Index

North Sea FLOW Measurement Workshop

Paper 2.1

On Line Condition Based Monitoring of Gas USM's

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1 INTRODUCTION

Gas Ultrasonic flow meters (GUSM's) have been in use for fiscal and allocation measurement in the UK for some 12 years now. It has generally been the accepted practice in the UK for the GUSM's to be removed from service on a periodic basis for a wet flow calibration at one of the approved gas flow centres in Europe. The period between each recalibration is usually determined by two main criteria;

- The sales / allocation agreement pertinent to the metering system
- The GUSM repeatability from its previous calibration(s)

Most systems have generally adopted a rule set whereby a new GUSM must be recalibrated after 6 months in service and again after an additional 6 months. If the flow weighted mean shift between each calibration has been less than 0.3% on two subsequent recalibrations then the GUSM would generally qualify for a relaxation in calibration frequency to 12 months. It must be emphasised however that this is not the case for every system.

The BERR measurement guidelines have recognised the possibility of using diagnostics data as a means of extending the interval between re-calibrations.

Extract: Para. 4.8.2

"*Multi-path ultrasonic meters offer a number of inherent diagnostic capabilities that can be used to give at least a qualitative indication that the meter has not shown any drift in its operating characteristic.*

Should these self-diagnostic facilities become sufficiently well understood, it may be possible to extend the interval between meter calibrations beyond the current 12 month horizon; it may even ultimately be possible to abandon the strategy of removal and recalibration altogether, in favour of a continuous 'health-checking' regime. This is in fact the ultimate goal of Government, operators and meter manufacturers".

The paper is a study of a GUSM at an onshore site, used as a practical means of demonstrating the above. The site was built in 1998 and included a large custody transfer measurement system, incorporating four 20 inch, 4-path chordal design GUSM's (Fig. 1). The GUSM's were put in service in 1999, and have subsequently undergone repeated flow calibrations at the Advantica Test Facility in England

This paper will document the stability of one of the GUSMs over the years, including the negligible impact of upgrading transducers and electronics, and present the diagnostic information that has been obtained since the implementation of the data logging. It will also attempt to demonstrate that Condition Based Monitoring software can be used as a value adding assurance tool, and a credible means of extending re-calibration intervals.

2 CURRENT MAINTENANCE PHILOSOPHY

As specified in the introduction, the generally accepted practice in the UK is for GUSMs to be removed from service on a periodic basis for a flow calibration at one of the approved gas flow centres in Europe. This means that operators who utilise GUSM's are faced with the following issues.

- Financial cost of the calibration, including logistics and attendance at the test centre
- Safety concerns around the removal and handling of large pieces of equipment
- Planning and scheduling to ensure minimal down time without any gas deferral
- ETS legislation governing the venting and release of Hydrocarbon gases
- Availability of test slots, particularly for GUSMs above 10"
- Potential for damage to the GUSM during removal, transportation or reinstallation (Fig. 3 and 4)

Fig 1. Skid Overview

Fig 2. Flow Control Valves and Noise Reduction "horns"

Fig 3 and 4. Transportation challenges!

It is recognised that regular recalibration gives assurance to the operator, partners and the regulator that any systematic drift in GUSM accuracy is corrected in a timescale proportional to the financial risk.

It should also be recognised that current practice is to perform retrospective production corrections on GUSMs demonstrating shifts of greater than ± 0.3% FWME [Ref.1], despite the calibration facilities claiming uncertainties of approximately ± 0.2%, not the "order of magnitude" smaller uncertainty (± 0.03%) that fundamental metrological principles require for a true calibration.

3 THE CONDITION BASED MONITORING SOFTWARE

Condition Based Monitoring is an attempt to move towards the "ultimate goal" detailed in the BERR Extract shown in Section 1. An attempt to create a "smarter" measurement system which will allow the operator to better understand metering performance, and replace a ***purely*** calendar based re-calibration and maintenance philosophy, with a condition based methodology where diagnostic data can be used to influence, and hopefully reduce, re-calibration and maintenance costs.

In 2006, the metering system was extensively upgraded. The upgrade included new flow computers and supervisory systems, new GUSM electronics and transducers, and the installation of a new diagnostic data monitoring and logging software package.

The new software package was developed as a means to simplify and improve diagnostic monitoring to the extent that it becomes practical for the operator to use and benefit from (if the man hours involved on connecting, collecting and analysing the information is too high, there is an argument for sticking with calendar based calibrations).

Unlike conventional USM diagnostic software, which logs intermittently and provides "snapshots" of GUSM performance, the Condition Based Monitoring (CBM) software package is more sophisticated. It allows up to 16 separate diagnostics to be monitored, and logged, on a 24/7/365 basis. It has various functions designed to allow the operator to quickly and easily check the status of the GUSM, as well as analyse its long-term performance. After initial set-up, it requires no operator intervention. It simply monitors, logs and reports automatically.

