# Using velocity profiles to determine an accurate volume flow rate at small and large dimensions

## Utilisation des profileurs de vitesse pour une évaluation optimale du débit à petite et grande échelle

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## RÉSUMÉ

L'effet Doppler acoustique est utilisé depuis maintes années afin de mesurer les vitesses et débits pour les liquides et gaz. Dans le cadre de la surveillance des réseaux, le législateur impose un équipement des canaux tant en mesure de volume que de qualité. En réseau d'assainissement, le calcul de débit par les techniques ultrasoniques peut s'effectuer de différentes manières : les plus répandues sont les techniques telles que le Doppler continu, le Doppler pulsé et la corrélation d'écho présentant la détermination des profiles de vitesse, le temps de transit. La corrélation d'écho utilisée comme technique d'évaluation du signal pour la détermination du débit pour les fluides bi-phasiques (eau/air ou eau/matériaux). Cet article présente l'utilisation de la corrélation d'écho en tant que mesure de vitesse par résolution spatiale contribuant au calcul du débit pour des canaux ouverts de petites ou grandes dimensions.

## ABSTRACT

The acoustic Doppler effect is used since years to carry out velocity and flow rate measurements in liquids and gases. As part of networks supervision, the legislator lays down the channel equipment in quantity and quality measurements. In sewer systems, flow rate determination by ultrasonic technologies are done by Continuous Doppler technology (CW), pulse Doppler and cross correlation, both offering spatial resolution of the velocity measurement and transit time. Cross correlation is used for signal evaluation for several flow rate meters; as stand alone instrument a 2-phase fluid is required. This article presents the use of cross correlation to measure a spatial resolved velocity and the conversion into a grid measurement to evaluate the volume flow rate in open channel flow at small and large dimensions.

## KEYWORDS

Volume flow rate measurement, flow velocity profile, ultra sonic cross correlation, chirp coded pulses, grid measurement

# 1 INTRODUCTION

The acoustic Doppler effect is used since years to carry out velocity and flow rate measurements. To determine the flow rate in waste water first versions were realized with continuously working (CW) acoustic sources and separate detectors. Stochastic considerations together with assumptions of the velocity profile allow to determine the mean velocity, but usually with quite poor accuracy for the volume flow rate. To improve the accuracy a spatial resolution can be realised with Pulse Doppler technique. This ADCP technique offers the determination of velocity profiles with spatial resolutions of some decimetres as typical minimum dimensions. Therefore it is mainly used in larger dimensions such as oceanography or river investigations. The cross correlation technique offers much higher accuracy for the velocity determination and also for the spatial resolution. It can be used for small dimensions because the spatial resolution may be as small as 1-2 cm. It will be described how the velocity profile can be fitted to a modified log law resulting in a complete velocity information along the ultrasound measuring path. To measure in larger dimensions too, chirp coded pulse is used. This technique is therefore applied for larger sites with the demand for high accuracy.

In sewer networks, the velocity determination is not the main objective but the flow rate evaluation. It will be explained how the velocity information is used to result in an accurate flow rate. This is realised by use of a grid measurement.

# 2 DETERMINATION OF VELOCITY PROFILES

To use the acoustic Doppler effect for velocity and flow rate measurements of water and wastewater in pipes, open channels and water courses a minimum pollution is required. The measuring principle is based on the echo technique; in fact the velocity of small particles or air bubbles is measured. Generally this is a good approach as this velocity is the same as the flow velocity. To understand the differences between Doppler, pulse Doppler and cross correlation devices a short description of the technical realisations is given. It is also explained how the cross correlation technology can be extended to measure in larger dimensions as well. First test applications confirm the applicability of this approach.

## 2.1 Ultrasonic echo devices

There are many simple ultrasonic devices on the market for flow rate measuring. These normally use continuously working piezo-ceramic electric sensors and separate detectors (Teufel 2004). The detector measures the reflected ultrasonic echo of scattering particles; i.e. air bubbles or any solid particles. These devices are used for flow rate measurements; the measured velocity is used to calculate the flow rate. Due to lack of spatial resolution this velocity is not the mean velocity; the achievable accuracy as flow rate meter is quite poor.

