Operational experience with liquid ultrasonic meters

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1 Abstract

Statoil have 8 to 12 years experience from several metering stations using liquid ultrasonic meters:

- One metering station comprising two ultrasonic meters in series operated on a very light condensate at inlet separator conditions (Operated at very low flow rates).
- One metering station comprising two ultrasonic meters in series and a prover used to measure low viscosity fluid at inlet separator conditions.
- One metering station comprising one ultrasonic meter with a turbine master meter which is calibrated on site using a compact prover at a yearly interval
- One metering station comprising one ultrasonic meter with an ultrasonic master meter which is calibrated on site using a compact prover at a yearly interval using a turbine meter as calibration transfer.
- One export metering station with five metering runs and a bidirectional prover used for high viscosity crude at a stable flow rate
- One metering stations comprising two ultrasonic meters in series and a prover used for high viscosity crude.

The company experience with liquid ultrasonic meters will be investigated.

For allocation metering stations large cost reductions could be realized by utilizing a design with two liquid ultrasonic meters in series and by omitting a prover. The cost reductions in project phase can be realized by omitting valves, prover and parallel metering tubes thereby reducing weight and space requirements and the total number of items representing a cost. In operation phase, duplication of all instruments will have a great value for monitoring purposes and can be used to increase calibration intervals. The costs related to maintenance of valves will also vanish.

The company experience with liquid ultrasonic meters is evaluated in order to quantify long term reliability, stability and reproducibility. An estimate of uncertainty for a design with two liquid ultrasonic meters in series without a prover will be provided.

2 Introduction

Many of the liquid metering stations built by Statoil these days are allocation metering stations to be installed at offshore facilities. Many of these metering stations have to be fit into an existing facility. For existing facilities there are normally strict limitations on available space and sometimes weight. Even for metering stations to be installed at new facilities it is of great importance to reduce weight and space requirements.

For many of these metering stations the pressure is so close to the vapour point that a prover will not be feasible without a pump to increase the pressure. Due to cost, space and weight constraint it is often not feasible to install a pump in the line.

For allocation metering, the measurement regulations of Norwegian Petroleum Directorate, Comments to §4, opens up for used of simplified metering stations when there is a cost disproportion between a conventional system compared to a simplified system.

A significant simplification which reduces weight and space requirement is to omit the prover and replace it by a master meter. An even greater simplification which greatly reduces weight and space requirements is to install two meters in series and omit both prover and master meter in a separate by-pass.

Operational experience with liquid ultrasonic meters

In this paper we look at the experience with liquid ultrasonic meters to quantify reliability, stability and reproducibility with the objective of quantifying the uncertainty of a metering station with two meters in series without a master meter or prover in a by-pass loop.

3 The concept of a metering station with two meters in series

Since the late 1990's Statoil has built many gas metering stations for allocation comprising ultrasonic gas meters in series. Based on the experience with such metering stations this is now the preferred metering concept.

Typically such a metering station consists of two flow meters in series and a duplicated set of all other instruments as shown in Figure 5.1-1.

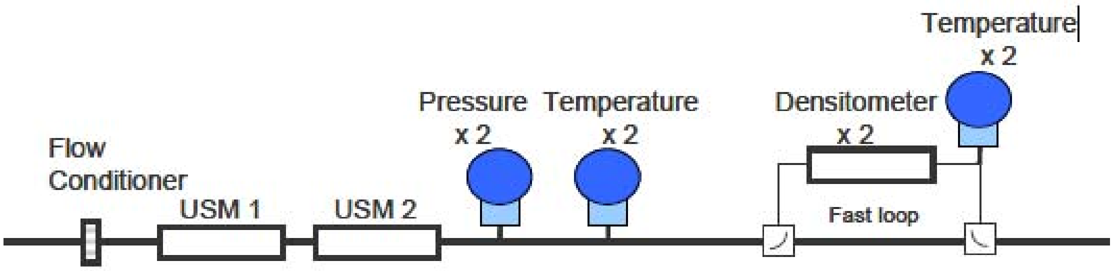


Figure 5.1-1 Metering station with two meters in series

The metering station has a hot stand by solution as two independent set of measurement results are provided on a continuous basis. Each set of measurements are based on a separate set of instruments.

The calibration frequencies for pressure, temperature and density transmitters are significantly reduced due to excellent possibilities for condition monitoring and excellent stability of the instruments. Statoil is now allowed to perform full calibration (accredited) of one instrument for each parameter (pressure and temperature) every 3 years. This is allowed under the condition that the deviations between the instruments are continuously monitored. It is also required to perform a control of the deviation between two instruments towards strict limits after 1.5 years. Reduction of calibration interval is allowed for under the Norwegian Petroleum Directorate regulation ref. “the measurement regulations” section 26.

The regulation requires the operator to monitor condition parameters of the gas ultrasonic flow meter and only requires the operator to recalibrate the flow meter if the meter has a poor maintenance history. Ref. The measurement regulation - section 25.

There are no metering valves in the system. Hence all direct and indirect project and operational costs related to valves vanish.

Most faults are easily identified by deviation between duplicated measurements. Experience has shown that it is often easy to perform fault finding with this metering configuration. Effective fault finding is based on setting up a list over potential causes for the symptom you see (hypothesis) and thereafter trying to falsify the hypothesis in a prioritized order. The duplicated set of measurements readily provides the measurements needed to falsify many of the different hypotheses you normally come up with.

Experience has also shown that this metering configuration is reliable.

4 Risks of a metering station with two meters in series

If we anticipate a metering station with:

- Two liquid ultrasonic meters in series
- No parallel meter runs
- No prover or master meter
- Two flow meters which are only replaced for calibration if they have a poor maintenance history.

This metering concept represents an increased risk over a conventional liquid metering in two main aspects:

1. Risk for shut down of production to perform maintenance or calibration.
2. Risk for monetary loss due to uncertainty of the meter factor of the ultrasonic meters.

As there are no parallel metering run, the flow will have to be shut down to inspect or clean the line or to replace a meter for calibration or maintenance

The ultrasonic flow meters are vulnerable to deposits. The risk should be considered to be considerable if a continuous measurement is required, a shut down will represent a monetary loss and the process fluid may give off deposits like wax or scale. Such conditions will have to be dealt with in the design of the metering stations.

It is important to be aware that in the upstream area the pressure is normally so high that double block and bleed is required. To meet this requirement it may be required to install to fully independent valves and a bleed between the valves. We have also experienced that the requirements for double block and bleed functionality for maintenance has become stricter over the years and that valves earlier accepted as having double block and bleed functionality no longer is accepted.

Risk for shut down for maintenance or to recalibrate a meter will depend on the reliability and long term stability of the ultrasonic meters. In later sections of this paper the experience with liquid ultrasonic meters will be investigated in order to provide information on reliability and stability of liquid ultrasonic meters.

As there is no prover in the metering system the uncertainty of a metering system with two meters in series is regarded to be higher than for a conventional system. An increase of uncertainty represents a risk for monetary loss (Ref. [1] “Cost Benefit Analyses in the Design of Allocation Systems” by Phillip Stockton NSFMW 2009 2.6 Exposure to Loss (Risk Reduction).

A general principle in Cost Benefit analysis is that a Party will not be willing to pay more for a future risk reduction than the value of the risk reduction. In later sections of this paper the risk for loss with a metering concept with two meters in series will be quantified.

5 Skirne - Two meters in series – no prover

5.1 Skirne - Description

This metering station consists of two ultrasonic meters in series. Each meter has an upstream section containing a flow straightener believed to be of the Etoile type. There is no prover or master meter. The metering station is placed at the outlet of an inlet separator. The pressure is just above the vapour pressure of the separator. The metering station is used for allocation measurement of a satellite field.

The metering station has a bypass arrangement for each of the two meters. The by-pass makes it possible to remove each of the two meters without shutting down production. In the project phase a proposal to remove the by-passes was rejected because it was proposed to late in the project phase. The costs of removing the valves from the design were stated to be higher than keeping them in the design. The by-passes have still not been used.

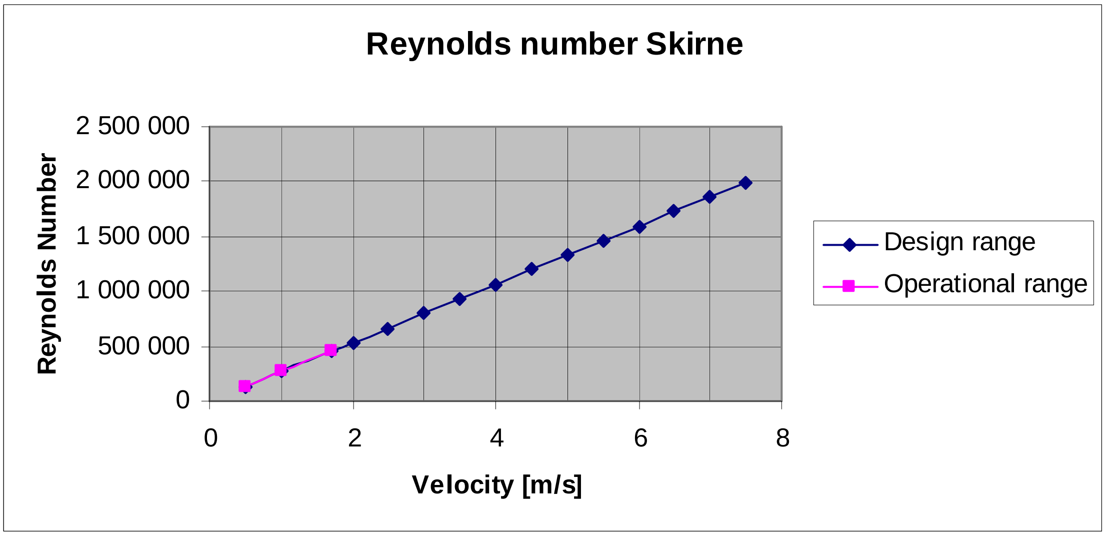
The metering station has a full bore in line water cut meter at a vertical pipe section downstream the metering station. A density meter is installed in a pitot tube driven bypass at a vertical pipe section upstream the metering station. The condensate has very low density and viscosity and the water content is rapidly varying, normally in the range up to 2 [%].

Due to the low economic risk related to uncertainty in measurement, the meters are not subject for regular calibration at an onshore calibration facility.

The following table contains key information for this metering station.

Installation Year	yyyy	2003
Pipe inner Diameter	(mm)	100
Meter nominal diameter	Inch.	4
Upstream straight length	Number of ID	13,4
Downstream straight length	Number of ID	7
Flow straightener type		Etoile
Filter	Yes / No	No
Meters in series (Yes / No)	Yes / No	Yes (2)
Number of meters in parallel		-
Normal pressure	Barg	44
Normal temperature	DegC	22
Normal density	Kg/m3	644
Normal water content	%	0,9
Normal Viscosity	mm2/s	0,3759
Meter flow range	M3/h	10 – 220 m3/h
Operational Flow range	M3/h	15 – 50 m3/h
Operational Velocity range	m/s	0,5 – 1,7 m/s
Reynolds number at Operational Velocity range		130 000 – 450 000
Operational Reference (Master meter / compact prover / bidirectional prover).		No

The following chart shows the Reynolds number in the operational range for the meters.



5.2 Skirne - Initial flow calibration

At the time of calibration it was an ongoing discussion whether the so called Reynolds number compensation should be allowed to be active in the meter. The functionality of the Reynolds number compensation was regarded to be kind of a black box representing a risk for the traceability for the meter. Folkestad ref [4] concluded that the Reynolds number compensation should not be used in metering systems with prover.

Hence two calibration series were conducted, one with the Reynolds Number compensation turned on in the first meter and off in the second meter in series. In the next series the Reynolds number compensation was turned off in the first meter and on in the second meter in series.
As can be seen from Figure 5.2-1 the linearities of the ultrasonic flow meters are

USM (Ultra Sonic Meter)1:
Reynolds number compensation ON Across total range (10 – 220 m3/h): Linearity = 0,09% (band)
Reynolds number compensation OFF Across total range (10 – 220 m3/h): Linearity = 0,42% (band)

USM (Ultra Sonic Meter)2:
Reynolds number compensation ON Across total range (10 – 220 m3/h): L = 0,12% (band)
Reynolds number compensation OFF Across total range (10 – 220 m3/h): L = 0,55% (band)

Judging from the calibration results only it seems to be vice to have the Reynolds number compensation active. At this metering station the Reynolds number compensation is active.

