

In-situ effects on ultrasonic gas flowmeters

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Abstract

This paper describes the course of events which led to the discovery of a significant mis-measurement on Gjøa platform's gas export from the operator's point of view. The mis-measurement has persisted since Gjøa's start-up, almost five years ago. The paper closes with lessons learnt from a two year long investigation and tries to clear up some common misconceptions on ultrasonic gas flowmetering.

The gas export on Gjøa is a cross-border measurement between Norway and UK. There has therefore been a large emphasis on the accuracy, calibration and diagnostic capabilities of Gjøa's gas export since the beginning, for operators and regulators from both countries alike. The design of the gas export system comprise of two 12" ultrasonic meter runs with 100% capacity to facilitate removal of flowmeters for calibrations without stop of production. The diagnostic capabilities of the export USM are fully utilised by logging of hourly and daily diagnostic data.

An accidental switchover from duty to stand-by meter run led to the discovery that metering run one was overmeasuring metering run two by ca. +2%, appearing as a sudden change in flow rate. Furthermore, sudden but stable flow profile changes were observed on meter run two which temporary led to 2-3% more flow. Process venturi meters in vicinity of the export meters could not confirm the flowrate changes measured by the gas export station during the switchover. Tracable calibrations onshore show no evidence that the flowmeters have drifted or are erroneous. Three flowmeters are swapped among two metering runs, all flowmeters have therefore been installed in any of the metering runs. The mis-measurement is therefore not related to any of the individual flowmeter but the meter run in operation, which increases the suspicion on flow profile effects as the root cause.

In conclusion, operators have to increase their awareness over profile parameters and its influence on flowmeter performance. Non-ideal in-situ flow profiles might have serious effects on the measured flow, even when the USM has passed the ISO 17089 type test. The type test should not be seen as a guarantee that the flowmeter is able to handle all perturbations, but rather as an uncertainty budget when the profile is unknown. When the flow profile is non-ideal, a more detailed assessment of the profile and its implications is required. A non-ideal profile can cause a systematic bias and lead to significant mis-measurements over time. Transferability of traceable onshore calibrations must be questioned when the profile measured on-site is different from that obtained during calibration.

1 Introduction

Gjøa is a semi-submersible floater, located in the North Sea ca. 47km from the Norwegian shore. Construction started in 2007 with Statoil as the operator during the construction phase, while Engie took over as operator for the production phase in end of 2010. Five subsea templates from Gjøa field and three from Vega field are tied-back to the Gjøa platform.

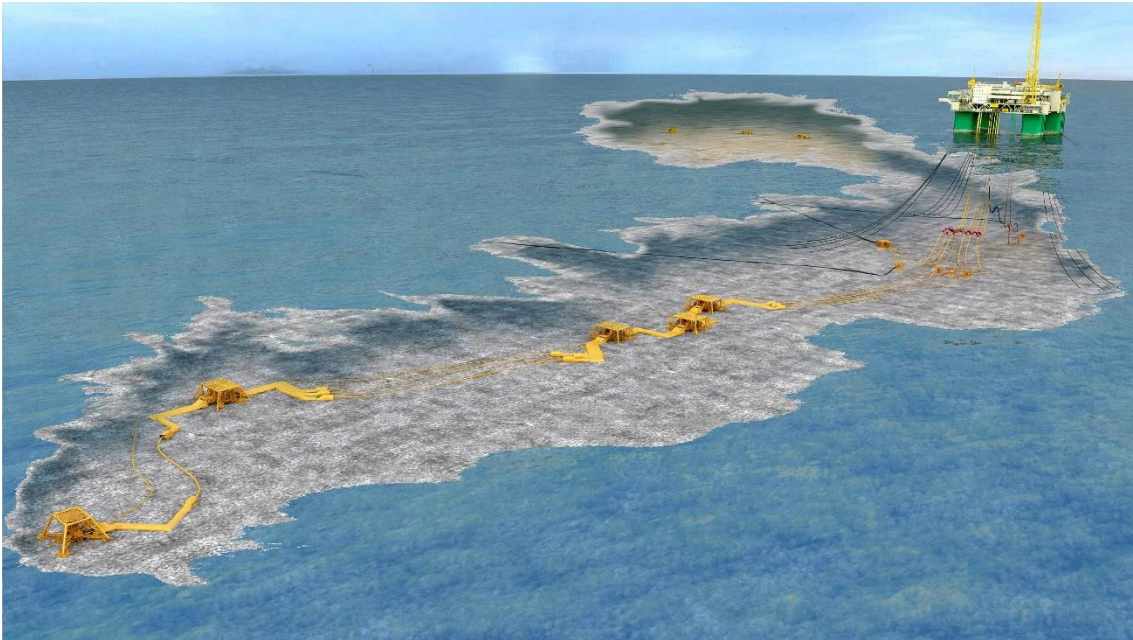


Fig 1-1: Gjøa illustration (Statoil 2015)

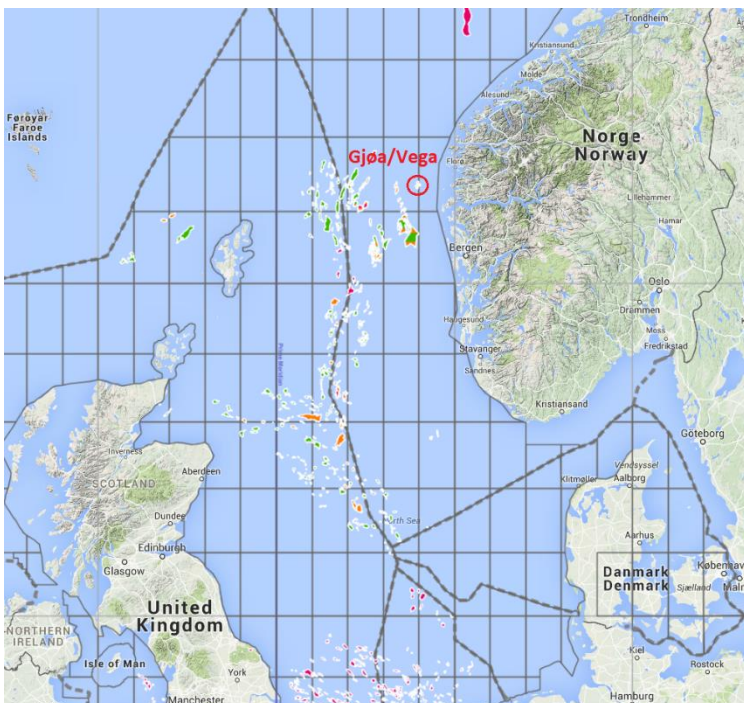


Fig 1-2: Position of Gjøa semi (Norsk Oljemuseum 2015)

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The produced oil is exported to the Mongstad refinery via the Troll pipeline, while the gas is exported via the Gjøa gas pipeline (operated by Gassco) and the Far North Liquids Associated Gas System (FLAGS, operated by SEGAL consortium) for further processing at the St.Fergus gas plant in the UK. Gjøa represents the majority of gas transported in the FLAGS, as its capacity is ca. 33 MSm³/d (Shell 2015a), while Gjøa's export capacity is approx. 18 MSm³/d (Norwegian Petroleum Directorate 2015). Gjøa's fiscal gas export measurement is therefore critical due to:

- Gjøa's substantial contribution to quantities transported through FLAGS
- Cross border export from Norway to UK
- Allocation of various platforms connected to FLAGS

The importance of Gjøa's gas export measurements for both nations has been present from day one and has therefore been designed to comply to metering regulations from both UK and Norway.

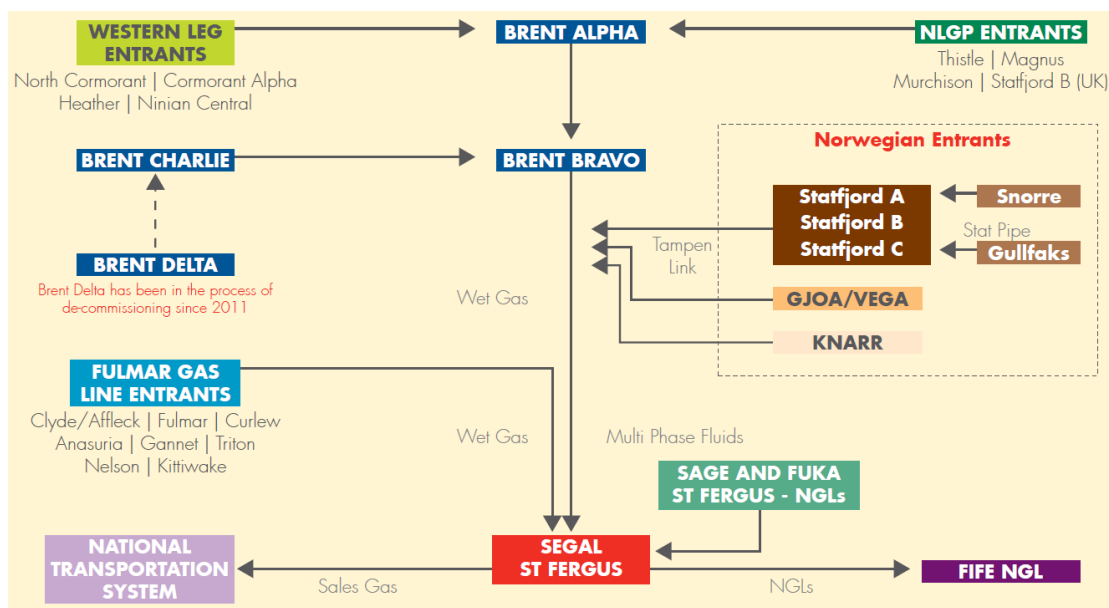


Fig 1-3: FLAGS Overview (Shell 2015b)

2 System description

2.1 Gjøa's fiscal gas export system

2.1.1 Arrangement and layout

Following equipment are of relevance for this investigation:

- Fiscal ultrasonic meter in meter run 1 (in spring 2013: SN# 2259)
- Fiscal ultrasonic meter in meter run 2 (in spring 2013: SN# 2257)
- Spare fiscal ultrasonic meter in logistics base onshore (in spring 2013: SN# 2258)
- Non-fiscal process venturi 27FE1131 (compressor venturi)
- Non-fiscal process venturi 27FE1312 (PPS venturi)