To obtain spatial resolution too, short pulse bundles are sent into the medium. This kind of sensor does not require a separate detector; only one sending and receiving ceramic is used normally. Knowing the sound velocity *c,* it is easy to determine a spatial resolution (*l* = distance to the detector) by measuring the time *T* between sending and receiving the echo. This can be seen in picture 1.

$$l = \frac{c \cdot T}{2} \qquad (1)$$

Usually the echoes are gathered in time frames resulting in spatial windows which are used to determine velocity. This principle is shown in picture 1 too. The direct measurement of the Doppler shifted frequency $f_s$ considering $v$ as particle velocity is difficult:

$$f_s = \frac{f \cdot c}{c - 2 \cdot v \cdot \cos\alpha} \qquad (2)$$

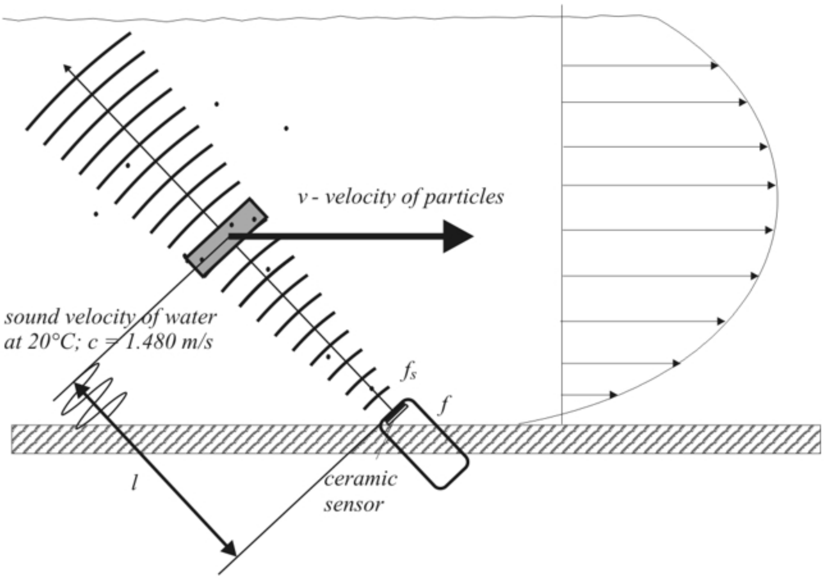


Figure 1: Doppler system

Some numbers may explain this: for a sending frequency of 1,000,000 Hz the typical shift is about 100 to 1,000 Hz. It hence is more difficult to accurately determine this frequency directly than overlapping the echo frequency with the basic frequency and determining the beat frequency $\Delta f = (f_s - f)$ . The resulting formula is:

$$v = \frac{(f_s - f) \cdot c}{2 \cdot f \cdot \cos\alpha} \tag{3}$$

Picture 2 shows the beat frequency

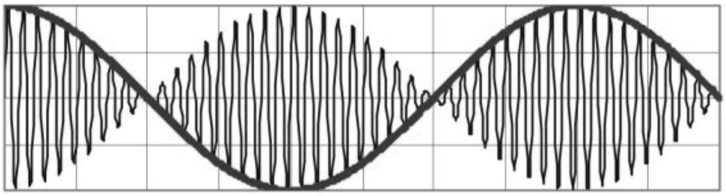


Figure: Beat frequency

The determination of the beat frequency is possible only if there are enough cycles of the basic frequency within the beat frequency. Due to this, the spatial resolution of this Doppler devices is restricted to a minimum of typically 0.30 to 0.40 m. Usually an easy frequency determination is implemented; it is calculated indirectly by measuring the time between the zero crossings of the beat frequency. This measurement fails at low velocities and it becomes impossible at 0 m/s, where the corresponding frequency is 0 Hz, too ($1/T \to \infty$).

## 2.2 Cross correlation technology

Correlation is more and more used as a mathematical tool for flow rate measuring especially for signal evaluation since fast and powerful microprocessors have become available. Used in stand-alone flow rate meters, it is meanwhile used for measurements in two-phase fluids, too. Picture 3 describes the measuring principle schematically.