The ultrasonic meters where calibrated on a liquid with
808.1 [kg/m3] and cinematic viscosity of 1.77 [mm^2/s]

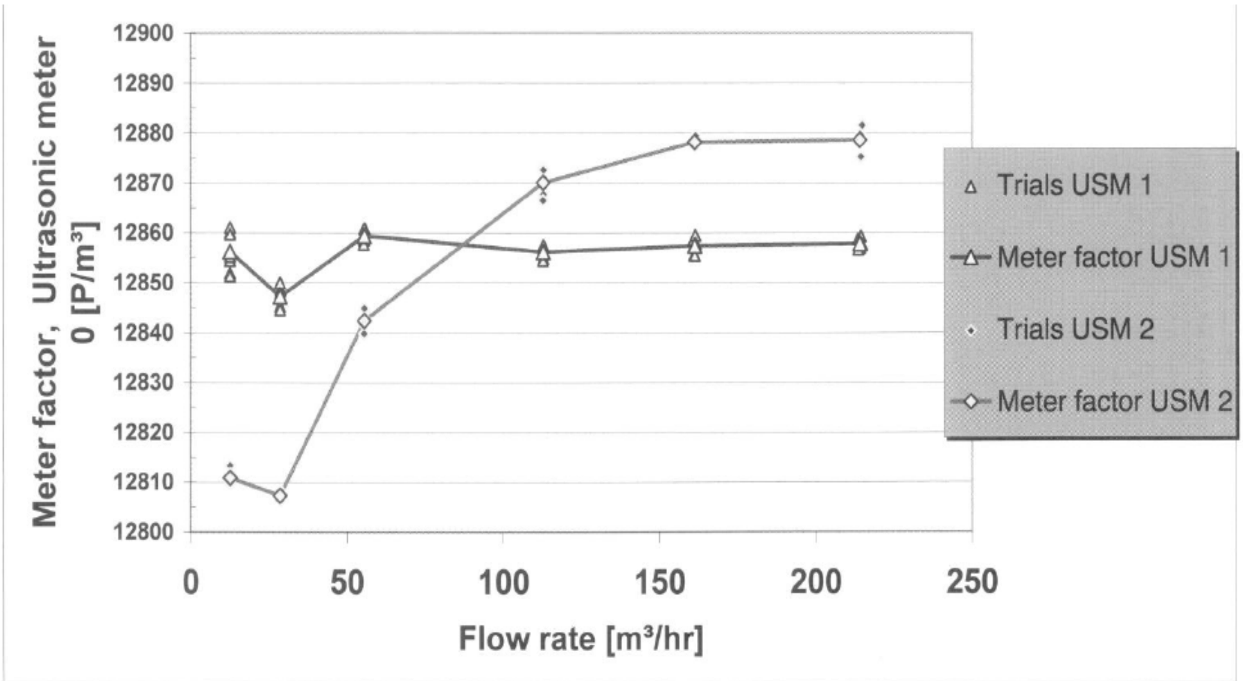


Figure 5.2-1 Results from initial flow calibration in Trapil
Reynolds number compensations active on meter 1
Reynolds number compensations inactive on meter 2

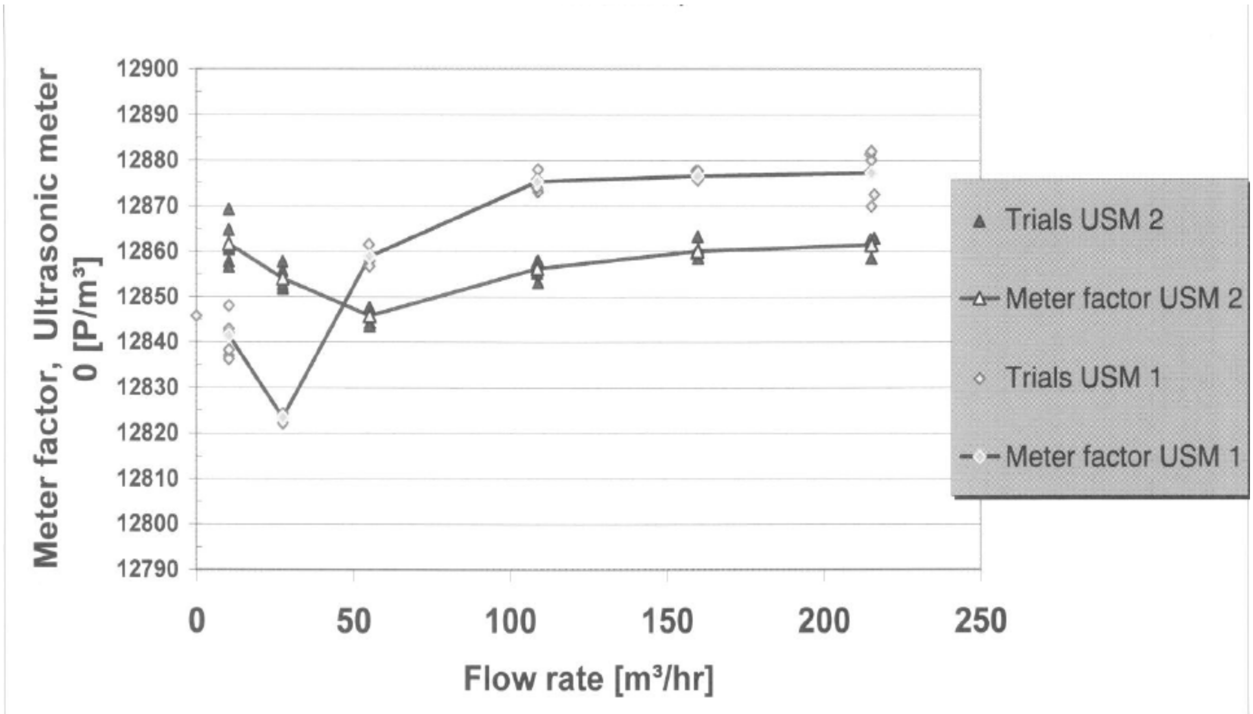


Figure 5.2-2
Reynolds number compensations active on meter 2
Reynolds number compensations inactive on meter 1

5.3 Skirne - Operational Experience

It has been observed fall out of path 1 (the lowest horizontal path) in particular for the first of the two ultrasonic meters in series but also for the second ultrasonic meter. The tests performed by the vendor demonstrate that both ultrasonic meters are fully functional and that the problems must be related to the fluid or the flow profile. The service report states that the reason for fall out of path 1 is that the meter is unable to transmit ultrasonic sound through the fluid.

As can be seen from the chart in section 5.1 the Reynolds Number in the operational range is in the range 130 000 to 450 000. Hence the flow is clearly turbulent.

The figure below indicates the minimum flow rate required to establish and maintain a homogeneous mixture of water in hydrocarbon liquid in a horizontal pipe without any mixing devices (ref [5] NFOGM Handbook for water fraction metering.) The situation for this metering station is even worse than illustrated in the Figure as the density is significant lower than the example in the following figure. This clearly demonstrates that the velocity in this metering station (up to 1.7 [m/s]) and hence the energy dissipation is far to low to be sufficient to break up water in small droplets and provide a homogeneous mixture of water in oil over the cross section.

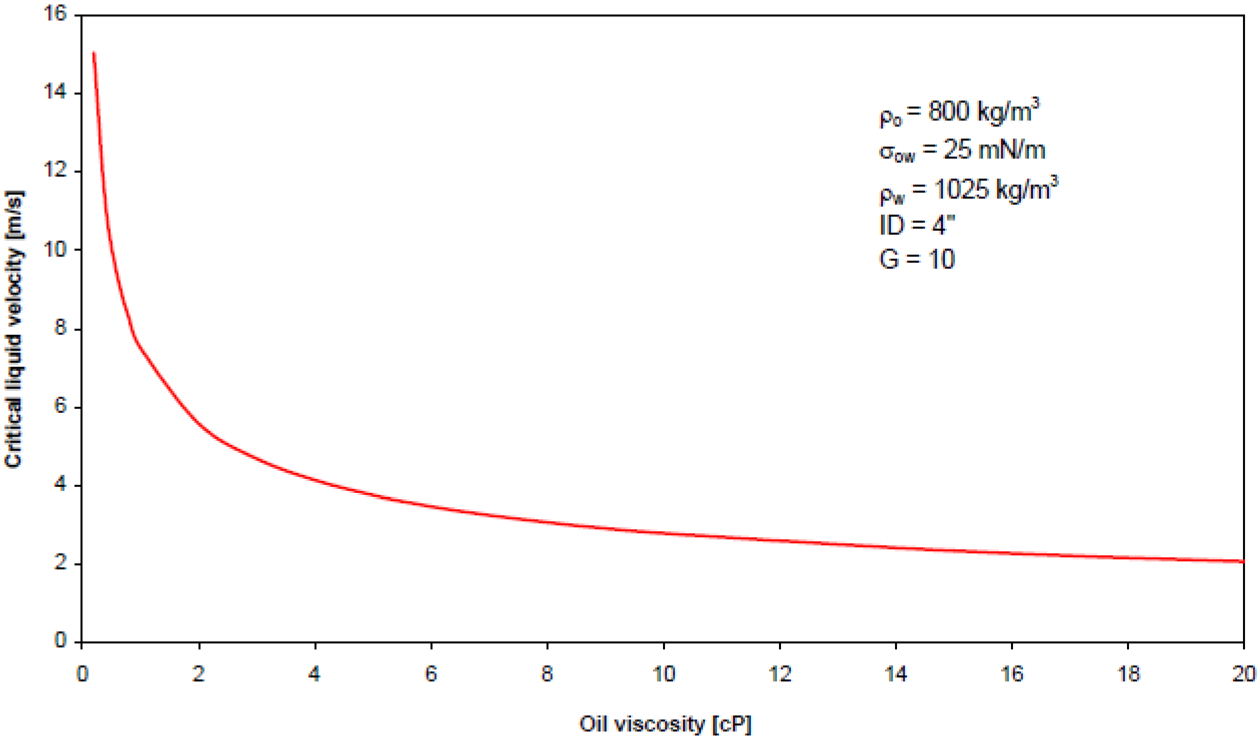


Figure 10.2 Critical liquid velocity as a function of the oil viscosity in order to maintain a concentration ratio of 0.9 (G = 10) between the bottom and the top of a horizontal pipe. . The flow will be homogeneous as long as the actual liquid velocity is greater than the critical velocity given by the diagram. The model is only expected to be valid for water fractions below 10 –15 %.

Hence it seems reasonable to conclude that the water concentration will be higher at the bottom of the pipe, and that water droplets are the likely reason that ultrasonic sound does not seem to pass through the fluid for the bottom path.

From this example it is worth noting that:

1. There is no relation between Reynolds number for the hydrocarbon fluid and the degree of mixing of water and hydrocarbon liquid. Even though the Reynolds Number for the hydrocarbon fluid flowing through the pipe is well within the turbulent area, this can not be used as an indication that the mixture of water and hydrocarbon liquid is homogeneous.
2. A water fraction of as low as 0,5 – 2 [%] in a light hydrocarbon liquid may cause problems for an ultrasonic flow meter by significantly affecting the lowest path.

The vendor noted in his report that the swirl number for the two meters was 0.122 for the first meter and 0,088 for the second meter. Both swirl numbers are within the recommendation of maximum 0,2 from the manufacturer.

Except from the problem caused by fluid / flowing conditions there has not been recorded any problems with the meters.

It is worth noting that the by pass has still not been used.

5.4 Skirne - Operational experience – deviation between the to meters

As ultrasonic meter number 1 in particular is not working properly due to the fluid conditions at the metering point, it would be unfair to the meter to evaluate uncertainty based on the deviation between the two meters. Contrary to the other metering stations evaluated in this paper there are no prover or third party yearly calibrations providing a reference with low uncertainty for the meters. However, the difference in hourly accumulated volume from the two meters seems to be varying in the range from – 1 [%] to + 1 [%]. Differences of up to 1.5 [%] has been seen. -0.3 [%] seems to be a reasonable estimate of the long term difference between the two meters as evaluated from 2006 to 2011. There has not been found any significant linear correlation between this difference and water fraction, pressure or temperature.

6 NOB - Two ultrasonic meters in series and a bidirectional prover

6.1 NOB - Description

NOB is the short name for New Oseberg Blend. That is a mixture of the original Oseberg Blend with a smaller part of Grane crude oil at Sture Terminal. NOB metering station is used to measure part of Grane oil into the blend.

The metering station is an allocation metering station. Liquid ultrasonic meters were selected due to the high viscosity of the crude oil. The metering station consists of 2 ultrasonic meters in series and a bidirectional prover.

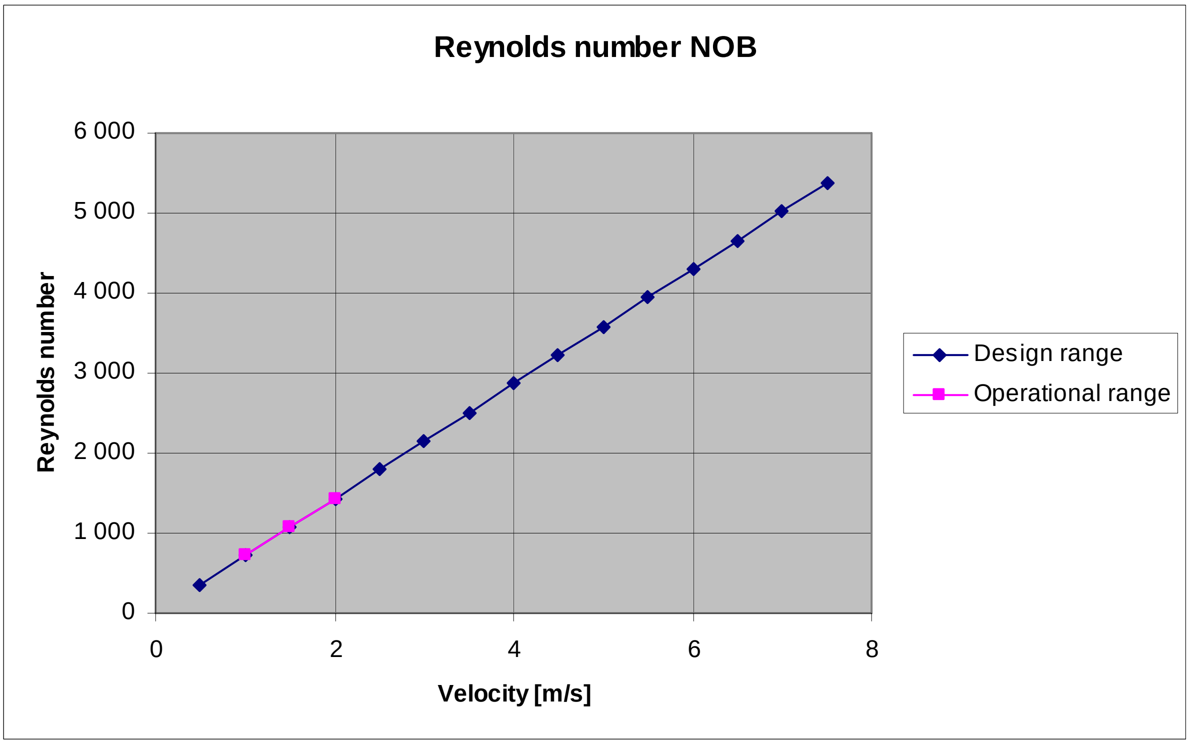
The following table contains key information for this metering station.

Installation Year	yyyy	2004	
Pipe inner Diameter	Mm	154	
Meter nominal diameter	Inch.	6	
Upstream straight length	Number of ID	22	*) Both upstream USM1 and between USM1 and USM2

Operational experience with liquid ultrasonic meters

Downstream straight length	Number of ID	22ID / 8 ID *)	*) USM2
Flow straightener type		Etoile *)	*) Upstream USM1 only
Filter	Yes / No	No	
Meters in series (Yes / No)	Yes / No	Yes *)	*) Two meters in series
Number of meters in parallel		-	
Normal pressure	Barg	2.5	
Normal temperature	DegC	30	
Normal density	kg/m3	930	
Normal water content	%	0.50	
Normal Viscosity	mm2/s	200	
Meter flow range	M3/h	600	
Operational Flow range	M3/h	80-120	
Operational Velocity range	m/s	1.3 - 2	In contracted part of meter
Operational Reference (Master meter / compact prover / bidirectional prover).		Bidirectional pipe prover	

The following chart shows the Reynolds number in the operational range for the meter.