Again, unlike conventional USM diagnostic software, each individual diagnostic check has operator entered control limits, and alerts the operator if a control limit has been breached. All such alerts have time-based filters to eliminate non-actionable transient occurrences, and ensure that only actionable alarm conditions are brought to the operators' attention. There are also low-flow cut-offs, which disable the checking at lower flow velocities. This again is designed to eliminate non-actionable alarms

There is a diagnostic summary function to allow the operator to check, at a glance, if there are any current alarms, and also whether any occurred in recent days (Fig. 9).

There is a full 2-year historical trending package which allows the operator to retrospectively analyse the flow conditions and diagnostics to check the significance of any control limit breaches, even weeks or months after the event, for example, at an independent audit by partners or measurement authorities.

The flow and diagnostic data can be viewed in real time using the Graphical User Interface (GUI). The GUI contains an overview screen (Fig.5) to give an indication of the condition of all the streams being monitored, a meter monitor screen (Fig. 6) to summarise and display the data from each GUSM, and a Mimic screen (Fig. 8) to allow the operator to see which, if any, control limits have been breached, with the ability to "drill down" from each mimic button to allow further investigation of each diagnostic (Fig. 7).

Diagnostic data is reported by means of daily and hourly diagnostic reports (Fig. 10), and also output to 24 hour Excel® compatible logs which contain the raw diagnostic data as well as easy to understand chart plots. These are invaluable when looking at longer-term trends, or numerically analysing data (Figs. 11, 12, 33, 34, 37 and 38)

The software package can be set up to allow for remote access to the data if required.