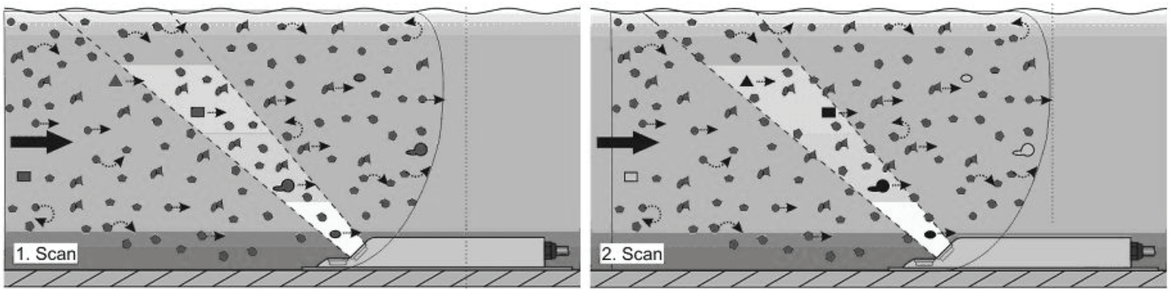


Figure 3: Acoustic cross correlation method

The picture shows the cross correlation sensor of the NIVUS OCM *Pro* CF (Teufel 2006). This acoustic sensor at the bottom sends a short ultrasonic impulse into the water with an angle of 45° towards the flow direction. The sensor then receives the echoes of the flow field, dividing them into time frames which can be converted into spatial windows. After a fixed and known very short time a second impulse is sent into the water again. The echoes are sorted into the same time/spatial windows as for the first impulse. This two echoes are then correlated due to the basic equation:

$$\varphi_{f,g}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t)\cdot g(t+\tau)\, dt \tag{4}$$

or as digital expression:

$$\varphi(\Delta T) = \frac{\sum_{i=1}^{N} f_i \cdot g_i(\Delta T)}{\sqrt{\sum_{i=1}^{N} f_i^2 \sum_{i=1}^{N} g_i^2}} \tag{5}$$

with *f* = echo function of digital picture 1 ;*g* = echo function of digital picture 2

The cross correlation of both echoes allows to calculate the temporal movement in each window. Taking the flow direction angle and the time difference between the 2 echo pulses into account it is possible to calculate the mean velocity. The method offers a spatial resolution of the length of a discrete oscillation, but to achieve a better mean the minimum window length is set to about 0.01 m. The maximum size is variable and may reach up to 0.10 m. The velocity is calculated in 16 windows which are used to determine a velocity profile.

The velocity profiles in full filled pipes are well known and the flow rate determination is straightforward (Fiedler 1992). For part filled open channel flows an additional height measurement is required. Therefore the sensor additionally has an ultrasonic height sensor as well as a hydrostatic sensor. Using external sensors is possible too. The height value is used to define the window positions. Calculating flow rate from the velocity will be discussed later.

## 2.3 Chirp coding of ultrasonic pulses

There is one major limitation for cross correlation used by the OCM Pro CF. The maximum height in which velocities are measured is 1.00 m. For larger distances only empirical or numerical calculations can be used taking the measurements along the first meter into account. This limitation is caused by a de-correlation between the 2 impulses. Before the second impulse is sent into the water, all echoes from the first echo need to be collected in advance. Therefore the time between the 2 pulses is getting longer while the distance to the sensor increases. As the distance to the ceramics is growing, the intensity of the reflected echoes decreases due to the normal propagation of waves; this 2 effects lead to poorer correlation.

To improve measuring, ceramics with a larger diameter have been chosen. As a result the lower spreading angle keeps the intensity of the ultrasonic beam higher. This first step discards explosion requirements (ATEX); with more ultrasonic power the intensity problem of the echoes could be ignored. Reducing the time between the two impulses is more difficult. We finally decided to use a chirp coding of the “normal” ultrasonic burst:

$$U = U_0 \cdot \sin(\omega \cdot t) \tag{6}$$

where $U$ is the amplitude of the ultrasonic wave, $\omega$ the frequency and $t$ the time. For chirp coded signals the frequency $\omega$ is not longer a constant but depending on time. A linear chirp e.g. utilizes $\omega = \omega_0 + k \cdot t$ with $k$ as a constant. We did not consider other chirps, thus as exponential. Picture 4 shows linear up and down chirp coded impulses in comparison to a "normal" impulse:

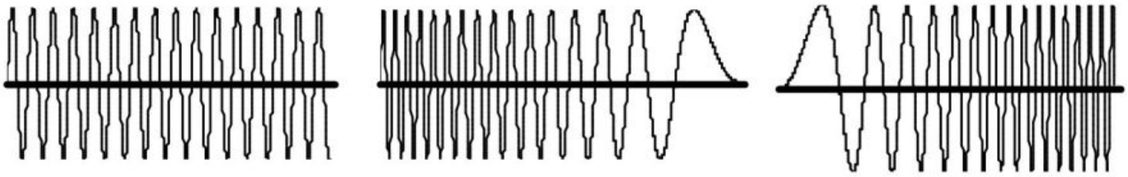


Figure 4: "Normal" burst, up-burst, down-burst

To use chirps, ceramic oscillators are required which can be induced to oscillate in a larger frequency range. Under ideal conditions the 2 bursts are orthogonal and do not interfere with each other. Of course the filter has to be dynamic, too; but this is quite easy to realise with digital filters. The ideal orthogonally is not possible and also disturbed due to the interaction of the ultra sonic impulse in the $3/4 \cdot \lambda$ coupling plate and in the water. Beside the good correlation of this pulses a higher energy can be involved with larger bursts. This results in larger distances that can be measured.

## 2.4 Test measurements

Before we started field tests the instrument has been investigated in our test lab. Of course we were not able to have flow heights of several meters but we modified our normal channel to check the reading of the device. In picture 5 you can see a sketch of the setup.

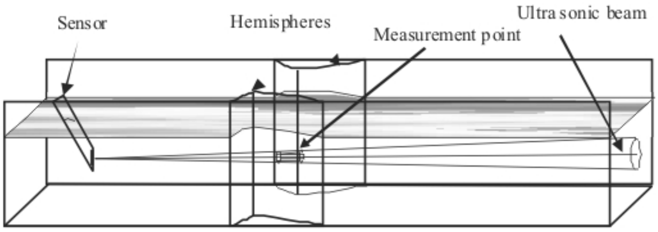


Figure 5: Sketch of the test in our lab

The dimensions of our standard channel are 0.347 m x 0.70 m x 10 m. The sensor was installed to measure along the channel, with a measuring path length of approx. 10 m. The width of the channel could be reduced to around 0.25 m by using two small half-shells which were movable along the complete channel to modify velocities along the measuring path.

This simple test showed an excellent accordance between the velocity measurements of the instrument and the installed reference of the test rig. Other successful applications meanwhile indicate the potential of the instrument. The applicability in different degrees of pollution e.g. covers a range from very high pollution in the influent of the waste water treatment plant of London up to very clean water in the effluent of the waste water treatment plant of Hamburg.

# 3 CONVERSION TO VOLUME FLOW RATE MEASUREMENTS

The volume flow rate determination by ultra sonic cross correlation technology is based on the continuity equations. A description of the velocity field has to be based on the realistic flow profiles. For each measurement along an ultrasonic path a realistic evaluation of the velocity field through a section and the water area itself is necessary to obtain an accurate flow rate. Knowing the open channel flow of course is essential to propose a mathematic function to describe the involved phenomenon.