6.2 NOB - Operational experience

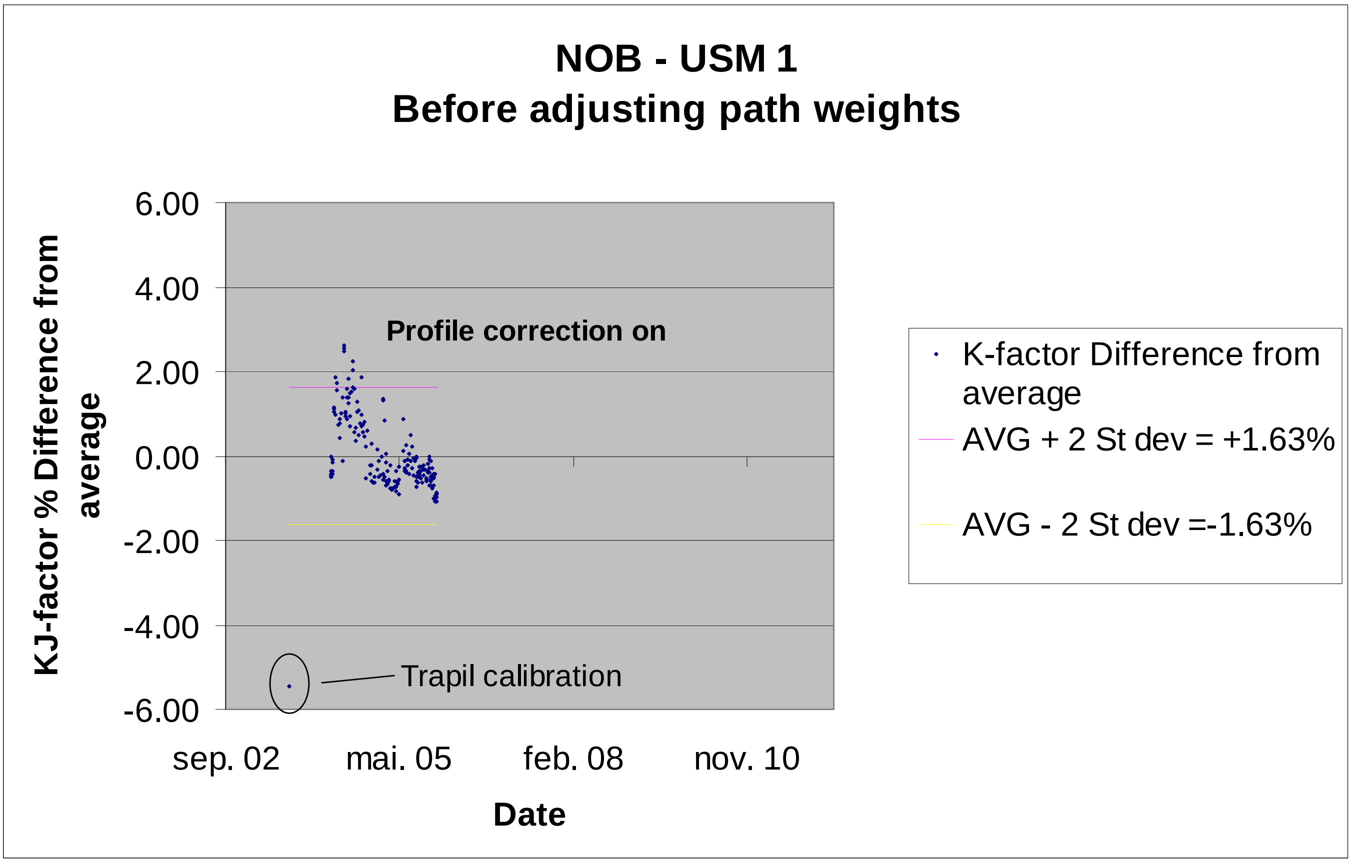
The paper Experience with ultrasonic meters on high viscosity oil [2] was presented by Øyvind Nesse at the North Sea Flow Measurement Workshop in Tønsberg 2007.

The paper documents how the K-factor variations were regarded to be too high. Subsequently, the weighting factor for the 5 paths was changed to increase the weight of the outer paths and reduce the weight of the centre path. At the same time the Reynolds number compensation in the meter was turned off. The change was implemented 2005-12. The following figures shows the K-factors achieved before and after the changes.

There has not been registered any physical failure for any of the meters

6.3 NOB - Uncertainty evaluation

The following figure shows the K-factors achieved under the calibration at TRAPIL and the first 1.5 years in operation.

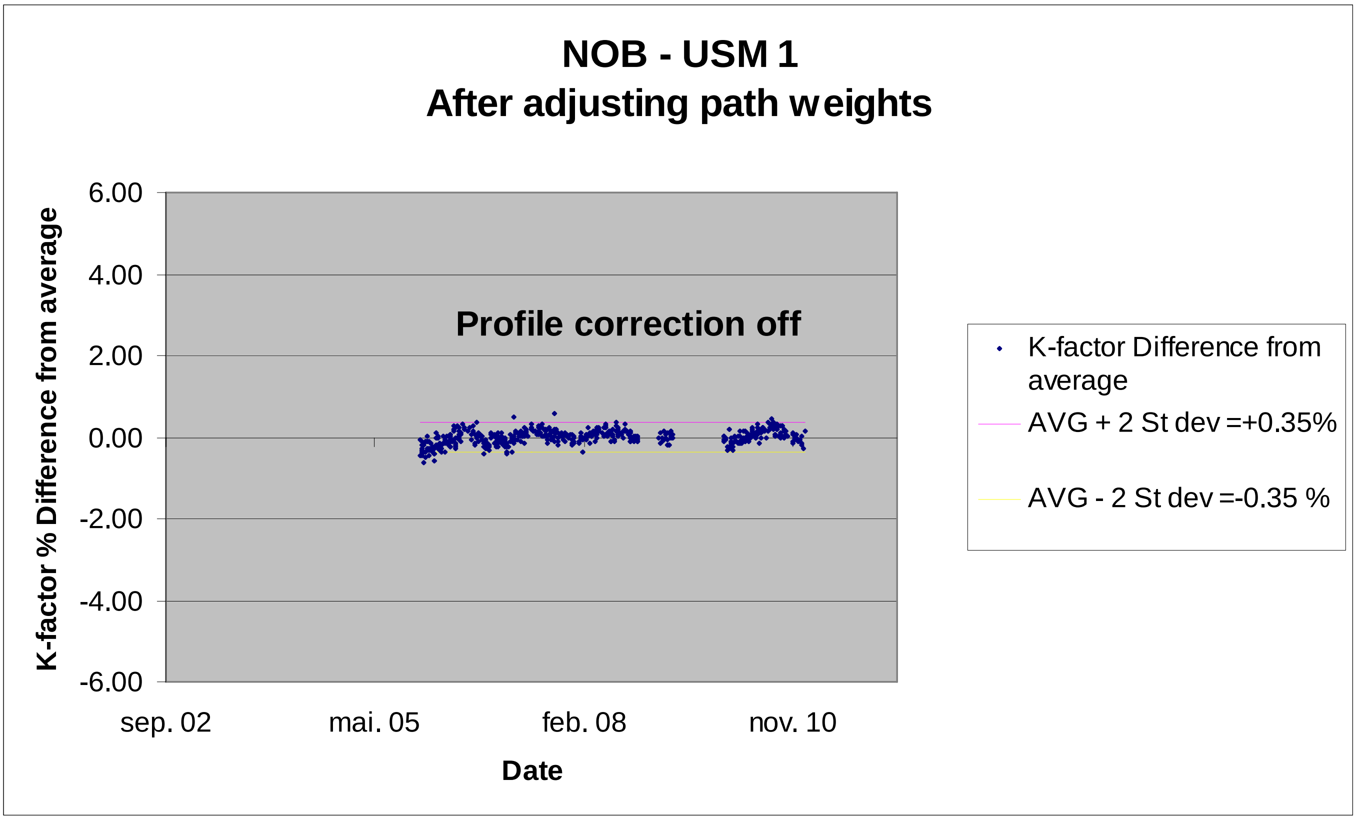


The calibration in Trapil was performed on a fluid with viscosity of 4.72 [mm2/s]. At operational conditions the viscosity is approximately 200 [mm2/s]. The K-factor achieved in TRAPIL was 5712 [pulses/m3]. The average K-factor achieved in operation was 6040.8 [pulses/m3].

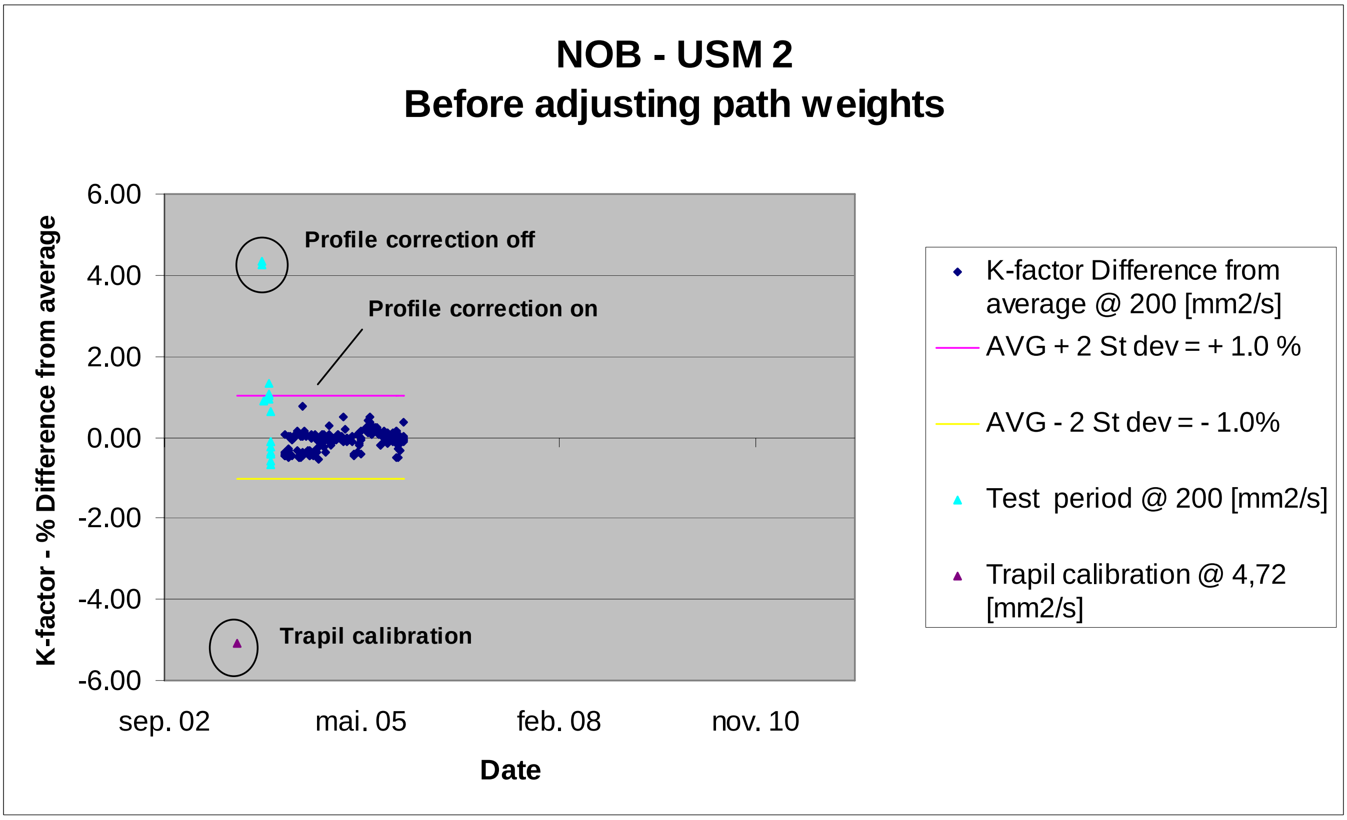
It is worth noting that if the K-factor achieved under the calibration at Trapil calibration facility had been used during operation, an systematic error of approximately 5 [%] would have been the result.

An optimization of the meters was then performed ref: “Experience with ultrasonic meters on high viscosity oil” [2] presented by Øyvind Nesse at the North Sea Flow Measurement Workshop in Tønsberg 2007.

The following figure shows the K-factors achieved since. The average K-factor achieved after the path weights were adjusted was 5997 [pulses/m3] in this period.



The following figure shows the K-factor for USM 2 achieved at the calibration facility before the meter was put into operation and the K-factors achieved during the first 1.5 years of operation.



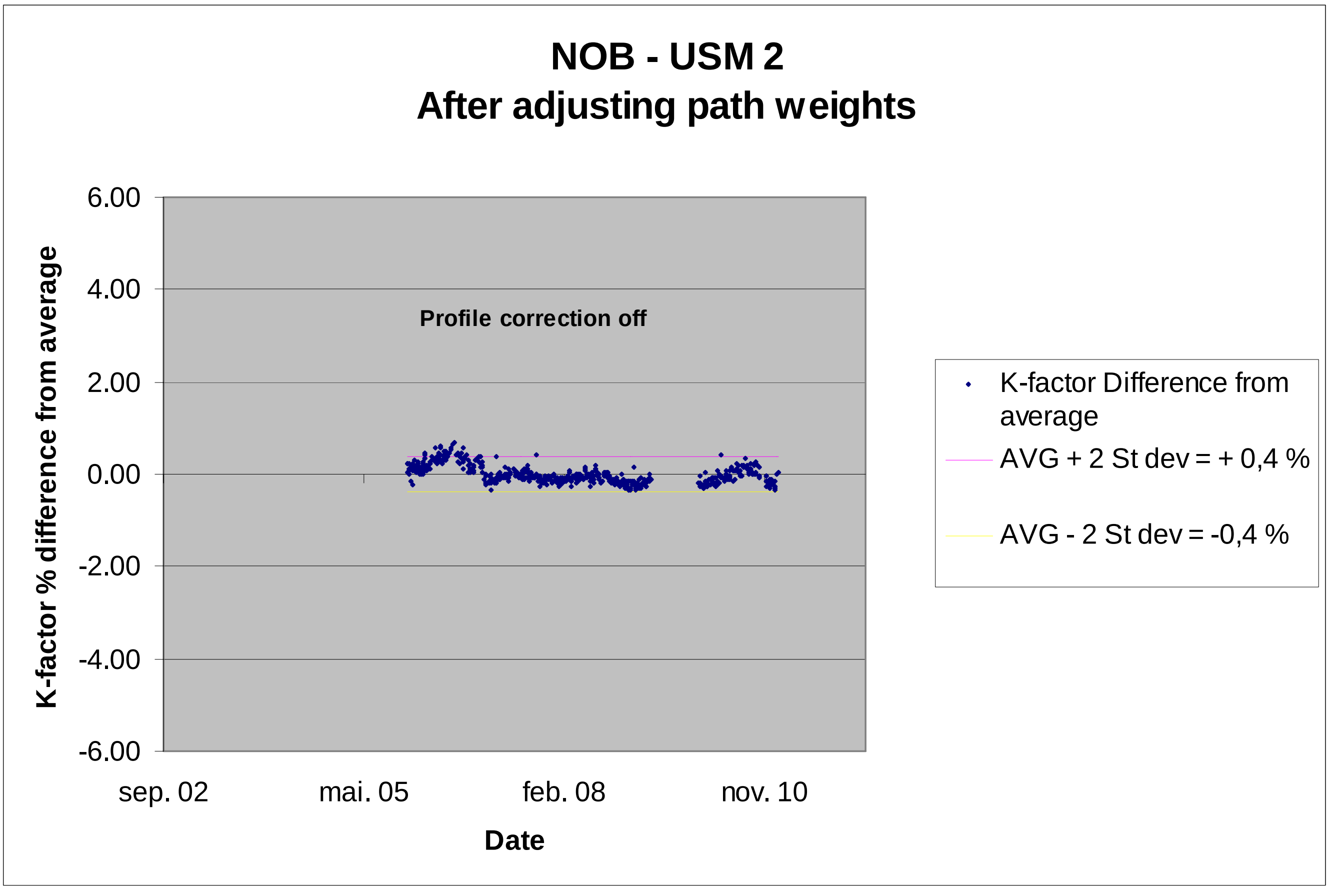
The calibration in Trapil was performed on a fluid with viscosity of 4.72 [mm2/s]. At operational conditions the viscosity is approximately 200 [mm2/s]. The K-factor achieved in TRAPIL was 5714 [pulses/m3]. The average K-factor achieved in operation was 6021 [pulses/m3].

