted.

5.8 Flow rate versus time

The velocimeter can compute and display in real time the flow rate by integrating the velocity profile on a user's defined area.

The flow rate is computed by spatially integrating the velocity profile. The integration is carried out by summing the flow rates through several small regions (indicated by the shaded region in the figure below), each of them corresponding to one measured channel. The velocity is assumed to be uniform throughout each region. The cross-section of the conduit is always assumed to be circular, with a diameter equal to the spacing between the anterior and posterior wall indicators.

The formula below indicates how the flow rate is computed. "e" is the thickness of the semi-annular region and "v" the velocity component perpendicular to the cross section. These two relationships do not explicitly contain the diameter. The diameter is only used to determine the number of channels contained in the conduit.

For an even number of channels the flow rate is given by:

$$ Q = \frac{\pi e^2 \sin^2\theta}{2} \left[V_{\frac{N}{2}} + V_{\frac{N}{2}+1} + \sum_{i=1}^{\frac{N}{2}-1} (V_i + V_{N-i+1})(N - 2i + 1) \right] $$

For an odd number of channels the flow rate is given by:

$$ Q = \frac{\pi e^2 \sin^2\theta}{2} \left[\frac{1}{2} V_{\frac{N+1}{2}} + \sum_{i=1}^{\frac{N-1}{2}} (V_i + V_{N-i+1})(N - 2i + 1) \right] $$
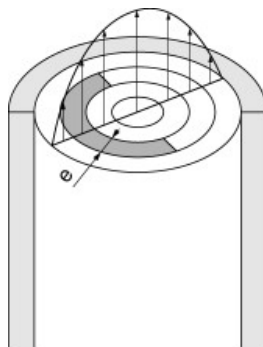
A precise evaluation of the flow rate is possible only if the axes of the pipe and of the ultrasonic field lie in the same plane, and if the flow field is axially symmetric. The size of the ultrasonic beam must also be much smaller than the diameter of the pipe.

Knowledge of the Doppler angle θ is necessary for the computation of the flow rate. The flow rate is based on the computation of velocities in the flow axis. It is therefore necessary to compute these velocities from the only velocity component measured by the velocimeter which is the velocity in the direction of the ultrasonic beam. The graph below illustrates the error introduced in the flow rate computation as a function of the Doppler angle, for a few errors in the input value of the Doppler angle.
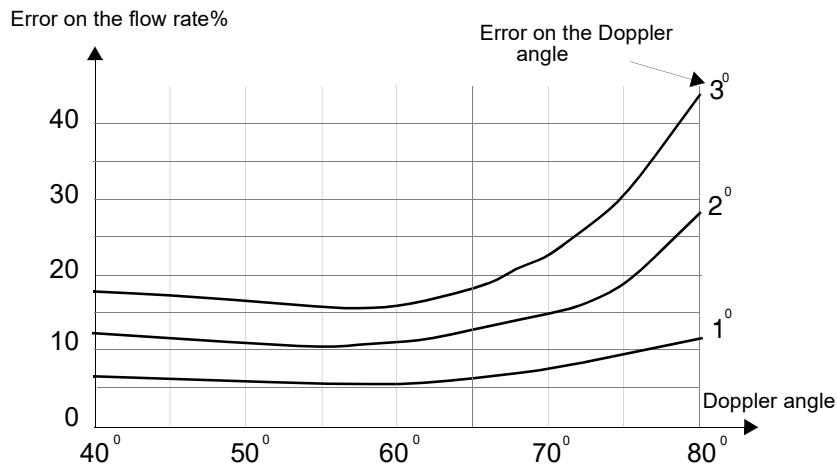
The wall indicators

The diameter of the conduit is defined in an interactive manner, by placing on the velocity profile two indicators, one defining the position of the anterior wall, the other the position of the posterior wall. These indicators are represented by two cursors. These cursors are enabled when the flow rate computation mode is selected. The user should define the section used for the computation of the flow rate by placing the two cursors on the corresponding walls. The gate located at the position of the wall indicator belongs to the flow rate section. The left mouse button is used to place the first cursor and the right button mouse places the second cursor.

5.9 Raw data acquisition

UDOP allows to acquire raw data. The acquired raw data are the demodulated I and Q signals, after amplification. They are also filtered by the spatial filter. UDOP can acquire up to 15'000 couples of I, Q signals. Each value is recorded as a 16 bits signed integer.

After the trigger of the raw data acquisition process, UDOP records a user defined number of gates for each of the following emission until it reaches the user selected number of emissions. The position or depth of the first gate is defined by means of a cursor placed inside the velocity profile. The following gates, if any, are placed as defined by the resolution parameter.

Computation and display of data profiles

At the end of the acquisition process, the user can repeat the acquisition and therefore adding to the current acquired block of data a new block, or can store the acquired data to a file.

To access this acquisition mode, click on the button named "acquire raw data" located in the "Tools" panel available in the menu bar.

Note: The acquisition of raw data is only available when the assisted mode is disabled

6 Applying real time filters

The display of data profiles can be improved by the use of real time filters. These filters reduce the noise level and the variance of the measured profiles. Two types of filters can be applied for all the computed data profiles:

- a moving average filter
- a median filter

The use of any of these filters do not affect the data value contained in the internal memory of the velocimeter. They will only modify the displayed data profiles. This allows the user to post process the data profiles in replay mode afterwards or with other user's software.

The median filter is recommended when the data profiles contain random spikes particularly when the velocimeter is operated with a sensitivity parameter value equal to "high" or "Very high". The application of this filter greatly improves the display of the data profiles.

6.1 The moving average filter

The moving average filter computes the arithmetic mean value for all the displayed gates based on a define number of profiles. The mean values of each gate are computed independently, which means that values of one gate does not affect the computation of other gates. Each time a new data profile is acquired, a new filtered data profile is computed using the N last measured profiles, where N is a user's defined number.

When the moving average filter is applied to data profiles containing low Doppler energy the zero values that may some times appear can be optionally rejected from the computation. This option is enabled if the check box named "Reject zero" is marked. This option allows to compute an unbiased mean data profile.

To apply the moving average filter:

Select the menu named "Filters" and click on the named of the filter to apply. The button named "Define" allows to fixe the filtering parameters.

⚠ The use of the moving average filter can mask any aliasing that may be present on velocity values. For this reason, only apply this filter if you are sure that the profiles do not contain any aliased values.

6.2 The median filter

Median filters reject erroneous values by ordering a set of values by increasing order and output as a filtered value the value located in the middle of the ordered table. The main

advantage of this filter is its aptitude to reject values far from the mean value like random spikes.

The median filter is recommended when the data profiles contain random spikes particularly when the velocimeter is operated with a sensitivity parameter value equal to "high" or "Very high". The application of this filter greatly improves the display of the data profiles.

7 Measuring the sound speed

The DOP4000 allows to measure the sound speed in a liquid by measuring with precision the time that is taken by an ultrasonic burst to propagate over a define distance.

7.1 Preparing the measurement

Before using the software, you should first install the probe as defined in the figure below. The probe must be placed at a defined distance (Dmes) from a reflector. The reflector must be a plan surface, placed perpendicularly to the US beam axis of the probe.

Be sure that the probe is completely immerged. The distance between the reflector and
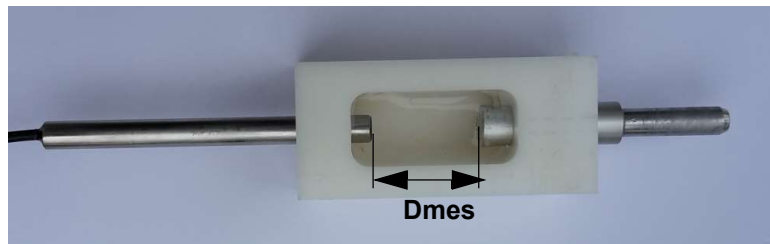
Dmes

the surface of the probe (Dmes), which is named "Reference distance" in UDOP, must be in the range 15 to 50 mm and must be measured with precision as any error in the measured distance will be directly transferred to the sound speed measured value.

7.2 Measuring the sound speed

Go in the menu "Tools" and click on the button named "Measure sound speed". The velocimeter opens a new panel in which you must enter an expected sound speed value and the reference distance Dmes. The expected sound speed value helps UDOP software to find a correct set of measuring parameters. If the entered expected value is to far away from the real value, UDOP software will not be able to find automatically a correct set of parameters. In such a case the user must use the manual mode.

The parameters must be selected in order to have a clear echo coming from the reflector. UDOP adapts the parameters in order to achieve this task. If you prefer to select by your self the parameters, you can by-pass the calibration procedure and keep the current set of parameters. To do this click on the button named "Here". If you would like that UDOP select the parameters for you click the button "Continue".

Note: A long burst gives better results than a short burst. So try to use the longest. (32 cycles),

After a click on the "Continue" button, UDOP shows the portion of the echo profile that must correspond to the echo coming from the reflector.
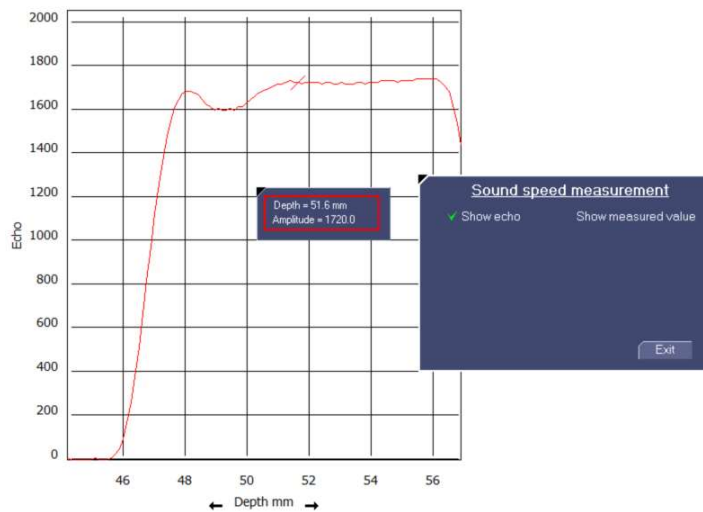
Place the cursor in the middle of the echo step and click on the button "show measures" to see the measured values and its statistics.

At any time you can visualize again the echo profile. A click on the button "Keep and exit" ends the measurement of the sound speed and keeps the measured value as the current sound speed value.

Note: Beside the measured value appears and approximate value. This value results from the measurement of the arrival time of the burst. Its precision is lower then the measured value based on the measurement of the phase of the demoduated echo signal.

8 The parameters

The velocimeter is controlled by a defined number of parameters which are user selectable for most of them. Correct values of these parameters are of prime importance.The following chapter describes the meaning of these parameters and their influences on the measured values.

The velocimeter contains a default setup, named "Default parameters" which can not be changed, and which guarantees that the velocimeter will work correctly. It is highly recommended to always start from this setup any measurements on new facilities.

8.1 The Pulse Repetition Frequency (PRF)

The pulse repetition frequency or PRF determines the maximum measurable depth as well as the maximum Doppler frequency which can be measured unambiguously. The maximum depth is simply given by half the distance covered by the ultrasonic burst when it travels in the medium during a time equal to the time between two emissions. As the PRF is nothing else than the sampling rate of the ultrasonic echo, the Nyquist limit defines the maximum Doppler frequency shift that can be measured unambiguously. Therefore the PRF defines the maximum velocity for a given emitting frequency. As a consequence, both limits, the maximum velocity and the maximum depth, are linked together as expressed below:

$$P_{max} \bullet V_{max} = \frac{C^2}{8 \cdot f_e} \qquad P_{max} = \frac{C}{2 \bullet F_{PRF}} \qquad V_{max} = \frac{F_{PRF} \bullet C}{4 \bullet f_e}$$

where P_{max} is the maximum measurable depth, V_{max} the maximum measurable velocity, fe the emitting frequency and C the speed of sound in the medium.

How to choose a correct PRF value

The choice of a PRF value should normally be based on the velocity values that have to be measured rather than on the depth that has to be reached. Whenever possible, one should try to select a value which does not induce aliasing. The best way to select a correct value is to start with a high value (near the maximum) and to reduce this value until at least 50% of the velocity scale is covered. The desired analyzed depth can be then adapted by changing the resolution, the position of the first gate or the number of gates.

Note: Due to internal computation time, the maximum depth can never reach the depth computed by the above formula, based on the sound speed and the PRF. Its value is always a little bit lower.

⚠ Never apply a filter during the selection process of a PRF. Any aliasing that can appear will be masked by the moving average filter.

8.2 The velocity scale factor

UDOP allows to measure velocities of liquids coming towards or going away from the transducer. By definition, the velocity is positive if the particle goes away from the transducer and negative if it goes in the other direction. The maximum velocity that can be measured without inducing aliasing is a function of three parameters, which are:

the emitting frequency;

> The more the emitting frequency is high, the more the Doppler frequency shift is high. Therefore an increase in the emitting frequency will decrease proportionally the maximum measurable velocity.

the speed of sound in the liquid;

> The speed of sound is the key factor that converts the Doppler frequency shift in velocity. There is a direct proportionality between these two parameters.

the pulse repetition frequency;

> The pulse repetition frequency defines the maximum measurable Doppler frequency in accordance to the Nyquist limit. Therefore, the higher the PRF is, the higher the Nyquist limit is and the higher the maximum measurable velocity is. Unfortunately, the PRF defines also the maximum measurable depth.

The ultrasonic processor of the DOP velocimeter outputs the velocity values in a signed byte format, which allows 256 different velocity values. The range of velocities covered by these 256 values can be adapted by the user in order to cover a portion of the maximum measurable Doppler frequency shift which is defined by the Nyquist limits or PRF/2. This portion of velocity range can correspond to the entire range (value of 1) or 10% of the entire range (value of 0.1).

8.3 Position of the first gate

When the first gates are close to the surface of the transducer, the burst duration and the ringing of the ceramic do not allow any measurement in these gates due to saturation of the electronic receiver.This can be visualized in the display of the received echoes, where the level of the signal at low depths (close to the transducer) is saturated (values above 2000). This saturation is normal and can not be avoided.

The position of the first measurable gate depends on the emitting frequency, the burst length, the emitting power, the amplification level and the ultrasonic probe connected to the instrument. Its minimum value is around 3 millimeters.

The position of the first gate can be changed by clicking on the depth axis and moving the mouse left or right. If the assisted mode is active, a change in the measured depth range may induce also a change the measurable velocity range.

Note: The origin of the measured depth is the surface of the transducer.

8.4 The resolution and burst length

UDOP defines the resolution as the distance between the center of adjacent sampling volumes and NOT the thickness of the sampling volume. In ultrasonic Doppler velocimetry, the shape and lateral sizes of the sampling volumes (measured perpendicularly to the ultrasonic beam axis) are defined by the geometry of the ultrasonic beam. The longitudinal size of the sampling volumes, or their thickness, is defined by the burst length and/or the bandwith of the electronic receiving unit.

The DOP4000 has a fixed bandwidth of 250 kHz which defines a longitudinal dimension of the sampling volume from about 0.8 mm in water. If the duration of the emitted burst is longer than the value associated to the bandwidth, the longitudinal dimension of the sampling volume is determined by the burst length.

It may often appear that the selected resolution implies an overlapping of the sample volume. This is the case when the resolution is lower than the thickness of the sampling volume. This always appears for all resolution below 0.8 mm.

The selected resolution R is smaller than the thichness of the sample volume

The selected resolution R is bigger than the thichness of the sample volume
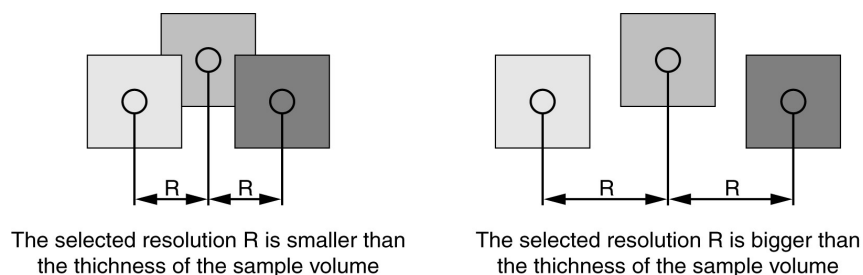
When the selected resolution corresponds to a distance longer than the longitudinal dimension of the sampling volume, the sampling volumes do not touch each other any more and some non measured spaced are present between the sampling volumes. In order to avoid this phenomena, UDOP computes the average value of the gates that can be placed between two sampling volumes, using the highest resolution.

The thickness of the sampling volume is displayed in the "Operating parameters" window. If the sampling volumes overlapped each other an indication is displayed.

Note that the borders of the sampling volumes are not as well defined as represented in the figure above. The borders increase and decrease "slowly" due to the finite bandwidth of the receiver.

The ultrasonic beam produced by the transducer does not have a constant diameter along the analyzed depth. The consequence of the divergence of the ultrasonic beam is that the lateral dimensions of the sampling volumes are not the same for all the sample volumes. Generally their lateral dimensions increase when the measured depth increases. The rate of this increase depends on the frequency and dimensions of the transducer.