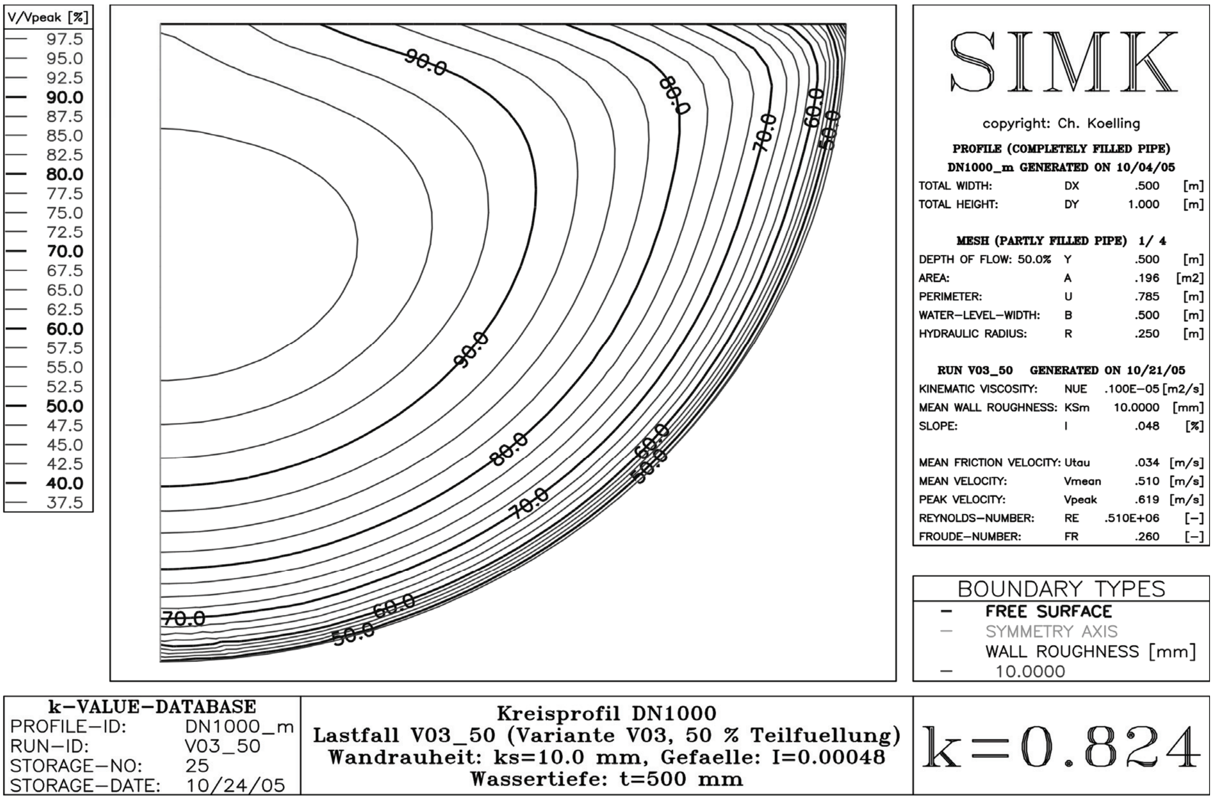
## 3.1 Velocity profile along the ultrasonic beam

The open channel flows in sewer networks present complex characteristics which dramatically influence the velocity field. It has been pointed out that there is a presence of secondary currents for this type of flow (Tominaga 1989). The secondary current strongly influence the water surface like a break which involve that the maximum must not be completely on the water surface but may be deeper resulting in a dip-phenomenon.

This thematic is not new and different description of formula have been given. This present document propose a experimental approach of the velocity profile which is easily applicable. The former investigations contribute to the establishment of an experimental function library. The function choice has been determined by numerical investigations. The CFD software used was SIMK developed by Kölling (Kölling 1994): it solves the Navier-Stockes equations for open channel flows using RSM (Reynolds Stress Model) as turbulence model, finite elements as discretisation scheme. The different investigations converge to a choice of the most appropriate function:

$$V_{1D}\left(\frac{z}{h}\right) = A \times \left(\frac{z}{h}\right) \times Ln\left(\frac{z}{h}\right) + B + C \times \left(\frac{z}{h}\right). \tag{7}$$

It has been verified that A, B, and C can be determined from cross correlation measurements.



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**PROFILE (COMPLETELY FILLED PIPE)**
**DN1000_m GENERATED ON 10/04/05**

| | | | |
|---|---|---|---|
| TOTAL WIDTH: | DX | .500 | [m] |
| TOTAL HEIGHT: | DY | 1.000 | [m] |

**MESH (PARTLY FILLED PIPE) 1/ 4**

| | | | |
|---|---|---|---|
| DEPTH OF FLOW: 50.0% | Y | .500 | [m] |
| AREA: | A | .196 | [m2] |
| PERIMETER: | U | .785 | [m] |
| WATER–LEVEL–WIDTH: | B | .500 | [m] |
| HYDRAULIC RADIUS: | R | .250 | [m] |

**RUN V03_50 GENERATED ON 10/21/05**

| | | | |
|---|---|---|---|
| KINEMATIC VISCOSITY: | NUE | .100E–05 | [m2/s] |
| MEAN WALL ROUGHNESS: | KSm | 10.0000 | [mm] |
| SLOPE: | I | .048 | [%] |
| MEAN FRICTION VELOCITY: | Utau | .034 | [m/s] |
| MEAN VELOCITY: | Vmean | .510 | [m/s] |
| PEAK VELOCITY: | Vpeak | .619 | [m/s] |
| REYNOLDS–NUMBER: | RE | .510E+06 | [–] |
| FROUDE–NUMBER: | FR | .260 | [–] |