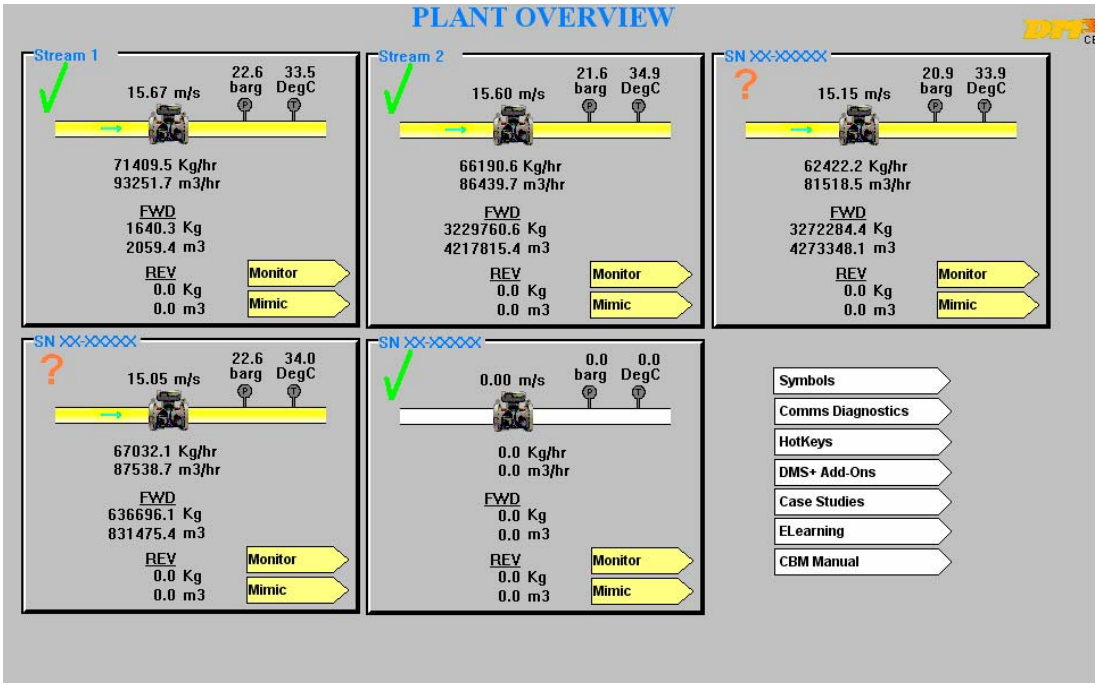


Fig 5. Overview Screen

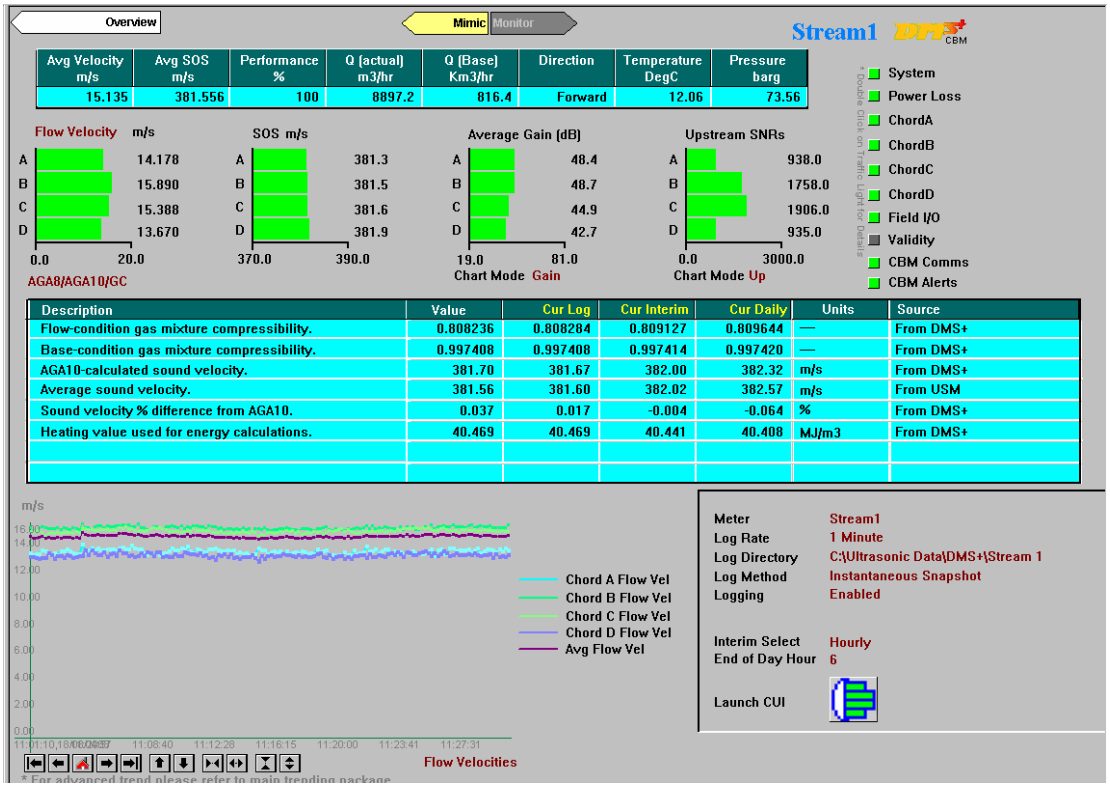


Fig 6. Monitor Screen

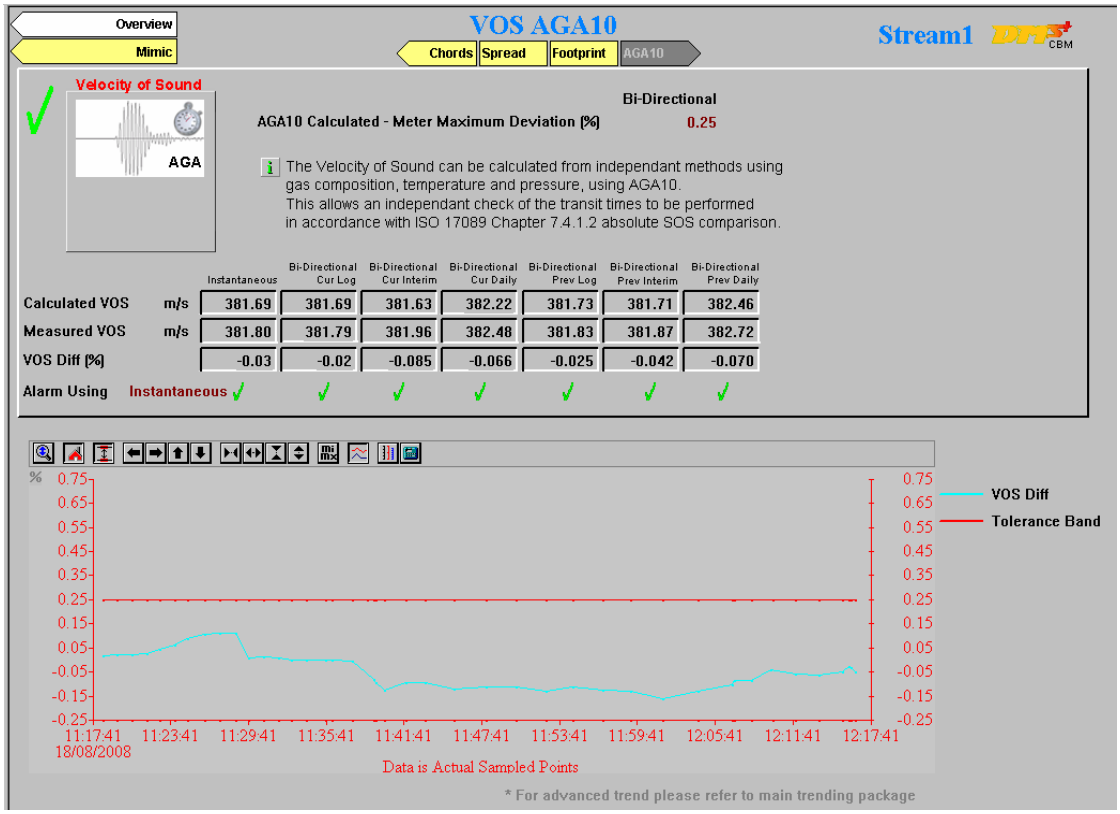


Fig 7. Diagnostic Detail Screen (AGA-10)