8.5 The number of gates

The DOP4000 can measure simultaneously up to 1000 gates. The number of gates that can be measured depends on the selected PRF, the position of the first gate and the selected resolution.

The user has the choice to let the instrument select automatically the number of gates in order to cover the selected depth or to fix it. In such a case the position of the first gate and the number of gates define the measuring range and therefore the analyzed depth.

8.6 The sensitivity

The algorithm used to measure the Doppler frequency computes the mean frequency of the Doppler spectrum. When the Doppler energy decreases, the mean value become more and more unstable due to the noise included in the spectrum. In order to avoid the apparition of random values on the screen, UDOP computes also the level of Doppler energy received and allows the user to cancel the computation of the Doppler frequency if the level of the Doppler energy is below a user's defined value. In such a case the canceled values are replaced by zero values.

The sensitivity parameter contains 5 different values, which define the level below which the computation is canceled. As it can be sometimes useful to accept the computation of the mean Doppler frequency in presence of very low Doppler energy, two levels named "Very high" and "High" can be used in such a situation. When "High" is selected, some noise may appear on the screen. When "Very high" is selected it is normal to have noise displayed on the screen.

The choice of a sensitivity value do not introduce any bias if the Doppler energy is high.

The sensitivity parameter can be used to obtain information on the quality of the measured values. No changes should result if the sensitivity parameter is modified. Any changes will mean that the level of the Doppler energy is too low. In such a case, to correct this situation, the following options should be investigated:

- a modification of the emitted power;
- a modification of the amplification (TGC);
- an increase in the amount of particles contained in the liquid.

8.7 The number of emissions per profile

The measurement of the Doppler frequencies is based on the correlation that exists between different emissions. As each emission can be seen as a particular realization of a random process, the more samples are available, the lower the variance of the estimated quantity will be. This is the case for the mean Doppler frequencies, which are first moment orders of Doppler spectrum.

The algorithm used to estimate the Doppler frequency is based on the assumption that the particles that generate the echoes during the measurement of the Doppler frequency remain inside the ultrasonic beam and their velocities are constant. For low velocities in steady flows this assumption is valid, but for transient ones, with high velocities, a compromise has to be taken between the quality of the estimation (minimum variance) and the measuring time.

The number of emissions per profile should be selected according to the type of flow investigated and to the width of the ultrasonic beam. For low velocities in steady flows, a high number will decrease the variance and therefore should be selected. For high velocities in unstationary flows this number should be adapted to the degree of variation of the velocities versus time.

Reducing the number of emission per profile increases the acquisition rate. By means of a filter, like the moving average the noise can be reduced.

8.8 The time between profiles

The number of emissions per profile defines also, with the PRF value, the time necessary to measure a profile. This time is defined by the following relation:

$$T_{profile} \cong T_{tran} + T_{PRF} \bullet (N_{Stb} + N_{PRF})$$

where TPRF is the period of the pulse repetition frequency, Ttran a time lapse used to transfer data (see below), NPRF the number of emissions per profiles and NStb, a fixed number of emissions used for internal computations, which is equal to 16.

The above equation gives an approximate value. The additional time Ttran, which may fluctuate, corresponds to the mean time used to transfer the measured data from the internal ultrasonic processor to the internal memory. This time may occasionally vary quite a lot due to the Windows environment.

⚠ In order to reduce the jitter in the transfer time Ttran it is highly recommended to run only the UDOP program and to not use the multi tasking capability of the Windows environment.

If the assisted mode is selected, the UDOP software try to find the best compromise between the PRF, the number of emissions per profile, the velocity scale, and the requested acquisition rate.

The time stamp attached to each profile is the time measured when the profile is transferred from the ultrasonic processor to the internal memory. This time, measured with a resolution of 100 microseconds, is unaffected by the operating system.

UDOP displays continuously the mean value of the time between profiles in the status window. This mean value is based on the last 8 previous profile. The maximum and minimum values are displayed beside the mean value in the status window.

Time bewteen profile = 69.4 ms   [69.4 69.5]

Mean   Minimum   Maximum
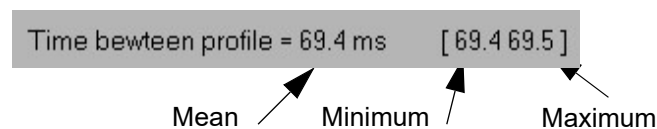
If the acquisition rate is to high, the label "Time between profiles" is displayed in red. The indicates that the time between profiles is not constant. Different solution can be applied to correct this situation:

- reduce the size of the main UDOP window
- reduce the number of gates
- reduce the number of curves displayed
- Increase the time between profiles

8.9 The emitting frequency

The choice of an emitting frequency depends on different factors which are:

- the desired size of the sampling volume;
  the emitting frequency contributes to the definition of the longitudinal dimension of the sampling volume. As this dimension is linked to the duration of the burst, for a given number of cycles in the burst, a higher emitting frequency will give a better resolution.

- the attenuation of the ultrasonic signal;
  the attenuation of ultrasonic waves depends on their frequencies. Low frequencies are less attenuated than high frequencies. The attenuation coefficient may vary quite a lot and depends on the material.

- the maximum measurable velocity;
  the maximum measurable velocity is inversely proportional to the emitting frequency.

- the backscattered energy;
the ultrasonic energy backscattered by the particles depends on the ultrasonic frequency. High ultrasonic frequencies backscatter more energy than low ultrasonic frequencies

All the above comments should be considered when selecting the emitting frequency.

The DOP4000 can selected a period of the emitting between 100 and 2220 nanoseconds, with a resolution of 20 nanosecond.

8.10 The emitted pulse

The emitted ultrasonic power has to be selected in order to receive enough backscattered energy from the particles and to avoid as much as possible saturation in the receiver stage. The display of the echo profile may be used to verify this point. Try whenever possible to avoid a high emitting power. A high emitting power induces more ringing in the transducer and more dissipated energy. It is generally better to increase the amplification (TGC) in state of increasing the emitting power. The DOP4000 can use 3 different emitting powers.

It is possible to disable the emitted pulse on channel 2, 3 and 4. In such a case a pulse is emitted on channel 1 and the echoes can be recorded on a another channel. This allows to emit on one transducer and to receive the echoes from an other one.

8.11 Definition of the amplification level (TGC)

Correct values of the amplification level are important. A to high level may induce saturation in the receiver stage of the DOP4000, which induces wrong measurement values. The amplification level can be defined by four different methods.

The first one simply defines a constant value in all the measuring range

The second one, which is named the slope method, defines the amplification level at two particular depths, named "Start value" and "End value", which are the first and last displayed depth. Between these depths, the amplification level vary exponentially.

The third one, is based on the information issued from the assisted mode. The TGC is automatically defined in order to establish some kind of optimum amplification curve.

The fourth one, which is named the custom method, allows to define the amplification level in user's defined regions, which can be placed anywhere in the measuring range. The number of possible regions depends on measuring range.

The value of the amplification level displayed by the instrument gives the increase of the signal level, from the transducer to the input of the internal A/D converter. 256 different

levels of amplification are available, covering a range of 80 dB.

The amplification level should be selected on the basis of the modulus of the echo profile. This display shows the intensity of the received echoes which are processed by the internal ultrasonic processor. Any saturation of the receiver stage is seen on that display by a region of maximum values which are independent of the flow regime and conditions. The user should adapt the amplification level or TGC in order to remove all these fixed overflow values.

Note: If the amplification level has to be reduced and if the liquid investigated does not attenuate to much the ultrasonic waves, it is recommended to decrease the emitting power. This reduces the intensity of the received echoes and any undesirable effects, such as the ringing inside the transducer.

The 2 figures below show 2 different situations. The figure A shows a situation where a reduction of the amplification level is absolutely necessary. In Figure B the amplification level is correct.
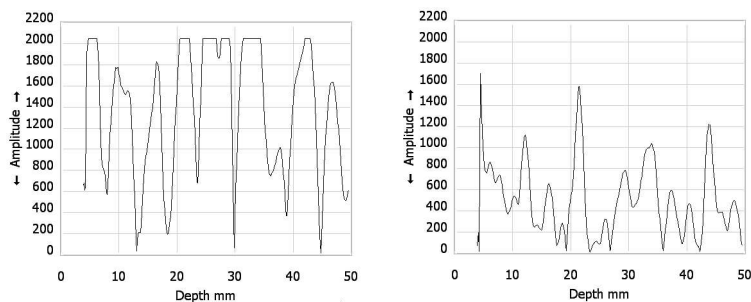
A   B

The saturation appearing at depths located just after the surface of the transducer is normal and can not be removed. This saturation is generated by the ringing effects of the transducer following the emission. The depths affected by this phenomena depend on the emitted burst emitted (frequency, burst length) and on the transducer. At these depths correct measurements are not possible.

8.11.1 Uniform amplification

In this mode the amplification level is the same for all depths. This mode is easy to use and can be used for instance when the analyzed range is small. When measuring profiles in liquid for which the attenuation of ultrasonic waves is small this method may also be convenient.

8.11.2 The Slope method

In this mode the amplification varies exponentially between two fixed depths which are the first and the last displayed depth. At these two particular depths, named "Start value" and "End value", the amplification level can be selected.

The slope method is only available is the optional software package "Variable TGC" is installed.

8.11.3 The Custom method

In this mode the amplification curve is defined by a series of contiguous cells, inside which the amplification level is uniform.

The position and size of a cell are defined in the velocity or in the echo profile by placing two cursors. The left mouse button is associated to the start of the cell (red cursor) and the right mouse button to the end of the cell (blue cursor). The defined cell appears in yellow inside the profile. When the cell is defined a TGC value can be associated to it by entering a value in the edit zone named "cell value"

The portion of the profile which define a cell is displayed in yellow. The resulting custom TGC amplification curve is displayed on the right side of the screen

Note: All the custom TGC amplification values are saved with the parameters when the user records a measurement on a file. These values are also saved with the current parameters. Defining an other TGC amplification curve does not destroy the values defined in the custom mode.

8.12 The Doppler angle

The velocimeter always measures the projection of the real velocity vector on the ultrasonic beam axis and gives therefore only one component of the velocity vector. It can happen sometimes that the direction of the real velocity vector is known, as in the case of flows in long tubes where the direction of the velocity vector is parallel to the axis of the tube. In such a case, it is possible and useful to compute directly the module of the velocity vector by using the Doppler angle. The Doppler angle (named θ in the next figure) is the angle between the axis of the ultrasonic beam and the direction of the real velocity vector.

UDOP uses the simple formula below to convert all velocity components measured in the

direction of the ultrasonic beam (VUS) in real velocity values (Vreal). To select this computation mode, simply enter an non zero value.

$$V_{real} = \frac{V_{us}}{\cos\theta} = \frac{f_d \cdot C}{2 \cdot \cos\theta \cdot f_e}$$
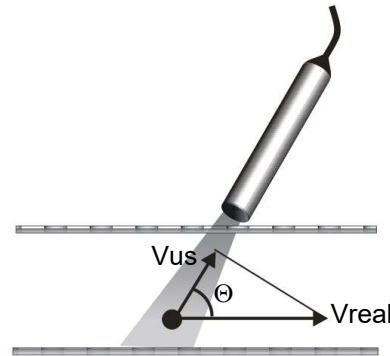
8.13 The speed of sound

The knowledge of the speed of sound in the medium is necessary to transform the Doppler frequency shifts in mm/s, and the time of flight of the ultrasonic waves in millimeter. A good knowledge of the sound velocity in the medium is necessary to obtain good quantitative measurement values, as all errors in this parameter are directly transferred to the measured values. Tables exist for a lot of liquids. One may find in the annex of this manual such a table.

When measuring through a wall or when using a wave guide, it may be necessary to take into account the sound speed inside the wall and inside the coupling medium. This is possible when the assisted mode is disable. The operating parameters table contains a button named "use US coupling parameters" that allows to enter the sound velocity and the thickness (or length) of the wall and of the coupling medium. If these parameters are used (button checked), the first measuring gate is really placed inside the liquid at a correct distance from the wall.

8.14 The dynamic extender

The dynamic extender is a special hardware contained in the DOP4000 which extends the dynamic of the incoming Doppler signals. This electronic circuitry is especially efficient in case of strong stationary echoes, coming, for instance, from walls or reflections inside the high temperature sensor system.

The idea based around the dynamic extender is to remove as much as possible the stationary echoes before the final amplification of the Doppler signals. This method improves the dynamic range by a factor of 16 dB.

8.15 Using the dynamic extender

The dynamic extender should be used if strong stationary echoes are present. These type of echoes, which often saturate the receiving amplifier, can be clearly seen when the user displays the echo profile.

The dynamic extender can be activated by means of two buttons. The first one is located in the Tool menu and the second one is located in the fast access parameters panel. When activated a green mark is displayed in the icon of the button.

After the activation of the dynamic extender the TGC must be defined correctly. A click on the button named "defined TGC" located below the dynamic extender button contained in the fast access parameter panel (located left to the graphic) allows to display the necessary information, the echo profile and the TGC amplification curve. Reducing the emitting power is often a good solution if the intensity of the echoes located at the maximum measuring depth are very strong. Try to define a TGC curve that avoid any saturation. Some iterations will be certainly necessary to optimize the amplification curve.

Note: Always remove any filters (mean average or median) when defining the working parameters

9 Auto correction of the aliasing

The aliasing is inherent to the fact that the ultrasonic Doppler velocimetry uses a pulsed emission. This implies that the maximum measurable Doppler frequency is the half of the pulsed repetition frequency (Nyquist limit).

Nevertheless, UDOP offers two ways to overcome that limitation.

The first method is based on the assumption that the velocity can't change more than a define amount between two adjacent gates. This method implies that:

- the measured velocity profile contains always at least one correct velocity value (not aliased) at a known depth.

- The noise level must be much below the velocity deviation used to correct the profile.

The second method uses two different pulsed repetition frequencies and a special algorithm. This method allows to measure Doppler frequencies many times higher than the Nyquist limit and does not require any a priori knowledge. The basic idea of this method is to take into account the phase difference resulting from a change in the PRF between two successive emissions. By selecting the deviation between the two PRF, the user can define the maximum measurable velocity. More the PRF are close to each other, bigger will be the measuring range, but also bigger will be the noise in the measurement. UDOP defines the difference between the two PRF in percent.

To apply the auto correction of the aliasing, the following points must be respected:

- the assisted mode must be disabled;

- the velocity scale factor must equal to 1

To enable or disable the auto correction of the aliasing, simply click the button named "Aliasing auto correction is" which is found in the panel named "Filters". This click opens a panel in which you can select the auto correction method and their related parameters.

9.1 Auto correction using the jump method

This method is based on the assumption that the velocity can't change more than a define amount between two adjacent gates. Therefore, the user needs to enter:

- The depth or the gate which will be used as the reference gate, the gate for which aliasing never appears.

- The acceptable maximum deviation between 2 gates. This value is defined as a percentage of the maximum measurable velocity, which corresponds a Doppler frequency equal to PRF/2.

- In order to be able to see corrected values, the velocity scale can be increased. The multiplication factor is entered in the parameter named "multiply display velocity scale".

When this method is enabled, each time a velocity profile is measured, UDOP will apply the following correction mechanism:

- Initialize the correction factor to 0

- Starting from the reference gate, if the velocity difference between the present gate and the next following gate (at a higher depth) is above the defined limit, the correction factor is incremented or decremented of an amount corresponding to the uncorrected velocity scale. The correction factor is then added to the value of the following gate.

- Repeat this mechanism for all the gates up to the last gate.

- Repeat the same algorithm for the gates located at a depth lower than the reference gate.

I order to see how the correction works, it is possible to see on the same graph the corrected and the uncorrected profiles. The 2 buttons "Show uncorrected profiles" and "Show corrected profiles" define how the profiles are displayed.

Note: If the auto correction of the aliasing is enabled, a calibrated velocity profiles in mm/s or mm*10 is added to the internal memory and therefore will be present in the binary data file.

9.2 Auto correction using the two PRF method

The two PRF method uses two different pulsed repetition frequencies and a special algorithm in order to correct aliased values. This method always computes 2 velocity profiles. The first one is the same as the standard profile and uses the highest PRF. The second one is computed from the difference between the two PRF. As this second profile is more noisy than the standard profile, it is used as a reference profile. Each value issue from the standard profiles is compared to the reference profiles. The computed deviation defines how many times the full scale velocity value, corresponding to the highest PRF, must be added or substracted to the value of the standard profile.

The correction mechanism may be improved by applying a filter to the reference profile. This reduce its noise level and therefore improves the computation of the deviation. Two types of filter are available, the moving average and the median.

In case of high level of corrections some peaks may still be present in the corrected profiles. The special designed "Jump filter" can then be applied to reduce considerably the presence of these peaks.