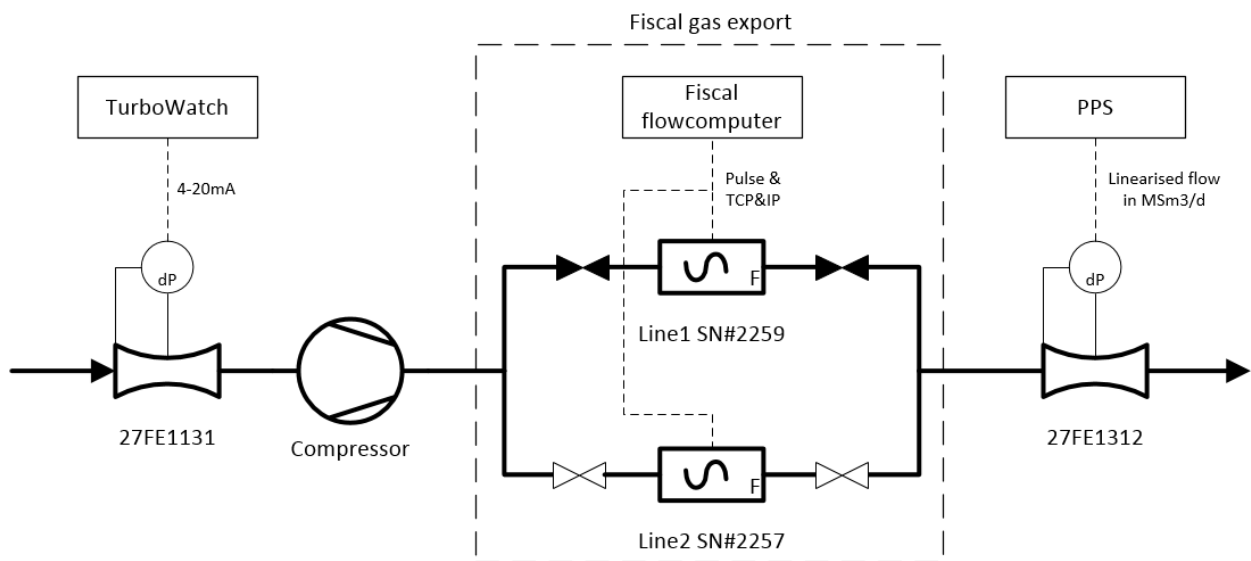


Fig. 2.1.1-1: Gjøa's fiscal metering station with process flowmeters up- and downstream

The fiscal USMs are arranged in a parallel configuration designed for 2 x 100% flow. Under normal operation, one run is on duty while the other run is on stand-by. The non-fiscal process flowmeters are package flowmeters of the compressor system and the Pipeline Protection System (PPS). These flowmeters are not relevant for the fiscal export, but are used as benchmark during the investigations.

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The fiscal metering station features following elements (in order of flow direction):

- Equally sized, symmetric header with blind tees at both ends
- Double block & bleed isolation valve of "split gate" type
- CPA flow conditioner flanged on the isolation valve
- 15D upstream straight length
- Ultrasonic flowmeter
- 9D downstream straight length
- Dual gas chromatographs
- Dual pressure and temperature transmitters and single densitometer

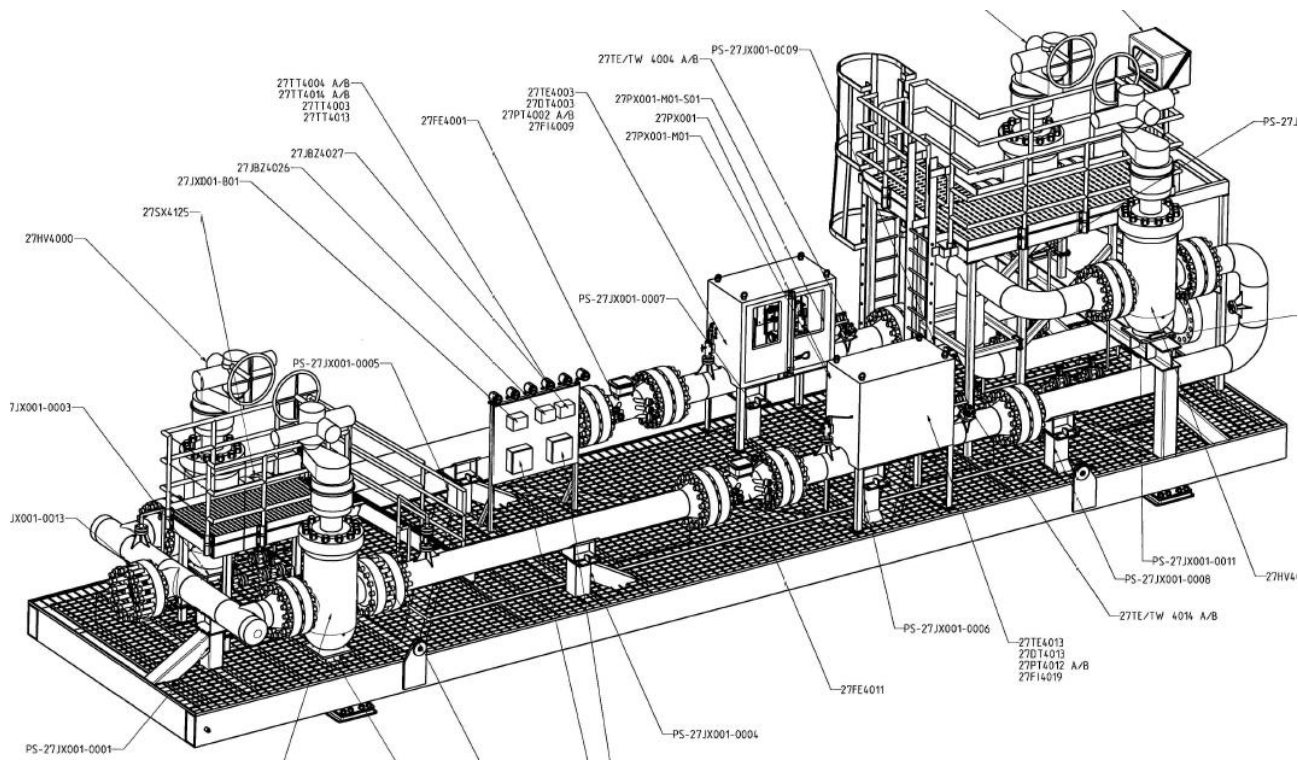


Fig 2.1.1-2: General arrangement fiscal metering station (GDF SUEZ E&P NORGE 2010)

2.1.2 Fiscal Ultrasonic Flowmeter (USM)

All three flowmeters are transit time USMs with six sound paths on four planes. Sound paths are crossed on the first two planes, while the two lower paths are single sound paths without crossing. Hence, path one and two are crossed on the 1st plane while path three and four are crossed on the 2nd plane. Path five and six are single paths, located in plane three and four respectively.

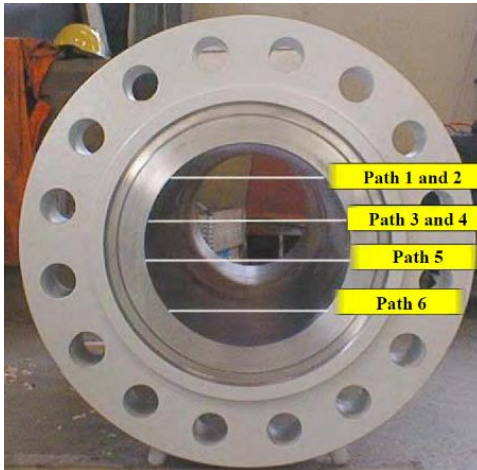


Fig 2.1.2-1: Cross section of an ultrasonic gas flowmeter used on Gjølå semi (FMC Technologies 2008)

The ultrasonic technology and the setup of the transducer paths is well known for all models of all manufacturers. However, the interpretation of the transit time measurements and their conversion into a flowrate is naturally proprietary information and well protected. It is nevertheless of utmost importance for the operator to know the basics of the proprietary algorithms in order to find the reason for an eventual mis-measurement. Transit time measurements from all six sound paths are used for evaluation of profile flatness, asymmetry, cross-flow and swirl.

Profile flatness

The ratio between the flow velocities in the center of the pipe and the top/bottom of the pipe is defined as the profile flatness. This ratio is expressed as a percentage of the core velocity. Hence, values close to 100% means that the flow velocities on the top and bottom of the pipe are the same as the velocities in the center of the pipe. A low profile flatness means that the top/bottom velocities are lower than the core velocities and indicate a more "pointy" axial velocity profile.

Symmetry

The ratio between the flow velocities on the top two levels and the bottom two levels is defined as symmetry. This ratio is expressed as a percentage. Positive values mean that the flow on the top is faster than the flow on the bottom.

Swirl and Cross-flow

The ratio between the axial and tangential flow velocities is defined as swirl and cross-flow. Hence, 1% swirl means that the tangential velocities amount to 1% of the axial velocities. The profile is interpreted as swirling, if the tangential flow directions on the first and second level are the same. Hence, assuming that the gas flow turns around the entire pipe. The profile will be interpreted as cross-flow if the tangential flow directions are opposite for the first and second level. Hence, assuming that there is at least one swirl center in the top section of the pipe.

