Discussion of Installation Methods and Errors of Multipath Acoustic Discharge Measurements in Closed Conduits

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ABSRACT

It is widely accepted that ultrasonic flow measurement can provide an accuracy of up to ±0.5%. However, these accuracies can only be achieved if the installation of the flow meter is carefully executed. The installation error can influence the overall accuracy of the flow meter very strongly and depends on the skills of the installation crew and the surveying equipment used by the time the flow meter is installed. Very often the installation cost for a multipath flow meter can be as high as the cost of the flow meter itself. This article aims to compare four different installation methods for multipath acoustic flow meter and to discuss the installation errors caused by them.

2 REVIEW OF INSTALLATION METHODS

The installation and surveying of acoustic transducers can be reduced to a sequence of measuring length and angle in space. The aim of all the surveying methods are to define the position of the drilling point of the transducer in a conduit and to measure as accurate as possible all characteristic dimensions such as path length (L), path angles (φ), and diameter (D) (figure 1). In cases where variable weights are used according to OWICS [VOS], the elevation levels (d) or angular position (α) need also to be measured.

The **Tape Measure method** is extensively applied around the world. It is a straight forward method which uses only simple and inexpensive tools. The positions of the acoustic transducers are defined using steel tape measure and level. The first step for laying out the transducer drilling points is to define a common line which is parallel with the pipe axis at the 3 o'clock line and at the 9 o'clock line. From this, the 54° and the 18° lines are marked off. A cross section is defined from which the axial distance for the inner and outer transducers are marked. The intersecting points define the theoretical drilling points which have to be corrected in the axial and radial direction because the transducer is protruding into the flow. Since this method is restricted to length measurements only, various procedures have been developed to "square up the box" improving the accuracy on the path angles and elevation angles (figure 1).

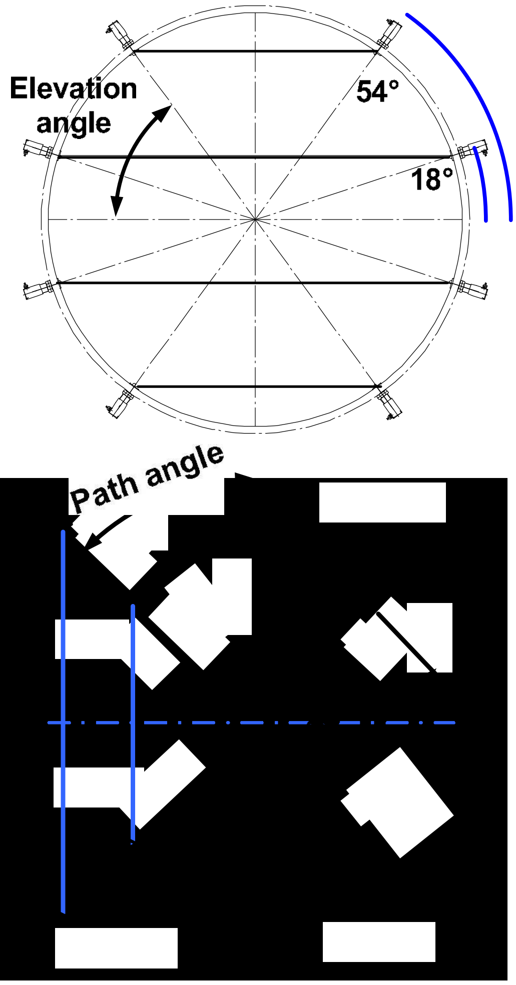

Figure 1: Typical multipath (8 path) arrangement of transducers in a circular conduit

Table 1 shows the measuring errors on the geometrical parameters which go into the integration formula of the flow rate calculation. The diameter and the path length are measured with a tape measure, or for smaller diameters with calibers, to an accuracy of ±0.1%. A total of 15 penstocks were resurveyed around the world with a total station theodolite in order to estimate the measuring errors on the elevation and the path angles. The standard deviation for the path angle was 0.3° and for the elevation angle 0.25°. For an uncertainty confidence interval of 95%, the total errors of path and elevation angle measurement are ±0.6° and ±0.5° respectively.

Diameter, D	Path length, L_i	Path angle, φ_i	Elevation angle, α_i
±0.1%	±0.1%	±0.6°	±0.5°

Table 1: Measuring errors on the geometrical parameters for the tape measure method

The advantage of the tape measure method is that only simple, reliable, and inexpensive tools are needed available all over the world. Further, no extensive training of the installation crew is necessary. The disadvantage is the missing accuracy on the path angles and the elevation angles.