In order to see how the correction works, it is possible to see on the same graph the uncorrected profiles, the reference profiles and the corrected profiles simultaneously. The 3 buttons "Show uncorrected profiles", "Show reference profiles" and "Show corrected profiles" define how the profiles are displayed.

Note: If this auto correction method is used and the echo profile is displayed, UDOP shows on the same graph the echo profile resulting from the 2 PRF (2 curves). As artifacts are very sensitive to the PRF value, this display insures that for both PRF values no artifacts are present in the profiles.

9.3 Structure of the recorded data for the two PRF method

When this auto correction method is enabled and the velocity profiles are displayed, the coded velocity values of the reference profile are always added just after the coded velocity values of the standard profile. Moreover, an additional velocity profile, calibrated in mm/s or mm/s*10 is added as a last profile. This calibrated profile is computed from the corrected velocity profile.

In case of UDV 2D/3D the calibrated profiles are not present as the file already contains calibrated profiles. Nevertheless the coded values issue from the reference profiles are included.

If the echo profiles are displayed the two echo profiles issue from each PRF are recorded, the first one corresponding to the highest PRF.

10 Storing and reading measures

This chapter explains in detail how UDOP reads and records measured data profiles and how it transfers these data to files.

10.1 How data profiles are recorded

When running, UDOP measures continuously data profiles. By means of a panel, the user can stop the measuring procedure, clear the internal memory or start of a new measurement. Moreover, it is possible to select the profiles that will be recorded to a data file. "The advanced Trigger option offers the capability to control the recording procedure by an external trigger signal.

The internal memory is designed in such a way that when a data profile has to be transferred in the internal memory, the velocimeter checks for the first available free position and fill this position with the measured values. If no more free positions are available, the velocimeter replaces the oldest measured data profile by the new one, like in a FIFO memory (first in, first out). The amount of profiles that the internal memory can contain is fixed and is equal to 64'000 profiles. The state of the internal memory is always indicated in the status bar. When the memory is full a label entitled "Memory: full" is displayed. In order to insure that all the data profiles are measured and recorded with the same set of parameters, UDOP erases the internal memory each time a parameter is changed.

As data are transferred to the PC via the USB port, the exchange of information between the velocimeter and the PC must follow the USB rules. This means that the PC checks every millisecond if a transaction is pending. Unfortunately, it may appears that the acquisition rate can not be followed by the PC. In such a case, which is seldom, the time between profiles is no more constant. The time between profiles is then displayed in red to inform the user of that situation. Reducing the number of gates and/or increasing the number of emissions pro profile helps to overcome that situation.

Each time a data profile is recorded, additional information linked to the profile is also recorded. The additional data are:

- the time stamp in milliseconds * 10
- the number of the current block
- 1 mark byte
- the number of the channel;
- the data type
- the size of the recorded profile

UDOP puts in its internal memory all the computed and displayed data. This means that if the user has selected the display of both the velocity profile and the Echo profile, both profiles will be recorded and will be available in a file if desired. The amount of bytes used to record a profile will vary, depending on the number of gates used in a profile and the type of data displayed. For instance, if the instrument displays the velocity and the echo, using 435 gates, each recorded profile will use:

$$435 + 435 + 22 = 892 \text{ bytes.}$$

The added 22 bytes are the additional information bytes.

10.2 Controlling the acquisition

The acquisition of data is controlled by buttons located in the record panel as displayed below.

This panel can be placed anywhere on the screen. When the cursor of the mouse changes to the following figure ⊕ (which arises when it is placed over the panel), maintaining the left button down and moving the mouse moves the panel.

The "Record" button allows to record the future. After a click on that button, the internal memory is cleared and the record panel displays only a single "Stop" button. This button allows to end the acquisition process and store the data.

The "Store" button stores all data contained in the internal memory and therefore record the passed.

The "Clear and restart" button erases all the memory content.

10.3 Advanced recording features

The internal memory can be divided in many blocks. Up to 65536 blocks can be defined. The maximum size of each block is defined in the "Preferences" panel (Menu Preferences -> Record Options) in the button labeled "Do not keep in a block more profiles than", with a limit of 64'000 profiles, which corresponds to the maximum available memory space.

This allows to record on a single data file many events or acquisitions. Moreover, before storing each block, the user can visualize and select a portion of the measured profiles. Each block is formed by contiguous data profile (in time).

After a click on the "Stop" button or "Pause", the following panel appears.
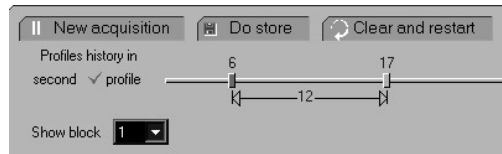
By moving the two cursors on the sliding bar the user can display the acquired data and keep in the recorded data file only the profiles of interest. All the profiles outside the two cursors will not be included in the record.

If the button "New acquisition" is clicked, UDOP starts a new measurement, and adds to the internal memory a new block of data.

If the button "Do store" is clicked all the selected profiles from all blocks contained in the internal memory will be saved to a data file.

Moreover, the user can keep in memory a defined number of profiles just before the user click on the "Record" button. This number of profiles is defined in the "Preferences" panel ("Preferences" -> "Record Options"), in the button named "Number of pre-recorded profiles"

10.3.1 The Pause button

The "Pause" button stops the acquisition and allows to display the content of the current recorded block by moving the cursors located on the sliding bar of the panel displayed below:
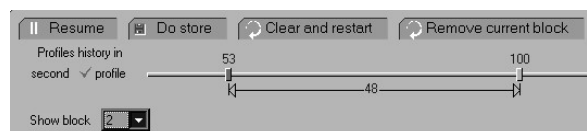
This enables to keep in the recorded data file only the profiles of interest, displayed in green. All the profiles located outside of the two cursors will not be included in the data file.

If the button "Resume" is clicked, UDOP starts a new measurement, and adds a new block of data.

If the button "Do store" is clicked all the blocks are store to a data file.

If the button "Remove current block" is clicked the current block is erased, and the previous block is accessed.

10.3.2 Skipping profiles

It may be useful some time to increase the acquisition time. This can be performed by not recording all the measured profiles and skipping some of them. UDOP includes this feature. In the "Preferences" panel ("Preferences" -> "Record Options"), the button named "Number of skipped profiles" defines the number of profiles that will not be recorded (place in memory) after the acquisition of a profile. Nevertheless, these skipped profiles are measured and displayed. If this value is set to a non zero value, the status window indicates that some profiles are skipped by displaying beside the profile counter the following icon:

The counter does not take into account the skipped profile.

10.3.3 USB transfer rate

UDOP continuously acquire profiles and send the resulting profiles via the USB port. In order to avoid delay in the transmission, the profiles are sent to the USB port by packages if the acquisition rate is to fast. The maximum rate at which the profiles are sent to the USB is defined in a parameter named "USB transfer period" found in the Preferences -> Option panel. A value of 20 ms fit most applications. If the transfer rate follow the acquisition rate, the time between profile is displayed in white. If the acquisition rate can't be followed, the time between profiles is displayed in color.

10.4 External trigger mode

In trigger mode, the acquisition of data profiles is controlled by the state of one of the two external BNC connectors labeled Sync1 or Sync2.

When the Trigger mode is enabled, UDOP waits until the trigger condition appears on the BNC. The Trigger condition can be a logic low (voltage below 0.4 Volt) or a logic high (voltage above 3.6 Volt).

> **CAUTION:**
> Never apply a voltage lower than 0 volt or higher than 5 Volt to the external BNC Sync1 and Sync2 (trigger input).

To enable the external Trigger mode:

- Open the panel "Parameters" from the menu

- Click "Trigger parameters"

- Mark "Enable external Trigger"

- Select which BNC connector must be the Trigger input.

Once the Trigger condition is detected, the UDOP acquires the number of profiles as defined in the field named "and record". If the button named "Wait for Trigger between each profile" is checked, the acquisition of the next profile will wait until theTrigger condition is detected at the BNC. Therefore each profile must satisfy the Trigger condition.

After the last profile has been acquired, UDOP stops the acquisition. The user can then store the measured data or repeat a new acquisition.

UDOP checks if it must acquire an other set of profiles, which is the case when the value entered in the button named "Repeat the sequence" is greater than 1.

Note: The time stamp attached to the first profile acquired just after the Trigger event is always 0 and should be considered as the time origin.

10.4.1 Field labeled "Keep all profiles"

If the field labeled "Keep all profiles" is unchecked:

> When more than one sequence has been entered in the field named "Repeat the sequence" UDOP will open the record panel to allow the user the visualize and select the profiles to keep.

If the field labeled "Keep all profiles" is checked:

> When more than one sequence has been entered in the field named "Repeat the sequence" UDOP will directly jump to the acquisition of a new sequence, waiting for a new trigger condition, and will therefore keep all the acquired profiles.

10.4.2 Pre Trigger

If the value entered in the "Pre Trigger" field is 0:

- UDOP does not measure any profiles before the trigger event appears and wait for the trigger condition. The delay between the trigger event and the first emission of the profile that corresponds to the first recorded profile is very short

(< 1 µs). UDOP can also wait a user's defined time if the value entered in the field named "After Trigger wait" is not 0.

- If the value is not zero, UDOP continuously measures profiles and keep in its memory the amount of profiles defined in the "Pre Trigger" field. The delay between the Trigger event and the first emission of the first profile may therefore vary.

10.5 Storing data to a file

After a click on the Store button, the software opens a panel in which the user can:

- select the directory in which the data file will be placed
- enter the file name
- add a comment
- choose the type of generated data file

The "Browse" button allows to select the working directory in which the data will be placed. The current working directory is displayed in the edit area. This working directory is by default selected from the "Preferences" panel. Any changes in working directory will be transferred to the "Preferences" panel.

Do not enter any file extension in the file name area. UDOP will always add the following extension:
- ".bdd" for all binary data file
- ".add" for all ASCII data file
- "_stat.add" for all statistical ASCII data file
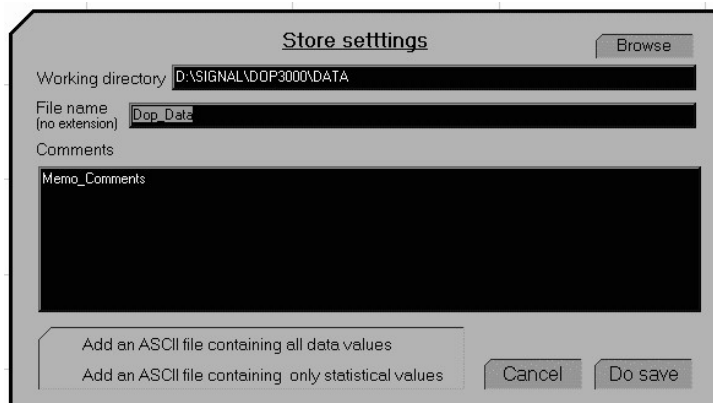
In the comment area, the user can enter any text. The comment will be included in all type of data file.

UDOP always generate a binary data file. The binary format is the only format that contains all the information related to the measurement. The binary file contains a copy of all the parameters and all the measured data values are recorded on it. The binary file format is also the only format that can be read by the UDOP software. All data recorded in the binary file are raw data; this means that the recorded data do not take into account any real time computation, such as the applied filters, the velocity offset, the Doppler angle. This allows the user to post-process the data afterwards.

10.6 The ASCII file format

The ASCII file format is mainly used to transfer data profiles to other software. This format does not contain the parameters and can not be read afterwards by the UDOP software. All applied computation parameters, are used and output data are calibrated (velocities in mm/s). This means that the output values take into account all the parameters, such as the sound speed value, the velocity offset, etc....

The resulting output file is a table of values where each line corresponds to a data profile and each column to a particular depth or gate. At the end of each profile 3 columns are added. These 3 columns contain the time stamp in milliseconds followed by the number of the block or sequence and the number of the channel.

The first data lines of the table gives the depths of the gates following by a second line that gives the units of the measured values. The depths are measured form the surface of the transducer to the beginning of the sampling volume. If more than one graph is recorded (for instance velocity and echo) this first lines contains more than one set of depths and units. In simultaneous multiplexing mode there are one set of lines for each channel.

The structure of the ASCII data file is illustrated in the following figure

Each line of data may contain more than one profile. This is the case for instance when the velocity and the echo profile are displayed during the acquisition. The number of curves or profiles depends on the data type. Each curve is recorded one after the other in the line. More information on the number of curves in function of the data type may be found in the chapter related to the binary format.

Statistical computation in ASCII file format

An additional statistical output data file is also available in an ASCII format. This file gives the mean, the standard deviation, the minimum and maximum values of all the profiles. In this file, the time informations (time stamp) is replaced by statistical values of the time between profiles. The first line of the table gives the mean value, the second the standard deviation, the third the maximum values and the fourth the minimum values. The table below gives an example of an ASCII output file with statistical values:

```
ASCUDOPV2.00.1
Memo_Comments

Gate depth [mm]
    1.775    2.525    3.275    4.025    4.775    5.525    6.275    7.025    7.775    8.525
   mm/s     mm/s     mm/s     mm/s     mm/s     mm/s     mm/s     mm/s     mm/s     mm/s    TBD [ms] No block Channel
Mean Values based on :43 values
  113.06   115.93   115.99   114.09   115.71   115.82   115.44   115.61   115.77   116.47    33.29      1        1
Standart deviation
    6.11     6.57     6.11     7.04     6.71     6.75     6.47     7.31      6.5     6.29     1.38      1        1
Maximum
  125.97   125.97   125.97   125.97   125.97   125.97   125.97   125.97   125.97   125.97    40.8      1        1
Minimum
  104.97   104.97   104.97   104.97   104.97   104.97   104.97   104.97   104.97   104.97    32.7      1        1
```

data values

Time between profiles in ms

Gives the number of the acquisition block or sequence

Probe channel

10.7 Structure of the binary file format

The binary file contains eight blocks which are described below in details. The offset value indicates the offset in bytes from the beginning of the file.

An identification block
offset: 0 to 15

> These 16 bytes identify an UDOP binary file. Bytes 0 to 7 always contain the following ASCII characters: BINUDOPV. The software version number in ASCII follows these bytes in the following format: x.yy.z (for instance 2.00.1). The last 2 bytes of the identification block are always: 0DH, 0AH

A block that contains the comment associated to the measurement
offset:16 (10H) to 527

> These 512 bytes contain ASCII characters typed by the user in order to identify the measurement. This block always ends with the 2 following bytes, 0DH 0AH, so 510 bytes are available for comments.

Storing and reading measures

A block that contains information on the hardware of the instrument
offset:528 (210H) to 547

These 20 bytes contain information related to the hardware of the instrument and the installed options.

A block that contains the values of all the parameters
offset: 548 (224H) to 10787

This block contains all the parameters that define the operating conditions of the UDOP for all the channels. 256 parameters are available for each channel. The parameters are stored in a signed integer format using 32 bits. The table below gives the position and the signification of these parameters. The value of the position mentioned in the table is relative to the beginning of the table for a channel. The parameters table for channel 1 is in first position and is followed by channel 2, 3 and so on.