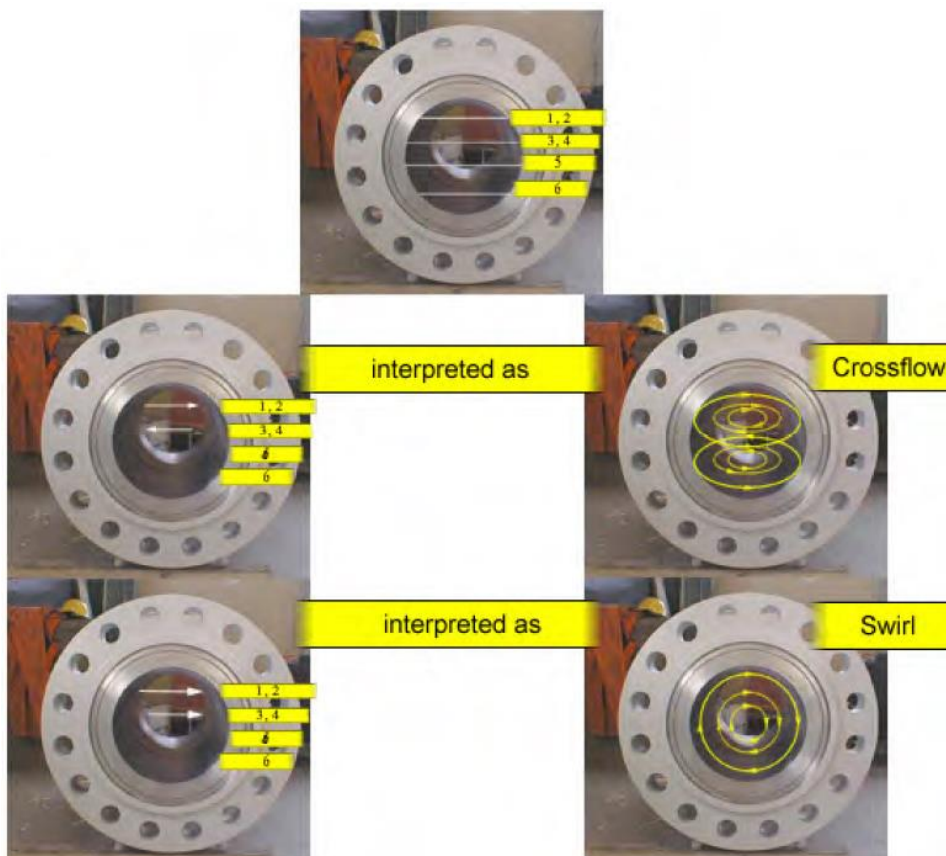


Fig. 2.1.2-2: Interpretation of path velocities (FMC Technologies 2008)

2.1.3 Accredited onshore calibration of fiscal USMs

All gas export USMs are subject to a six monthly re-calibration where the duty flowmeter is replaced by a calibrated USM and sent to an accredited calibration laboratory onshore. All flowmeters performed well during all calibrations and showed less than 0,3% drift from their previous calibration.

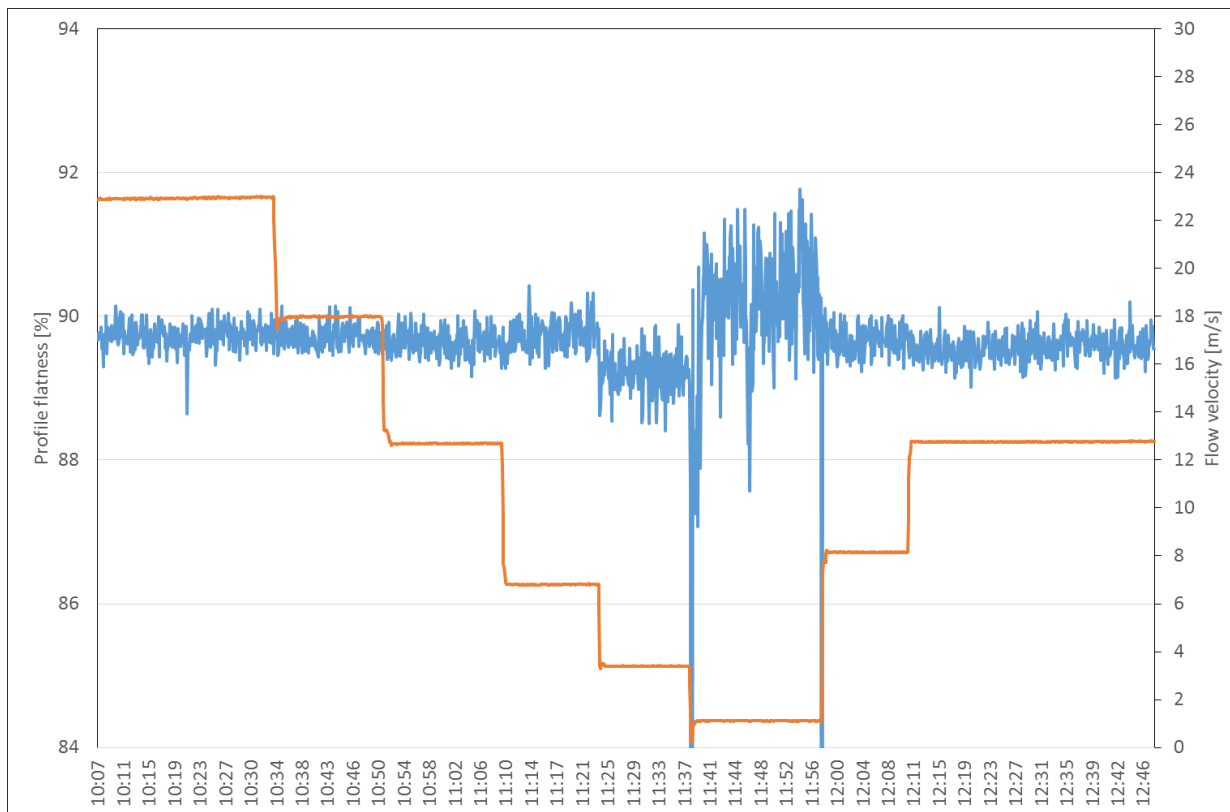


Fig 2.1.3-1: Profile flatness during a typical onshore calibration

2.1.4 Condition monitoring

All fiscal flowmeters are under constant supervision. The diagnostic capabilities of the ultrasonic flow meters are fully utilised on Gjølå. Following parameters are logged hourly and monitored on a monthly basis:

- Deviation of measured Speed of Sound (SOS) against calculated SOS (AGA10)
- Profile flatness
- Swirl
- Symmetry
- Signal to noise ratio

Cross-flow is usually not used for condition monitoring as the cross-flow experienced on Gjølå is not stable enough to be monitored. Footprint as described in ISO 17089 is available, but usually not monitored as even small changes in flow profiles lead to significant changes in the footprint.

3 Order of events

Several incidents in spring 2013 raised doubts on the technical integrity of the fiscal gas export station with USM SN#2259 and SN#2257 installed in meter run one and two respectively.

- **December 2012 Meter run two taken into operation with SN#2257**

Installation of SN#2257 in run two as new duty flowmeter, with SN#2259 switched to stand-by in run one. SN#2258 was removed from run two for scheduled re-calibration.

- **February 2013 Accidental swap from meter run two to meter run one**

The control system accidentally swapped from metering run two to metering run one. A sudden step change of ca. +2% in flow could be observed, while all diagnostic parameters were normal without any alarms.

- **April 2013 Detection of profile peaks on metering run two**

Sudden and temporary changes of the flow profile were observed on metering run two with SN#2257. The profile flatness increased from ca. 85% to ca. 95%, while swirl and asymmetry changed in value and direction. The increased profile flatness led to an increase of average flow velocity and resulted to an increase of flow by ca. 3%. These profile peaks were extremely repetitive and stable for ca. 10s – 3h, before returning back to its usual flow profile. SN#2257 showed no errors or configuration changes since it was installed in December 2012. All diagnostic parameters were normal.

- **June 2013 Flowtest with metering run one**

An in-situ flowtest was performed to check whether metering run one is exposed to the same profile peaks as in metering run two. When the export was swapped to run one, a +2% step change could be reproduced like earlier. However, neither the downstream PPS venturi or the upstream compressor venturi could confirm the change of flow. Metering run one showed no signs of profile peaks as expected.

- **September 2013 Parallel flowtest with both meter runs**

A parallel flow test was initiated to measure the flowprofile of both flow meters at the same time. The export was switched from single run to parallel export, then run two was closed for single export with run one. Single run export with run one was measuring more than single export with run two as observed earlier. Furthermore, it could be observed that parallel export with both runs measured almost no swirl and assymetries. The measured flow during parallel export was between single export with run two and run one.

- **October 2013 New parallel flowtest with replacement of SN#2257**

A new parallel flow test was initiated in October 2013 as SN#2257 (the USM which measured profile peaks) shall be re-calibrated and replaced with SN#2258. The purpose was to see whether the profile peaks and step change phenomenon can be reproduced with a different flowmeter in run two. This made it also possible to check SN#2257 with an onshore calibration. SN#2257 was replaced with SN#2258 and the same test done in september 2013 was repeated. Both step change and profile peak phenomenons could be reproduced, with a different meter in run two. All observations during the test were predicted, and the test proved that both phenomenons are independent of the flowmeter in use and applies to all export USMs. This raised suspicion on other flowmeters on Gjøa, as the same brand and model of flowmeters were also utilised in other parts of the process system. All USMs were switched to parallel operation in order to limit the amount of swirl and a potential mis-measurement.

Further investigations and Computational Fluid Dynamic (CFD) simulations were carried out by Christian Michelsen Research (CMR) and Metropartner. The investigations were concluded in January 2015, details of the executed CFD simulation are covered in a separate NSF MW paper (Sætre, et al., 2015).

4 Observations for profile peaks

The properties of the observed profile peaks in metering run two can be summed up as follows:

4.1 Stable and predictable profile changes

Changes in the measured flow profiles are very stable and predictable. Profile flatness increases, swirl and asymmetry change value and direction. All other diagnostic parameters are stable. The observed changes in flow profile have been observed on every investigated profile peak. The increase of the profile flatness leads to an increase of measured flowrate of ca. 3%, as an increase of the flow velocity in the vicinity of the pipe wall leads to an increase of average flow velocity. Flow peaks have not been detected so far during any calibration.

	Run two normal operation	Run two operation during peaks
Profile flatness	83%	96%
Swirl	-1,8%	+1,8%
Symmetry	+5,2%	-2,9%

Tab. 4.1-1: Typical profile parameters in periods with profile peaks

4.2 Unpredictable occurrence

Occurance of profile peaks cannot be predicted. The appearance of profile peaks vary between once every 48h and several times within 12h. Profile peaks could be observed since SN#2257 was installed in December 2012, but not before. It was not possible to relate the profile peaks to opening, closing & leakage of valves or operation of any other process equipment. Profile peaks have been observed with any flow velocity between 0% - 87% of design flowrate.