For the installation of ultrasonic transit time flow meters according to IEC 41 or ASME PTC 18 2002 standard [IEC, ASME], more accurate surveying instruments are typically used. Over the past two decades, different methods have been developed all of them facilitating a precise surveying instrument. The most traditional and widely used method was introduced by Accusonic Technologies, USA, which facilitates a mechanical theodolite. In the late 1990's at the Swiss Federal Institute of Technology (ETH) in Switzerland, a method was developed based on two motorized mechanical theodolites as part of a dissertation. This system was used only in a few applications. Rittmeyer AG, Switzerland, developed in the late 1990's a method based on a total station theodolite. This method has been used in several dozens of applications.

The **mechanical theodolite method** is a surveying method which is based on a mechanical theodolite (which can measure angles only), steel tape measure, and auxiliary material. The basic concept is to set up the theodolite in such a way that the theoretical transducers locations 4 are symmetrically arranged around it. The mechanical theodolite is roughly placed midway between the transducers upstream and downstream. The first task is to align the line passing through the lens, such that it coincides with the center line of the conduit. This is accomplished by placing two pieces of paper targets on both ends of the metering section with help of wooden boards. The centre point on each side is found by swinging an arc eight times 1. The theodolite is now placed so that the two centre points creating the centre line of the conduit is passing through the lens of the theodolite. The theoretical transducer positions are located by horizontal and vertical swing angles 3. Because the acoustic transducer is protruding into the conduit, a correction in axial and radial direction is applied 5. The theodolite is removed for the installation of the transducers. For the final measurements the theodolite is set up at the same place, and the as-built are measured. The path length L and the diameter D are measured with the tape measure. According to the procedures of Accusonic Technologies, the radius is measured eight times originating from the centre of the paper target 1 on both sides of the metering section. The average of the sixteen measurements defines the diameter of the conduit. The path as well as the elevation angles are measured with the theodolite.

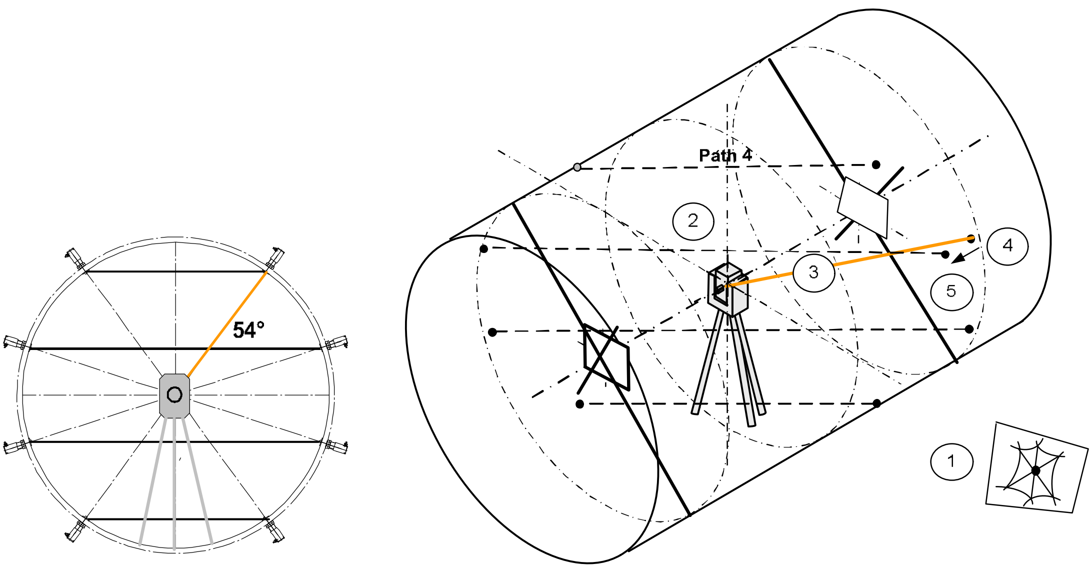

Figure 2: The schematic of an installation set up with a mechanical theodolite

The measuring errors for the diameter D and the path length L are the same than for the tape measure method. The angle measurement error is within ±0.1° which is due to the ability to set up the theodolite on the true conduit centre line.