A block that contains the TGC values
offset:10788 (2A24H) to 31267

This block contains the values that define the amplification level for all the channels. Each amplification value has a byte format. The maximum amplification is given for a value of 255. Each channel contains 2048 values

DOP4000 parameters table

0	Emitting frequency in kHz	40	bit 0: if set record binary data file	107	UDV 2D/3D simulation, Shift TR1
1	assisted Mode: 1 if true		bit 1: if set record ASCII data file	108	UDV 2D/3D simulation, Shift TR2
2	User Depth in mm		bit 2: if set record Statistical ASCII data file	109	UDV 2D/3D simulation, Shift TR3
3	User Velocity in mm/s	41	internal use	110	UDV 2D/3D simulation, Adapt PRF
4	Quality factor (between 0 and 1000)	42	internal use	111	Flow rate Unit
5	PRF in μs	43	if 1, emit and receive on the BNC probe In/Out		0 : ml/min
6	Emission enable if 1	44	internal use		1 : ml/s
7	Emitting power (0=Low, 1=medium, 2=High)	45	internal use		2 : dl/s
8	Burst length	46	hardware Internal delay in ns	112	Flow rate scale
9	Indice first gate	47	Trigger delay in ms	113	Auto Correct Aliasing Control word 1
10	Resolution (n+1)*0.166ns	48	Trigger Number of recorded profiles in Block	114	Auto Correct Aliasing Control word 2
11	if 1 auto resolution mode	49	Trigger: Number of blocks	115	sound speed in wall
12	if 1 auto selection of number of gates	50	Trigger: Auto record starting counter value	116	Length of wall
13	Number of gates	51	Nb profiles in block in multiplexer mode	117	sound speed in couplant
14	Number of emissions/profile	52	bit 1: if set multiplexer enables	118	length of couplant
15	Velocity scale factor (between 0 and 3141)		bit 2: if set UDV MD mode	119	US emitting frequency divider
16	Wall filter coefficient * 1000		bit 3: if set UDV 3D, else UDV 2D	120	demodulation frequency divider
17	Number of emissions for stabilization		bit 4 to 13: channel selected if bit = 1	121	DOP4000 control register 1
18	Sensitivity parameter		bit 15-31 : first channel	122	DOP4000 control register 2
19	Sound speed in m/s	53	Nb blocks in multiplexer mode	123	Nb classes for histogram
20	Doppler angle in degrees	54	Nb of profiles used by median filter		
21	Module scale (between 256 and 2048)	55	if 1, echo mode		
22	Velocity offset	56	internal use		
23	Tgc Mode (0:uniform, 1:slope, 2:auto, 3 custom)	57	internal use		
24	Tgc value at the beginning (between 0 and 256)	58	number of points for gate FFT		
25	Tgc value at the end (between 0 and 256)	59	if 1, Gate FFT use Haming window		
26	TGC gate size (0:0.666 ns 1: 1.333 ns)	60	internal use		
27	Bandwidth definition (from 50 kHz (0) to 300 kHz(5), step 50 kHz	61	Time scale for V(t) in ms		
28	Overall gain 0: 0db 1:6dB, 2:14 dB, 3:20dB	62	sound speed measuring distance in m*10		
29	0:acquisition rate 6 MHz, 1: 12 or 40 MHz	63	UDV MD, emit probe reference		
30	internal use	64	UDV MD, receive probe reference		
31	Type of measurements	65	UDV MD, distance between probes, mm*10		
	0 : Data_Type_Velocity	66	UDV MD, Doppler angle in deg		
	1 : Data_Type_Echo	67	UDV MD, Vx max in mm/s *10		
	2 : Data_Type_Energy	68	UDV MD, Vy max in mm/s *10		
	3 : Data_Type_Gate_FFT	69	UDV MD, Vz max in mm/s *10		
	4 : Data_Type_Phase_deg_10	70	UDV MD, TR1 frequency offset -127 -> 128		
	5 : Data_Type_Vitson	71	UDV MD, TR2 frequency offset -127 -> 128		
	6 : Data_Type_Frequency	72	UDV MD, TR3 frequency offset -127 -> 128		
	7 : Data_Type_Frequency_TR1	73	UDV MD, Scale angle for TR1, in rad*1000		
	8 : Data_Type_Frequency_TR2	74	UDV MD, Scale angle for TR2, in rad*1000		
	9 : Data_Type_Frequency_TR3	75	UDV MD, Scale angle for TR3, in rad*1000		
	10 :Data_Type_Echo_TR1	76	UDV MD, Module scale for TR1		
	11 : Data_Type_Echo_TR2	77	UDV MD, Module scale for TR2		
	12 : Data_Type_Echo_TR3	78	UDV MD, Module scale for TR3		
	13 : Data_Type_Energy_TR1	79	UDV MD, depth from in mm		
	14 : Data_Type_Energy_TR2	80	UDV MD, depth to in mm		
	15 : Data_Type_Energy_TR3	81	UDV MD, Resolution mm*10		
	16 : Data_Type_Velocity_mm_s_10;	82	UDV MD, quality factor		
	17 : Data_Type_Velocity_mm_s	83	Current channel		
	18 : Data_Type_Flow_ml_min	84	skip profile		
	19 : Data_Type_Diameter_10	85	Simul Velocity scale factor		
	20 : Data_Type_Aliasing_Refer	86	liquid attenuation in dB/cm * 1000		
	21 : Data_Type_Aliasing_Refer_TR1	87	Simul selected gate in IQ display		
	22 : Data_Type_Aliasing_Refer_TR2	88	none		
	23 : Data_Type_Aliasing_Refer_TR3	89	UDV MD Nb skipped vectors		
	24 : Data_Type_Frequency_Hz_10	90	Raw data acquisition, Nb PRF		
	25 : Data_Type_Depth_mm_10	91	Raw data acquisition, Nb gates		
	28 : Data_Type_TGC	92	Raw data acquisition, First gate		
	29 : Data_Type_IQ	93	Overall gain in dB		
	30 : Data_Type_Angle_Deg_10	94	Cursor 1 on gate		
32	Display: 0 horizontal 1: vertical	95	Cursor 2 on gate		
33	Max number of profiles in a block	96	Cursor 3 on gate		
34	Trigger mode	97	Cursor 4 on gate		
	bit 1: if set external trigger mode	98	UDV 2D/3D simulation, from		
	bit 2: if set trigger on a low logic level	99	UDV 2D/3D simulation, To		
35	Number of profiles keep before trigger	100	UDV 2D/3D simulation, X source pos		
36	Filter 0:none 1:Moving average, 2 median	101	UDV 2D/3D simulation, Y source pos		
37	Nb profiles used in moving average	102	UDV 2D/3D simulation, Z source pos		
38	if 1 zero rejected in moving average	103	Max attenuation in simulation in dB		
39	Nb profiles kept before pressing record	104	UDV 2D/3D simulation, Part density		
		105	UDV 2D/3D simulation, Velocity field type		
		106	UDV 2D/3D simulation, Rotation speed		

Storing and reading measures

A block that contains the values of the data profiles
offset 31268 (7A24H) to the end of the file

This block contains all the measured data profiles and starts with one or more pseudo profiles that gives the measurements depths. The appellation of pseudo profile means that these first profiles are not measured data but are recorded the same way as normal data profile. The data type information byte identify this type of profile. These pseudo profiles give the values of the abscissa of the graphs. If only one channel is used, only one pseudo profile is added to the data file. This first profile contains as many abscissa values as the number of curves or graphs. If many channels have been measured, there will be one pseudo profile for each channel, the first one corresponding to the starting channel.

Each profile is formed by the following bytes. Starting from the beginning of the profile:

A   1 word (2 bytes) that gives the total number of bytes used by all the curves inside a profile.

B   1 word (2 bytes) that gives the number N1 of bytes of the following curve or graph. If N1 = 0 no data follow and the next bytes are those described from point E.

C   1 byte that identify the type of data:
See parameter 31 in the parameter table

D   N1 bytes of data
Each data value are in a byte format except for
Data type:
4, 16, 17, 19, 24, 25, 30 data in format 16 bits
Data type:
18 data in format 32 bits

if data type is 29 (raw data) the format is 16 bits signed integer, and the raw data are recorded as follow:
I1,Q1,I2,Q2,I3......In,Qn   (n = N1/2)

After these data bytes the next one has the meaning defined at point B.

E   a long word (4 bytes) that gives the time stamp in milliseconds * 10

F   a (2 bytes) word that gives the block number

G   a mark byte

H   1 byte that gives the state of the BNC Trigger input

I   1 reserved bytes (no meaning)

J   a byte which gives the number of multiplexer channel

K   a word (2 bytes) that gives the total number of bytes used by the profile (same value as in point A).

10.7.1 The time stamp

At each profile a time stamp is attached, which gives the time at which the profile is measured (time of the transfer from the ultrasonic processor to the internal memory). The accuracy of this time is not affected by any Windows operations and its unit is in milliseconds * 10.

Depending on the acquisition mode (passed or future), UDOP software fixes the time origin to:

- the first profile in the block when the user select to acquire the passed

- the time when the user click on the "Record" button when the user select to acquire the future.

- the Trigger event if the external Trigger mode is enabled.

10.7.2 Structure of a binary profile

If the aliasing is corrected (Auto correction ON), the binary profiles contain one (or more in UDV 2D/3D) additional curve. This curve contains the corrected velocity values, calibrated in mm/s or mm/s*10 depending the value of data type information byte.

If the corrected method is based on the two PRF method, the added curve contains the corrected curve.

Table 2:

compute data type value in ()	Auto correction of the aliasing		
	Off	Two PRF	Jump
Velocity (o) Velocity + V(t) (33) Velocity + color code (50)	- coded velocity (byte)	- coded velocity (byte) - reference profile (byte) - calibrated velocity (word)	- coded velocity (byte) - calibrated velocity (word)
Echo or Energy (1,2)	- coded echo (byte)	- coded echo Prf 1(byte) - coded echo Prf 2(byte)	- coded echo (byte)
Velocity + Echo/ Energy (30,31)	- coded velocity (byte) - coded amplitude (byte)	- coded velocity (byte) - reference profile (byte) - coded echo Prf 1(byte) - coded echo Prf 2(byte) - calibrated velocity (word)	- coded velocity (byte) - coded amplitude (byte) - calibrated velocity (word)
velocity + gate spectrum (32)	- coded velocity (byte) - coded FFT amplitude (byte)	Not available	Not available
Velocity + flow rate (36)	- coded velocity (byte) - flow rate value (1 long int)	- coded velocity (byte) - reference profile (byte) - calibrated velocity (word) - flow rate value (1 long int)	- coded velocity (byte) - calibrated velocity (word) - flow rate value (1 long int)

10.7.3 Structure of a binary profile in UDV 2D/3D

In UDV 2D/3D mode, the first curves in the profile always contain the coded Doppler frequency issue from each receiver (1 curve for each receiver, starting by receiver 1), except in echo mode where they contain the echo amplitude. These curves are followed by calibrated values depending on the selection of the computed mode.

If the computed mode is "Doppler frequency", calibrated curves are only added if the auto correction of the aliasing was enabled. These added curves contain the Doppler frequency issue from each receivers in Hz*10

Storing and reading measures

If the computed mode is "Velocity Vx, Vy", the following added curves contain the velocity components Vx, Vy and Vz in 3D. The unit depends on the value of data type information byte (mm/s or mm/s*10

If the computed mode is "Velocity Module, phase", the following added curves contain the modulus of the velocity vector, in mm/s or mm/s*10 depending on the value of data type information byte, followed by the azimuthal angle in degree*10 and by the elevation angle, in degrees *10, in case of UDV 3D.

Table 3:

compute data type value in ()	Auto correction of the aliasing		
	Off	Two PRF	Jump
Frequency(40)	- coded Freq Rec1(byte) - coded Freq Rec2(byte)	- coded Freq Rec1(byte) - refer profile Rec1 (byte) - coded Freq Rec2(byte) - refer profile Rec2 (byte) - calib Freq Rec1(word) - calib Freq Rec2(word)	- coded Freq Rec1(byte) - coded Freq Rec2(byte) - calib Freq Rec1(word) - calib Freq Rec2(word)
Echo (41)	- coded echo Rec1(byte) - coded echo Rec2(byte)	- coded echo Prf 1, Rec1 - coded echo Prf 2, Rec1 - coded echo Prf 1, Rec2 - coded echo Prf 2, Rec2	- coded echo Rec1(byte) - coded echo Rec2(byte)
Velocity components (42)	- coded Freq Rec1(byte) - coded Freq Rec2(byte) - calibrated Vy (word) - calibrated Vz (word)	- coded Freq Rec1(byte) - refer profile Rec1 (byte) - coded Freq Rec2(byte) - refer profile Rec2 (byte) - calibrated Vy (word) - calibrated Vz (word)	- coded Freq Rec1(byte) - coded Freq Rec2(byte) - calibrated Vy (word) - calibrated Vz (word)
Velocity module and azimut (43)	- coded Freq Rec1(byte) - coded Freq Rec2(byte) - calibrated module(word) - calibrated azimut (word)	- coded Freq Rec1(byte) - refer profile Rec1 (byte) - coded Freq Rec2(byte) - refer profile Rec2 (byte) - calibrated module(word) - calibrated azimut (word)	- coded Freq Rec1(byte) - coded Freq Rec2(byte) - calibrated module(word) - calibrated azimut (word)

Table 4:

compute data type value in ()	Auto correction of the aliasing		
	Off	Two PRF	Jump
Frequency(60)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte)	- coded Freq Rec1(byte) - refer profile Rec1 (byte) - coded Freq Rec2 (byte) - refer profile Rec2 (byte) - coded Freq Rec3 (byte) - refer profile Rec3 (byte) - calib Freq Rec1 (word) - calib Freq Rec2 (word) - calib Freq Rec3 (word)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte) - calib Freq Rec1 (word) - calib Freq Rec2 (word) - calib Freq Rec3 (word)

Table 4:

Echo (61)	- coded echo Rec1 (byte) - coded echo Rec2 (byte) - coded echo Rec3 (byte)	- coded echo Prf 1, Rec1 - coded echo Prf 2, Rec1 - coded echo Prf 1, Rec2 - coded echo Prf 2, Rec2 - coded echo Prf 1, Rec3 - coded echo Prf 2, Rec3	- coded echo Rec1 (byte) - coded echo Rec2 (byte) - coded echo Rec3 (byte)
Velocity components (62)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte) - calibrated Vx (word) - calibrated Vy (word) - calibrated Vz (word)	- coded Freq Rec1 (byte) - refer profile Rec1 (byte) - coded Freq Rec2 (byte) - refer profile Rec2 (byte) - coded Freq Rec3 (byte) - refer profile Rec3 (byte) - calibrated Vx (word) - calibrated Vy (word) - calibrated Vz (word)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte) - calibrated Vx (word) - calibrated Vy (word) - calibrated Vz (word)
Velocity module and azimut (63)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte) - calibrated module(word) - calibrated azimut (word) - calibrated elevation (word)	- coded Freq Rec1 (byte) - refer profile Rec1 (byte) - coded Freq Rec2 (byte) - refer profile Rec2 (byte) - coded Freq Rec3 (byte) - refer profile Rec3 (byte) - calibrated module(word) - calibrated azimut (word) - calibrated elevation (word)	- coded Freq Rec1 (byte) - coded Freq Rec2 (byte) - coded Freq Rec3 (byte) - calibrated module(word) - calibrated azimut (word) - calibrated elevation (word)

10.8 Conversion of a coded Doppler frequency

The recorded Doppler frequency values are coded and are in a byte format. In order to convert these coded values in a Doppler frequency Fdop in Hz, you should applied the following relation

where:

$$F_{Dop}[Hz] \;=\; \frac{Val \bullet Par[15] \bullet 10^3}{Par[5] \bullet 256 \bullet \pi}$$

Val   is the coded value extracted from the file. It has a value between -128 et +127

Par[x]   is the binary value (format signed integer 4 bytes) located at offset x from the beginning of the binary parameters bloc.

The relation above is valid only if the velocity offset value is 0 (equal range for positive and negative value). If the velocity offset is not 0 the recorded binary values have to be corrected by the following algorithm before using the above formula.

Val = Val + Par(22)

ICOR = 0

IF Val > 127 then ICOR = -256

IF Val < -128) then ICOR = 256

Val = Val + ICOR

Val = Val - Par(22)

The Doppler frequency in Hz can be converted in a velocity by the relation below, which gives the velocity component in the direction of the ultrasonic beam.

$$V[m/s] = \frac{F_{Dop} \bullet Par[19]}{2 \bullet COS(Par[20]) \bullet Par[0] \bullet 10^3}$$

where:

FDop   is the Doppler frequency in Hz computed by the preceding relation.

Par[x]   is the binary value (format signed integer 4 bytes) located at offset x from the beginning of the binary parameters bloc.

10.9 Extraction of the depth of a gate

The depth of a gate is given by its position in a profile. The gate located at the lowest depth is placed at the beginning of a profile. The following equation can be used to extract the depth in millimeters of a particular gate

:

$$Depth[mm] = Par[19] \bullet \left[\frac{Par[9] + (Par[10] + 1)(i - 1)}{2 \cdot Par[29]} - \frac{Par[46]}{2 \cdot 10^6} \right]$$

where:

Par[x]   is the binary value (format signed integer 4 bytes) located at offset x from the beginning of the binary parameters bloc.

i   the gate number, starting from 1.

Note: The binary data file includes also a pseudo profile that contains the values of the depths of all the gates.

10.10 Reading a binary DOP file

UDOP can read and replay a measure from a binary file. The binary file format is the only file format that can be read by the UDOP software. Reading or replaying a measure allows the user to visualize slowly the measured profiles, to post process the data profiles and also to re-record the data with new processing conditions. This last point enables to change the file format, to compute statistical values and to save and keep only a portion of the measured data profiles.

When replayed, the data profiles can be visualized step by step, in a forward or backward direction, or continuously with the adjunction of a user's defined delay between each profile. In replay mode, the status window displays no more the time between acquired profiles but the time elapsed from the first profile of the file in milliseconds. All the menus that are used to define a parameter value that fixes the acquisition characteristic are disabled and only the value used during the acquisition of data profiles are shown.