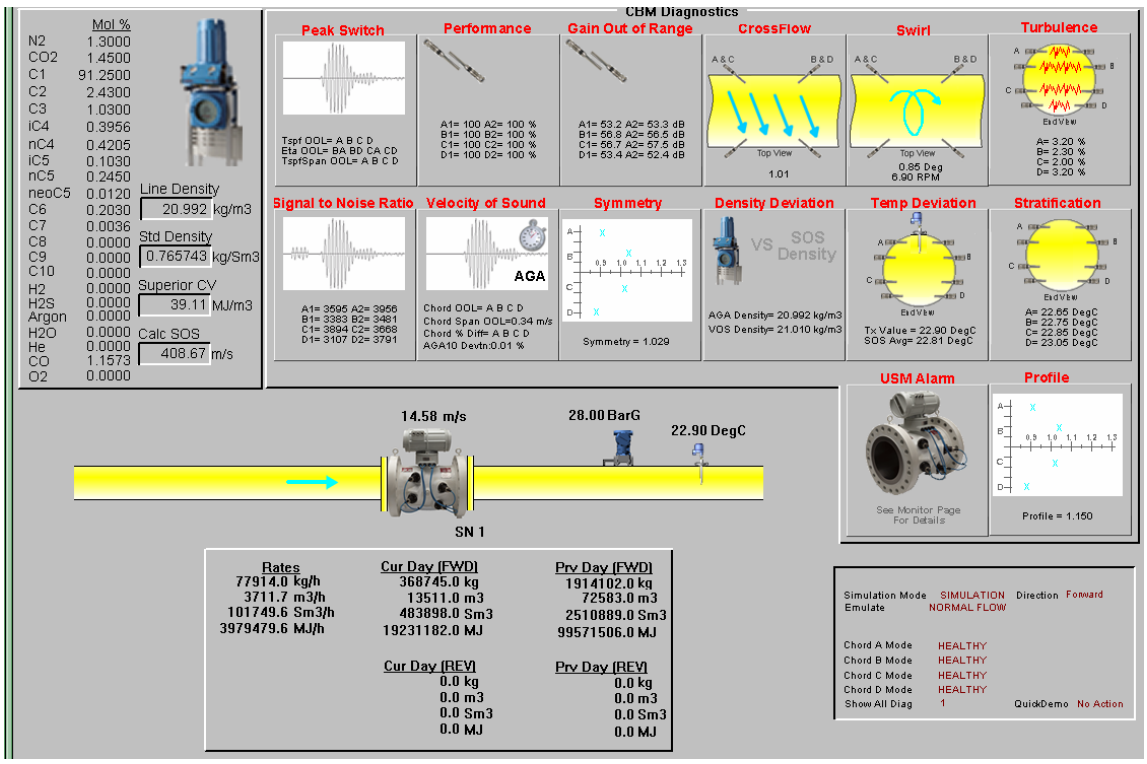


Fig 8. Mimic Screen – “Buttons” enabled for display

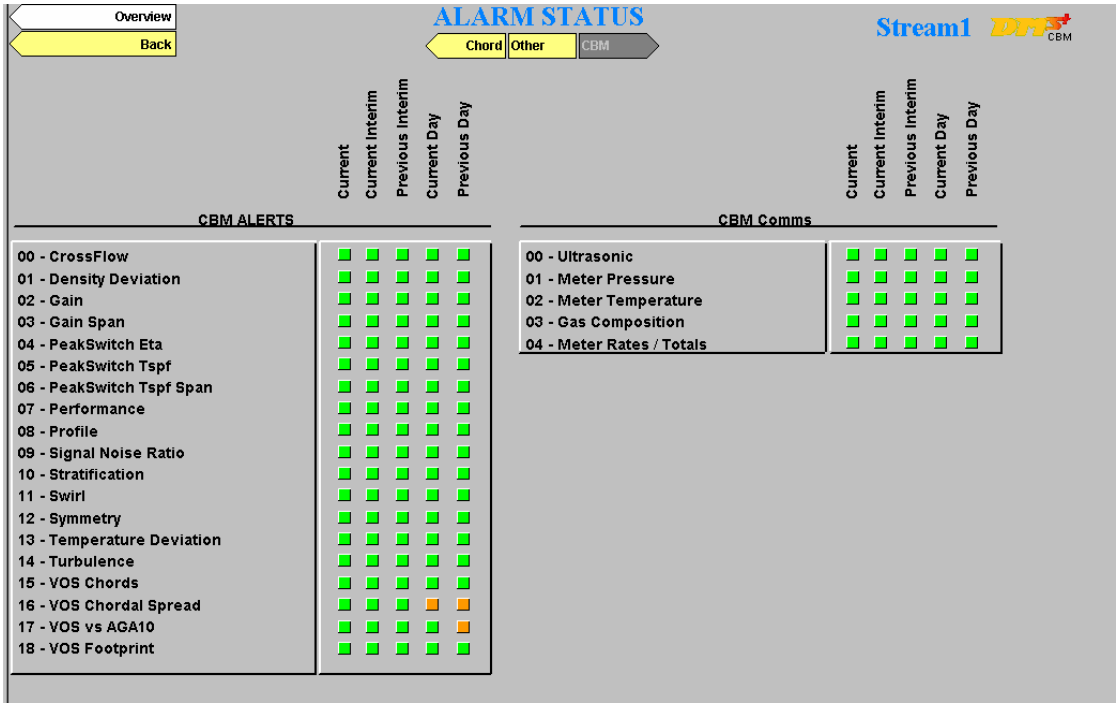


Fig 9. Current and Historical Alert Screen

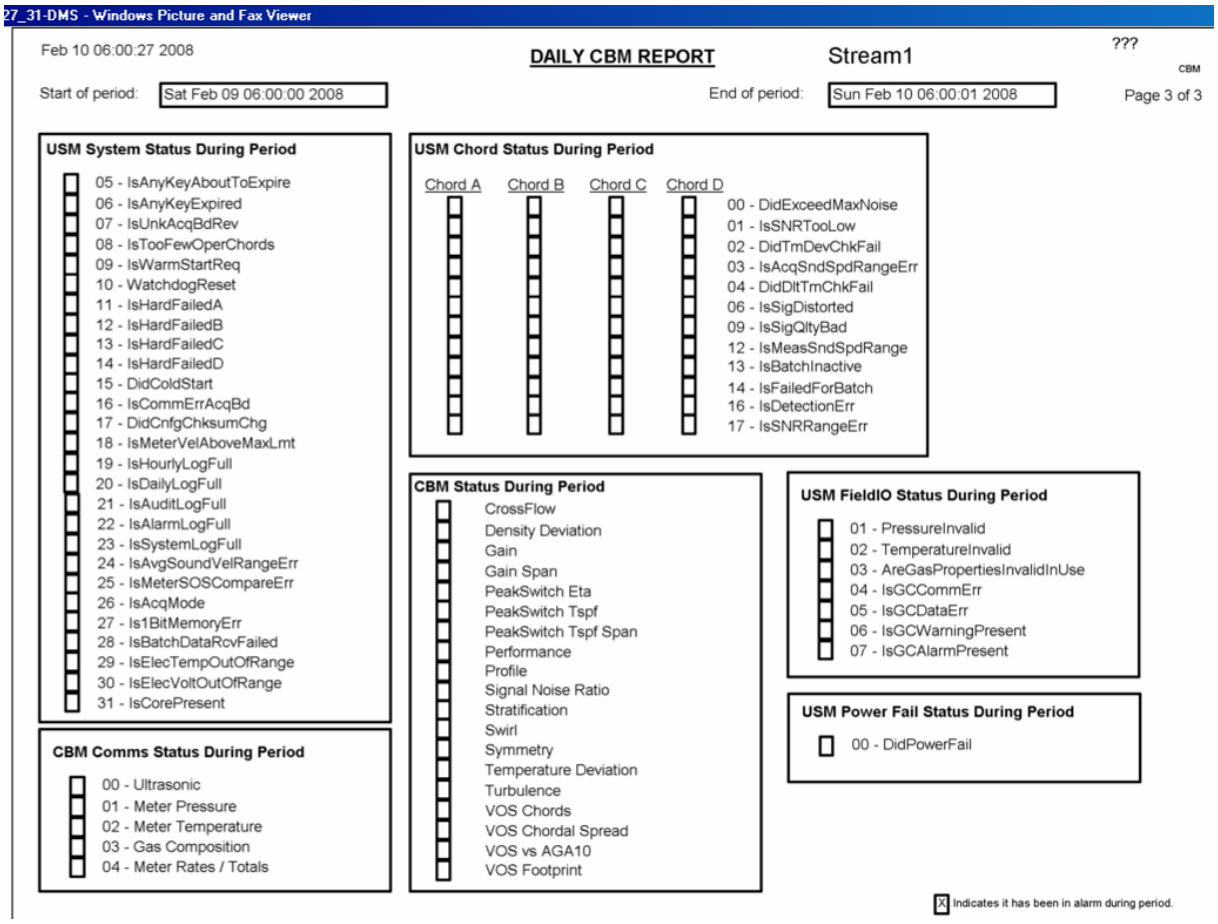


Fig 10. Alerts Detail from Daily Report – No Control Limit Breaches

4 DEMONSTRATING GUSM STABILITY USING DIAGNOSTIC INFORMATION

In order to attempt to demonstrate the stability and accuracy of the GUSM, and measurement system, it was necessary to consider:

- The site installation when compared to the calibration facility – was the transfer of the calibration valid?
- The stability and performance of the GUSM, based on diagnostic information, when in service
- The integrity of the complete measurement system (GC, PT, TT, gas sampling and pressure let down systems)

5 METHODOLOGY FOR ANALYSING DIAGNOSTIC INFORMATION

The diagnostic parameters collected, details of which can be found in Ref. [2] [3] [4], fall into 3 categories.

Functional Diagnostics – is the GUSM operating correctly? Is it showing any signs of degradation?

- Gains (dB)
- Signal-to-Noise Ratio
- Performance (%)

Process Condition Diagnostics – were conditions in the metering stream stable, and suitable for custody transfer measurement?

- Turbulence (%)
- Profile Factor
- Symmetry
- Crossflow
- Swirl Angle

Measurement Integrity Diagnostics – was the measurement system operating accurately, to within design specifications?

- AGA-10 SOS comparison
- Measured / calculated density comparison
- Independent GC, PT, TT and DT checks and calibrations

The methodology employed to check the data, and check for stability, was as follows:

- The daily diagnostic logs were combined into weekly trends. These weekly data trends were studied, to understand the performance of the system, and check for normal metering operation. Any anomalies could be investigated to check if they are significant (See Fig 11 and 12 for example of weekly trends).