Diameter, D	Path length, L_i	Path angle, φ_i	Elevation angle, α_i
±0.1%	±0.1%	±0.1°	±0.1°

Table 2: Measuring errors on the geometrical parameters for the mechanical theodolite method

The advantage of this method is that still rather simple tools are used, and therefore the probability of failure is very small. Compared to the tape measure method, the use of a theodolite is a very good enhancement since it allows measuring the angles precisely. The application of this method does not require extensive training of the installation crew. One of the disadvantages is the time used and the number of people required to set up the theodolite. For larger conduits or conduits with a very steep slope as shown in figure 4, elaborated scaffolding is needed to position the theodolite and the paper targets on both sides of the centerline. A Further disadvantage is that this method requires having access to the inside of the pipe.

The **total station theodolite method** is based on a total station theodolite. A total station theodolite has an integrated distance meter which allows measuring the distance to a target point. The accuracy of the angle measurement is ±5 seconds; the distance measurement is ±0.5mm. The tools required are a total station theodolite, a laptop to carry out the calculations, and several reflecting targets.

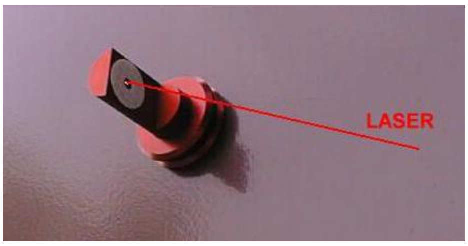

Figure 3: Reflecting target, showing the laser beam pinpointing the transducer location

The total station theodolite is set up before or after the metering section at any location inside or outside of the conduit. The first task is to mathematically define the exact shape of the conduit. This is done by measuring the coordinates of 40 reflecting targets placed on the surface of the conduit and fitting them to a mathematical shape describing an elliptical cone by using least square fitting and Taylor development [COO]. Based on the shape of the conduit, the x-y-z coordinates of the acoustic transducers are calculated already including the correction in axial and radial direction due to protrusion of the sensors. The integrated laser pointing system allows pinpointing all locations of the drilling points for the transducers. If necessary, the theodolite is removed and the transducers are installed. For the as-built measurement, the theodolite is placed back into working position with help of five reference points. The x-y-z coordinates of the acoustic transducer are measured and then the path length L, the path angles φ, and the path distances d are calculated. The diameter D of the conduit is derived from the shape of the conduit.

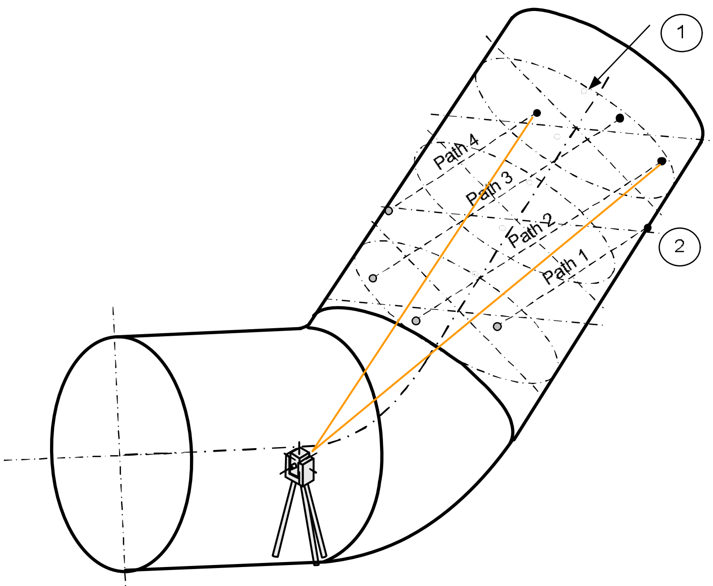

Figure 4: The schematic of an installation set up with a total station theodolite

Even though the total station theodolite is capable of measuring the angles and the length very precise, the ability of the reflecting targets to represent the true point is defining the measuring errors. The measuring error on the diameter D and the path length is ±1mm, or is in the worst case ±0.1%. The path angles and the elevation angles can be measured to within ±0.05°. Interesting to note is that with a total station theodolite, the measuring errors are greatly improved for larger diameters. As an example, for a 1m in diameter the measuring errors are ±0.05° for the angles and ±0.1% for the length, but for 2m in diameter the measuring errors will be ±0.022° and 0.05% respectively.