Note: An easy way to visualize the parameters values used in a binary data file consists to recall the parameters from the file. ("parameters" -> "Recall parameters" -> "From file")

To read a measure

Click on the text named "file" located in the menu bar then select "Get data file". This opens the get file window:
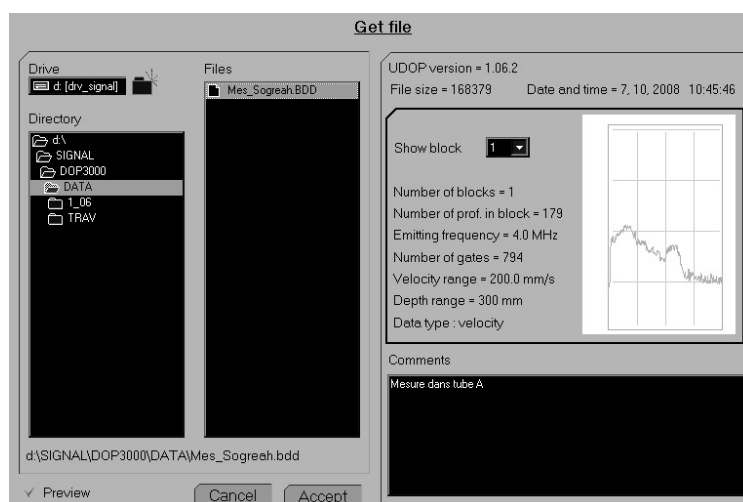
If the preview button is checked, the content of the selected file can be visualized. It shows the first profile in the selected block.

A data file must be selected in order to see the button "Accept". Any click on this button transfers the content of the data file into the memory, closes the "Get File" window and starts the display of the profiles.

The way the profiles are displayed is controlled by the following panel
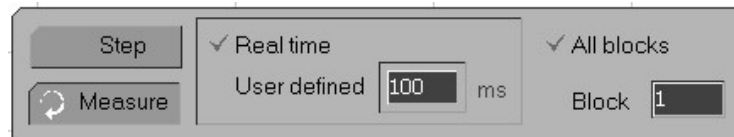
This panel allows to visualize the profiles using two different methods.

The first one replays continuously the data profiles. The display rate is the same as during the measurement if the button named "Real time" is marked or at a user's defined rate if the button named "User's defined" is marked.

The second one replays the data profiles step by step. A sliding bar and four additional buttons allow to choose the profile.
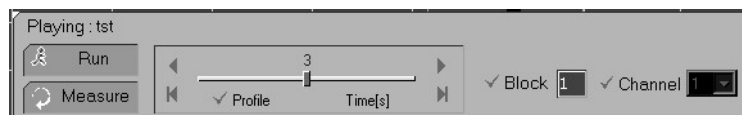
More the cursor of the sliding bar is moved away from its middle position more fast is the update rate of the display.

If many blocks of data are available, it is possible to visualize only the profiles that belong to same block. This is the case if the button labeled "All block" is not marked. In such a case, the button labeled "Block" allows to select the block. The same procedure applies if the data file contains many channels.

To leave the replay mode click on the button labeled "Measure".

10.11 Updating data files

Udop allows to convert many UDOP data files acquired by a previous software version to the current software version of UDOP. This allows to keep all data files up to date. The

conversion takes place in a batch process. To execute this procedure, the following steps must be performed:

1. Place all the binary data files that must be converted in an empty directory of your choice.

2. Execute UDOP

3. Select the command located in the file menu "Update files".
   This command opens a panel which allows to select the source directory (the one mentioned above) and the destination directory. If an ASCII data file must also be created during the conversion process, be sure that the respective ASCII requested line is checked (green mark).

3. Execute the command by a click on the button "Execute"

Note: This batch procedure takes only into account the binary data files (*.bdd). The file names remain unchanged. This means that if the source and destination directory are the same, the files will be overwritten.

It is highly recommended to keep a copy of the original data files.

Do not apply this batch procedure on data files acquired by a software version of UDOP that is newer than the one you used.

This Update procedure can also be used to convert WDOP data files, the one coming from a DOP2000.

10.12 Comparing recorded data profiles

UDOP allows to read a single or many profiles from different bdd data files and to display them in a single graph. This enables an easy way to see any differences between profiles.

To access this function execute the following procedure:

- Select Compare profiles in the File menu

- Select New comparison

- Select the file from which you would like to read profiles

- Once selected, fill the option panel:
  The displayed profile will result from a computation of a mean profile computed

from the two limits, Compute mean from and To for the profiles located in the blocks region defined by From block and To, for the specified channel Using channel, considering the curve selected in On the curve. The value placed in the button named and multiply by will be used during the computation. This allows for instance to invert the sign of the velocity. Also checking the button named Reject zero values improves the computation of the mean value by not including unmeasured points (zero value).

- Accept will display the resulting profile.

- A mouse click on the legend displayed on the top panel, allows:
  - to edit the legend
  - to remove the profile

- Clicking on the Add button allows to add more profiles and therefore perform comparisons. Simply repeat the above procedure.

- Clicking the Save this comparison button not only save the displayed information (selected files and curves) but also allows to create an ASCII files containing the data values of each displayed curves. For each curve, the ASCII file contains 2 lines of calibrated data values in a floating format (in mm/s or other unit, depending the data). The first line giving the X values and the second line the Y values.

- Clicking the Get a comparison button allows to recall and display a saved comparison (*.cdp file).

Storing and reading measures

11 Using the multiplexer

The DOP4000 contains 4 channels. All the channels are independent of each other. Each channel has its own BNC connector and its own collection of functioning parameters.

The DOP4000 can acquire profiles from the different channels sequentially, that means each channel is selected and used one after the other (sequential acquisition mode), or it can acquire profiles from the channels simultaneously, both mode are available

When the multiplexer is enabled in sequential acquisition mode, the acquisition of data profiles follows the procedure described below:

- the instrument selects the first channel, which can be any one of the 4 available channels;
- it acquires a user's defined number of profiles;
- it switches then to the next selected channel;
- it repeats this acquisition procedure until the last channel is measured or when the user press on pause.
- if more than one acquisition sequence has been programmed, UDOP closes the current sequence by closing the current block, and starts a new sequence by selecting again the first selected channel.
- when the last sequence ends, UDOP can:
  stops the acquisition process and store the measured data
  or
  roll over the measured data, and therefore replace the measured profiles by new ones, repeating all the previous sequences.

When the multiplexer is enabled in the simultaneous acquisition mode the acquisition of data profiles follows the procedure described below:

- the instrument selects the lowest channel number;
- emits an ultrasonic burst;
- switches to the next selected channel;
- emits an ultrasonic burst on that channel;
- repeats the above procedure until the last channel is detected;
- selected again the lowest channel and emits a second ultrasonic burst.

- repeats this procedure until the number of emitted burst as been send for all the channels.

In simultaneous acquisition mode a delay corresponding to one PRF exists between the measured profiles.

Note: In simultaneous acquisition mode, all the channels must have the same PRF value, the same emitting power, the same number of emissions per profiles and must measure the same type of data (same value of data type).

Before enabling the multiplexer, the functioning parameters of all the channels that will be used must be defined. These parameters are defined the same way as in non multiplexing mode. Simply select the channel and define the parameters and the type of data that must be measured.

11.1 To select a channel:

- enter in the menu "Channels";
- be sure that "Use only channel" is checked;
- point the channel that must be selected and click

Note: UDOP allows to copy all the parameters from one channel to an other channel. To do this:

- select the channel that must be defined if you would like to apply the parameters only for that channel
- select the channel that must used as the reference channel
- click the button labeled "To current channel" or the button named "To all used channels" depending your choice

11.2 Enabling the multiplexer in sequential acquisition mode

Before enabling the multiplexer you must:

- define the channels that will be included in the multiplexing acquisition. To do this, check the box which corresponds to the number of the channel (a cross indicates that the channel will not be included).
- define the channels that will be used as the first channel in the sequence.
- define the number of times the multiplexing sequence will be repeated;

- define if the external trigger mode must be used or not;
  If the external trigger mode is enabled, it is possible to wait for a trigger condition at the start of each sequence. In such a case, the button named "Trigger each sequence" must be checked.

- define if the acquisition must be stopped at the end of the acquisition of the last channel from the last sequence. In such a case the "Roll over the channels" button must be unchecked

- define if the all the measured profiles must be displayed in the same graph. This is possible only if all the channels measure the same type of data:

  If the external trigger mode is selected, the acquisition will start when the external trigger condition is found. At the end of the acquisition of the last channel from the last sequence, the acquisition will be stopped and the record control panel will allow to display the acquired profiles.

  If the external trigger mode is not selected and "Roll over the channels" is checked, at the end of the acquisition of the last channel from the last sequence, the acquisition will be restarted, erasing the previous acquired profile.

- Finally enable the multiplexer

  When the multiplexer is enabled, the menus can not be accessed and the parameters can't be changed.

  The multiplexer is disabled after a click on "Use only one channel".

Note: If the trigger mode is enabled in sequential acquisition mode, the settings from the Trigger panel are ignored. This means that no pre-trigger profiles are available and no wait after Trigger is possible.

11.3 Enabling the multiplexer in simultaneous acquisition mode

Before enabling the multiplexer you must:

- select the simultaneous acquisition mode by checking the button named "Simultaneous acquisition";

- define the channels that will be included. To do this, check the box which corresponds to the channel (a cross indicates that the channel will not be included):

- define if the external trigger mode must be used or not;

- Finally enable the multiplexer

Note: In simultaneous acquisition mode, some restrictions apply.
All the channels must have:

- the same PRF value,
- the same emitting power,
- the same number of emissions per profiles,
- must measure the same type of data (same value of data type).
- the same trigger conditions,
- the same value of skip profiles
- if the auto correction of the aliasing is active, it must be active for all the channels with the same settings.

When the multiplexer is enabled, the menus can not be accessed and the parameters can't be changed.

The multiplexer is disabled after a click on "Use only one channel".

If the trigger mode is selected, UDOP will used the parameters found in the Trigger panel. Udop will record the number of profiles defined in the parameter named "and record" and will repeat the acquisition sequence the number of times defined in the parameter named "Repeat the sequence". The Trigger condition will not be checked between the sequence.

Note   In simultaneous acquisition mode, all the measured profiles are displayed in the same graph. The recorded number of profiles is defined the same way as in non multiplexing mode.

12 2D / 3D Ultrasonic Doppler Velocimetry

2D or 3D Ultrasonic Doppler Velocimetry measuring technique is a method that enables the measurement of two velocity components (U and W) or three velocity components (U,V and W) simultaneously along a line.

UDV-2D and UDV-3D have all the advantages of classical ultrasonic Doppler velocimetry, such as the capacity to realize measurements in non translucid liquids. One of the most interesting property of these techniques compared to other techniques that can measure simultaneously more than one velocity component is its real time feature. Only few tens of milliseconds are necessary to compute and display a complete set of 2D or 3D velocity profile.

12.1 UDV-2D/3D measurement principle

UDV-2D is based on a 3 transducers system, whether UDV-3D is based on a 4 transducers system. Only one transducer is used as an emitter. The two or three others are used as receivers.

For UDV-2D measurements the three transducers are arranged as displayed in figure 1. The two receivers are placed on each side of the emitter and at the same distance from it. All ultrasonic beam axis cross at the same point and are contained in the same plane. The piezo surface of these three transducers are not necessarily alined along the X-axis. This arrangement allows to measure velocities along the ultrasonic beam of the emitter in many points. The depths over which measurements are available depend on the geometry of the ultrasonic beam of the transducers, on their distance between each other and on the receiver angle (the angle between the emitter's beam and one of the receiver's beam).
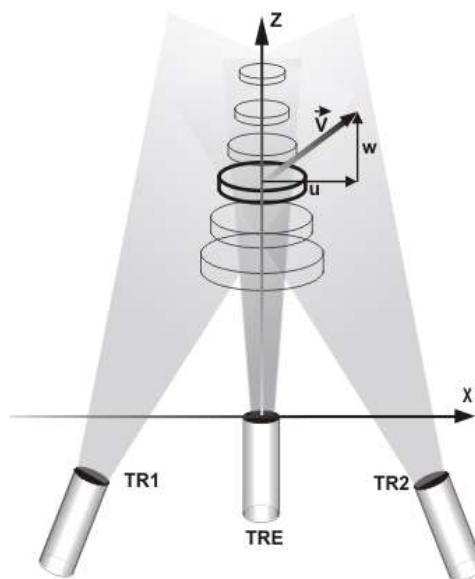
Figure 1

For UDV-3D measurements, the same kind of arrangement is used, as one can see in figure 2. A central transducer is used to emit ultrasonic bursts and three lateral transducers, placed uniformly (120 degrees) around the emitting transducer, are used to receive the echoes. Again, the piezo surface of these four transducers are not necessarily within the same XY-plane.
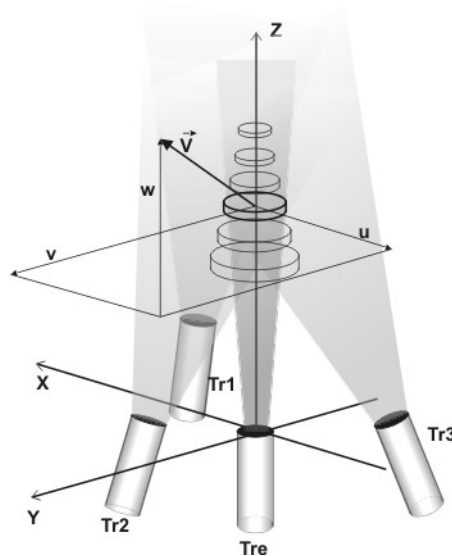
Figure 2

UDV-2D/3D coordinate system

Each set of emitter-receiver gives one Doppler frequency profile. These profiles are processed by the software of the instrument in order to give the velocity components in the following cartesian coordinates system:

For 2D

- The origin of the coordinate system is placed on the center of the emitter's piezo surface.

- The Z axis coincides with the axis of the emitting transducer, and is pointing away from it.

- The X axis is perpendicular to the Z axis and is pointing from the emitter towards receiver 1.

For 3D:

- The origin of the coordinate system is placed on the center of the emitter's piezo surface.

- The Z axis coincides with the axis of the emitting transducer, and is pointing away from it.

- TheY axis is perpendicular to the Z axis and is pointing from the emitter towards receiver 2, crossing its US beam axis.
- The X axis is such as (x,y,z) is a direct orthonormal coordinate system

12.2 UDV 2D/3D spatial resolution

In UDV 2D/3D the definition of the lateral dimensions of the sampling volume is not as simple as in 1D. This results mainly from the fact that each couple emitter-receiver is not the same. Emitting on one transducer and getting the echoes from an other one means that the radial location of the centers of the sampling volumes change over the measuring depth, as represented in the figure below.

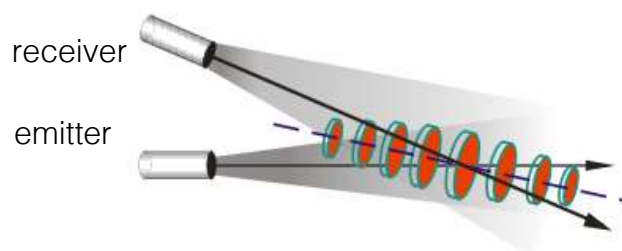As UDV 2D/3D uses 2 or 3 couples emitters-receivers, for a defined depth, more than one sampling volumes will be involved. Therefore, correct measurements will be available only if the flow field in each sampling volume is identical. In such a case, the sampling volumes corresponding to a particular depth, can be combined in a unique one, called global sampling volume, which has a much bigger dimension than in ID.

12.3 UDV-2D/3D probes

The UDV-2D/3D mode uses standard probes. Their choice and the way they are arranged (distance to the emitter, receiver angle) depends on the measuring range, the depth to be analyzed and the velocity range.

For quantitative measurements it is necessary to take into account the shape of the ultrasonic beam generated by each transducer. UDOP software takes into account the ultrasonic beam properties, by asking the user to specify the type of transducers he uses as emitter and receiver. A careful analysis shows that a narrow beam is needed for the emitter and a wider beam for the two receivers.

Geometrical parameters also have to be entered, such as the distance between the emitter and a receiver, the shifted distance and the angle between the ultrasonic beam generated by the emitter and the one generated by any receiver.

In order to optimally choose transducers and the geometry, it is greatly recommended to use the simulation software which is included in UDOP.

12.4 Connecting the UDV 2D/3D probes

UDV-2D and UDV-3D probes are connected to channels input, located in the front panel, as displayed in the figure below.
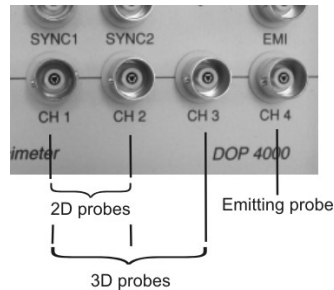
- The DOP BNC connector named "CH4" must be connected to the emitting probe.

- In UDV 2D mode, the receiving probes TR1 must be connected to "CH1" and the receiving probes TR2 must be connected to "CH2".
- In UDV 3D mode, the receiving probes TR1 must be connected to "CH1", the receiving probes TR2 must be connected to "CH2" and the receiving probes TR3 must be connected to "CH3"

Please note that it is not necessary to turn off the power supply of the DOP when the probes are connected.

12.5 Measuring UDV 2D/3D profiles

The measurement of UDV 2D/3D profiles uses its own parameters. UDOP saves the current channel parameters before switching to UDV 2D or 3D mode.

Note: The assisted mode is not available in UDV 2D/3D mode. If the assisted is selected, UDOP opens a panel that will inform that the assisted mode will be disabled.