Before the metering system was put in full operation it went through a test period using the process fluid. The first calibration point in this series contain two point with approximately 4 [%] higher K-factor than the average K-factor. The data record contains a note stating that the Reynolds number compensation was turned off at this point. Even though the presence of a fault at this point can not be excluded, the data record does not contain evidence of any such fault. Hence the data record does not contain support to exclude the data point for the purpose of this paper.

It is worth noting that if the K-factor achieved under the calibration at Trapil calibration facility had been used during operation, an systematic error of approximately 5 [%] would have been the result.

An optimization of the meters was then performed ref: "Experience with ultrasonic meters on high viscosity oil" [2] presented by Øyvind Nesse at the North Sea Flow Measurement Workshop in Tønsberg 2007.

The following figure shows the K-factors achieved since. The average K-factor achieved after the path weights were adjusted was 6009 [pulses/m3] in this period.



This demonstrates that at these process conditions with very low Reynolds number and flow being laminar rather than turbulent the K-factor of the meter seems to be less predictable than well into the turbulent regime. Without a prover at the metering station, the measurement result would have been disastrous. The flow meter was later improved by changing path weights. It remains to be demonstrated how well the K-factor in operation can be predicted by calibration in a calibration facility at these Reynolds numbers. Spread in K-factors achieved in operation also indicates that the variation of the K-factor over the operational range seems to be as high as 0,8 [%] even after optimization.

7 GOHS - Custody transfer export metering station with 5 metering runs in parallel and a bidirectional prover

7.1 GOHS – Description

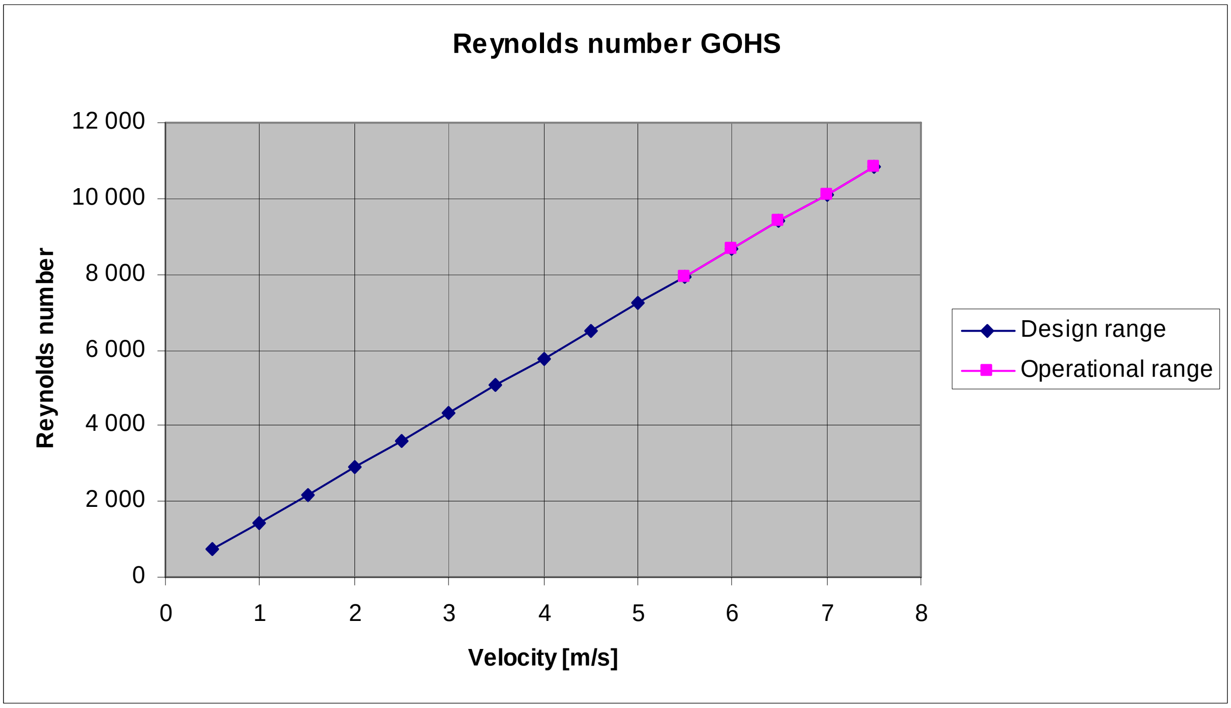
GOHS is Grane Oil Handling Sture. Grane crude oil is entering Sture Terminal from the Grane offshore field through a pipeline. At Sture the oil is heated, stored in caverns and shipped to tankers. Grane export oil metering station is measuring the oil from storage at Sture to tankers. The oil is heated to bring the viscosity down to approximately 200 [mm2/s].

The metering station consists of 5 ultrasonic meters in parallel and a bidirectional prover.

The following table contains key information for this metering station.

Installation Year	yyyy	2003	
Pipe inner Diameter	Mm	311	
Meter nominal diameter	Inch.	12	
Upstream straight length	Number of ID	18	
Downstream straight length	Number of ID	5	
Flow straightener type		Etoile	
Filter	Yes / No	No	
Meters in series (Yes / No)	Yes / No	No	
Number of meters in parallel		5	
Normal pressure	Barg	3.5	
Normal temperature	DegC	30	
Normal density	kg/m3	930	
Normal water content	%	0.50	
Normal Viscosity	mm2/s	200	
Meter flow range	m3/h	2500	
Operational Flow range	m3/h	1500-2000	
Operational Velocity range	m/s	7.5 - 10	In contracted part of meter
Operational Reference (Master meter / compact prover / bidirectional prover).		Bidirectional pipe prover	

The following chart shows the Reynolds number in the operational range for the meter.



7.2 GOHS - Operational experience

The metering station is equipped with a large bidirectional prover. There seems to be no problems with achieving repeatability when proving the meters towards the bidirectional prover.

The lack of linearity of the meters over the operational range was experienced to provide K-factor variation outside traditional limits for K-factor monitoring. The paper "Experience with ultrasonic meters on high viscosity oil" [2] was presented by Øyvind Nesse at the North Sea Flow Measurement Workshop in Tønsberg 2007. In the paper Nesse demonstrated how the K-factor variation showed a statistical correlation to temperature and flow rate variation. Nesse demonstrated how he quantified the correlation and developed a tool to predict K-factor based on flow rate and temperature. Nesse further demonstrated how the control limits was based on the difference between the predicted K-factor and the achieved K-factor rather than towards the historical K-factors only. In this way Nesse was able to keep control with the metering run and the meter despite an original K-factor variation which was regarded to be outside reasonable control limits.

It has been experienced up to 20 – 25 [%] water through the metering station. The ultrasonic meters still works at these water fractions. However, it has been experienced that the K-factor variation increases at these water fractions.

It has also been experienced two times that a flow straightener has been broken inline during operation. The flow straightener is of the Etoile type. The break down of the flow conditioner caused a significant increase in the K-factor variation, Ref. [2]. To avoid future problems the material thickness of the flow straightener and the quality of the welding was improved. There has not been experienced any break down of the flow straightener since.

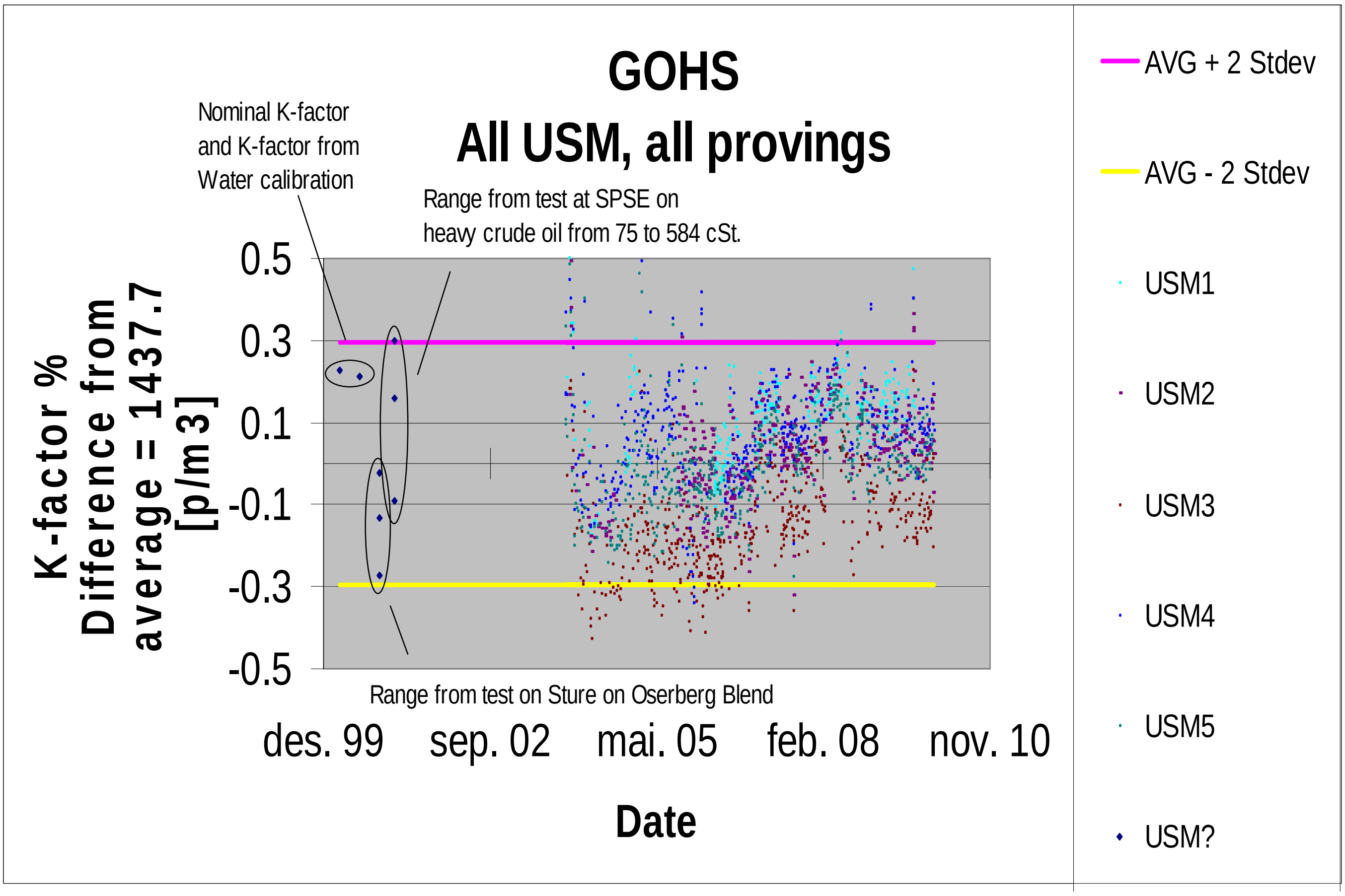
7.3 GOHS - Uncertainty evaluation

The following figure shows the nominal K-factor, K-factor from water calibration at the factory for one of the meters, the K-factor range from a test performed on Oseberg Blend on Sture for one of the meters, the K-factor range from test at SPSE for one of the meters and finally the K-factors achieved for all 5 ultrasonic meters on this metering station from 2004 to 2009. (K-factors for each of the meters until 2011 are consistent with this picture and can be seen in the figures below.)

The nominal K-factor is taken from Ref [4] Folkestad NSFMW 2001 paper 15 section 5.
The average K-factor from water calibration is taken from Ref [4] Folkestad NSFMW 2001 paper 15 figure 2.
The K-factor range from test at SPSE is illustrated by the Lowest, the average and the highest K-factor taken from Ref [4] Folkestad NSFMW 2001 paper 15 figure 32.
The K-factor range from the test on Oseberg Blend crude at Sture is illustrated by the lowest, the average and the highest K-factor taken from Ref [4] Folkestad NSFMW 2001 paper 15 figure 6.