Diameter, D	**Path length, L_i**	**Path angle, φ_i**	**Elevation angle, α_i**
±0.1%	±0.1%	±0.05°	±0.05°

Table 3: Measuring errors on the geometrical parameters on the total station theodolite

The advantage of the total station theodolite method is that the theodolite can be set up at any location inside or outside of the conduit which is very beneficial for large conduits or conduits which have a steep slope. The set up procedure is fast and only one person is needed. The disadvantage is that a total station theodolite is expensive and is not readily available all over the world. The handling of the theodolite requires advanced training.

The **"ETH method"** requires two mechanical motorized theodolites measuring angles very precisely and a personal computer. One of the theodolites is equipped with a laser pointing system. Both theodolites are remotely controlled. The basic concept of this system is rather simple. If a point in space is targeted from two theodolites 3 with known locations in the conduits coordinate system, the x-y-z coordinates of this point can be calculated based on three measured angles. Two remotely controlled theodolites are set up before and after the metering section. At the beginning, the unknown coordinate system of both theodolites with respect to each other is determined by calibrating the theodolites with the calibration bar 1 with a known distance from pin to pin. The calibration is needed to define the distance between the theodolites in space. With the application software, the geometry of the conduit is scanned with up to 240 points semi automatically 2. This data are then least square fitted to a cylinder and the coordinate systems of the theodolites are transferred into the coordinate system of the conduit. The rather elaborated calculations are performed by a personal computer. Similar to the total station theodolite method, the x-y-z coordinates of the acoustic transducers are calculated but already including the correction in axial and radial direction. The laser pointing system locates the drilling points of the acoustic transducers. The theodolites are removed for the installation of the transducers. After this, the theodolites are set up roughly at the same position and calibrated into the conduits coordinate system, with help of some reference points. The x-y-z coordinates of the transducer locations are measured and the as-built of the geometrical parameters are calculated by the application software.

The measuring errors on the geometrical path parameters and the diameter are in the same range than for the total station theodolite method. Even though the theodolite measures the angles very precisely, the uncertainty comes from the ability to calibrate the two theodolite to each other and the ability to pinpoint the target points. The advantage of the ETH method is that the systems can be set up fast and the geometrical parameters are measured very accurate. The disadvantage is that a lot of equipment is needed which is very expensive, and it does not allow for external surveying as with the total station theodolite. The handling of the theodolite and the application SW requires advanced training.

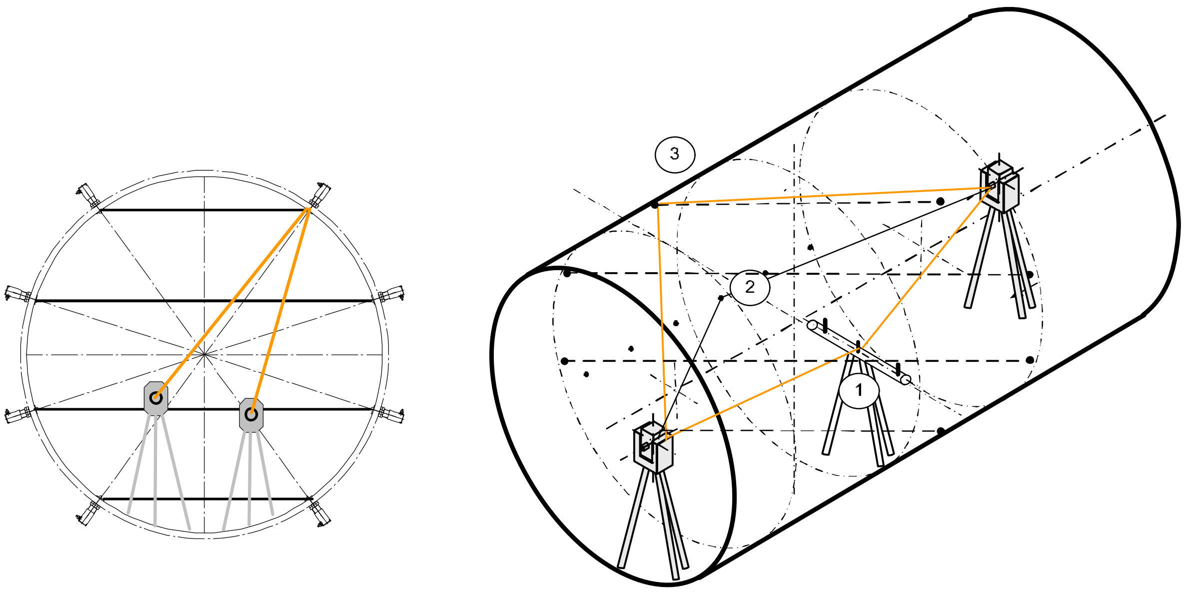

Figure 5. The schematic of an installation set up with two motorized mechanical theodolites