After selecting the UDV 2D or 3D mode, UDOP opens a panel in which it is possible to choose the probes and to define the way the probes are arranged. The operating ultrasonic frequency is defined by the emitting probe.

On exit, if the apply button is clicked, UDOP uses the current parameters linked to the UDV 2D/3D mode and starts the measurement of the Doppler frequencies. As in UDV 1D mode the parameters can be changed and adapted using the normal mode. Nevertheless, a restriction applies:

- The same TGC values are used for all the receivers and only the uniform mode is available.

We recommend to execute the following steps:

- Select the position of the first gate;

- Select the number of gates, the resolution and the PRF in order
  to cover the desired depth;

- Select a value of 1 for all the velocity scale factors;

- Select the maximum TGC value;

- Apply the changes.

You should first investigate the Doppler frequencies and the echo profiles. In order to be sure that there is no saturation on all receivers, you should have a look on the echo profile. The echo profile will also help you to see if some artefacts are present. For their detection we recommend to use the floating PRF panel (see preferences options). This panel allows a fast access to the modification of the PRF value step by step. A good PRF value is the one for which a small change in its value does not imply any changes in the echo profiles and in the Doppler frequency profiles.

The auto correction of the aliasing is a tool that can extend the range of the measurable Doppler frequencies and velocities. Do not hesitate to use it. This tool will also inform you if the measured profiles are aliased or not.

When stable profiles are measured you can then display the velocity components profiles or the modulus and angle profiles of the real velocity vectors.

UDOP can display the measured velocities as vectors. The selection of this type of display is available in the "Display" tab in the main menu. A click on "Show vectors" select this display. A second click will return to the profiles mode. Note that "Show vectors" is only visible when UDOP measures velocities.

The display of the vectors can be improved by moving the vertical position of the origin and of the end the depth scale (vertical axis). With the mouse go over the starting position or the end of the vertical axis (the mouse cursor will change) then click and drag vertically.

12.6 Type of data recorded in UDV-2D/3D

In case of UDV 2D/3D the following information are recorded for each measured profile in the binary data file:

Compute mode: Doppler frequency

- C1: Coded Doppler frequency profiles receiver 1

- C2: Coded Doppler frequency reference profiles receiver 1

- C3: Coded Doppler frequency profiles receiver 2

- C4: Coded Doppler frequency reference profiles receiver 2

- C5: Coded Doppler frequency profiles receiver 3

- C6: Coded Doppler frequency reference profiles receiver 3

- C7: Calibrated reference profile in Hz*10 of receiver 1

- C8: Calibrated reference profile in Hz*10 of receiver 2

- C9: Calibrated reference profile in Hz*10 of receiver 3

Notes: Curves C2,C4, C6, C7, C8 and C9 are only present if the auto correction of the aliasing is enabled and uses the two PRF method.
Curves C5,C6, and C9 are only present in UDV 3D

Compute mode: Echo

- C1:Echo profile receiver 1

- C2: Echo profile receiver 1, second PRF

- C3:Echo profile receiver 2

- C4: Echo profile receiver 2, second PRF

- C5:Echo profile receiver 3

- C6: Echo profile receiver 3, second PRF

Notes: Curves C2,C4 and C6 are only present if the auto correction of the aliasing is enabled and uses the two PRF method
Curves C5 and C6 are only present in UDV 3D

Compute mode: Velocity Vx, Vy, Vz

- C1: Coded Doppler frequency profiles receiver 1

- C2: Coded Doppler frequency reference profiles receiver 1

- C3: Coded Doppler frequency profiles receiver 2

- C4: Coded Doppler frequency reference profiles receiver 2

- C5: Coded Doppler frequency profiles receiver 3

- C6: Coded Doppler frequency reference profiles receiver 3

- C7: Calibrated velocity component Vx

- C8: Calibrated velocity component Vy

- C9: Calibrated velocity component Vz

Notes: Curves C2,C4 and C6 are only present if the auto correction of the aliasing is enabled and uses the two PRF method.
Curves C5,C6, and C7 are only present in UDV 3D

Compute mode: Velocity modulus, phases

- C1: Coded Doppler frequency profiles receiver 1
- C2: Coded Doppler frequency reference profiles receiver 1
- C3: Coded Doppler frequency profiles receiver 2
- C4: Coded Doppler frequency reference profiles receiver 2
- C5: Coded Doppler frequency profiles receiver 3
- C6: Coded Doppler frequency reference profiles receiver 3
- C7: Calibrated velocity modulus
- C8: Calibrated velocity azimuthal angle in deg*10
- C9: Calibrated velocity elevation angle in deg*10

Notes: Curves C2,C4 and C6 are only present if the auto correction of the aliasing is enabled and uses the two PRF method.
Curves C5,C6, and C8 are only present in UDV 3D

The recorded information on the ASCI file are similar, but no coded profiles are present.

12.7 Add user's specific ultrasonic probe

UDV 2D/3D needs to know the shape of the ultrasonic beam generated by the transducer. If the user wish to use non standard probes, he must add the probes to the list of available probes.

The button named "Define probe" in the probe selection panel allows to add probes to the list. After a click on that button a new panel opens. To add the probe you must follow the following steps in the "UDV MD probe parameters"

- click the "Add" button
- enter the name of the added probe in the edit zone labled "Reference"
- enter the parameters attached to the probe:
  - US frequency in kHz
  - diameter of the US beam measured at the probe surface

- diameter of the US beam measured at the focal zone
- distance from the surface of the probe to the focal zone
- divergence of the beam (half angle)
- attenuation coefficient in dB/mm. Note that the attenuation coefficient is only used in simulation mode.

A click on the "Done" button close the panel. The new added probe appears then in the list of available probes.

13 UDV Simulation software

A simulation software is available to help the selection of the geometry, the type of transducers and the operating parameters for UDV-2D and UDV-3D measurement. This software also allows to simulate the 1D behaviour. It simulates flows, which are characterized by defined velocities along each axis (Z in 1D, Y,Z in 2D and X,Y,Z in 3D). It shows the influence of the parameters such as the angle of the receivers. We really recommend you to use it.

To execute the simulation software select the menu "UDV Mode" and then click the button named "UDV simulation"

In simulation, the display is divided into two main areas; the frist one displays the result and the second one shows the control area. Before doing any simulation you must define the operating condition and the way the transducers are arranged.

13.1 UDV 1D simulation

The 1D simulation is mainly intended to show how a high pulsed repetition frequency may distroy the spatial resolution. As nothing allows to distinguish an emission from an other one, at a defined sampling time we will collect all the echoes coming from the following depths:

$$P = \sum_{i=0}^{N} \frac{c \cdot [t + i \cdot Prf]}{2}$$

where t is the sampling time, c the sound velocity and Prf the pulsed repetition frequency. In order to keep a good spatial resolution, the first echo (i=0) must strongly dominate. This is true if

- the liquid attenuates the ultrasonic waves
- the PRF is low
- the particle is far away

The 1D simulation allows to investigate how the above parameters influence the measured data profile.

If the maximum measured depth, the one corresponding to the selected PRF value, is lower than the simulation depth, the simulation software will take into account the particles located deaper than the maximum depth and therefore will allow to investigate how the previous echoes influence the current one.

13.2 Define probes and geometry in UDV 2D/3D

A click on the button named "Define probes and geometry" opens a panel, which enables the user to define the type of transducers and the way they are arranged.
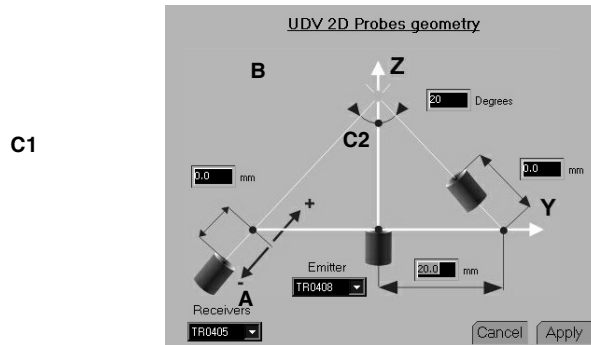
The frequency of all the transducers must be the same. The emitter should have the thinnest beam as possible. So try to use a piezo diameter as large as possible in order to reduce the divergence of the beam. The receivers should have a large beam so try to use a small piezo diameter. Often, a compromise should be taken in order to optimize the size of the sampling volumes and the depths over which measurements must be realized. The minimum size of the sampling volume always appears at the depth that corresponds to the crossing of all the ultrasonic beams axis.

The following parameters must be defined:

Distance between emitter and receivers (A)

> This distance is the distance in millimeters between the center of a receiver and the emitter when the receiver is not shifted (C1,2,3 value = 0).

Receiver angle (B)

> This angle is the angle in degrees between the US beam axis of a receiver and the US beam axis of the emitter. It must be the same for all recievers.

The shifted distances (C1,C2 and C3)

> The receivers are not necessarily placed in the same plane as the emitter. The entered distance is the distance from the center of the receiver to the crossing point of the ultrasonic beam axis of the receiver and the normal to the beam axis of the emitter passing at the origin (Z=0). A positive value indicates that the receiver is moving in direction to the crossing point of all the ultrasonic beams axis.

*Transducer used as the emitter*

> Select a transducer from the list. The choice of the this parameter sets the ultrasonic frequency, which must be the same as the one used for the receivers.

The "ideal" selects a transducer operating at the same frequency as the receivers, with no divergence and a very narrow beam (0.1 mm).

Transducer used as the receivers

Select a transducer from the list. All receivers must use the same model of transducers.

When no simulation is runing, the simulation software displays the borders or the limits of the global sampling volumes over the measuring depth. These borders are displayed by 2 green lines. The 2 displayed red lines are the axis of the US beam of two receivers. As you can realize, the size of the global sampling volumes are much bigger in UDV 2D/3D mode than the normal sampling volume in UDV 1D mode. The choice of the ultrasonic probes and the way they are arranged have a very big influence on their sizes and their evolutions over the measuring range.
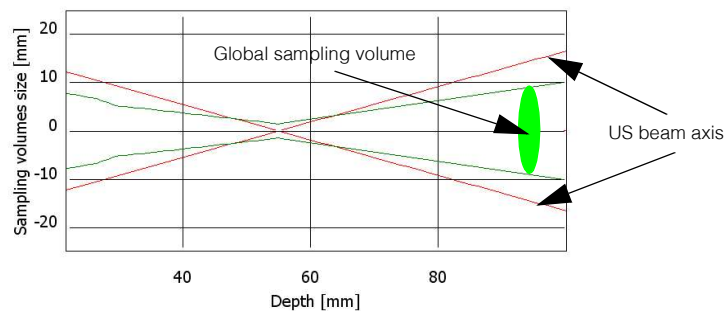
13.3 The simulation parameters

The simulation parameters are defined in a specific panel which is accessed by a click on the button named "simulation parameters".

The panel contains an area in which you can select between the 2D or 3D mode. All other parameters are standard UDV parameters, excepted the 2 following specific parameters:

Liquid attenuation

This parameter defines in dB/cm the attenution of the ultrasonic waves when they propagate into the liquid. This parameter is mainly used in 1D mode to study the influence of the previous emission.

Lowest echo level

This parameter defines the minimum level of the echo issued from a particle in order to take into account that particle. A very sensitive simulation enlarged the sampling volumes.

Particles density

The simulation is based on movements of particles distributed uniformly in the investigated depth. If not enough particles are simulated, holes or zero values will appear in the result. If to many particles are used, the simulation will take a very long time. In most situations, a value between 1 and 10 are used in 2D mode and between 0.5 and 0.05 in 3D mode.

The total number of particles that will be used is displayed beside this parameters.

Display scale factor

This parameter defines the velocity or Doppler frequency scale. The maximum scale value is equal to the theoretical value plus the percentage defined by this parameter.

13.4 Range and velocity field

The simulation is done over a range defined by two depths, measured along the ultrasonic beam axis of the emitter. Two inputs field define the first and last analyzed depths. Between these two limits, flowing particles will be simulated. Two types of velocity field can be simulated in 1D and 2D and only one in 3D.

In all modes the velocity field can be defined by a source of particles (a point), which emits particles in all directions. The module of the velocity vector is fixed for two specific directions (position 1 and 2) and vary linearly between these directions. The position of the source of particles defines the velocity field.

In 1D or 2D mode the velocity field can also be generated by a rotation of all particles around a fixed point, the source.

13.5 Doing a simulation

Six types of results are available:

Show flowing particles

This simulation shows where the particles are placed and how they moved. Moreover, you can see the locations of the partciles that are used to generate the echo from one couple emitter-receiver. These particles are displayed in green. You can clearly see that these particles are not distributed uniformly arround the emitter axis. This explains why:

- the way the probes are arranged is important;

- the sampling volumes are not the same for all receivers and therefore enlarge considerably the global sampling volume. (the global sampling volume is the volume that contains all the sampling volumes issued from all the receivers).

Show Doppler frequencies

This is maybe the most important simulation as the results issued from this simulation show how the parameters match the requirements. Two curves are displayed in each graph. The blue one shows the theoretical or reference curve (based on the input velocity field) and the red one the curve issued from the simulation. Any mismatch between these two curves tell that some parameters have to be changed or improved.

Show the velocity profiles

The results issue from this simulation show how close are the results from the theoretical value.

Show the velocity modulus and phase

The results issue from this simulation show an other type of profiles.

Show the simulated IQ signal

The results issue from this simulation show the evolution of the I and Q signals

Show the number of particles in gates

The results issue from this simulation show how many particles are contained in each gates. If this number is below around 10, the amount of generated particles must be increased via the "Particles density" parameter.

13.6 UDV 2D simulation: an example

The purpose of this chapter is to demonstrate the use of the simulation software.

We would like to measure 2D velocity profiles in a liquid flowing in a channel. The interesting depths are assumed to be from 30 to 60 mm.

The expected velocity are:

$Vy = 200$ mm/s
$Yz = 50$ mm/s

Let's start UDOP and select the channel 10, as UDV 2D/3D mode uses the parameters from the channel 10. As for all new measurements, select the factory settings. Then click on the button named "UDV simulation" available in UDV Mode menu.

The simulation software then starts. Let's open the probe selection panel by a click on "Define probe and geometry" and select the following values:

- for the emitter "TR0408LS"
- for the receivers "TR0405LS"
- "20" for the distance between the emitter and
   the receivers
- "20" for the angle between the emitter and
   the receivers
- "0" for the shifted distance of the receivers

After "Accept" you will see then on the screen a display that shows in red, the US beam axis of the transducers and in green, the evolution of the borders of the global sampling volumes. You can notice that the measurement depth does not fit our requirement. So

let's define the measuring range. Click on the button named "Velocity and depth" and enter the following values:

- 60 mm in the button named "To mm"
- 30 mm in the button named "From mm"

The needed velocity range is defined by the position of the source of particles and by the value entered for the two specific positions of the direction vector. In our case, let's enter:

- 200 mm/s for the velocity vector in position 1 and 2
- 30 mm for Z position of the source
- 100 mm for Y position of the source

We are now ready to perform the first simulation. Click:

- "Accept"
- "Run simulation"

During the simulation the software computes and displays, in red the computed Doppler frequencies, and in green the theoretical values or the expected values.

The US beams cross at a depth which is a little bit to far away from the starting depth. The size of the sampling volumes can be reduced if the distance between the receivers is reduced. Click:

- "Stop";
- "Define probes and geometry";
- Enter "15" for the distance between the emitter and
  the receivers;
- "Accept".

As you can realize, the US beams cross now at around the middle of the depth range and the size of the sampling volumes are more or less constant. Let's do the simulation, and click "Run simulation".

All the Doppler frequencies are measured correctly. Let's have a look on the velocity profiles. Click:

- "Show velocity profiles"

They are also measured correctly and the variance of the measurement is correct. The way we setup the transducers are now correct and the selected parameters fit our requirement. These parameters can be used by UDOP after exiting the simulation software, and if desired, the real UDV 2D mode can be executed.

One thing the simulation can't do, is the definition of the TGC level. So, for all new settings, it is necessary to define a correct TGC level. This is realized by means of the display of the echo amplitude. Note that the TGC is the same for all the receivers and only the Uniform definition is available.

14 Measurement sample volume

In order to precisely locate the depth of the measurement, the shortest possible signal emission should be used. Unfortunately, increasing the spatial resolution decreases the accuracy of the estimation of the Doppler frequency. The relationship between these two parameters is presented in detail in this section.