**k–VALUE–DATABASE**

| | |
|---|---|
| PROFILE–ID: | DN1000_m |
| RUN–ID: | V03_50 |
| STORAGE–NO: | 25 |
| STORAGE–DATE: | 10/24/05 |

**Kreisprofil DN1000**
**Lastfall V03_50 (Variante V03, 50 % Teilfuellung)**
**Wandrauheit: ks=10.0 mm, Gefaelle: I=0.00048**
**Wassertiefe: t=500 mm**

Figure 6: SIMK Modeling

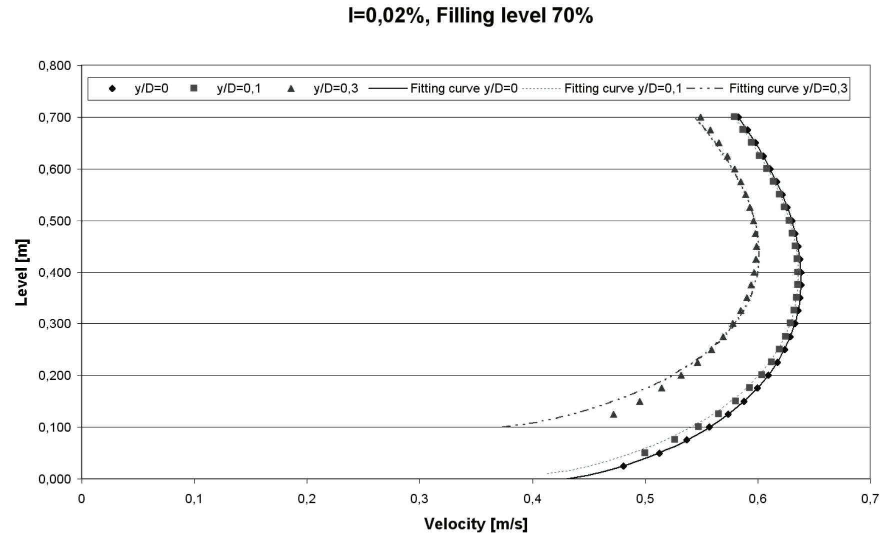

Figure 7: According curve to numerical values

The standard error between numerical value and fitting is lower than 2.5 % in each application. Special specifications to cross correlation technique have been realized to adapt this function to real measurement (Spatial-temporal integration of the function).

## 3.2 Determination of a grid measurement

To solve the flow equation, the establishment of a grid measurement is essential: this grid needs to be done with one or several sensors (beams). Main investigations on these topic describe fully developed conditions with exponential or potential approach. However, most of the considerations do not sufficiently take asymmetry into account. Asymmetry is an eternal problem in sewer networks. Bends, pipes arrivals are often presented in sewer systems. The equipment from these networks needs the recognition of the phenomenon. Indeed, these disturbances dramatically distort the 2D velocity profile. Bonakdari & Al (Bonakdari 2007) mentioned that 27×DN to arrive to fully developed conditions under some circumstances. As presented in the pictures 8 and 9, numerical investigations from us in collaboration with the FH Münster show that asymmetry due to a 90° arrival of DN 300 (full filled pipe) into a DN 700 (50% of filling) with the 25 % flow ratio is still present after 50×DN. From the facts, it is indispensable to take asymmetry into account by introducing additional sensors permanently and temporary.

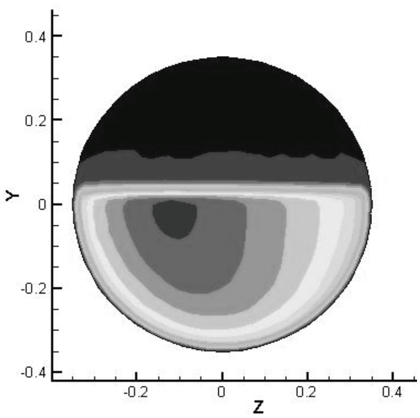

Figure 8: Velocity filed after 40DN

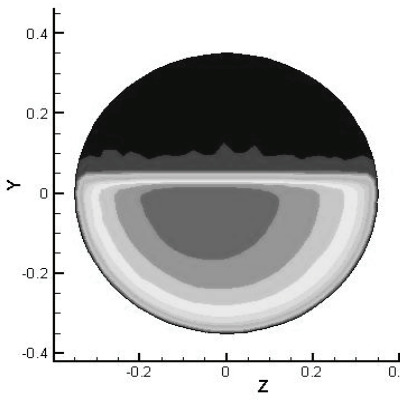

Figure 9: Velocity filed after 50DN

Moreover, the transversal adapted function to set up a grid measurement has to take into account this phenomenon. The appropriated function needs to consider wall conditions, ultra sonic beam characteristics and the number of sensors. The wall region determination has been inspired from shear stress investigation done by Yang (Yang 2005). With a simplified approach the wall region is considered and used for further flow rate determination. After further investigations a special polynomial approach has been chosen to describe the transversal flow profile.

$$V(z,y)=\sum_{i=0}^{n}A_i(z)y^i \tag{8}$$

It is obvious that the parameters $A_i$ can be calculated easily using a simple regression.