3 INSTALLATION ERRORS

The uncertainty of an acoustic discharge measurement is the sum of errors from different sources and can be divided into; 1) installation errors, 2) integration errors, and 3) instrument errors.
The instrument errors are designed into the flow meters processing unit by the manufacturer and are essentially defined by the error on the determination of the transit times. The integration errors are influenced by the velocity distribution, the presence of secondary flow profile, and the applied integration technique. The protrusion effect can also be added to the integration error because the transducer alters the flow around it. The out of roundness of a penstock can introduce further errors on the integration but it can be neglected for out of roundness of less then 1%.
The installation errors can be characterized as the errors on the geometrical path parameters ΔLwi, $\Delta\varphi$, Δdi and the cross section measurements ΔD. At this point, it should also be noted that when the flow meter is in operation, further errors on the geometrical path parameters and diameter can be caused by reversible deformation of the conduit due to the change in internal pressure and change in ambient temperature. A change in temperature will cause to change the diameter of the conduit but for normal conditions it can be neglected. The change in diameter due to the internal pressure should only be considered if the radial expansions is not hindered for instance by stiffening rings, saddles etc. The weight of the water between to saddles can cause further errors, but it can be neglected under normal condition [VOS].
Characteristic for the installation errors is that by using modern surveying tools they can be defined and accounted for. But often the tools and the know-how are not available, and therefore these errors have to go into the instruments systematic error. The installation error is strongly influenced by the skills and know-how of the installation crew and the surveying equipment used. These errors are determined at the time the acoustic paths are installed.

The influence of the angular position di of the transducer is studied by using numerical simulation on the angular path misalignment. Voser [VOS] has shown that for a path misalignment of 0.5° and 1.0° for the outer path, at the 54° angular position, a systematic error of 0.2% and 0.32% respectively will be introduced and for the inner path, at the 18° angular position, a systematic error of 0.12% and 0.26% respectively. Installation errors can be studied by analyzing the influence of the geometrical parameters Lwi, φi, D in the quadrature integration formula (2).

Systematic errors of a function F(x1, x2,….xn) with respect to measuring errors in x1,x2,….xn can be determined in a first approximation by a linearization [HEI].

$$\text{relative systematic error } e_{\text{rel}} = \frac{\Delta F}{F_0} = \frac{F - F_0}{F_0} = \frac{1}{F_0} \sum_{k=1}^{n} \left(\frac{\partial F}{\partial x_k} \right)_{F_0} \Delta x_k$$

$$x_k = x_{k,0} + \Delta x_k \qquad \text{k} = 1,..,\text{n}$$

For worst case analysis, which produces a "conservative" error figure, all terms have to be taken positive and for the Δxk's the maximal possible values have to be chosen. To note is that the statistical error of a function can also be described by the Gaussian error propagation law which might produce a more typical value. But since many of the error sources are systematic, the favored approach is to use the "worst case" result, particularly where accuracy guarantees are important. Discharge through the conduit is determined from integration of individual path readings, resulting in an equation which sums up the weighted path readings. Usually the integration for a multipath acoustic flow meter is performed according to IEC 41 appendix J [IEC].

$$Q = k \cdot \frac{D}{2} \sum_{i=1}^{N} W_i \cdot \bar{v}_{axi} \cdot L_{wi} \cdot \sin \varphi_i \tag{2}$$

The mean axial velocity along the acoustic path i is given by the well known formula

$$\bar{\text{v}}_{\text{axi}} = \frac{\text{L}_\text{i}}{2\cos\varphi_\text{i}} \left(\frac{1}{\text{t}_\text{d}} - \frac{1}{\text{t}_\text{u}} \right) \tag{3}$$

The relative systematic error can be expressed with the following formula.

$$\frac{\Delta Q}{Q} = \frac{\frac{1}{D}\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{\text{t}_{\text{di}}} - \frac{1}{\text{t}_{\text{ui}}} \right) \cdot L^2 \tan\varphi_i \Delta D + 2\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{\text{t}_{\text{di}}} - \frac{1}{\text{t}_{\text{ui}}} \right) L \cdot \tan\varphi_i \cdot |\Delta L_{wi}| + \sum_{i=1}^{N} W_i \cdot \left(\frac{1}{\text{t}_{\text{di}}} - \frac{1}{\text{t}_{\text{ui}}} \right) \cdot L^2 (1 + \tan^2\varphi_i) |\Delta\varphi_i|}{\sum_{i=1}^{N} W_i \cdot \left(\frac{1}{\text{t}_{\text{di}}} - \frac{1}{\text{t}_{\text{ui}}} \right) \cdot L^2 \tan\varphi_i}$$