Consider a pulse which has been received by a transducer, given by:

$$R(t) = A(t - t_v)\sin[2\pi f_e(t - t_v)]$$

where $A(t-t_v)$ is the envelope of the received impulse and t_v is the time required for the signal to travel from the transducer to the target and back. For a periodic emitted pulse of period T_{prf}, the echo signal will be given by the convolution (denoted as x) of a train of Dirac delta functions with the received impulse.

$$R(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT_{prf}) \otimes A(t - t_v)\sin[2\pi f_e(t - t_v)]$$

The Fourier transform of the above expression is:

$$R(t) = cste \sum_{n=-\infty}^{\infty} [F_A(f_{prf} - f_e) - F_A(f_{prf} + f_e)]\delta(f - nf_{prf})$$

where cste is a constant and F_a is the Fourier transform of the impulse envelope. The frequency spectrum of the above equation generated by a non-moving target is given on the next figure by the heavy line, assuming an impulse envelope of the form $sinc^2(t/\tau_e)$, ωηερε τ_e is the length of the emitted pulse.

The movement of the target alters this spectrum in a complex manner. Each spectral component gets shifted according to the Doppler effect by an amount proportional to its frequency. The spectrum becomes, in the case of moving targets:

$$R(t) = \sum_{n=-\infty}^{\infty} \left[F_A\left(f_{prf} - f_e\right) - F_A\left(f_{prf} + f_e\right) \right] \delta\left(f - n\left(1 - \frac{2v\cos\theta}{c} f_{prf}\right)\right)$$

This new spectrum is given by the thin lines. A target which is moving at a constant uniform velocity will generate a series of Doppler frequencies. An accurate estimation of the target velocity requires a narrow spectrum, and thus a long emitted pulse. Such an emission will decrease the depth resolution. A compromise between the length of the emitted pulse and the depth resolution is difficult to attain, since the duration of the emitted pulse determines the energy available in the signal. For a given value of emitted pulse energy, decreasing the duration of the pulse means that the amplitude must increase. Unfortunately, it is impossible to increase the amplitude of the emitted pulse beyond a certain threshold without risking the appearance of unwanted phenomena such as cavitation. Reducing the length of the emitted pulse will reduce the signal to noise ratio (SNR) of the Doppler signal if it is not possible to increase the amplitude.

The duration of the impulse determines the depth resolution by determining the longitudinal size of the sample volume. The other dimensions are determined by the beam pattern of the transducer.

Consider an impulse of duration τ_e as illustrated in the next figure. In this figure, the right portion of the horizontal axis represents time, while the left portion represents the energy of the received impulse. The top vertical axis gives the amplitude of the emitted pulse, and the bottom the depth. The impulse propagates in time along a straight slanted line, with the slope being the speed of sound.
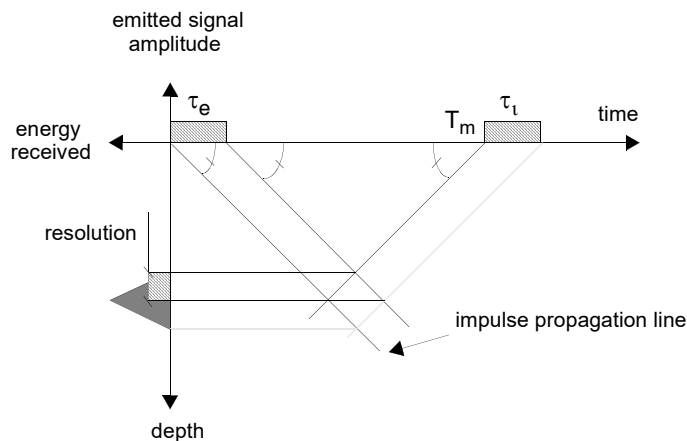
Consider a measurement time T_m on the time axis. By drawing a straight line which is perpendicular to the propagation line and which passes through T_m, the depth resolution may be determined by the projection of the intersection of these two lines on the depth axis.

The resolution is therefore:

$$Res = \frac{c\tau_e}{2}$$

and corresponds to the maximum attainable resolution for this type of emission. The integration of the demodulated signal over a time period τ_i reduces the depth resolution, as shown in the figure by the broken line. In the case where $\tau_i = \tau_e$, the energy distribution will be given by a triangle whose base measures $\tau_e c$

The demodulated Doppler signals must be filtered in order to eliminate the frequency generated by the demodulation process, which is equal to twice the emitted frequency. The low pass filter cut-off frequency should be as low as possible in order to reduce the noise, but not so low as to degrade the resolution.

Real Doppler signals always contain a certain amount of noise. The cut-off frequency will naturally affect the SNR. There is an optimum value of the product of the bandwidth and the impulse duration which will give the maximum SNR, provided the frequency and temporal characteristics of the noise are known [1]. This value also depends on the characteristics of the filter and the signal to be filtered.

15 Spectral content of the Doppler echo

The sample volume in which the velocity is measured is of a finite dimension. Each particle which traverses the ultrasonic beam backscatter the acoustic waves for a short time. The duration of the backscattering time depends on the angle of incidence as well as on the particle velocity, and is referred to as the transit time. If the fluid contains small particles possessing different acoustic properties than the fluid, the echo signal amplitude will evolve over time depending on the passage of a group of particles through the sample volume. This results in a modulation of the echo signal which serves to broaden its frequency spectrum. The signal is further modulated by the non-homogeneity of the fluid-particle medium. This spectral broadening depends on the velocity at which the particles traverse the ultrasonic beam. The higher the velocity, the faster the signal will be modulated and its spectrum broadened. Since the Doppler signal is related to the velocity, it is possible to evaluate the effect of the transit time as a function of the Doppler frequency. One of several researchers who studied this effect was Newhouse [2], who estimated the spectral broadening δf_d as:

$$\frac{\delta f_d}{f_d} = \frac{k\lambda}{D}\tan\theta$$

where k is a constant between 2 and 3, depending on the ratio of the intensity of the acoustic wave at its center to its intensity near the periphery, λ is the wavelength and D is the diameter of the ultrasonic beam. For example, with an emission frequency of 3 MHz (λ = 0.5 mm), a transducer diameter of 10 mm and a Doppler angle of 45 degrees, the spectral broadening is on the order of 10%.

The spectral broadening created by the modulation of the echo signal amplitude may also be explained based on geometric considerations. The finite dimension of the sample volume implies that each particle contained within it is viewed from a slightly different Doppler angle. This results in a spread of Doppler frequencies corresponding to this small angle change.

As the ultrasonic waves propagate, they encounter different structures which may create echoes stronger than the echoes from the particles within the fluid. Furthermore, these structures may themselves be moving. Therefore, the echo signal may contain a certain number of stationary and quasi-stationary echoes of low frequency and large amplitude, as well as the echoes from the particles within the fluid at higher frequencies but of smaller amplitudes. The difference between the amplitudes of these two types of signals may be 20 to 60 dB. For the case of moving flow boundaries, the velocity of the wall creates a Doppler effect which must be filtered out. These low frequency components may be eliminated by the wall motion filter. Unfortunately, this hi-pass filter also

diminishes the amplitudes of the already weak Doppler signals coming from the particles within the fluid.

16 Theoretical basis of the Doppler frequency estimation

The amplitudes of the echoes reflected by the particles within the flowing fluid are somewhat random in nature, corresponding to the random distribution of the particles in the fluid medium. Thus, the Doppler signals may be treated as random processes, and characterized by different moments. In order to be able to determine the probability of occurrence of this process, one must have access to a great number of actual occurrences of the process. In practice, it is difficult to obtain measurements of the exact same process under the exact same conditions at several different times. Therefore, a temporal average is preferable to an ensemble average. The temporal average and the ensemble average will not be the same unless the process is stationary and the analysis time is very long (tending to infinity). Considering the Doppler process as stationary, the average frequency may be expressed as the normalized first moment, or:

$$\mu_1 = \dot{f} = \frac{\displaystyle\int_{-\infty}^{\infty} f S(f) df}{\displaystyle\int_{-\infty}^{\infty} S(f) df}$$

where S(f) is the spectral density or probability density of the Doppler signal.

The Doppler frequency calculation algorithm is based on the fact that the inverse Fourier transform of the probability density of a stationary process is equal to the auto-correlation function [3]. The first moment μ_1 may be expressed in terms of the time derivatives of the auto-correlation function at the origin:

$$\dot{f} = \frac{1}{j2\pi} \frac{\frac{d}{dt}R(0)}{R(0)}$$

The auto-correlation function is estimated using the complex envelope of the echo signal.

17 Ultrasonic transducers

The material most often used in the construction of ultrasonic transducers is a piezoelectric ceramic. Another material which may be used is the polymer polyvinylidene fluoride (PVDF) which possesses good piezoelectric properties, and has the additional advantages of being more flexible and having a smaller acoustic impedance than ceramic materials. PVDF is, on the other hand, less efficient. With the advent of composite materials [6], ultrasonic transducers have been produced which are as efficient as ceramic materials and which have a small acoustic impedance. They offer the advantage of a better acoustic coupling between the transducer and the medium, as well as the ability to produce a shorter ultrasonic impulse, due to their relatively high coefficient of absorption. A typical design is illustrated below.
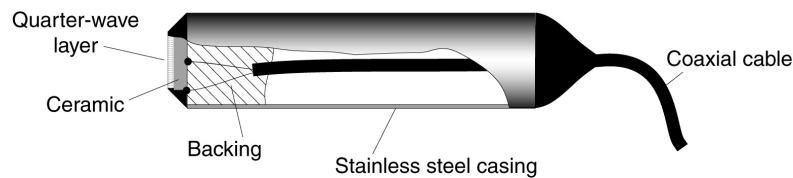
The electrodes are positioned so that the ceramic operates in a piston-like mode.

The transfer of energy from the ceramic (medium 1) to the surroundings (medium 3) is determined by the characteristic impedances or acoustic impedance z of the two media, defined as:

$$z = \rho c$$

where ρ is the density of the medium and c is the speed of sound.

By placing an additional layer between these two media, the energy transfer may be optimized. The acoustic impedance of this middle layer should be:

$$z_2 = \sqrt{z_1 z_3}$$

and its thickness:

$$e_2 = (2n - 1)\frac{\lambda_2}{4}$$

where n is an integer and λ_2 is the wavelength in the middle layer. This additional layer, called the quarter-wave layer, is used in the construction of most ultrasonic transducers.

The rear part of the transducer (called the absorber or backing) behaves like a shock absorber whose efficiency depends on its acoustic properties. The choice of the material

for the backing determines the type of acoustic impulses which may be emitted by the transducer. For a highly absorbent material, most of the energy is absorbed, tending to produce a short emission. For a weakly absorbing material, the energy at the rear of the transducer is returned to the front face, thereby increasing the energy transmitted out into the medium.

The electric energy transferred from the generator to the probe depends on their respective electric impedances. Adapting the electric impedance of the transducer to that of the generator using passive elements can optimize the transfer of energy. The reactive component (x_s) of the probe impedance ($z_s = r_s + jx_s$) may be eliminated with an inductance of $L = x_s/\omega$. An impedance transformer assures the compatibility of the generator impedance with the corrected probe impedance.
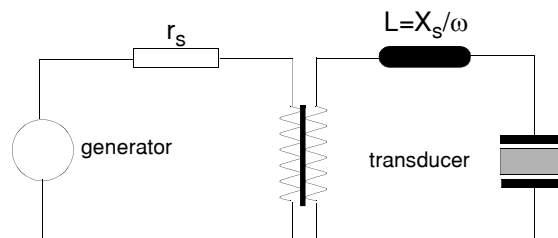
18 Ultrasonic field

18.1 Theoretical considerations

The generation of ultrasonic waves as well as their transformation into an electrical signal is of obvious importance to the quality of the information which may be obtained concerning the flow field.

In Doppler echography, the object is not to make use of a plane longitudinal wave, but rather an ultrasonic beam that is as thin as possible throughout the measurement depth. The geometry of the acoustic field generated by the ultrasonic wave determines the lateral resolution. The characteristics of the acoustic field depend on the size and shape of the piezoelectric element for a single element transducer, and on the combination of the individual emissions in the case of a multi-element transducer.

Using Huygen's principle, one may theoretically predict the geometry of the acoustic field. In this approach, the transducer is modeled as a combination of several adjacent point sources, each generating a spherical wave.

For a circular transducer of radius a operating in a piston-like manner, the intensity of the acoustic field along the axis is given by:

$$\frac{I_z}{I_o} = \sin^2\left[\frac{\pi}{\lambda}(\sqrt{a^2 + z^2} - z)\right]$$

where I_o is the maximum intensity, z is the distance from the transducer and λ is the wavelength.The acoustic field generated by a transducer possesses two characteristic regions, separated by the distance of the furthermost maximum of the above function.

This distance is given by:

$$Z_0 = \frac{4a^2 - \lambda^2}{4\lambda}$$

If $a^2 >> \lambda^2$, z_0 becomes:

$$Z_0 = \frac{a^2}{\lambda}$$

The zone between the transducer and z_0 is called the Fresnel zone, or the near field. In the near field, the intensity oscillates along the axis of the transducer, and the acoustic field is basically cylindrical with the same diameter as the transducer. The zone lying beyond z_0 is called the Frauenhofer zone or the far field. In the far field, the intensity of the acoustic field varies as the inverse of the square of the distance from the transducer z, and oscillates in the plane perpendicular to the axis of propagation. For a 5 mm transducer functioning at 4 MHz, the far field begins at a distance of approximately 1.6 cm.

In the far field, the acoustic field may possess intensity lobes as one moves away from the axis of the transducer. The relationship between the acoustic field intensity and the angle off the transducer axis depends on the directivity function:

$$D_r(\gamma) = \frac{2J_1(k a \sin\gamma)}{k a \sin\gamma}$$

where J_1 is the first order Bessel function of the first kind, and $k = 2\pi/\lambda$ the wave number. This function has roots at $(ka\sin\lambda) = 3.83, 7.02, 10.17$, etc. and defines lobes. The half angle of divergence of the main lobe γ_0 is given by:

$$\gamma_0 = \sin^{-1}\left(\frac{0.61\lambda}{a}\right)$$

and is approximately 5 degrees. for the above example. The acoustic energy contained in the secondary lobes is always much smaller than that contained in the main lobe. For a circular transducer, the acoustic energy contained in the secondary lobe is 18 dB less than in the main lobe.

Table 5: Near field value in mm
(c=1500 m/s)

Freq Mhz	Transducer diameter in mm							
	2	3	4	5	8	10	12	16
1	0.6	1.5	2.6	4.1	10.6	16.6	24.0	42.7
2	1.3	3.0	5.3	8.3	21.3	33.3	48.0	85.3
4	2.7	6.0	10.7	16.7	42.7	66.7	96.0	170.7
5	3.3	7.5	13.3	20.8	53.3	83.3	120.0	213.3
8	5.3	12.0	21.3	33.3	85.3	133.3	192.0	341.3
10	6.7	15.0	26.7	41.7	106.7	166.7	240.0	426.7

Table 6: Directivity in degrees (half-angle)
(c=1500 m/s)

| Freq Mhz	Transducer diameter in mm							
	2	3	4	5	8	10	12	16
1	66.2	37.5	27.2	21.5	13.2	10.5	8.8	6.6
2	27.2	17.6	13.2	10.5	6.6	5.2	4.4	3.3
4	13.2	8.8	6.6	5.2	3.3	2.6	2.2	1.6
5	10.5	7.0	2.6	5.2	2.6	2.1	1.7	1.3
8	6.6	4.4	3.3	2.6	1.6	1.3	1.1	0.8
10	5.2	3.5	2.6	2.1	1.3	1.0	0.9	0.7

18.2 Measuring the ultrasonic field

The measurement of the ultrasonic field generated by a transducer is realized by measuring the intensity of an echo coming from a small sphere. By moving the position of the sphere along a line perpendicularly to the axis of the ultrasonic beam and measuring the intensity of the echo for different positions of the sphere, a slice is obtained. This slice is used to measure the -6dB width of the ultrasonic beam, from which the size of the sampling volume can be estimated.

In order to achieve a good spatial resolution the size of the moving sphere must be as small as possible. Nevertheless, the size of the sphere must be big enough in order to be able to process the echo in good condition (high SNR). We recommend a diameter between 1 and 5 millimeters depending on the ultrasonic frequency.