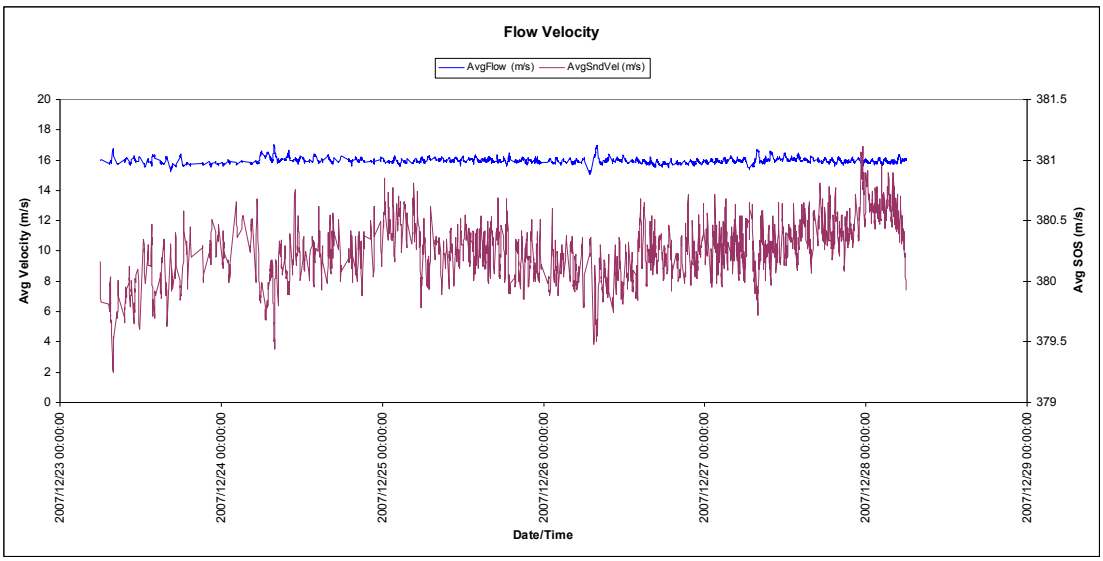


Fig 11. Weekly Trend – Flow Velocity and Measured SOS

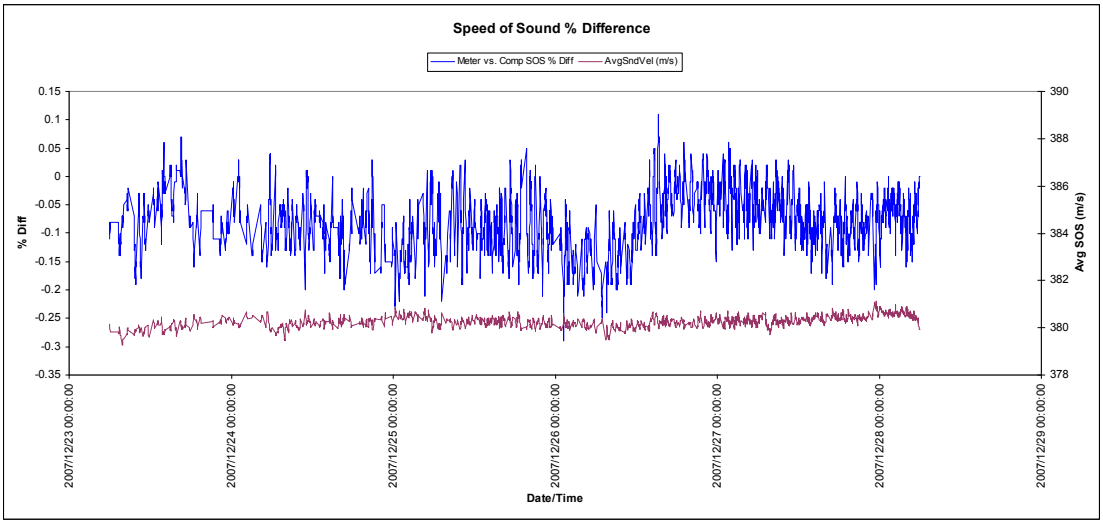


Fig 12. Weekly Trend – Measured SOS and AGA-10 comparison

The initial analysis of the flow data revealed that, for the vast majority of the time, the stream being studied was either:

- Flowing on its own at between 16-18 ms^{-1}
- Offline
- Flowing in parallel with a second stream at around 8-9 ms^{-1}

It was also clear that the metering system had performed as was expected since the logging began, with a study of the trended diagnostic data showing no occurrences of inexplicable or unusual data.

The mode of operation of the site meant that similar flow and process conditions were being repeated at regular intervals. This provided the opportunity to compare diagnostic data at similar conditions, as time passed, and look for any signs of drift or deviation. With this operational knowledge the data analysis methodology could be defined

5.1 GUSM Functionality Checks

The presence of Flow Control Valves (FCV's) downstream of the GUSMs on the skid (Fig. 2) meant that it was not possible to use Performance levels and S/N ratios as indicators, as these were both influenced by the FCV. It was possible to devise tests which comprehensively checked the functionality of the GUSM, for example:

- Check GUSM functionality and performance under similar flowing conditions by comparing gain levels and ensuring that neither the GUSM electronics or transducers are degrading over time
- Check gain, performance and S/N ratios when the GUSM is offline, again ensuring that neither the GUSM electronics or transducers are degrading over time

5.2 Process Condition Diagnostic Checks

- Compare the Profile Factor, Symmetry, Crossflow and Swirl data from the calibration facility to that from the metering skid and draw a conclusion on the validity of the calibration
- Use the regularly repeated, single stream, steady flow conditions to statistically analyse the Profile Factor data to check for a constant mean, and normal distribution at similar flow conditions
- Check that the parallel flow conditions which regularly occurred did not significantly affect the Process Condition Diagnostics

5.3 Measurement Integrity Diagnostic Checks

- Use the repeated, single stream steady flow conditions to statistically analyse the AGA-10 SOS data to check for a low percentage deviation, constant mean, and normal distribution
- Independently verify the calculated SOS by independently calibrating the GCs, PTs and TTs
- Check that the parallel flow conditions which regularly occurred did not significantly affect the AGA-10 SOS data (See Section 9)

6 SUMMARY OF THE FLOW CALIBRATION

As mentioned, The GUSM was upgraded as part of the metering system upgrade.
The following calibrations were carried out:

- As found calibration
- Upgrade transducers and re-calibrate
- Upgrade electronics and re-calibrate

The upgraded GUSM was calibrated at 1, 2, 5, 8, 12, 17 and 19 m/s. Data was collected for two minutes at each rate, providing around 120 samples for each diagnostic at each flow.

A calculated SOS from the calibration facility was also manually logged for each flow velocity to allow AGA-10 comparisons to be carried out.

The calibration was successful from both a GUSM uncertainty and diagnostic performance perspective, with the following being confirmed.

6.1 functional diagnostics

- The gains remained low, and consistent throughout the entire velocity range. (Fig. 13)
- The S/N Ratios were far in excess of the minimum value of 10 required by the processor for a successful measurement. (Fig. 14)
- The performance on all transducers was never lower than 86% (25% is the minimum required for successful flow calculation). (Fig. 15)