Calculating the transit times by means of a velocity profile given by Nikuradse [NIK], the influence of each parameter can be analyzed. Figure 6 shows the relative systematic error on the flow rate for measuring errors on the diameter ranging from 0.1 mm up to 10.0 mm. For example, in a 7 m diameter conduit the accuracy for this measurement must be 5mm to insure a relative systematic error of less than 0.1%. However, in a 1m diameter conduit the measurement error must be better than 0.5mm to reach the same relative systematic error.

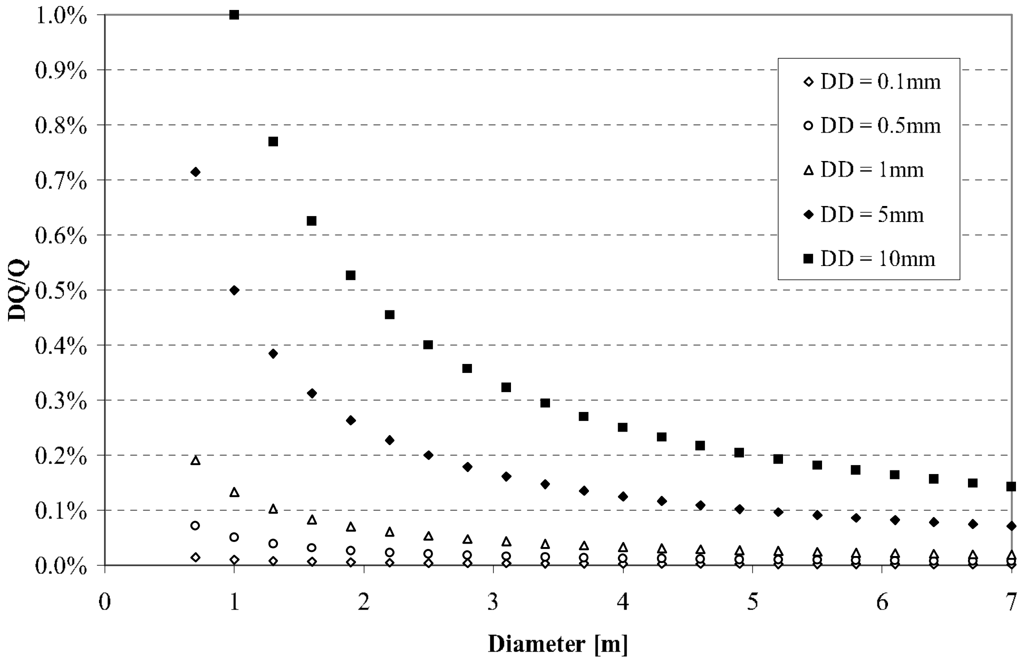

Figure 6: Influence of diameter measuring errors on a four path system flow meter

Figure 7 shows the relative systematic error on the flow rate for different measuring errors in the path length measurements. Both graphs show clearly that for larger conduits carefully conducted tape measurements will be sufficient. But for smaller diameters, machine shop gauges are required.