4.3 Variable in duration

The duration of profile peaks lasts typically 10-25min, but durations from 10s up to 3h have also been observed.



Fig. 4.3-1: Changes in profile flatness (red), symmetry (yellow) and swirl (green) in periods with peaks

5 Observations for step change

Gas export was switched from the duty run to the stand-by run in three occasions. A significant increase of flow could be observed every time when the export was switched from run two to one. Below figure shows the flow during single and dual run export with the PPS and compressor venturi as benchmark.

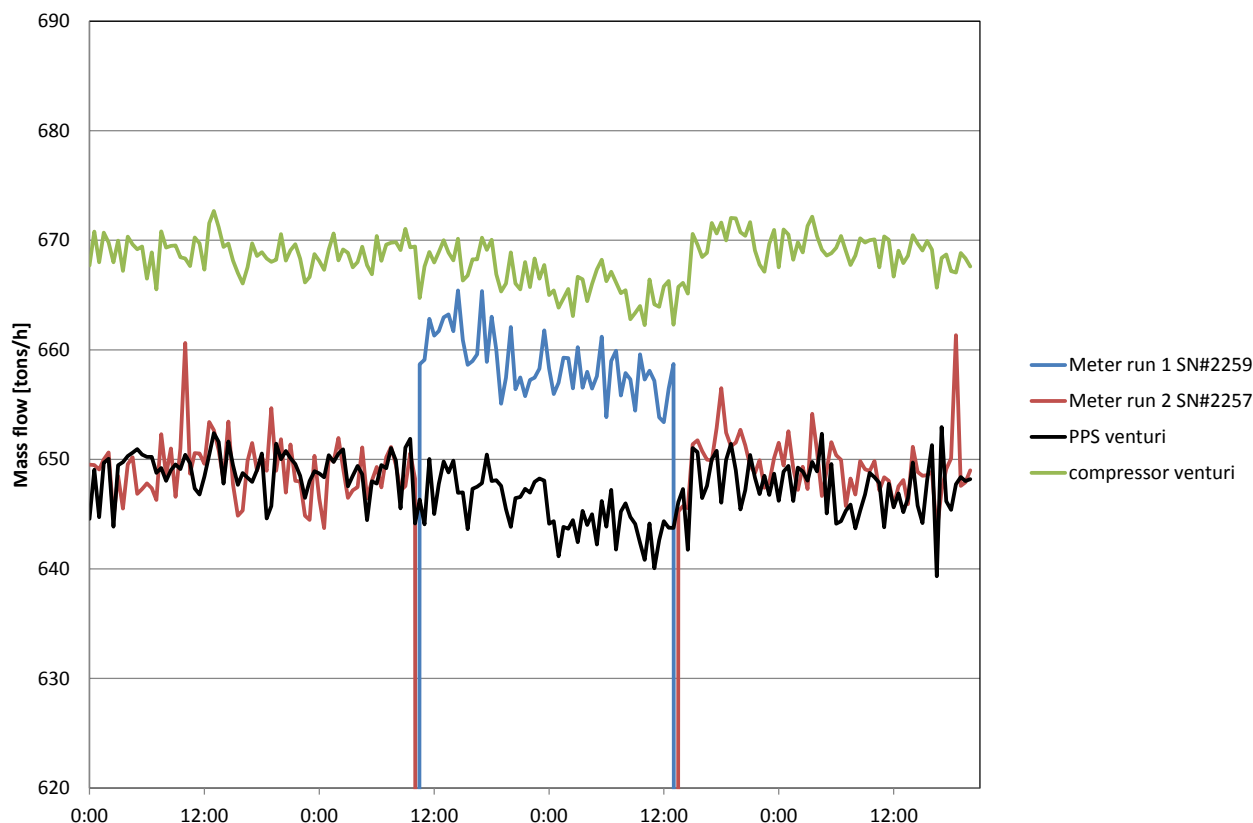


Fig. 5-1: Single export test in June 2013

	Deviation against PPS venturi		
	Dec 2012	Feb 2013	June 2013
Metering run 2, SN#2257	+0,39 %	+0,16 %	+0,15 %
Metering run 1, SN#2259	+1,88 %	+2,08 %	+2,04 %
Compressor venturi	+3,16 %	+3,44 %	+3,22 %

Tab. 5-1: Deviation against PPS venturi

Flow deviations from the PPS venturi were systematic, stable and reproducible for all incidents. In general, measured values from the PPS venturi agrees well with metering run two, while undermeasuring in comparison with metering run one and the compressor venturi. It was possible to reproduce the sudden change of flow each time when the metering run was changed.

6 Discussion

6.1 Malfunction and external influences

It is impossible that the step changes and profile peaks are a result of malfunctions or external influences, as both phenomenons are reproducible in occurrence and predictable in outcome. Malfunctions and external influences like transducer failure, influences from weather, compressor load or variation in power supply were checked and quickly ruled out as the reason for step changes and profile peaks.

6.2 Benchmark flow meters

The compressor venturi and PPS venturi up- and downstream were used as flow benchmark against the fiscal flowmeters in this investigation. A possible explanation for these observations could be the inability of the process venturis to measure the small and sudden flow changes. The export flowmeters are frequently calibrated at an accredited flow laboratory, while the Venturi dP transmitters are not calibrated and the condition of the venturi body is unknown. Further doubts can be raised, as USMs have a higher accuracy and are based on a different physical principle. It is possible that the venturis are physically not able to measure the subtle change of flow which has been registered by the high accuracy USMs. This possibility has been investigated and is explored in this chapter. The base equation for massflow measurement for a venturi is defined in ISO 5167-4 as:

(Equ. 6.2-1)

$$\dot{m} = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta p \cdot \rho}$$

with:

C	<i>flow coefficient</i>
ε	<i>expansion coefficient</i>
d	<i>throat diameter</i>
β	<i>beta coefficient</i>
Δp	<i>differential pressure</i>
ρ	<i>line density</i>

A rough uncertainty calculation indicated an uncertainty of ca. 2% for the Venturi meters. The high uncertainty results mainly from the very high Reynolds number, leading to a high uncertainty of the discharge coefficient, and an inaccurate fabrication of the venturi body.

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The measured venturi flow corresponds well with the USMs, except during switch of runs and profile peaks. This increases the suspicion that the USMs are exposed to non-idealities in the flow profile, while Venturi meters are not affected as they are based on mass/energy conservation along a single streamline. The offset of the venturis against the fiscal export could be explained with inaccurate fabrication of the venturi, which would offset the flow metering with a systematic error. The uncertainty assessment showed that the venturis should have been able to detect a sudden 2-3% flow change during step changes and profile peaks, as their uncertainty is estimated to roughly 2%. This, despite the different functional principle of an USM and dP flow meter.

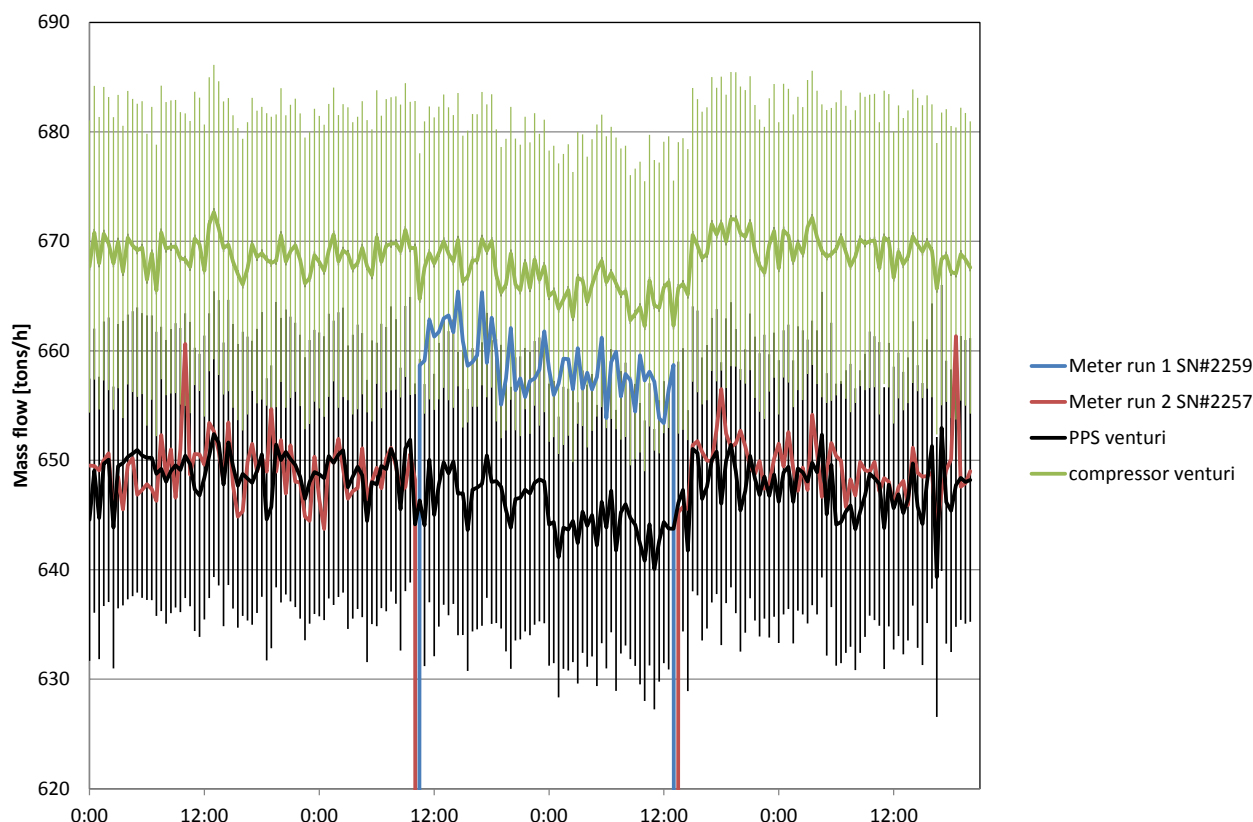


Fig. 6.2.5-1: Single export test 20th June 2013 with venturi uncertainties

6.3 Layout

Errors in the design of the metering skid or disturbances upstream of it can lead to significant disruptions of the flow profile and the performance of USMs.