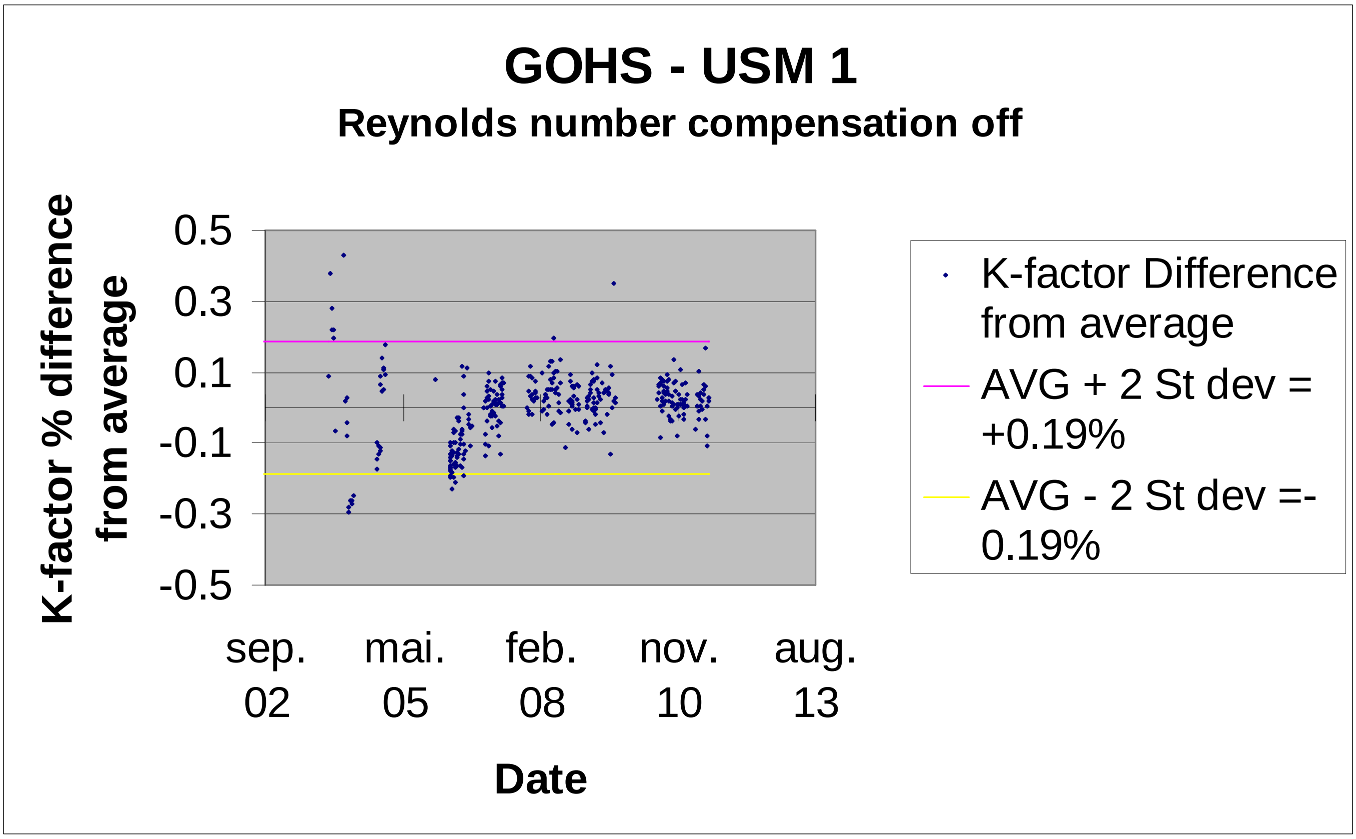
The test at SPSE was performed with meter serial nr. 104202 on heavy crude oil with kinematic viscosity ranging from 75 to 584 [mm^2/s] and Reynolds number ranging from approximately 3000 to 35 000. Ref [4] Folkestad NSFMW 2001 paper 15 figure 32.

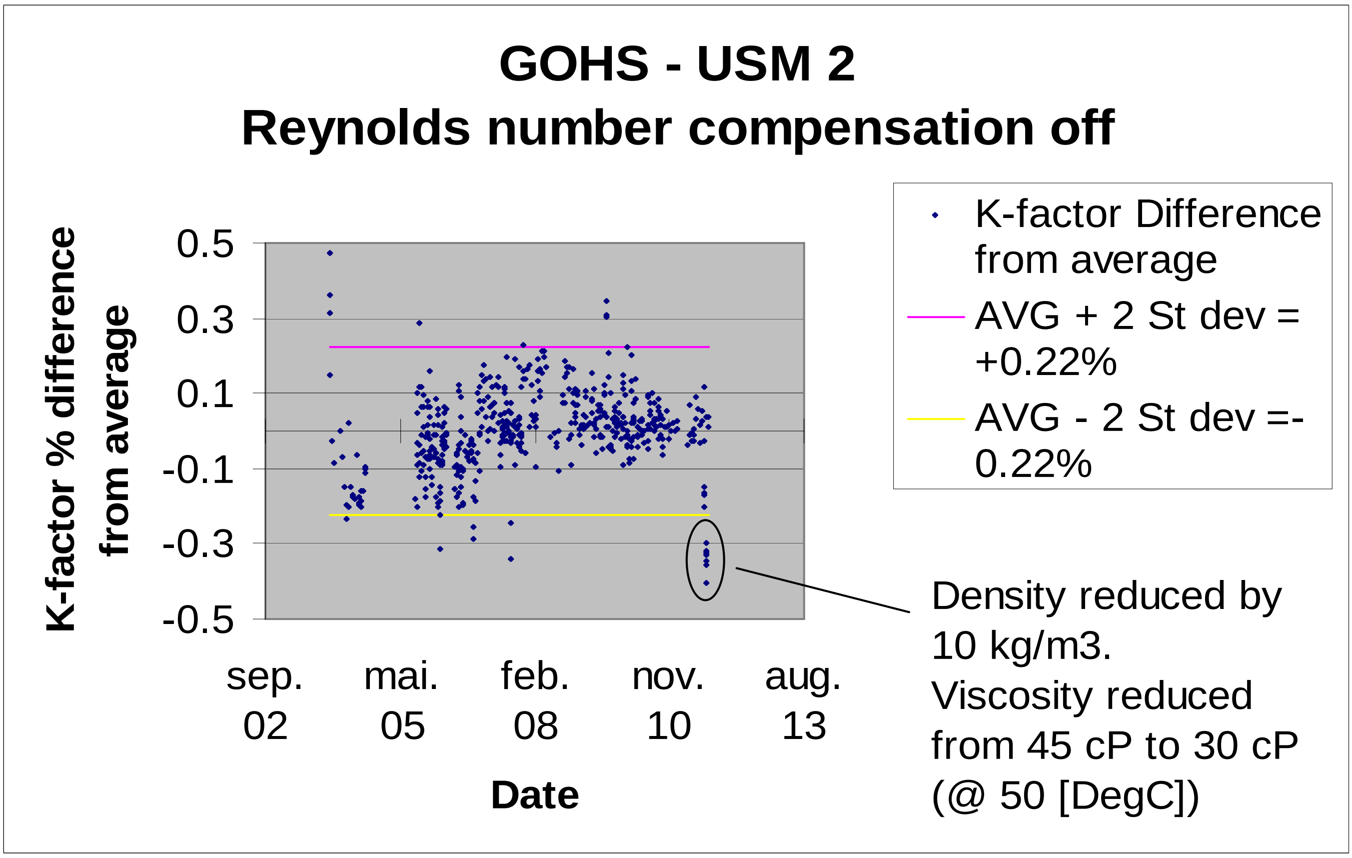
We currently lack information on which of the 5 ultrasonic meters which was used in the tests. The following figure contains the K-factor for all 5 meters and demonstrates that the results are consistent over a broad range of Reynolds Numbers and fluids.

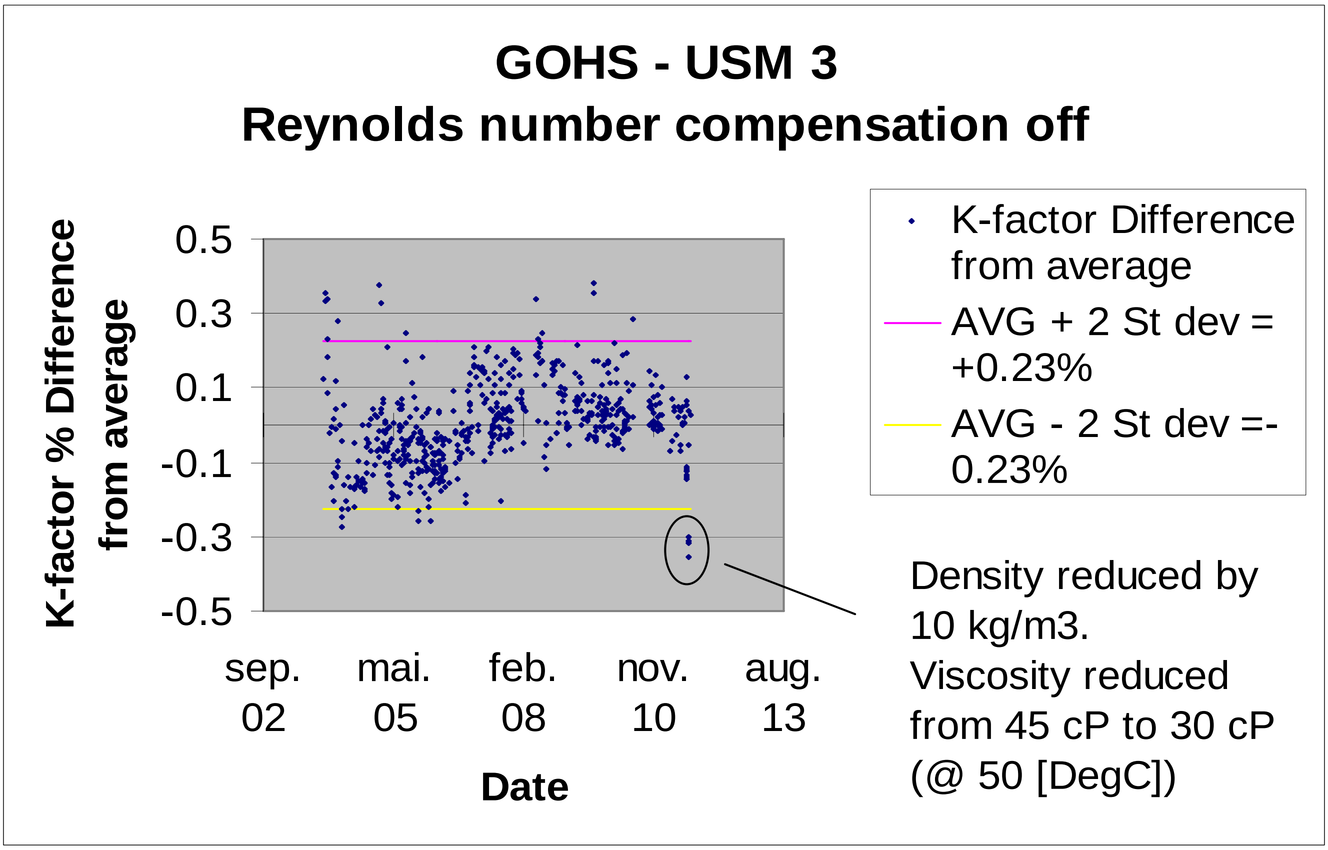


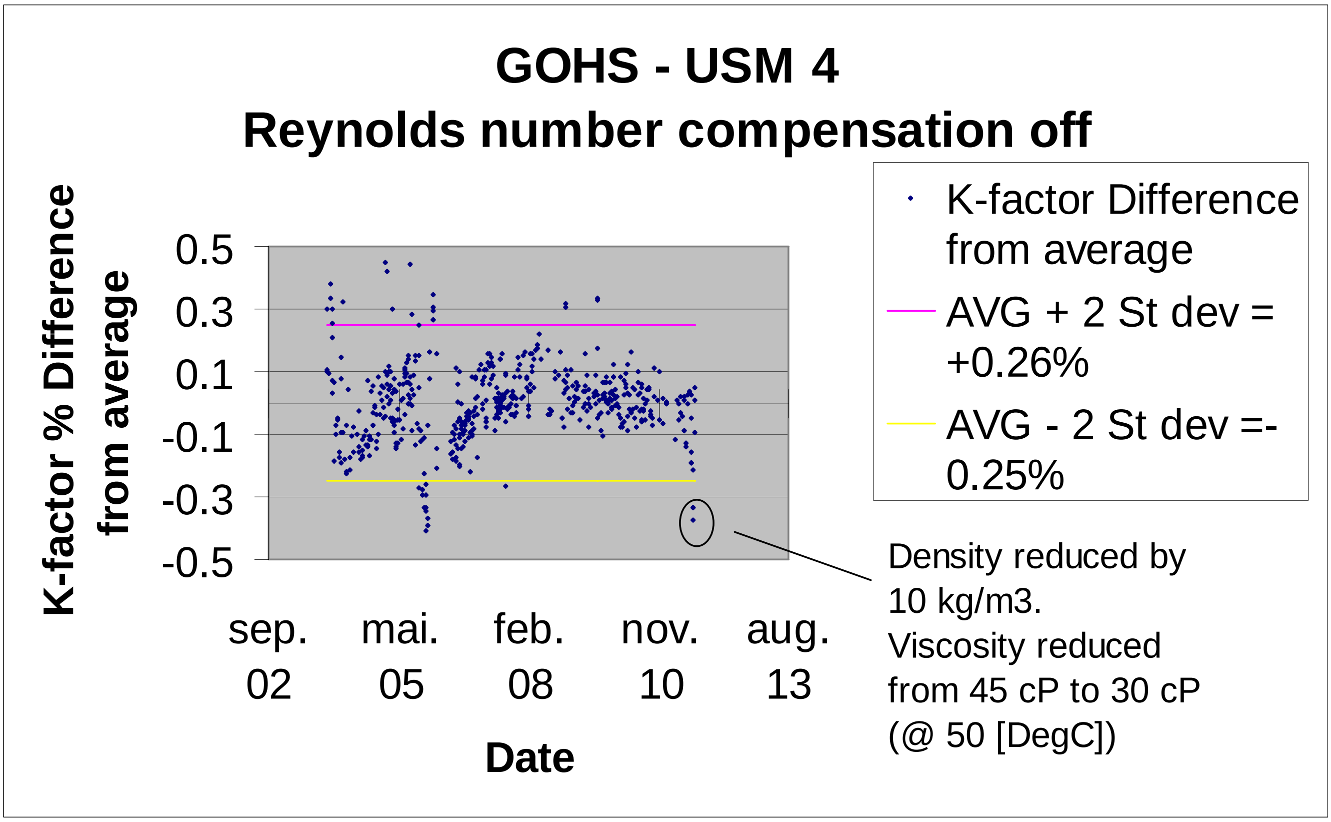
The following charts show all K-factors achieved in the period 2004 – 2011.