### 3.3 Flow calculation

The volume flow rate for sewer networks is defined by the equation $Q=\iint_S V(z,y)dzdy$ which corresponds to the resolution of the integral:

$$Q=\int_{z=0}^{z=h}\sum_{i=0}^{n}\frac{1}{i+1}A_i(z)\left(\left(\frac{B(z)}{2}\right)^{i+1}-(-1)^{i+1}\left(\frac{B(z)}{2}\right)^{i+1}\right) \tag{9}$$

The resolution of these integral can be done by using the standard techniques.

### 3.4 Initiation in lab conditions

Since 2003 NIVUS GmbH owns a test channel with dimensions 0.347m×0.7m×10 m. The flow in the channel is controlled by a certified electromagnetic device in a 250 mm full pipe. The channel has been equipped with several level measurements and three velocity sensors with equidistant spatial disposition. The following results present situation with a slope of 0.5% and a corresponding Strickler roughness of 110. The deviation of the flow rate in the range from 40 l/s to 120 l/s is about 0.5 %.
The measurements are carried out for stationary conditions. The following table presents the deviation from the electro magnetic reading for the flow rate measured with 1, 2 or 3 sensors connected to an OCM *Pro* CF.

| $Q_{MID}$ [l/s] | $Error_{MID}$ [%] | Error [%] 1 sensor | $\sqrt{(\rho-\rho_{01})^2}$ [%] | Error [%] 2 sensors | $\sqrt{(\rho-\rho_{01})^2}$ [%] | Error [%] 3 sensors | $\sqrt{(\rho-\rho_{01})^2}$ [%] |
|---|---|---|---|---|---|---|---|
| 40 | 0,5 | 1,31 | 0,97 | 0,70 | 0,81 | 0,78 | 0,71 |
| 60 | 0,5 | 0,96 | 0,78 | 0,71 | 0,61 | 0,67 | 0,53 |
| 80 | 0,5 | -0,41 | 0,32 | 0,01 | 0,28 | -0,21 | 0,22 |
| 100 | 0,5 | 0,50 | 0,24 | 0,30 | 0,26 | 0,82 | 0,21 |
| 120 | 0,5 | 0,42 | 0,11 | 0,26 | 0,22 | 0,71 | 0,19 |

Table 1: Error and standard deviation depending on the number of sensors

Of course, these results are done under lab conditions but demonstrate the high potential of the grid method. In sewer networks the conditions of installation and measurement are usually poorer and consequently these accuracy values in normal applications are higher. In addition the origin of the error of the model (important for sewer application) is not investigated even if they are identifiable (influence of the sensor to the flow field, very low level …). Consequently they will be the object of new investigations.

## 4 APPLICATION

Meanwhile the OCM *Pro* is used for many different applications. Especially in the influent to waste water plants there may be sedimentation in the channel. The sensor may still work at low sedimentation, but will finally fail. Secondly a wrong cross section, the complete big one is usually taken to calculate the flow rate. A float system (figure 9) can help to solve this problem. A wedge sensor is mounted below the float.

Figure 9: Float system using surfboards

An ultrasonic height sensor measures the sludge level to calculate the correct cross section. The velocity sensor measures from the surfboards to the bottom; there is no need to consider sedimentation, however grease is removed from time to time.

# 5 CONCLUSION

The cross correlation technology associated to a correct flow evaluation (in this situation grid measurement) gives accurate volume flow rate not only in small dimensions but also in large dimensions. However, it seems really important to respect in all applications the minimal distances after/before disturbances to take correctly the disturbances into account (measurable values). Moreover, the recognition of disturbance could only be done by installing a sensor with several beams or with several sensors, in a stationary or temporal way (minimum of representative events).

Of course, additional investigations need to be done to identify and to automatically correct systematic errors in order to optimise flow calculation.

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