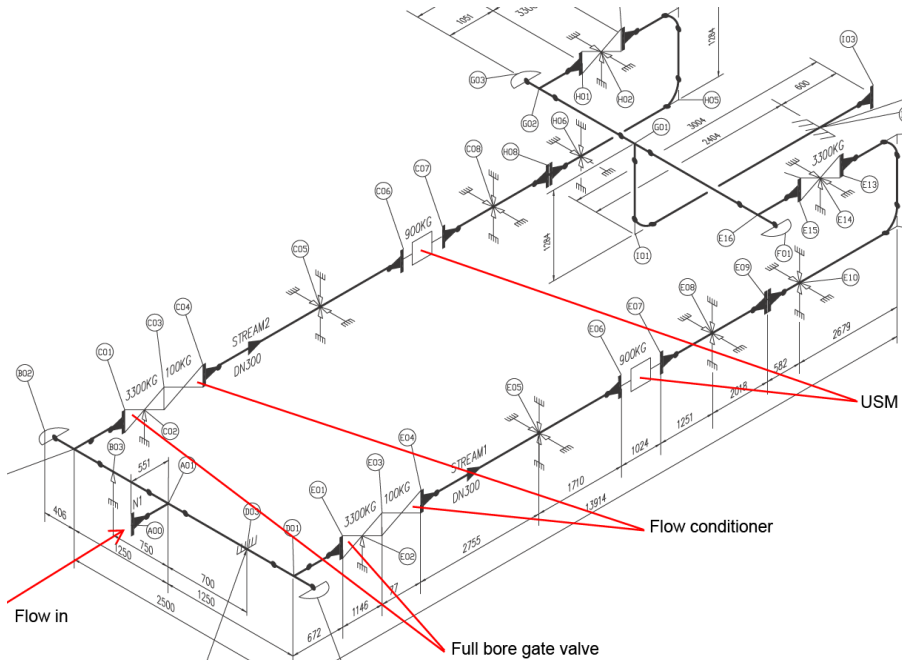


Fig. 6.3-1: Isometrics of the export metering skid (GDF SUEZ E&P NORGE 2010)

15D and 9D have been implemented as up- and downstream lengths for the USMs respectively, this is more than required according to NORSOK I-104. The flow conditioner is flanged directly on the isolation gate valve, which again is flanged directly on the inlet header. Upstream straight lengths are therefore not available for the flow conditioners. One could argue whether the isolation gate valve and parts of the blind tee from the header arrangement could be seen as upstream straight length as the gate valve is full bore.

The gas flows through a u-turn after which it follows ca. 38D of straight length, before it enters the metering skid header after a right bend. Although the inlet arrangement indicate that some swirls could be produced, especially after the last bend in front of the header, there are no evidences that this setup could generate severe disturbances in the flow profile.

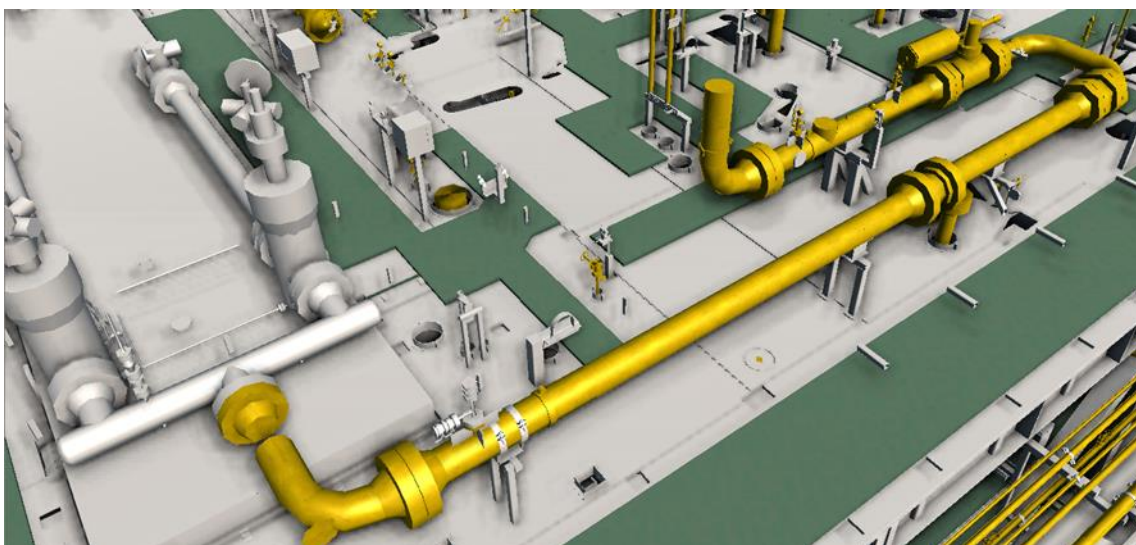


Fig. 6.3-2: Piping configuration upstream of the eksport metering skid (GDF SUEZ E&P NORGE 2010)

6.4 Tracable flow calibration

Gjøa's export USMs are subject to tracable re-calibrations after six months flowing time. Any defects on the flowmeters should be visible on the calibration results.

The export flowmeters are calibrated in accordance with ISO 17089 and the obtained flow weighted mean error (FWME) is compared against its previous calibration. A shift of 0,3% from its last calibration is contractually set as threshold value for claims on re-allocations.

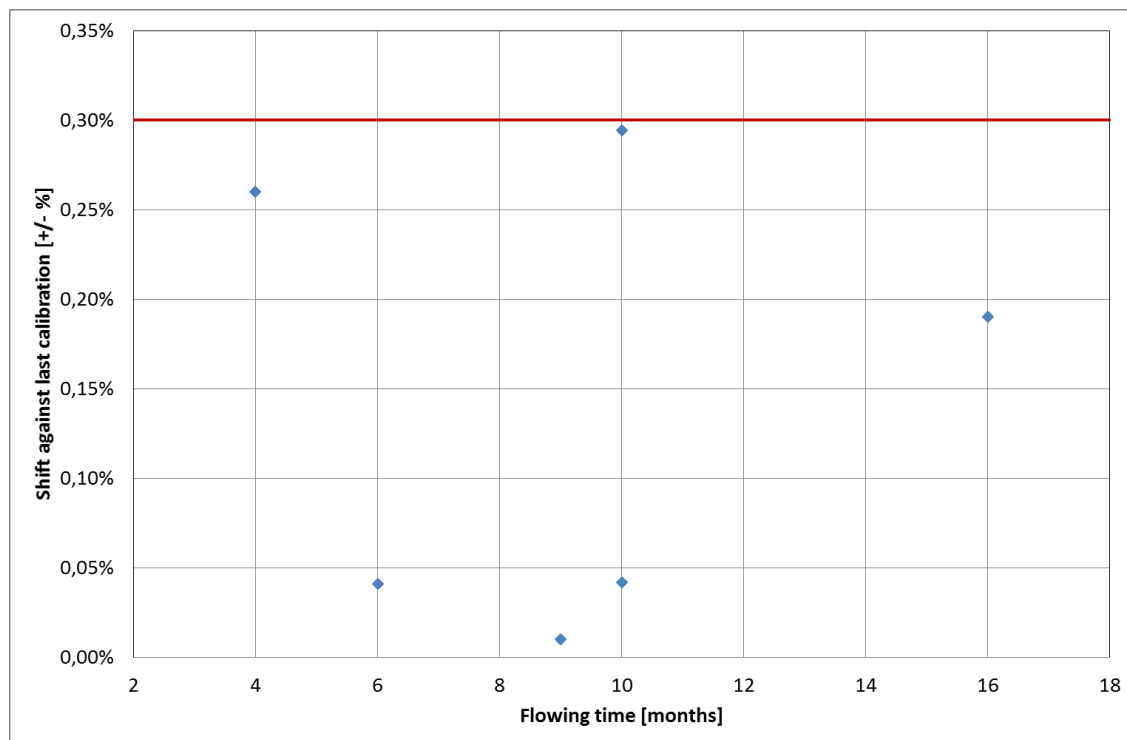


Fig. 6.4-1: Drift of export flowmeters vs. time in operation

Although very close, none of the calibrations have exceeded the threshold value of 0,3% shift from the last calibration. A relation between flowing time and shift of the flowmeters could not be found. Preliminary results from the investigations in 2013 indicated that operation of both export runs mitigated the mis-measurement. As a result, Gjøa started exporting with both runs since October 2013, causing extended flowing time for each flow meter, as only three flowmeters rotate among two metering runs. Plotting the shift against the calibrated flowrate for all calibrations gives a clear picture on the performance of each flowmeter at each flowrate.