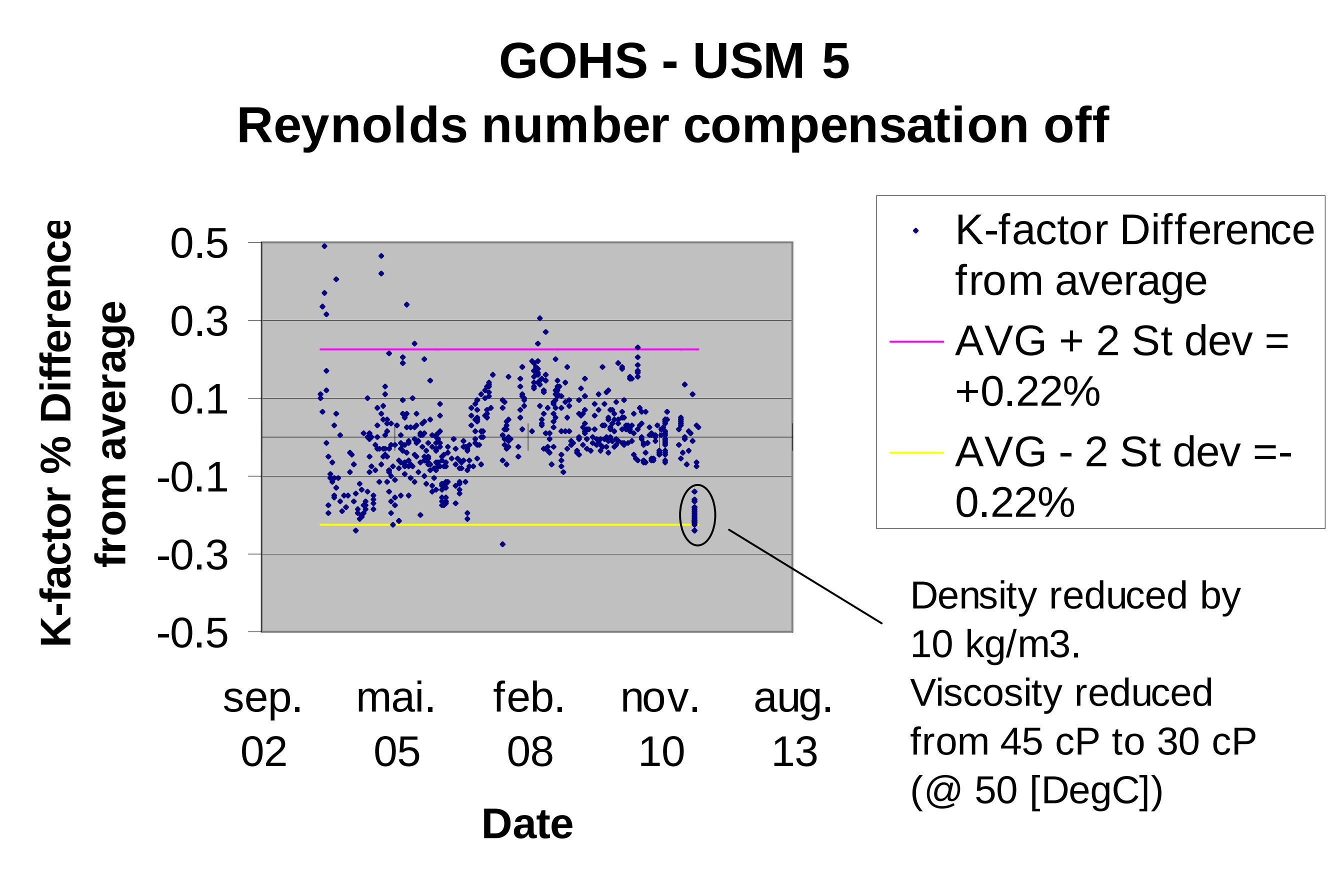
It is worth noting from the following charts, that in august 2011 the fluid was altered because of a temporary tie-in of a new field with lower density and viscosity. The density was reduced from 930 [kg/m3] to 920 [kg/m3]. The viscosity was reduced from approximately 45 to 30 [mm2/s] @ 50 [DegC] (The metering station is operated at 30 [DegC]). The change caused a shift in K-factor as shown in the figures.


GOHS - USM 1
Reynolds number compensation off
K-factor % difference from average
0.5
0.3
0.1
-0.1
-0.3
-0.5
sep. 02
mai. 05
feb. 08
nov. 10
aug. 13
Date
K-factor Difference from average
AVG + 2 St dev = +0.19%
AVG - 2 St dev =-0.19%


GOHS - USM 2
Reynolds number compensation off
K-factor % difference from average
0.5
0.3
0.1
-0.1
-0.3
-0.5
sep. 02
mai. 05
feb. 08
nov. 10
aug. 13
Date
K-factor Difference from average
AVG + 2 St dev = +0.22%
AVG - 2 St dev =-0.22%
Density reduced by 10 kg/m3.
Viscosity reduced from 45 cP to 30 cP (@ 50 [DegC])


GOHS - USM 3
Reynolds number compensation off
K-factor % Difference from average
0.5
0.3
0.1
-0.1
-0.3
-0.5
sep. 02
mai. 05
feb. 08
nov. 10
aug. 13
Date
K-factor Difference from average
AVG + 2 St dev = +0.23%
AVG - 2 St dev =-0.23%
Density reduced by 10 kg/m3.
Viscosity reduced from 45 cP to 30 cP (@ 50 [DegC])


GOHS - USM 4
Reynolds number compensation off
K-factor % Difference from average
0.5
0.3
0.1
-0.1
-0.3
-0.5
sep. 02
mai. 05
feb. 08
nov. 10
aug. 13
Date
K-factor Difference from average
AVG + 2 St dev = +0.26%
AVG - 2 St dev =-0.25%
Density reduced by 10 kg/m3.
Viscosity reduced from 45 cP to 30 cP (@ 50 [DegC])



Based on the charts above it seems reasonable to state that:
For Reynolds number in the range 8000 to 11 000. If the meters are calibrated on representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than 0.3 [%] at 2 standard deviation from the true value.

8 SNA Crossover - Ultrasonic meter with ultrasonic master meter and a helical blade turbine meter as master transfer meter.

8.1 SNA Crossover - Description

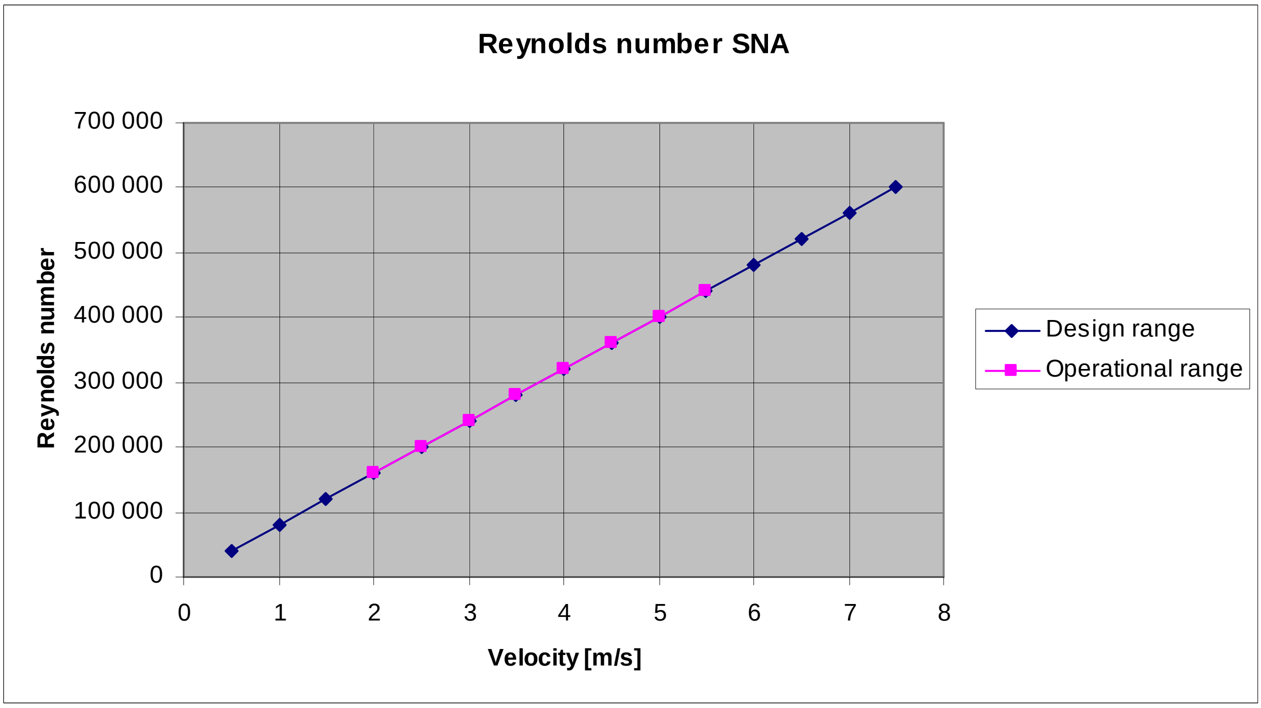
The following table contains key information for this metering station.

Installation Year	yyyy	1999	
Pipe inner Diameter	mm	200	
Meter nominal diameter	Inch.	8	
Upstream straight length	Number of ID	10	
Downstream straight length	Number of ID	5	
Flow straightener type		Contraction	6 inch – 4 inch reducer 10 D upstream flow meter

Operational experience with liquid ultrasonic meters

Filter	Yes / No		
Meters in series (Yes / No)	Yes / No	2	Master meter is also an ultrasonic meter.
Number of meters in parallel		0	
Normal pressure	Barg	50	
Normal temperature	DegC	60	
Normal density	kg/m3	810	
Normal water content	%	< 5	
Normal Viscosity	mm2/s	2,5	
Meter flow range	M3/h	150 - 800	
Operational Flow range	M3/h	200 - 600	
Operational Velocity range	m/s	0,5 - 6	
Operational Reference (Master meter / compact prover / bidirectional prover).			Calibrated towards an ultrasonic master meter once every 4 days. Helical blade turbine meter used as transfer meter during yearly calibration towards a third party compact prover.

The following chart shows the Reynolds number in the operational range for the meter.



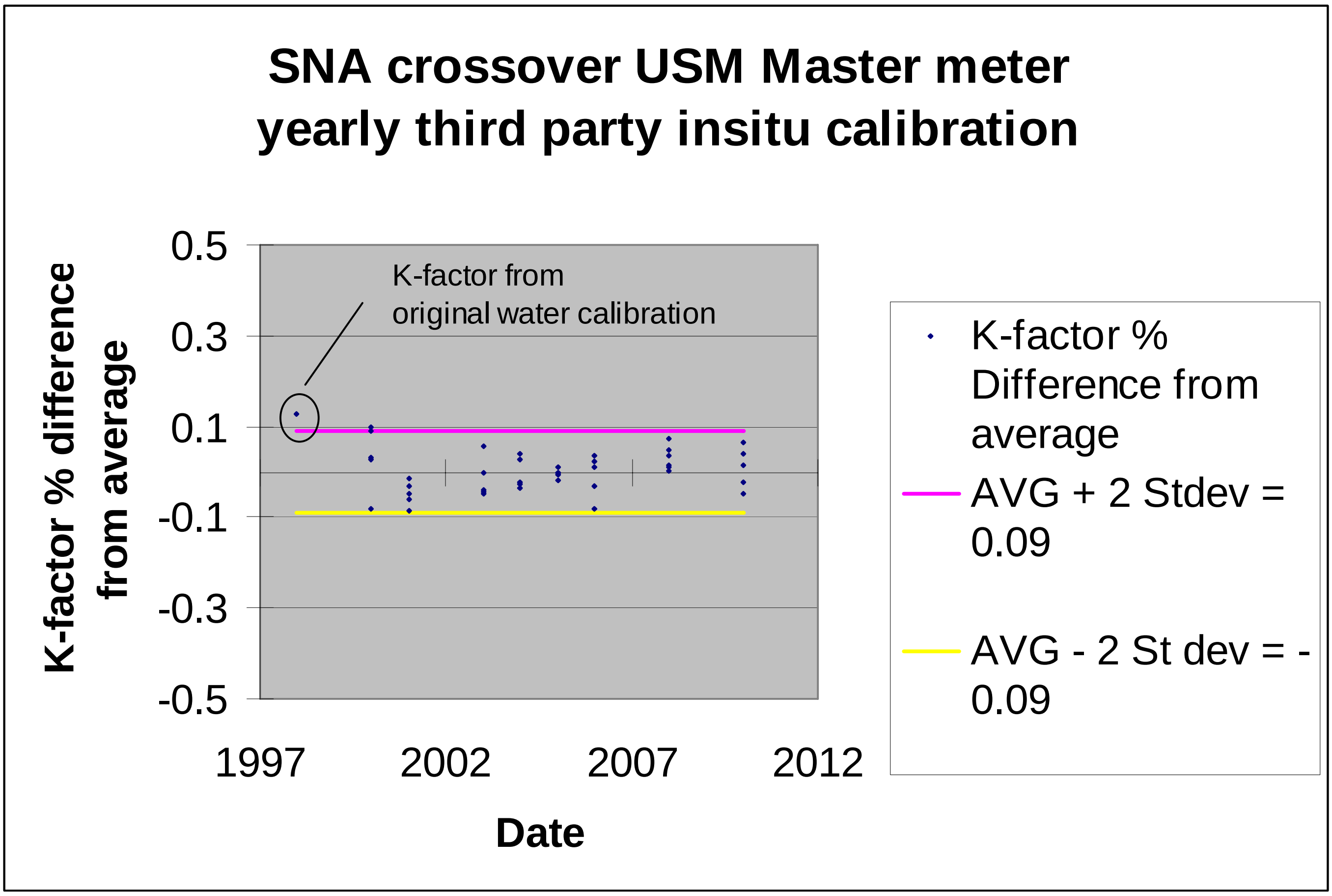
8.2 SNA Crossover - Operational experience

It has been experienced that water content of somewhere between 5% and 15 % has caused failure in the form of drop-out of the measurement from the Ultrasonic meter.

Flexible tubes were tried for the yearly recalibration towards the compact prover. Flexible tubes had to be replaced by fixed piping in order to remove visible pulsation of the tubes and consequently poor repeatability. Calibration using flexible tubes in combination with a compact prover has also been experienced to cause a large bias of 0,3 to 0,6 [%] over the flow range.

8.3 SNA Crossover - Uncertainty evaluation

The following figure presents the results from the yearly third party recalibration of the ultrasonic meter. The calibration was performed using the normal process fluid and a helical turbine meter as calibration transfer. Different points at the same date represents the results at different flow rates over the operational range.



Based on the charts above it seems reasonable to state that:
For Reynolds number in the range 150 000 to 450 000. If the meter is calibrated on representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than 0.09 [%] at 2 standard deviation from the true value.