18.2.1 X-Y handling system

The figure below illustrates the principle of the method.
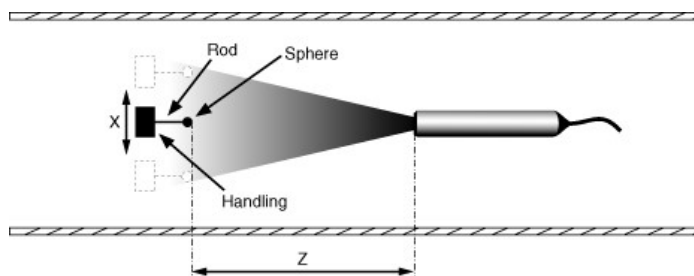
The sphere is handled by a small rigid rod (maximum 1/3 of the diameter of the sphere). The length of the rod must be around 3-5cm. The material of the sphere can be any solid. Stainless steel is a good choice. The system, rod+sphere, is mounted on a XY table, which must be capable of positioning the sphere with a minimum resolution of 0.1mm. The system sphere-transducer must be completely submerged. Enough liquid must surround the transducer in order to avoid the influence of the free surface of the liquid.
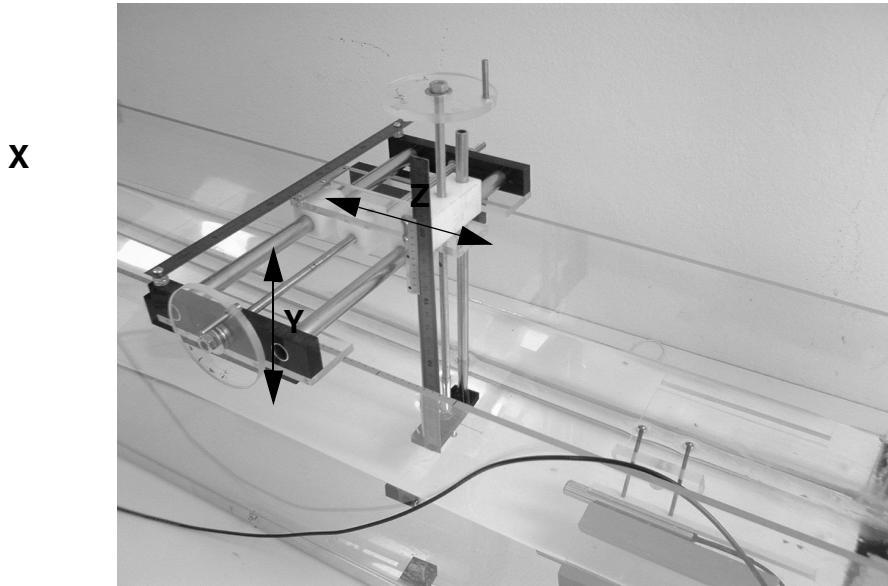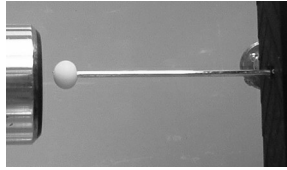
Sphere detail

By convention, we will note X and Y the movements which are perpendicular to the ultrasonic beam axis and Z the distance between the sphere and the surface of the transducer.

18.2.2 Measuring procedure

Before entering in the menu dedicated to the measurement of the ultrasonic field, the following procedure must be executed:

- the default factory settings must be recalled;
- the emitting frequency (which must correspond to the transducer) must be chosen;
- a "high" emitting power must be selected;
- a burst length of 2 cycles;
- the sound velocity must correspond to the liquid.

Then, you can enter in the ultrasonic field measurement menu. This menu is found in the "Tools" menu. After entering in this menu, UDOP measures the echo profile at the depth indicated in the "Slice depth" button.

The first thing to do, is to find the center of the ultrasonic beam in the XY plane. This is realized by selecting a distance Z=0 (sphere in contact with the transducer) and moving the sphere in the X and Y direction in order to place the sphere at the center of the transducer. The corresponding X and Y position must be entered in the two buttons labeled "Xorg" and "Yorg".

Note: Be sure that the ultrasonic beam axis of the transducer passes at that point. For that, place the sphere more far away from the transducer and check that you have the maximum level of the echo for the X and Y position you have entered.

You then place the sphere at a desired depth Z, without moving the position in X and Y direction of the sphere. The depth Z must be entered in millimeters in the field labeled "Slice depth". The echo profile displayed in the left panel, can be used to setup correctly the ultrasonic parameters. You must measure a clear echo from the sphere. If this is not the case, the button named "Parameters" can be used to access to the different parameters that define the operating conditions, such as:

- the PRF
  be sure that any changes in the PRF value do not induce any changes in the shape and value of the echo from the sphere. If some changes appear (which means the presence of artifacts), find a PRF value for which no artifacts appear;
- the emitting power;
- the TGC;
- etc...

Note: The module scale can be changed by a mouse click on the arrows located above and below the legend of the Y axis

Then, define the distance over which the sphere will be travelling. This value is entered in the button labeled "Measurement width". The step, which defines the measurement resolution, is entered in the field named "Measurement step".

At this stage, a slice can be measured. Click on the button named "Add slice". The left graph continue to display the echo profile, and a new graph will display the evolution of the maximum echo value when the position of the sphere is moved.

- move the sphere at its first location, which is indicated in the panel located in the middle of the right graph.
- wait a little bit in order to let the system stabilized. Then press the "space bar" to record the first point.
- move the sphere over a distance equal to the step, wait again a little bit and press the "space bar" to record the second point. Repeat this last procedure until the last X position is reached

Note: The recorded amplitude is the maximum amplitude find in all the gates of the echo profile displayed in the left panel.

After the last measured value, the graph of the echo profile is replaced by a graph that shows the evolution of the maximum amplitude of the echo in function of the position of the sphere. In this graph the amplitude is normalized (the maximum value always equal 1). The width of the ultrasonic beam at -6dB is also displayed inside the graph.

You can add up to 100 slices. Each slice must have a unique depth. If a slice has to be removed from the list, select the slice, and click the button named "Remove slice". If the slice at the current depth has to be measured again you don't need to remove it before. Simply click the "Add slice" button and answer "Yes".

18.2.3 Beam divergence and attenuation

From the measured slices, the divergence of the ultrasonic beam and the attenuation can be computed and displayed. The divergence of the beam shows the -6dB width of the beam versus the depths and the attenuation shows the relative reduction in dB of the maximum echo amplitude versus depth. These curves are displayed by a mouse click on the button labeled "Show divergence" and "Show attenuation"

18.2.4 Saving or reading an ultrasonic field measurement

All the measured values can be saved in a file in binary format. The user can attach to the data file a comment. The paragraphs below describes the format of the binary file.

Data file header

- 16 bytes for the header (example: UFD_DOPV6.00.1)
- 1 longint (4 bytes) that gives the number of bytes used by the comment.
- the characters of the comments (1 byte each).
- the operating parameters (1024 bytes). See chapter "Storing and reading measures".

Data values of the slices. Each slice contains the following bytes

- 1 longint (4 bytes) that gives the depth of the slice in mm
- 1 longint (4 bytes) that gives the number of measured positions
- 1 longint (4 bytes) that gives the X coordinate of the center of the transducer in mm*100
- 1 longint (4 bytes) that gives the Y coordinate of the center of the transducer in mm*100
- 1 longint (4 bytes) that gives the emitting frequency in kHz
- 1 longint (4 bytes) that gives the emitting power
  (0= high, 1=medium, 2=low)
- 1 longint (4 bytes) that gives the burst length
- 1 longint (4 bytes) that gives the ultrasonic beam width at -6dB in mm*100
- 1 longint (4 bytes) that PRF value in µs
- 1 longint (4 bytes) that TGC value in dB
- 1 longint (4 bytes) that Module_Scale factor
  (value that corresponds to 256)
- 3 longint (12 bytes) (reserved)

Then measuring points. Each point contains:

- 1 longint (4 bytes) that gives the position in mm*100
- 1 longint (4 bytes) that gives the amplitude of the echo in microVolt.

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Jorgen Arendt Jensen
Cambridge University Press, 1996, ISBN 0-521-46484-6

20 Ultrasonic data

Vl = longitudinal sound velocity [m/s],   r=density

Z=acoustic impedance [MRayls=(kg/(sxm2)x106]

Solids and Epoxys

Material	V_l	ρ	Z_l	Material	V_l	ρ	Z_l
Aluminium rolled	6420	2.70	17.33	Silicon very anisotropic	8430	2.34	19.7
Araldite 502/956 20 phe	2600	1.39	3.52	Silicon carbide	6660	13.8	91.8
Araldite 502/956 50 phe	2130	1.95	4.14	Silicon nitride	11.0	3.27	36
Araldite 502/956 90 phe	1520	8.40	12.81	Silver	3600	10.6	38.0
Beryllium	12890	1.87	24.10	Silver epoxy	1900	2.71	5.14
Bismuth	2200	9.8	21.5	Steel mild	5900	7.8	46.0
Brass 70cu 30 Zn	4700	8.64	40.6	Steel stainless	5790	7.89	45.7
Brick	4300	1.7	7.4	Stycast	2220	1.19	2.64
Cadmium	2800	8.6	24	Tantalum	4100	16.0	54.8
Carbon vitreous	4260	1.47	6.26	Teflon	1390	2.14	2.97
Concrete	3100	2.6	8.0	Tin	3300	7.3	24.2
Copper rolled	5010	8.93	44.6	Titanium	6100	4.48	27.3
Duraluminium 17S	6320	2.79	17.63	Tracon	2970	1.62	4.82
Epotek 301	2640	1.08	2.85	Tungsten	5200	19.4	101.0
Fused silica	5960	2.20	13.1	Uranium	3400	18.5	63.0
Germanium	5410	5.47	29.6	Vanadium	6000	6.03	36.2
Glass pyrex	5640	2.24	13.1	Wood cork	500	0.24	0.12
Glass quartz	5500	2.2	12	Wood pine	3500	0.45	1.57
Glass silica	5900	2.2	13.0	Zinc	4200	7.0	29.6
Glucose	3200	1.56	5.0	Zinc oxyde	6400	5.68	36.4
Gold	3240	19.7	63.8				
Granite	6500	4.1	26.8				
Induim	2560	7.3	18.7				
Iron	5900	7.69	46.4				
Iron cast	4600	7.22	33.2				
Lead	2200	11.2	24.6				
Lithium	7080	4.7	33.8				
Magnesium	5800	1.73	10.0				
Marble	3800	2.8	10.5				
Molybdenum	6300	10.0	63.1				
Nickel	5600	8.84	49.5				
Paraffin	3260	21.4	69.8				
Polyester casting resin	2290	1.07	2.86				
Porcelain	5900	2.3	13.5				
PVF2	2380	1.79	4.2				
Quartz x cut	5750	2.65	15.3				
Rubidium	1260	1.53	1.93				
Salt crystalline x direction	4.78	2.17	10.37				
Sapphire, alu. oxide	11.15	3.98	44.46				
Scotch tape 2.5 mils thick	1900	1.16	2.08				

Plastics

Material	V_l	ρ	Z_l	Material	V_l	ρ	Z_l
ABS	2230	1.03	2.31	Polyethylene low density	1950	0.92	1.79
Acrylic plexiglas	2750	1.19	3.26	Polypropylene	2740	0.88	2.40
Acrylic plexiglas M1-7	2610	1.18	3.03	Polystyrene	2320	1.04	2.42
Adiprene	1680	1.16	1-94	Polyurethane	1700	1.10	1.8
Bakelite	1590	1.40	3.63	PVC	2380	1.38	3.27
Cellulose Butyrate	2140	1.19	2.56	Vinyl rigid	2230	1.33	2.96
Delrin	2430	1.42	3.45				
Ethyl vinyl acetate	1800	0.94	1.69				
Neoprene	1600	1.31	2.1				
Mylar	2540	1.18	3.00				
Nylon 6/6	2900	1.7	4.93				
Polycarbonate	2270	1.22	2.77				
Polyethylene	1950	0.90	1.76				
Polyethylene high density	2430	0.96	2.33				

Liquids

Material	V_l	ρ	Z_l	Material	V_l	ρ	Z_l
Acetate	1270	0.871	1.02	Water sea at 25C	1531	1.025	1.569
Acetone	1180	0.891	1.05				
Alcohol ethanol	1207	0.79	0.95				
Benzene	1295	0.87	1.12				
Benzol	1330	0.878	1.16				
Carbipol	1460	0.988	1.431				
Chloroform	987	1.49	1.47				
Ethanol amide	1724	1.018	1.755				
Ethyl ether	985	0.713	0.703				
Freon	716	1.57	1.12				
Gallium @ 30°	2870	6.09	17.5				
Gasoline	1250	0.803	1.00				
Glycerin	1904	1.26	2.34				
Glycol	1480	1.019	1.511				
Honey	2030	1.42	2.89				
Kerosene	1324	0.81	1.072				
Mercury at 25 degrees	1450	13.5	19.58				
Oil baby	1430	0.821	1.17				
Oil corn	1460	0.942	1.42				
Oil mineral	1440	0.825	1.19				
Oil olive	1445	0.918	1.32				
Oil SAE 20	1740	0.87	1.51				
Oil silicon	960	0.818	0.74				
Oil transformer	1390	0.92	1.28				
Sodium (145 °C)	2500	0.917	2.29				
Trichlorethylene	1050	1.05	1.1				
Water at 20C	1480	1.00	1.483				
Water at 25C	1496	0.998	1.494				
Water at 30C	1509	1.00	1.509				
Water at 60C	1550	1.00	1.55				
Water salt 10%	1470						
Water salt 20%	1600						

21 DOP4000 technical specifications

Ultrasonic emission

period of the emitted pulse	variable between 100 ns (10 MHz) and 2220 ns (450 kHz), with a resolution of 20 ns
Emitting power	3 levels. Approximative instantaneous maximum level: low = 10 Vpp, medium= 30 Vpp, high= 60 Vpp
Number of emitted cycles	2 to 32, step of 2 cycles
Pulse repetition frequency	selectable values between 100'000 μs and 64 μs, step of 1 μs

Reception

Number of gates	variable between 1000 and 4, step of 1 gates
Position of the first gate	movable by step of 1 mm but not earlier than the end of the emitted burst
Amplification (TGC)	amplification range from -40 to 40 dB *uniform* *slope mode* exponential amplification between two defined depth values. *custom mode* user's defined values between -40dB and +40dB in cells; variable number (from 1 to 1024), size and position of the cells. *automatic computation*
Sensitivity	> -100 dBm

Sampling volume

lateral size	defined by the acoustical characteristics of the transducer.
longitudinal size	defined by the burst length internal filter bandwidth : 240 kHz (around 0.8 mm for c=1500 m/s ,defined at 50% of the received signal level)
Display resolution:	distance between the center of each sampling volume selectable between 0.170 and 20 μs, step of 0.170 μs.
Velocity resolution	1 LSB, Doppler frequency given in a signed byte format. Depends on velocity scale and emitting frequency

Ultrasonic processor

Doppler frequency	computation based on a correlation algorithm
Wall filter	stationary echoes removed by IIR high-pass filter 2nd order
Dynamic extender	Increase the dynamic of the Doppler signals by a factor of 16dB. User's selectable ON or OFF
Emissions per profile	between 512 and 8, any values

DOP4000 technical specifications

Detection level	**5 levels of the received Doppler energy may disable the computation**
Acquisition time per profile	**minimum: about 2-3 ms**

filters on profiles	**moving average:**
	   based on 2 to 1000 profiles
	   zero values included or rejected
	median, based on 3 to 32 profiles

Velocity scale	**variable positive and negative velocity range, movable origin.**
Maximum velocity	**Without aliasing correction, bi-directional** **0.5 MHz 11.72 m/s** **1 MHz 5.86 m/s** **2 MHz 2.93 m/s** **4 MHz 1.46 m/s** **8 MHz 0.73 m/s** **10 MHz 0.59 m/s** **(twice if uni-directional)** **With aliasing correction enabled, no limit (depends on flow conditions and noise level)**
Compute and display	**velocity profile** **Doppler energy** **echo profile** **velocity profile with echo profile or Doppler energy** **velocity profile with v(t) of a selected gate** **velocity profile and histogram** **echo or energy profile and histogram** **power spectrum of one selected gated** **velocity profile and time-space** **velocity profile and flowrate**
Cursor	**4 available cursors in tracking mode (follow the displayed curve). Statistical values available (Mean, standard deviation, minimum, maximum)**
External Trigger	**by external signal, change in the logic state (TTL/CMOS level)** **automatic record capability** **Trigger delay from 0 ms to 32s, step of 1 ms**
Velocity component	**automatic computation of the projected velocity component along the flow axis**
Replay mode	**replays a recorded measure from the disk**
Saving mode	**save the past, record the future (manual trigger)**
Additional tools	**auto correction of the aliasing** **measurement of the ultrasonic field**
Multiplexer	
Number of channels	**4**
Configuration parameters	**all channels have their own set of parameters**

DOP4000 technical specifications

Switching time	**2 μs**
Acquisition mode	**sequential (one channel measued one after the other)** **simultaneous (delay between channel of 1 PRF)** **UDV 2D/3D (available in option)**
Memory/Files	
Internal memory size	**2'097'152 profiles, divided in blocks from 1 to 65536 blocks**
Configuration parameters	**9 saved configurations with description**
Data file format	**binary** **ASCII** **ASCII statistical data**
Environment	
Power supply	**110 - 220 VAC, 50 - 60 Hz**
Host PC Operating system	**All windows version**
Communication	**USB 2, Connector type B**
US interface	**4 BNC, US probe In/Out (1 for each channel)** **1 BNC emitted burst, output** **2 BNC, TTL In/out, user defined, used as Trigger input and/or for synchronisation of many DOP4000**
External trigger input	**TTL level, pull up 330 ohm**
Temperature	**5 - 35 degrees**
Sizes	**264 x 155 x 69 mm**
Weight	**1.5 Kg**

Options

UDV 2D/3D software package

Symbols

Signal Processing S.A. - DOP4000 user's manual