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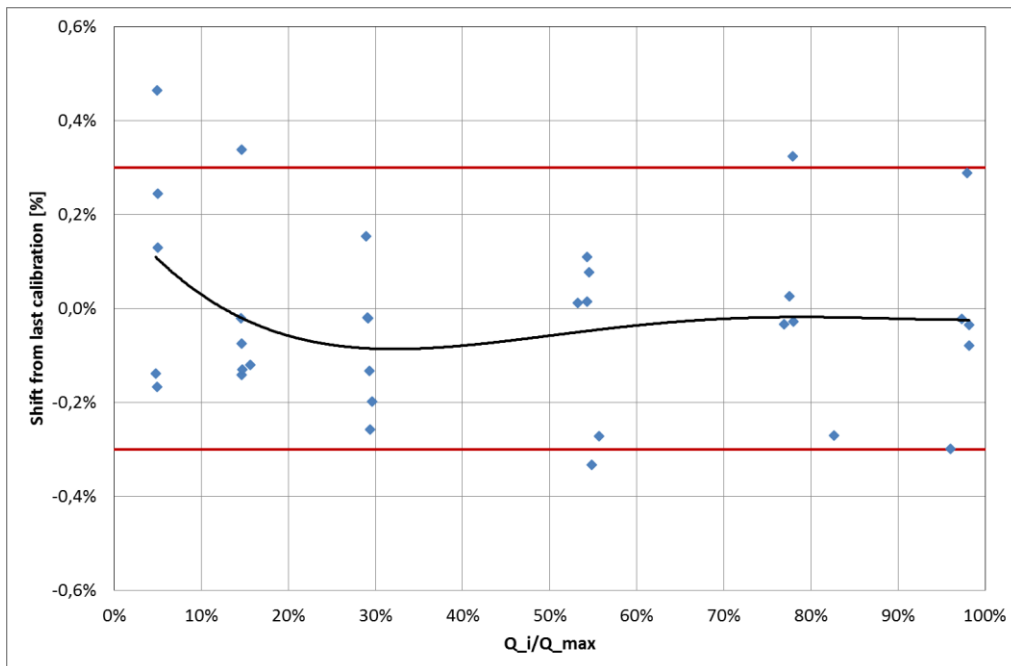


Fig. 6.4-2: Meter factor shift vs. flowrates for all calibrations

Although some of the meter factors have shifted more the 0,3% from the last calibration, none of the calibrations triggered any re-allocations as the FWA meter factor was below the threshold value and gas export was operated with meterfactors which have not shifted. Clusters of calibration points can be detected with no shift at all. FWA shift was below $\pm 0,1\%$ if a 4th order polynom is utilised to account for the outliers. Comparing the flowmeters against the flow laboratory yields an even better performance.

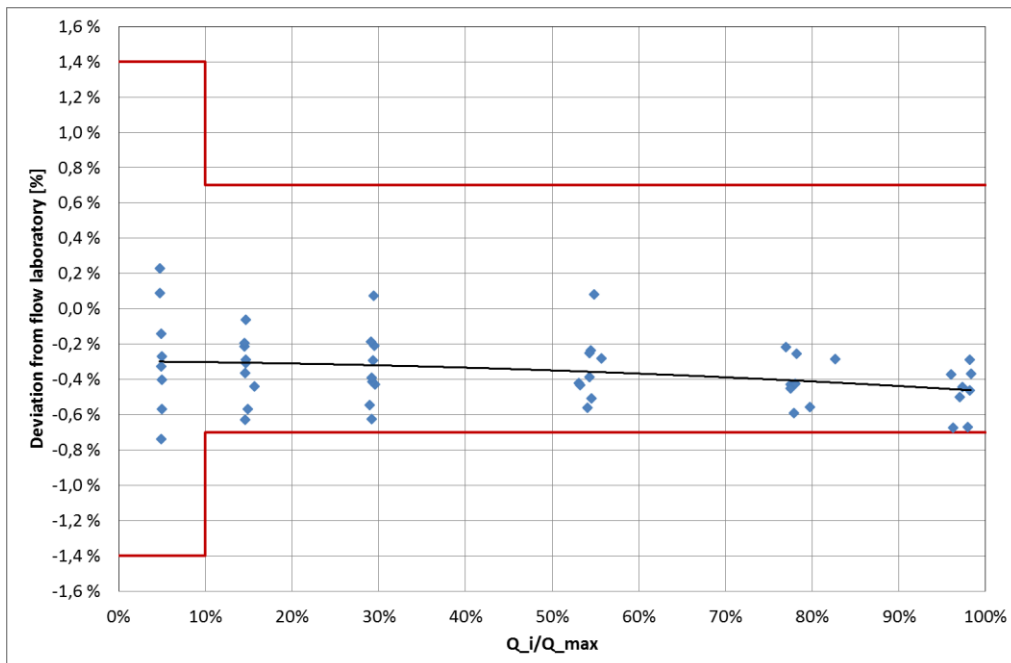


Fig. 6.4.-3: Deviation from flow laboratory vs. flowrates for all calibrations

Maximum allowed deviation according to ISO17089 is $\pm 0,7\%$ and $\pm 1,4\%$ for flowrates $> Q_{Transition}$ and $< Q_{Transition}$, respectively. The frequent recalibrations do not indicate that any of the flowmeters have been mis-measuring or shifted significantly. A correlation between time in operation and shift of the flowmeter could not be found.

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6.5 Flow profile

6.5.1 Profile during periods with peaks

Although the profile measured during periods with peaks is significant different from the normal operation in run two, profile abnormalities are not large enough to explain the observations offshore.

	Run two normal operation	Run two operation during peaks	Run one normal operation
Profile flatness	83 %	96 %	93 %
Swirl	-1,8 %	+1,8 %	+0,9 %
Symmetry	+5,2 %	-2,9 %	-1,0 %
PPS deviation	+0,24 %	+3 %	+1,9 %

Tab. 6.5.1-1: Typical profile parameters and flow during normal operation and periods with peaks

Note that the profile parameters during single export with run two becomes similar to the profile of run one, positive swirl and negative symmetry, leading to a positive deviation from the PPS venturi. The increase of profile flatness during periods with peaks explains the higher flowrate of ca. + 3% due to a higher average flow velocity. All diagnostic parameters such as signal to noise, SOS, path velocities etc. made sense and indicated no errors or conflicts in the flowmeter. As mentioned previously, the change in flow was not registered by the process venturis.



Fig. 6.5.1-1: Change of profile flatness during periods with peaks compared with SOS and signal to noise ratio

6.5.2 Historic flow profile meter run one and two

The diagnostic capabilities of the export USMs are fully utilised on Gjøa and extensive information on the flow profiles are available since startup. Deviation between theoretical and measured speed of sound is usually below 1 m/s while signal/noise ratios show no degradation. The investigation focusses therefore mainly on profile flatness and swirls.