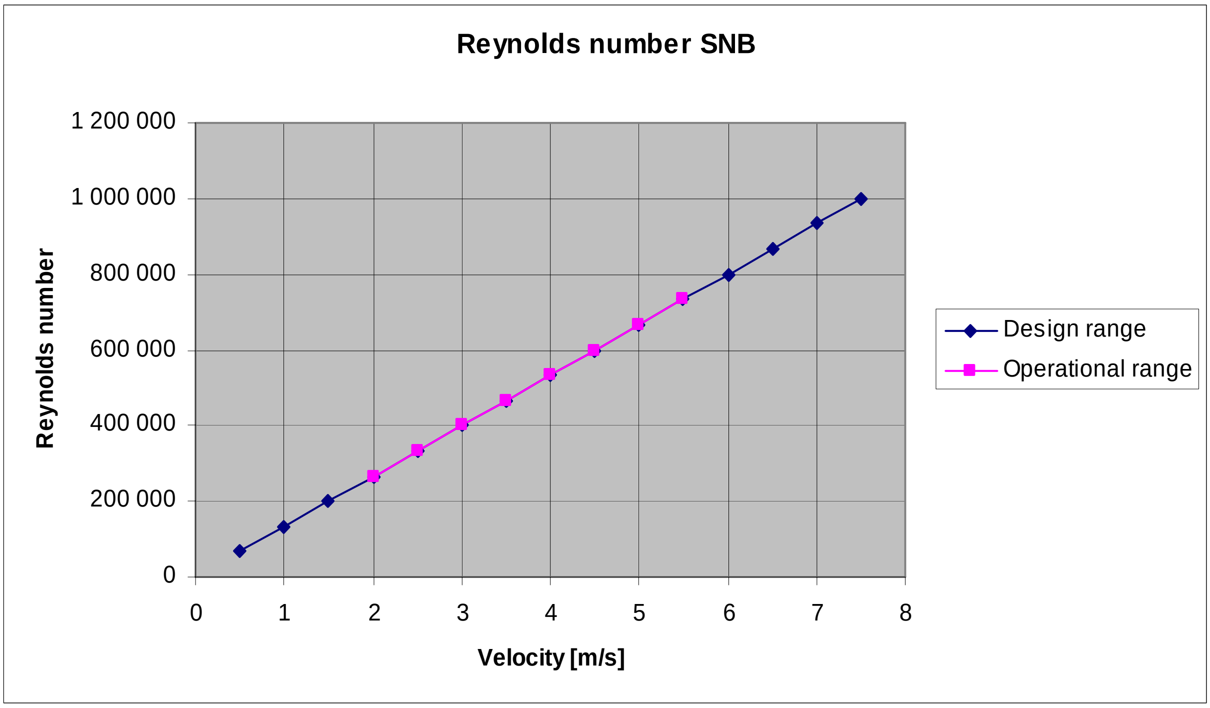
9 SNB - Ultrasonic meter with a Faure Herman turbine meter as master meter.

9.1 SNB – Description

The following table contains key information for this metering station.

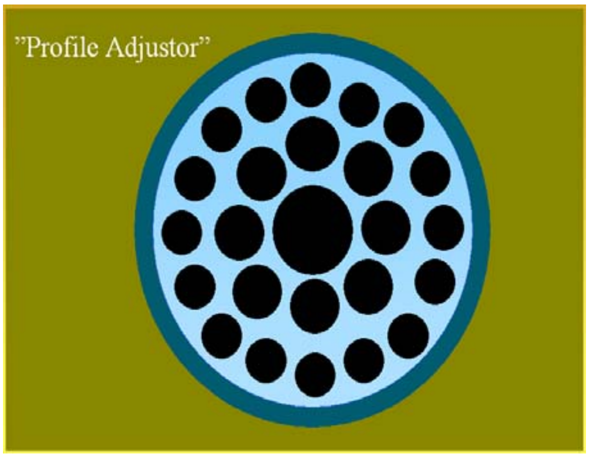
Installation Year	2001	yyyy	
Pipe inner Diameter	200	mm	
Meter nominal diameter	8	Inch.	
Upstream straight length	10	Number of ID	
Downstream straight length	5	Number of ID	
Flow straightener type	Mod Gallagher		A modified Gallagher plate with 1 hole in the middle.
Filter		Yes / No	The filter has been removed as it negatively affected the meter performance.
Meters in series (Yes / No)	1	Yes / No	
Number of meters in parallel	0		
Normal pressure	50	Barg	
Normal temperature	56	DegC	
Normal density	825	Kg/m3	
Normal water content	< 0,5	%	
Normal Viscosity	1,5	mm2/s	
Meter flow range	150 - 800	M3/h	
Operational Flow range	200 - 600	M3/h	
Operational Velocity range	0,5 - 6	m/s	
Operational Reference (Master meter / compact prover / bidirectional prover).			Calibrated towards the helical blade turbine meter once every 4 days. Helical blade turbine meter also used as transfer meter during yearly calibration towards a third party compact prover.

The following chart shows the Reynolds number in the operational range for the meter.



9.2 SNB - Operational experience

Manufacturer of the liquid ultrasonic meter recommends an installation providing a swirl factor in the meter which is less than 0,2. A Clogged strainer at 10D upstream of the meter gave a swirl factor of 0,8 to 1. The clogged strainer caused a change of more than 0,5 [%] in the K-factor. The strainer was then removed and replaced by a modified Gallagher Profile plate. There have been no problems since. The swirl indication of the meter was reduced from 0,5 to 0,01 by replacing the strainer with a modified Gallagher Profile plate as shown below.



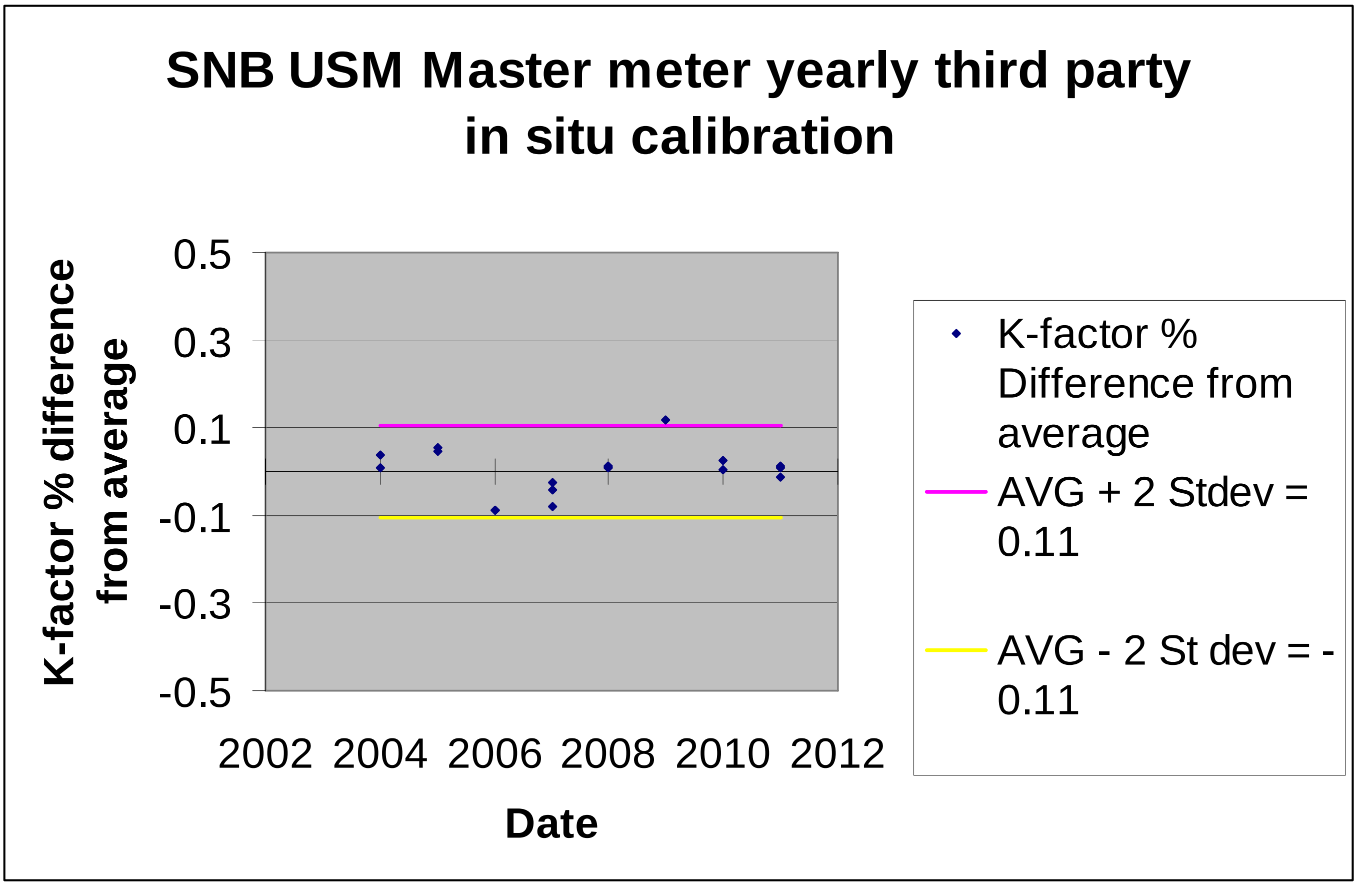
After having installed the Gallagher Profile plate in September 2003 the average K-factor at the yearly third party calibration on the normal fluid in situ was within 0,05 [%] of original water draw calibration.

The Strainer also seems to have affected repeatability negatively even when not clogged. Before the filter was removed the repeatability at yearly calibration towards the compact prover was about 0,05 [%]. After having removed the filter the repeatability at yearly calibration towards compact prover was in the order of magnitude 0,01 – 0,02 [%].

In early days it was tried to calibrate the ultrasonic meter directly towards a compact prover. Calibration of the ultrasonic meter directly towards a compact prover was not feasible as more than 100 trials were tried and the repeatability was still not within the requirement. 100 Trials did not give repeatability within the NPD requirement. The NPD requirement for repeatability was later increased. The test has not been evaluated relative the new NPD requirement for repeatability of 0,07 [%] for ultrasonic meters.

9.3 SNB - Uncertainty evaluation

The following figure presents the results from the yearly third party recalibration of the ultrasonic meter. The calibration was performed using the normal fluid and a helical turbine meter as a calibration transfer meter. Different points at the same date represent the results at different flow rates over the operational range. As the metering station is an allocation metering station, the calibration interval was eventually reduced to bi-yearly.



Based on the charts above it seems reasonable to state that:
For Reynolds number in the range 250 000 to 700 000. If the meter is calibrated on representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than 0.11 [%] at 2 standard deviation from the true value.

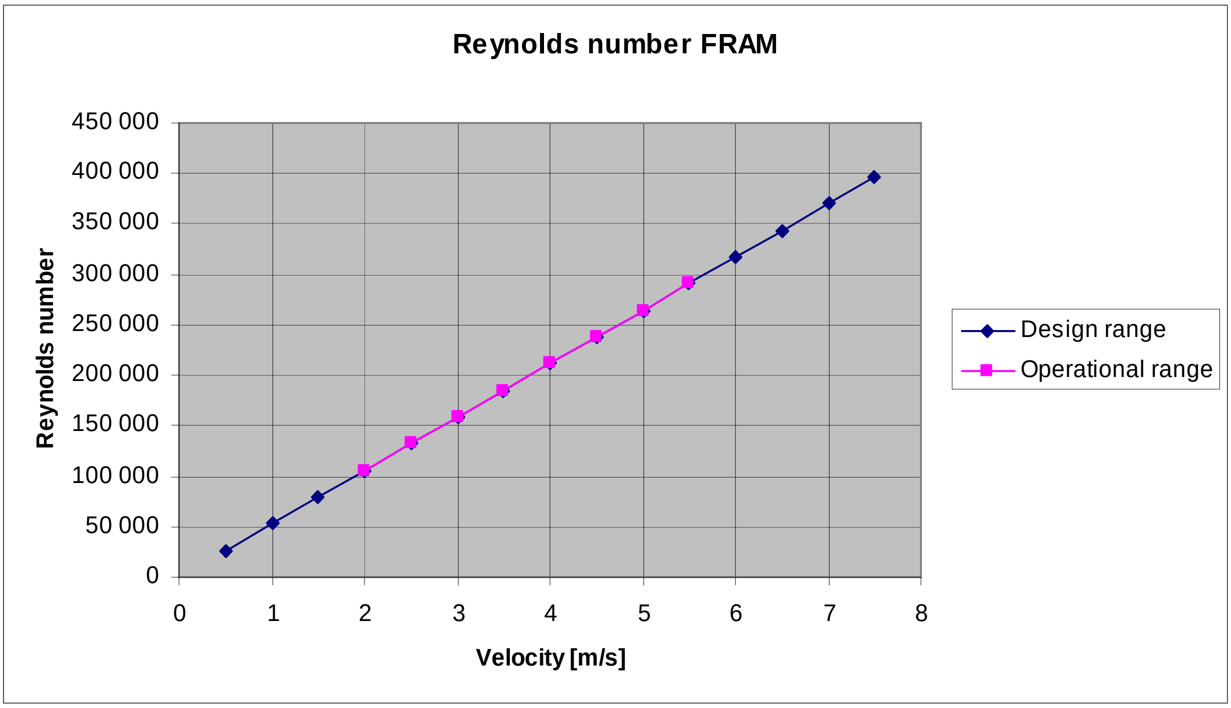
10 Fram - Two ultrasonic meters in series and a bidirectional prover.

10.1 Fram – Description

The following table contains key information for this metering station.

Installation Year	yyyy	2002	
Pipe inner Diameter	m	0,16110	(Throat diameter [m]: 0,125, Beta ratio: 0,77592)
Meter nominal diameter	Inch.	6”	
Upstream straight length	Number of ID	20 USM 1 (10 between USM 1 & 2)	
Downstream straight length	Number of ID	13 (USM 2)	
Flow straightener type		Etoile	
Filter	Yes / No	Yes	
Meters in series (Yes / No)	Yes / No	2	
Number of meters in parallel		0	
Normal pressure	Barg	25-30	
Normal temperature	DegC	40-50	
Normal density	Kg/m3	815-825	
Normal water content	%	0,5	
Normal Viscosity	mm2/s	2-3	
Meter flow range	M3/h	37-737	
Operational Flow range	M3/h	60-673	
Operational Velocity range	m/s	0,5 - 10 m/s	
Operational Reference (Master meter / compact prover / bidirectional prover).		Bidirectional prover	

The following chart shows the Reynolds number in the operational range for the meter.



10.2 Fram - Operational experience

It has been experienced that an Etoile flow straightener has broken inline during operation.