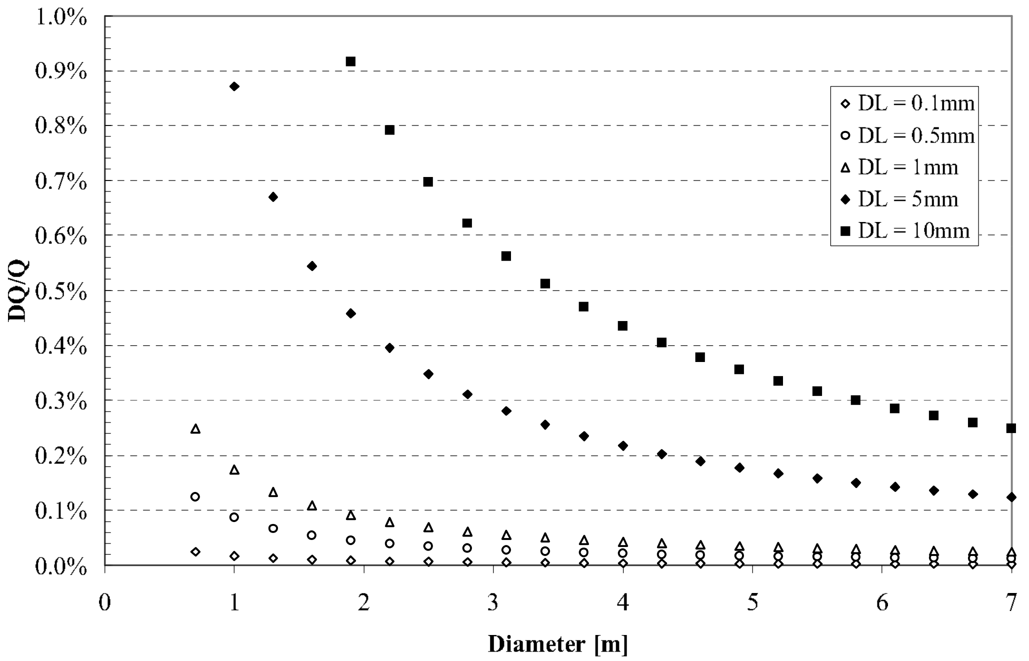

Figure 7: Influence of path length measuring errors on a four path system flow meter

The path angle measuring errors, shown in table 4, indicate that they have a large influence on the relative systematic error on the flow rate. For the full range of velocities and conduit diameters, a measuring error of 0.1° introduces a relative systematic error of 0.35% for path angles at 45°. But for path angles at 60°, the same measuring error of 0.1° causes a relative systematic error which is considerably higher.

Δφ[°]	**0.01°**	**0.05°**	**0.1°**	**0.5°**	**1.0°**
ΔQ/Q (φ=45°)	0.03%	0.17%	0.35%	1.7%	3.49%
ΔQ/Q (φ=60°)	0.05%	0.27%	0.54%	2.69%	5.37%

Table 4: Relative systematic errors for measuring errors on the path angles

The relative systematic errors on the flow rate for the different installation methods are listed in table 5. The ETH Method has not been listed separately because the measuring errors are comparable to the total station theodolite method. For all methods, the relative systematic errors for the diameter and for the path length are comparable. Even with very simple tools such as a tape measure good results can be achieved. For larger conduits, the total station theodolite method becomes more precise since the measuring errors on the length and angle measurements are independent of the conduits diameter. Yet, the mechanical theodolite method will not improve the measuring errors because of the more elaborated scaffolding needed to set up the theodolite and the paper targets on both sides of the metering section. The path angle and the elevation angles are the two parameters which distinguish the installation methods. Obviously, the tape measure method's shortcoming is the inability to lay out the transducers location at their specified location. The total worst case relative systematic error on the flow rate for the tape measure method is about ±2.72%. The mechanical theodolite and the total station theodolite method show a total relative systematic error of ±0.76% and ±0.53%, respectively. A more realistic value is shown in the parenthesis which is calculated according to the Gaussian error propagation law.

	Tape Measure	Mechanical Theodolite	Total Station Theodolite
Diameter, D	±0.10%	±0.10%	±0.10%
Path length, Li	±0.18%	±0.18%	±0.18%
Path angle, φi	±1.80%	±0.35%	±0.17%
Elevation angle, αi	±0.64%	±0.13%	±0.08%
	±2.72% (±0.96%)	±0.76% (±0.23%)	±0.53% ±0.18%)

Table 5: Summary of relative systematic errors

The as-built of the diameter, path length, and the path angle can be accounted for in the basic equations (2, 3). But the as-built of the elevation angles can not be accounted for unless as-built weighting coefficients according to OWICS [VOS] are facilitated. But both standards, the IEC 41 and the ASME PTC 18 2002 call for fixed weights which assume that the transducers are installed precisely at the theoretical defined angular position and do not allow for the use of the as-built weighting coefficients W_{iOWICS}. The tape measure method can only be improved if a total station theodolite is used for resurveying the existing location of the transducers. If it has to comply with the IEC 41 or the ASME PTC 18 2002 standard, the worst case total relative systematic error will add up to ±1.09%. If the as-built weighting coefficients according to OWICS can be used, then the worst case total relative systematic error will be as low as for both of the theodolite methods.