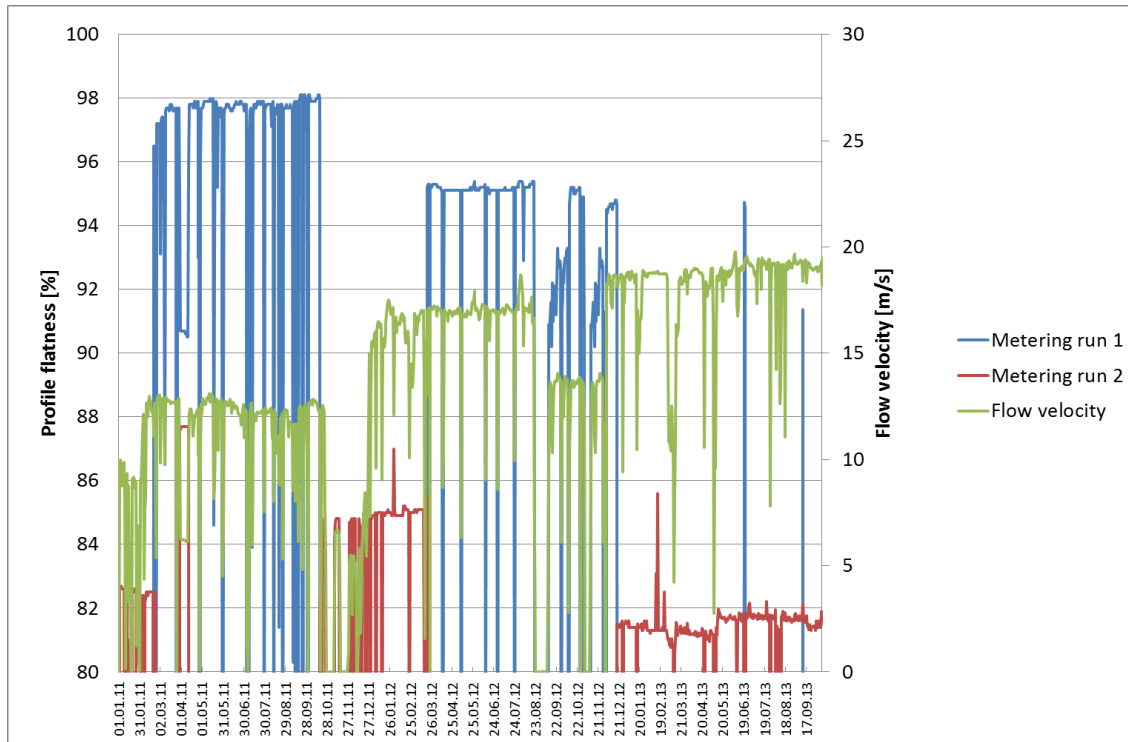


Fig. 6.5.2-1: Historic profile flatness for both meter runs

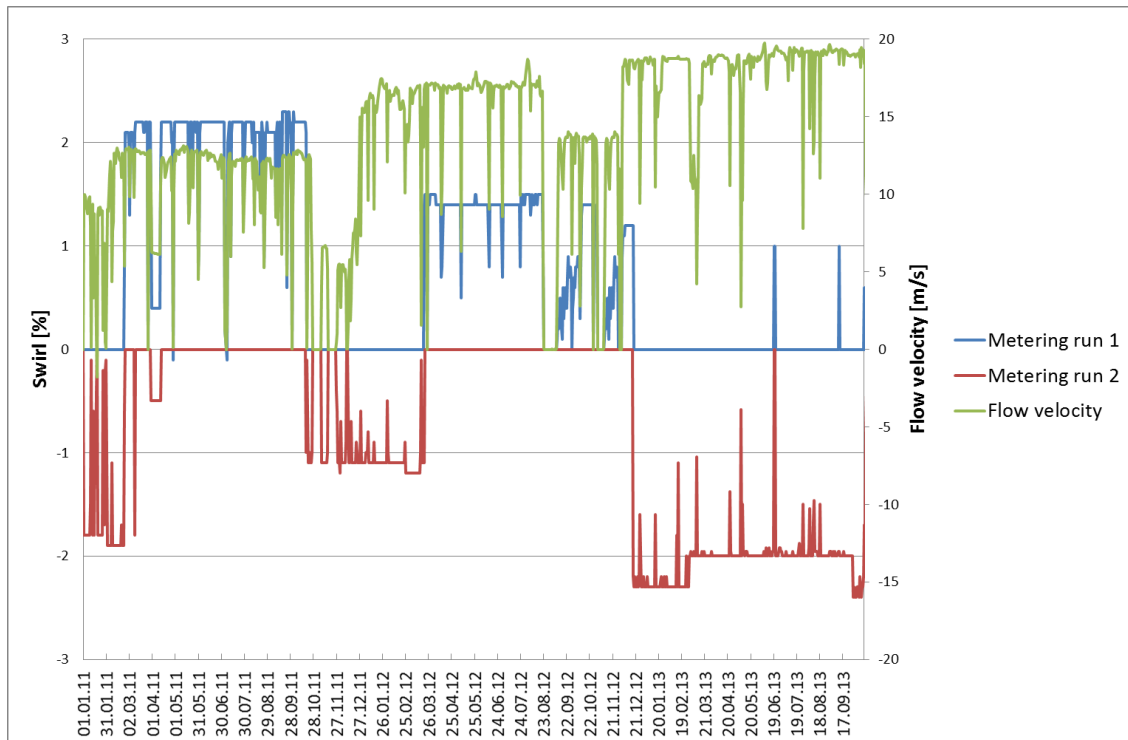


Fig. 6.5.2-2: Historic profile swirl for both meter runs

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Meter run one has always measured with a profile flatness > 90% and a positive swirl, while run two's profile is more pointy, < 80% flatness with a negative swirl. A different flow profile for different metering runs does not raise any immediate concerns, as both pipes have different flow paths. The specific flow profile for run one and run two has been confirmed by all flowmeters, as three flowmeters rotate between two metering runs. The flow profile anomalies are also not significant so that they should raise any immediate concerns. At an axial velocity of 20 m/s, swirls in the range of +/- 2% corresponds to a tangential velocity of 0,4 m/s only.

It is also not contradicting that run one gives a higher flow than run two as its profile is flatter. A flatter flow profile means that the top and bottom flow velocities are similar to the velocities in the core of the pipe, in contrary to a pointy profile where the top and the bottom is lagging behind. An integration across the entire pipe diameter results then into a higher average flow velocity for the profile which is flatter, when the core velocity is similar.

The measured flow profile during change of export runs is no different than during export with a single run. This increases the suspicion that the step change has always been present and further investigations confirmed that run one has always measured more than run two, since start-up.

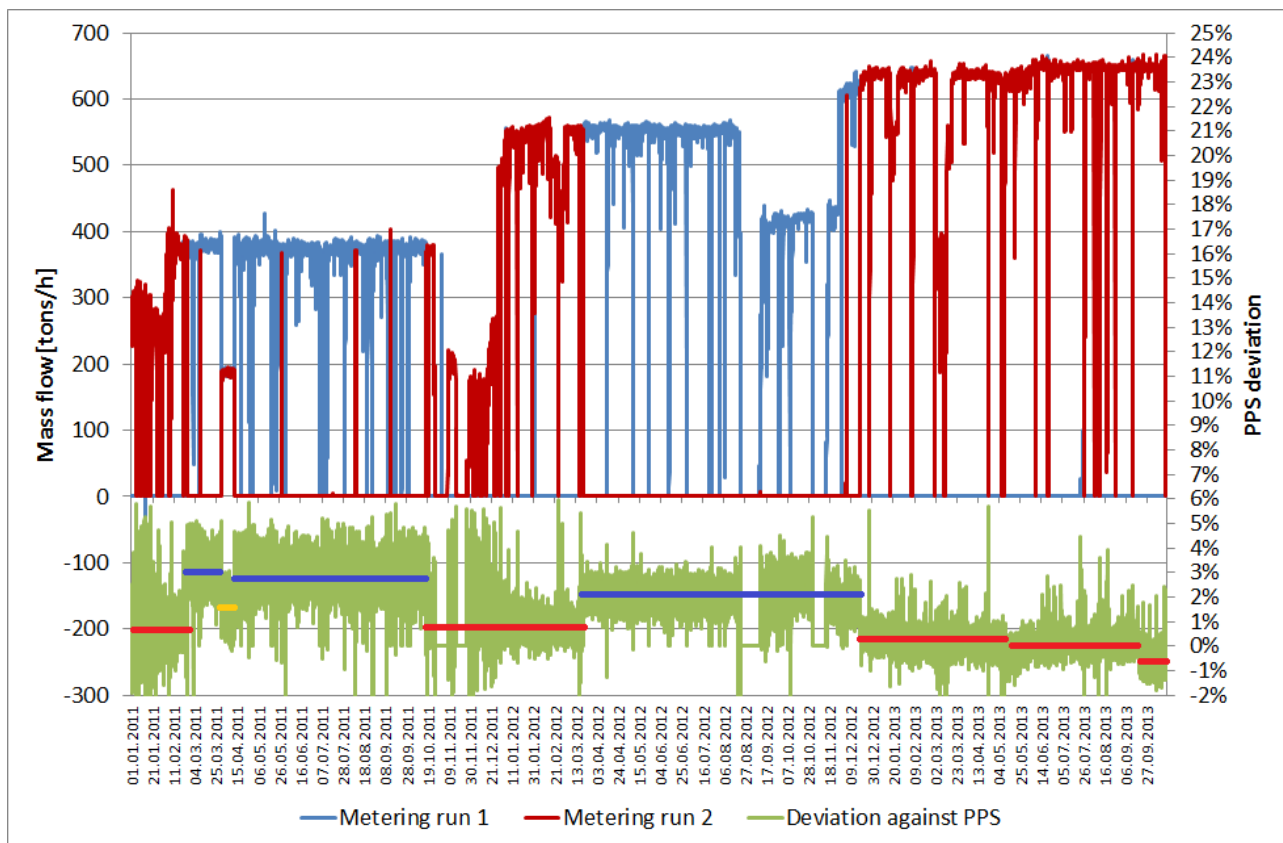


Fig. 6.5.2-3: Historic deviation against PPS venturi

Note that both runs were operated for a short period in 2011, resulting in a deviation from the PPS between that of run one and two. Although the behaviour of both metering runs is strange, there is still no firm proof that the meters are mis-measuring, as in theory, this effect could be caused by a higher friction or obstructions in run two.

6.6 In-situ flow tests

All incidents and flowtests where meter runs were switched during export showed, without exceptions, a step change of measured flow while all other process parameters were constant. An examination of the theoretical flow was made to assess the possibility whether pipe friction/restriction could have led to the observations made offshore.

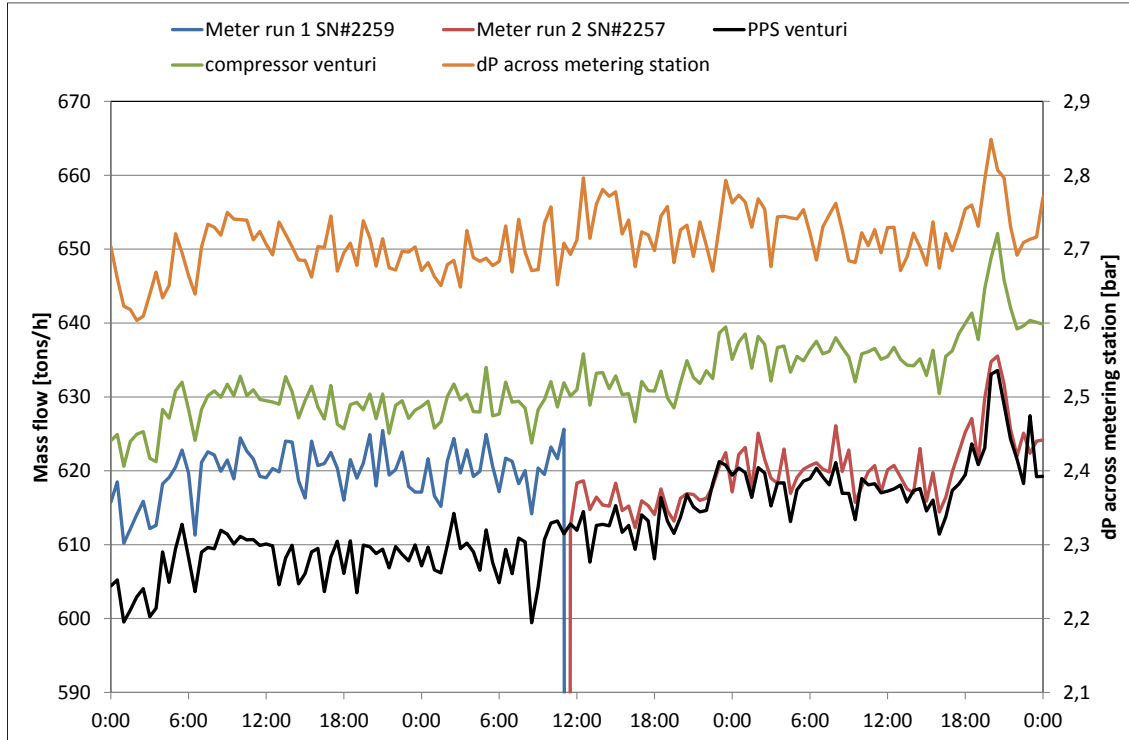


Fig. 6.6-1: Single export flow test

Flowtests where export was switched from duty to stand-by run did not give any clues on the root cause. Pressure transmitters directly upstream or downstream of the export station are not available, the measured dP includes therefore up- and downstream piping. It is not possible to calculate the theoretical flow explicitly as the roughness of the pipe is unknown and the dP measurement is not isolated for the metering station. However, based on the general flow equation, some qualitative assessments can be done nevertheless. When the pipe length and the gas properties are equal, then the general flow equation (Finch, et al., 1988) can be simplified to:

$$(Equ. 6.6-1) \quad \dot{Q} = K_1 \left(\frac{(P_1^2 - P_2^2) d^5}{f} \right)^{0,5}$$

Where:

\dot{Q} Flowrate [Sm³/d]

P_1 Pressure upstream [kPA]

P_2 Pressure downstream [kPA]

d Pipe diameter [mm]

f Darcy-Weisbach friction factor [-]

K_1 Constant for lenght, physical and base parameters $\left[\frac{1}{kPA \cdot km} \right]$

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As the diameter and physical properties for run one and run two are identical, their difference in flow must arise from a difference in pipe friction or differential pressure. Pressure measurements further up- and downstream the meter station suggests that run one creates a lower dP than run two. If meter run one should indeed measure more than run two, then the friction factor of run one must be significant lower than run two. Not only in order to measure more than run two, but the effect of run one's lower dP must be overcome in addition. It is strange that two identical pipes should have such a different friction factor. However, there is no proof that this is not the case.