During a short period the temperature conditions at the metering station caused wax build up. The metering station was shut down two times to remove wax. Fortunately new wells were brought on-line bringing the temperature over the wax formation temperature. Wax seriously affected the meters. The difference between the measurement results from the two meters was regarded to be unacceptable.

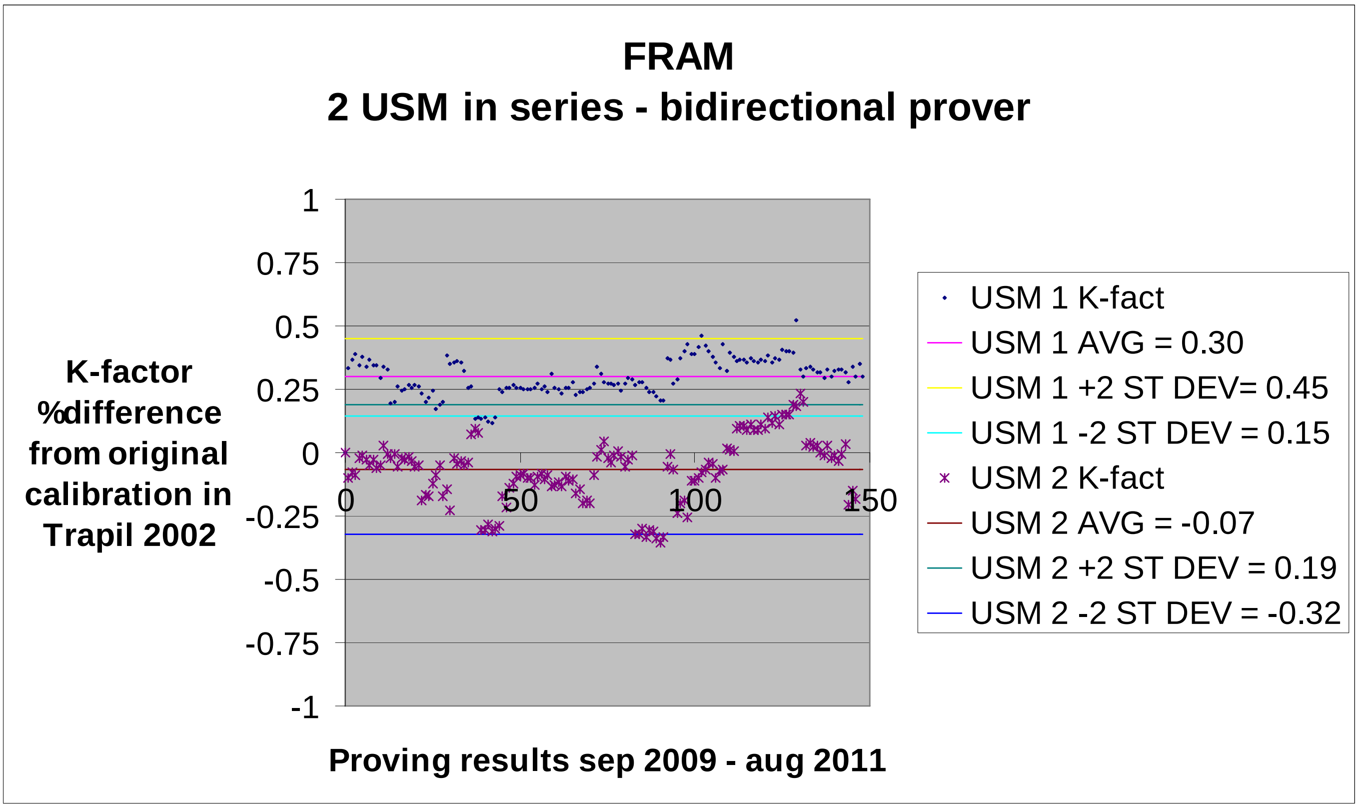
This is consistent with experience from another metering station (Vale) where wax caused the difference between a 2 path ultrasonic meter and a 5 path ultrasonic meter to increase to more than 15 [%]. In this case the wax problem was avoided by operating a heater upstream the metering station. The heater heated the wax over the melting temperature and the wax rapidly disappeared.

The experience with wax from the Fram metering station demonstrates that there seems to be no reason to frighten that wax will affect both meters equally and thereby causing a systematic error which is not discovered. The wax build-up seems to rapidly affect the meters significantly.

10.3 Fram - Uncertainty evaluation

The following chart shows the calibration results in the period September 2009 to august 2011. The proving results from before September 2009 were not readily available.

In this chart the difference from the calibration factor achieved in the original calibration at Trapil in 2002 and the individual calibration results in operation is shown. The average calibration factor from calibration on 95 octane petrol in Trapil 2002 has been chosen as the zero line.



If we now make the thought experiment that the calibration you base all your measurements on - could be any one of the achieved K-factors. If the thought experioment is applied on the charts above it seems reasonable to state that for:

USM1:
For Reynolds number in the range 100 000 to 300 000. If the meter is calibrated on representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than 0.45 [%] at 2 standard deviation from the true value.

USM2:
For Reynolds number in the range 100 000 to 300 000. If the meter is calibrated on representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than 0.32 [%] at 2 standard deviation from the true value.

It is important to note that this is a high estimate for uncertainty as this uncertainty estimate is based on one calibration only. If you did not have a prover you would clearly perform more than one calibration possibly on several fluids and create a K-factor curve for the meters. It is also important to note that if your measurement result is taken as the average of the two meters the uncertainty will be reduced correspondingly.

11 Summary

11.1 Design considerations based on operational experience

The experience from SNB demonstrates that a filter 10 Diameters upstream from the meter, and no flow conditioner in between, will negatively affect the meter. As there are no moving part in the ultrasonic liquid meter there is no reason to add filters upstream of the ultrasonic meter. The filter should be placed elsewhere if required at all.

A study performed in 2002 ref [3] concluded that the Etoile flow straightener seemed to be superior to the tube bundle flow straightener. However the Etoile flow straighteners design may be weak, we have experienced in-line break down of three different flow conditioners of this type. The problem was solved by increasing material thickness and welding quality. Let the piping discipline determine design requirements and verify the construction of such conditioners. Flow conditioners should be treated as a piping element.

The experience from SNB indicates that a flow conditioner plate seems to work just fine. However the pressure drop may be higher for a conditioner plate than for an Etoile flow conditioner. The pressure drop should be evaluated if important for the design.

Do not expose the ultrasonic meter for significant amounts of free water. Make sure to get rid of free water before the metering station. Water fraction as low as 0,5 to 2,0 [%] in condensate with viscosity of 0.4 [mm2/s] and density of 610 [kg/m3] has been experienced to negatively affect the lower path of an ultrasonic meter. Water fraction somewhere between 5 – 15 [%] has been experienced to cause fall out of ultrasonic meters for fluid with a viscosity of 2,5 [mm2/s] and density of 810 [kg/m3]. It has also been experienced that ultrasonic meters has stilled worked satisfactory at water fractions of 20-25 [%] in a fluid with viscosity of 200 [mm2/s] and density of 930 [kg/m3]. Hence the tolerance for free water seems to be higher for high viscosity / high density liquid than for low viscosity / low density liquids.

Further, high Reynolds number is no indication that you will have with sufficient mixing of water in oil. Make sure that the mixing of water in oil is calculated in accordance the ISO 3171 or by another feasible method.

If the metering station may be exposed to scale special care must be paid to the design. There is no experience from any problem with scale for any of the metering stations evaluated in this paper.

If the metering station may be exposed to wax special care must be paid in the design. It has been experienced that liquid ultrasonic meters is seriously affected by wax build up. It has also been experienced that a heater upstream the metering station can solve the challenge of wax appearance in the metering station (Vale). This may be a better solution than regular dismantling and cleaning or a design with flushing connections etc.

The experience with wax from the Fram metering station is that there seems to be no reason to frighten that wax will affect both meters equally and thereby causing a systematic error which is not discovered. The wax build-up seems to rapidly affect the meters significantly.

It has been tried to calibrate an ultrasonic meter directly by a compact prover. After 100 trials the repeatability was still not within the requirements.

11.2 Uncertainty evaluation based on operational experience

As claimed by the manufacturer there are no sign of K-factor drift for any of the meters evaluated in this paper.

As claimed by the manufacturer the long time reliability of the meters seems to be superior and no hardware failure of any of the meters are recorded.

The following table summarize the uncertainty evaluation based on operational experience as presented in this paper. The anticipated long time uncertainty for a flow meter based on a conventional metering station with a prover in included in the last row for reference. The uncertainty evaluated here is only the uncertainty of the ultrasonic flow meter it self. Other uncertainty contributions to the final measurement result like water in oil, density, pressure and temperature are disregarded in this paper.

Operational experience with liquid ultrasonic meters

Reynolds number	**Metering station**	**Meter**	**Pipe inner diameter [m]**	**Long term uncertainty at 2 standard deviations**	**Uncertainty when long term result is average of two uncorrelated meters in series. U1 =U / SQRT(2)**	**Risk for Loss when long term result is average of two uncorrelated meters in series R = 0.2 * U1**
800 – 1600	NOB	USM1	0.154	Non conclusive		
	NOB	USM2	0.154	Non conclusive		
8 000 – 11 000	GOHS	USM1	0.311	0.3 [%]	0.2 [%]	0.042 [%]
	GOHS	USM2	0.311	0.3 [%]	0.2 [%]	0.042 [%]
	GOHS	USM3	0.311	0.3 [%]	0.2 [%]	0.042 [%]
	GOHS	USM4	0.311	0.3 [%]	0.2 [%]	0.042 [%]
	GOHS	USM5	0.311	0.3 [%]	0.2 [%]	0.042 [%]
100 000 – 300 000	FRAM	USM1	0.161	0.45 [%]	0.32 [%]	0.063 [%]
100 000 – 300 000	FRAM	USM2	0.161	0.32 [%]	0.23 [%]	0.045 [%]
150 000 – 450 000	SNA	Master meter	0.200	0.09 [%]	0.06 [%]	0.013 [%]
300 000 – 750 000	SNB	Master meter	0.200	0.11 [%]	0.08 [%]	0.016 [%]
For reference:						
Any	With Prover			0.04 [%]	NA	0.008 [%]

Uncertainty at 2 standard deviations can be interpreted as:
If the meter is calibrated using representative fluids and flow rates before the meter is put into operation - you would expect to find the long term accumulated value to differ less than the stated uncertainty at 2 standard deviations from the true value. The value for uncertainty at 2 standard deviations is taken from the uncertainty evaluation for each metering station.
It is important to note that these are high estimate for uncertainty as the uncertainty estimate is based on individual proving results at single flow rates. In practice you would clearly perform calibration on more than one flow rate, and most likely on more than one fluid, to create a K-factor curve for the meters.

Uncertainty when long term result is average of two uncorrelated meters in series U1 =U / SQRT(2).
The reasoning behind this uncertainty estimate is that if you put 2 meters in series, you would achieve the lowest uncertainty by letting your measurement result be the average of the result from each of the meters. It might be to optimistic to regard the two measurements as uncorrelated. But this may counter the overestimation of uncertainty which arise as the uncertainty evaluation is based on individual proving results at single flow rates, while a calibration at a calibration facility would typically consist of several flow rates and most likely several fluids.

Risk for Loss when long term result is average of two uncorrelated meters in series R = 0.2 * U1:
Reference is made to [1]: “Cost Benefit Analyses in the Design of Allocation Systems” paper by Phillip Stockton presented at the NSFMW 2009. When designing metering stations for allocation, you would not be interested in investing a higher sum in reduction of measurement uncertainty than the corresponding reduction in risk for monetary loss.
Risk is normally understood as probability times consequence. Uncertainty at 2 standard deviations is only defining the normal distribution and is not equivalent to risk. Phillip documents in reference [1] (section 4.1 Risked Exposure to Lost Revenue - equation 11) how risk for loss can be calculated from the normal

distribution defined by uncertainty at 2 standard deviations.

Effectively:

Risk for Loss is equal to Uncertainty at 2 standard deviations divided by the square root of 8 times π.

Consequently:

Risk for loss = 0.2 * Uncertainty at 2 standard deviations.

It must be noted that the flow regime at Reynolds number below 8 000 – 10 000 seems to be different from the flow regime at higher Reynolds number. The range from 2 000 to 4 000 is called the transitional range where both turbulent and laminar flow may occur. Below the transitional range the flow will be laminar. It seems that the performance of the meter in the well developed turbulent range can be regarded separately from the performance in the laminar or the transitional range. This paper does not contain data to support an uncertainty evaluation at lower Reynolds numbers.

For Reynolds number above 8000 to 10 000 the following seems to be valid. If you are planning to use the meter without a prover you should make sure that the meter is calibrate for the relevant flow velocity range on a range of fluids which is certain to cover the range you might expect when using the meter. Be aware that the process conditions can be significantly different from what is stated in the process data sheet, so make sure to calibrate for a wide enough range.

12 Conclusions

There are no sign of significant K-factor drift for any of the meters evaluated in this paper.

The long time reliability of the meters seems to be superior and no hardware failure of any of the meters are recorded.

Special design considerations are required for metering stations which may be exposed to wax or scale (no experience with scale is presented in this paper). It has been experienced that an inline heater can dissolve wax and prevents wax formation in the meters.

Process design considerations are required to avoid exposing the ultrasonic meters for significant amounts of free water.

The risk for loss due to uncertainty in measurement will be increased by omitting the prover from a liquid metering station with ultrasonic meters. A cost benefit analysis may show that the risk which is added by omitting the prover is acceptable to the parties in an allocation measurement. A cost benefit analysis may show that the cost of adding a prover to the design is higher than the risk for loss for the parties. Hence it may be feasible to design a metering station with two meters in series without a prover or a master meter in a separate by-pass.

By putting two meters in series excellent facilities for monitoring is integrated in the design. Even though significant drift or failure of a meter is not expected from our experience, such monitoring will reveal significant drift or failure of one or both meters or the metering run. By putting two meters in series redundancy for the instruments are integrated into one metering run.

Based on the experience evaluated in this paper it may not be wise to design a metering station without a prover at Reynolds number below 8 000. At least consistent data will be required in order to prove that a design without prover is feasible at these Reynolds numbers. Lower Reynolds number than 8 000 will occur for heavy crude oil with high viscosity.

It is important to be aware that the meters evaluated in this paper was manufactured 8 – 13 years ago. The hardware, software and performance of the instrument may have improved (or deteriorated) since that. It is also important to be aware that the performance of the meters documented here is no guarantee for future performance at the same or at other flowing conditions. In the perspective of this paper, calibration and evaluation of calibration results will be required to demonstrate performance of a meter within the uncertainty requirements for the meter.

13 References

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