4 CONCLUSION

The tape measure method is a simple fast method for installing the transducers. Yet, this method does not provide the needed installation accuracy according to IEC 41 or ASME PTC 18 2002 unless it is resurveyed with a total station theodolite and OWICS can be facilitated. For accurate installations according to IEC 41 or ASME PTC 18 2002, both theodolite methods are sufficient. From a practical point of view, the mechanical theodolite method is a good choice for "well behaved pipes" and the total station theodolite method is a good choice for large and or steep pipes. If the penstock has to be surveyed from the outside because of minimizing the cost on the internal scaffolding or because the down time of the penstock has to be kept to a minimum, the use of a total station theodolite is certainly the best choice.

6 NOMENCLATURE

D	diameter	(m)
di	elevation level for path i	(m)
i	number of the acoustic paths	(-)
k	correction coefficient	(-)
Li	distance in the fluid between the transducer faces	(m)
Lwi	distance from wall to wall along the acoustic path i	(m)
N	number of the acoustic paths in on plane	(-)
Q	flow rate	(m3/s)
td	transit time of the acoustic pulse traveling downstream	(s)
tu	transit time of the acoustic pulse traveling upstream	(s)
vaxi	mean axial flow velocity along the path i	(m/s)
Wi	weighting coefficients for path i	(-)
W_{iOWICS}	as-built weighting coefficients for path i	(-)
αi	angular position for path i	(°)
ΔD or DD	measuring error on diameter	(m)
ΔL or DL	measuring error on path length	(m)
ΔQ/Q	relative systematic error on flow rate	(%)
Δφ	measuring error on path angle	(°)
φi	path angle between the axis of the pipe and the acoustic path	(°)

8 REFERENCES

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International Standard CEI/IEC 41, Third Edition 1991-11

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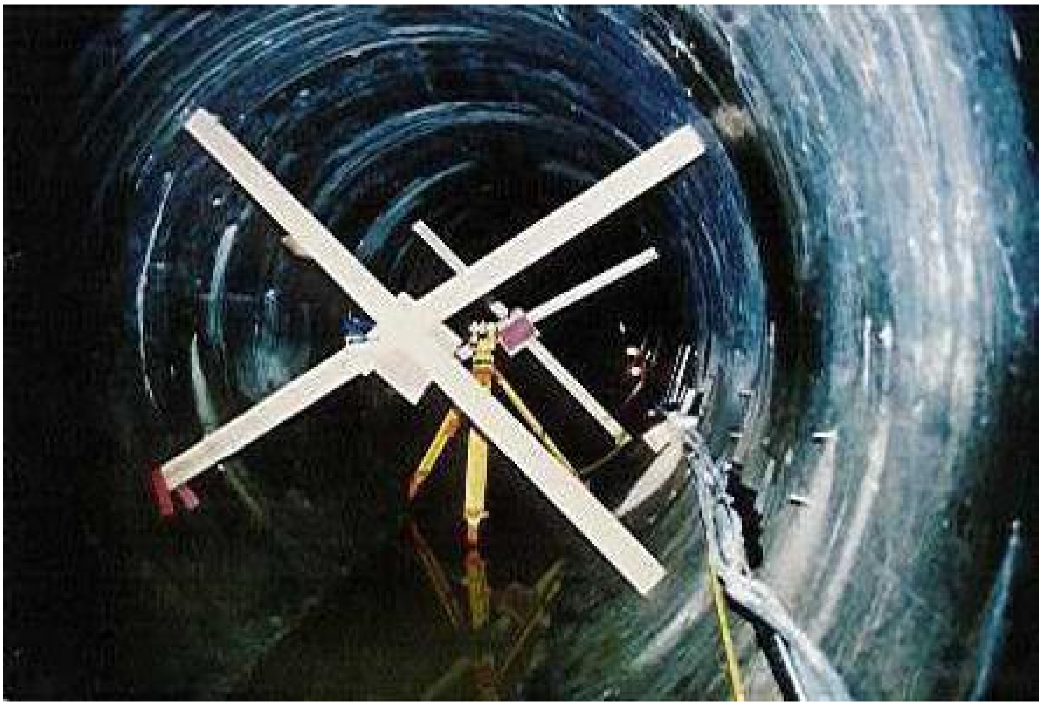
7 APPENDIX; APPLICATION PICTURES



Picture 1: Typical set up for the mechanical theodolite method (courtesy of Accusonic Technologies, Jim Walsh)

Picture 2: External surveying, typical set up for the total station theodolite method

Picture 3: Internal surveying, typical set up for the total station theodolite method