The parallel flow test in September 2013 marked a significant turning point in the investigations and revealed that the export USMs are indeed mis-measuring.

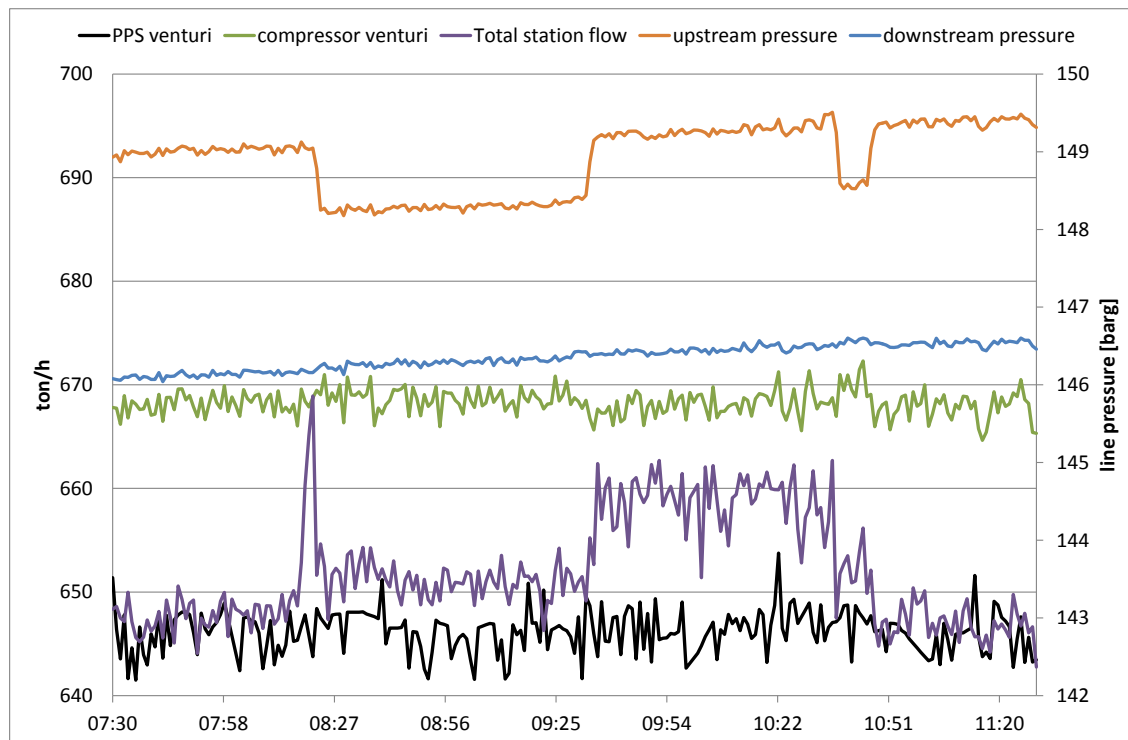


Fig. 6.6-2: Parallel export test

Export from run two is switched to export with both runs and then to export with run one only. The test data showed that run one measures most, followed by parallel export with both runs, while metering run two measures least. Fluid dynamics dictate that this is impossible.

The qualitative assessment of the change from run one to run two suggested that the friction factor of run one must be significant lower than run two, for the observations on the step change to become true. The friction factor for parallel export must be between that of run one and two as the same pipes are used. All things being equal, parallel export should deliver the largest flow due to the larger available pipe cross section, and not run one. The upstream pressure actually drops significantly during parallel export, compensating the gains from an increased diameter. This is expected when the pipe diameter is increased without increasing the compressor output. The gas flows out more easily and the system balances at a new, reduced upstream pressure. In order to establish the same conditions as during single run export, compressor load would have to be increased to create a higher upstream pressure. That again would, naturally, lead to a higher flow during parallel export than single run export.

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Furthermore, flow peaks with ca. +3% deviation from the PPS venturi were observed when switching over from run two to parallel export. This flow peak is reproducible and occurs every time when switching from run two to parallel export. However, a similar peak cannot be observed when switching from run one to parallel export. Neither the venturis or the dP across the metering station could confirm that this surge of flow has ever happened. This increases the suspicion that the USMs are influenced by the different in-situ flow profiles, while the Venturi meters are not affected.

The parallel test done in September 2013 was the first time when it was proved that the export flowmeters are mis-measuring and suggests that different friction factors or flow restrictions for run one and two cannot be the cause for the observations made offshore.

It was also observed that the characteristic profile flatness and swirls for run one and two have vanished during parallel export.

	Single run export			Parallel export		Onshore calibration
	Run one	Run two	Run two (during peaks)	Run one	Run two	-
Profile flatness [%]	93	83	96	90	89	89 %
Swirl [%]	+0,9	-1,8	+1,8	+ 0,1	- 0,4	0,1 %
Profile symmetry [%]	-1,0	+5,2	-2,9	+ 0,1	+ 1,3	1,6 %
PPS deviation [%]	+ 1,9	+ 0,24	+3	+ 0,7		-

Tab. 6.6-1: Typical profile parameters

Swirls seem to cancel each other out when exporting with both runs at the same time, which resulted in similar flow profiles as observed during onshore calibrations. Although logically on the first hand, it is not selfevident that the swirls of both runs will cancel each other out. Run two measures actually still a small amount of swirl and assymetry.

When considering table 6.6-1, a pattern between flatness and swirl can be observed. There is a correlation between a positive swirl, increased flatness and increased flow. Although it is logical that an increased flatness coincide with a higher flow, there is no logic that a positive (hence, clockwise) swirl should generate more flow than a negative swirl. The swirl direction should not influence the measured flow, only the amount of swirl.

A further parallel test was done in October 2013, this time flowmeter SN2257 was replaced with SN2258 to test whether phenomenons like the step change and profile peaks could be repeated with a different flow meter in meter run two. SN2258 in run two behaved exactly as predicted and showed step change and profile peaks like SN2257. Both meter runs have been put into operation after this test, as it is expected that the flowmeters will measure correctly when experiencing a similar flowprofile as during the calibration onshore.

It is now evident that the export meters are mis-measuring and that the error is related to all flowmeters regardless where they are installed. The investigations was handed over to CMR at this point, as computational fluid dynamic simulations and a detailed knowledge of the proprietary flow algorithm was required in order to find the cause for the observations on-site.

7 Conclusion

A mis-measurement on Gjøa's gas export was detected in early 2013. The reason for the mis-measurement was an incorrect swirl compensation of the flowmeters caused by a wrong path angle configuration for the bottom two paths. As a consequence, tangential velocity components were not compensated for but instead increased, causing the meter to overmeasure with positive swirl and undermeasure with negative swirl. The gas export has been mis-measured since start-up, since the flowmeter configuration was part of the factory configuration. Although this incident demonstrates that even very small errors can accumulate to a significant mis-measurement over time, the message of this paper is another.

The reason for the profile peaks is still not known, but subsequent CFD simulations carried out by CMR showed that the blind tee upstream might be the cause for the instable profile peaks in run two. This is explored in detail in another NSFMW paper (Sætre, et al., 2015). Lessons learnt from this incident may include the prevention of blind tees, improved location for the flow conditioner, installation of two meters in series with redundant technology and a detailed review of the flowmeter performance during the ISO 17089 type test.

Gjøa's export flowmeters are frequently traceable calibrated to ensure that they have not drifted more than 0,3% between calibrations. In addition, traceable flow laboratories are often thought to be the basis to compare against to ensure that the flowmeters are measuring "correctly". USM flow calibrations prove the measured flow for exactly one flow profile only, the flow profile during calibration. Even when calibrating the meter with up-/downstream pipespools and flow conditioner may not solve the problem, as the profile entering the spool is different between calibration and on-site. The transferability of the traceable calibration is dependent on the results of the ISO 17089 type test, as the profile in-situ will be different than during calibration. Calibrations so far did not show any evidence on any drifting of any flowmeter.

The ISO 17089 type test gives a hint on how the meter performs when exposed to a non-ideal profile. A flowmeter passes the ISO type test if it can prove that its FWME has not changed more than 0,3% due to a variation of upstream perturbations. Operators need to resist the urge to think of the ISO 17089 type test as a guarantee that the flowmeter performs under all upstream configurations, but rather consider it as an uncertainty budget when the expected profile is unknown. However, when the flowmeter is installed, it is subject to one single flowprofile only, as piping configurations do not change and profile non-idealities tend to be stable due to the highly turbulent flow. Therefore, any non-compensated profile anomaly will result in a systematic mis-measurement.

An analogy can be drawn to venturis and liquid USMs, which are calibrated by associating different meter factors to different Reynolds numbers, as their performance are strongly dependent on it. This is not relevant for gas USMs, as gas flow is usually highly turbulent due to the low viscosity and the high pipe velocity. Instead, the flow profile is of uttermost importance for the operation of gas ultrasonics. One can generally expect an USM to perform similarly when exposed to a similar flowprofile. So why are gas USMs not calibrated against their flow profile by associating a different meter factor to each flow profile?

One reason could be the flow dynamics in turbulent gas flows. Their impact on gas ultrasonics is multi-dimensional, in contrary to venturi meters and liquid USMs, and a gas flow profile is described by many factors such as flatness, swirl, cross-flow, symmetry and their different combinations. It is therefore not a trivial task to assign correction factors to every possible flow profile which could occur.

Operators need a better understanding on how their USMs cope with non-ideal flow profiles. How does non-ideal flow profiles influence their performance? What are the limits under which the USM can be operated without mis-measurements?

The performance of USMs, when exposed to a non-ideal profile, is still not fully understood and requires further investigations. A critical analysis of the flow profile and its impact on the measurement has to be done, once non-idealities are experienced during operations. The transferability of calibrations needs to be questioned, once the flow profile in-situ is different from the profile measured during calibration.

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