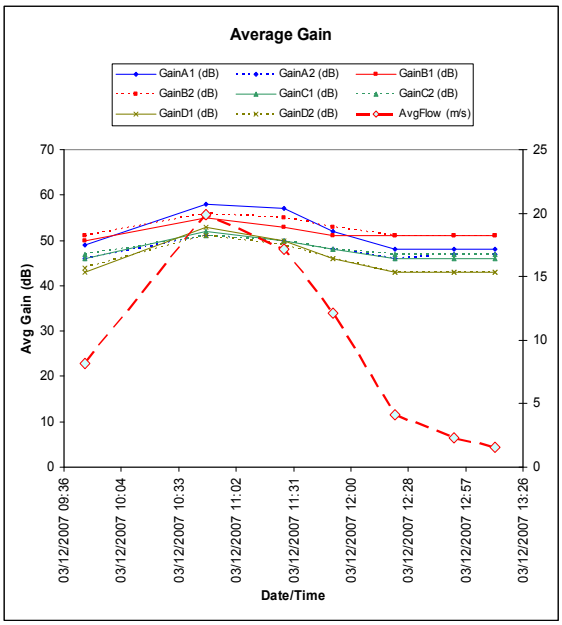


Fig 13. Gains

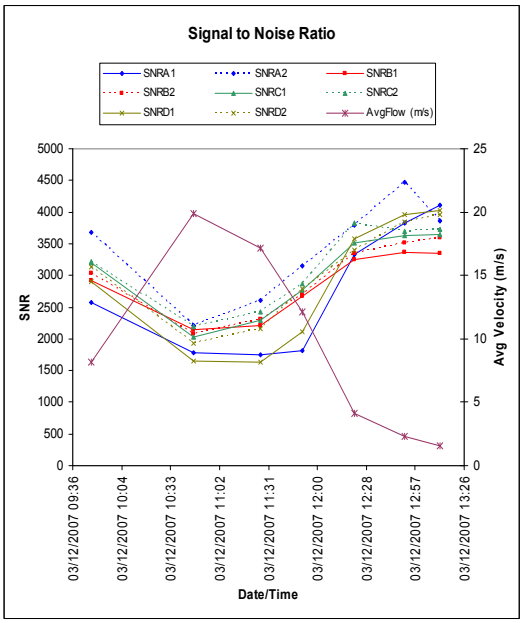


Fig 14. Signal to Noise Ratio

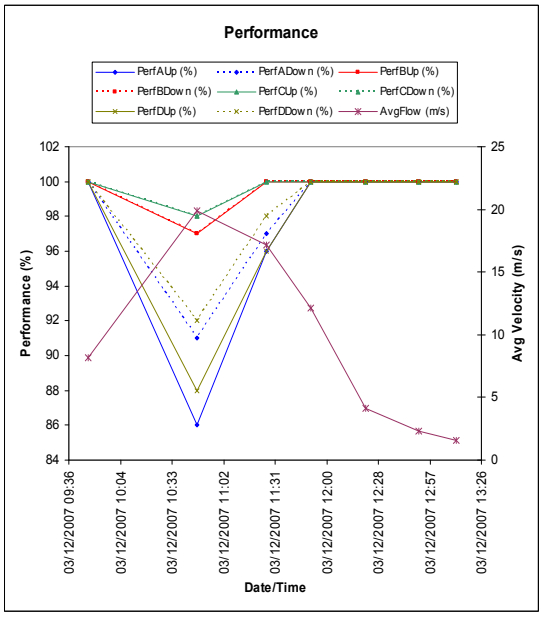


Fig 15. Performance

It was clear that there were no issues surrounding the functional performance of the GUSM after upgrading.

6.2 Process Condition Diagnostics

The Process Condition Diagnostics were entirely as expected for the test line used (Fig. 16)

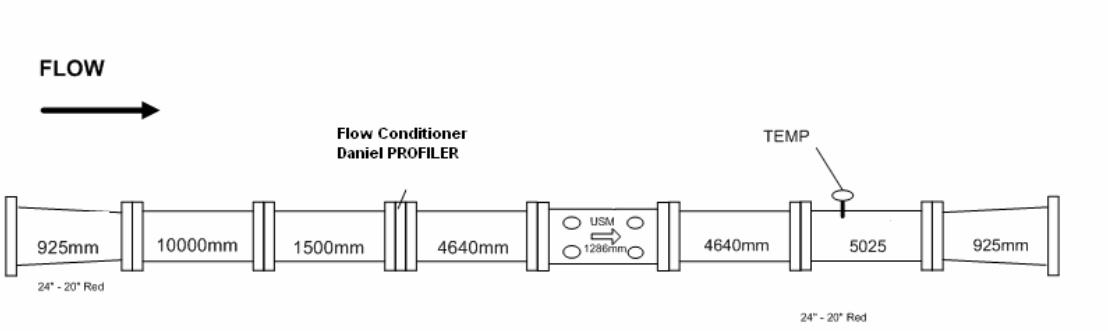


Fig 16. Flow Calibration – Stream Details

- The mean Crossflow reading was 0.998
- The mean Symmetry reading was 1.006
- The mean Profile Factor reading was 1.157
  (See Fig. 17)
- The Turbulence for the outer (A & D) chords was between 3.1 and 4.2% (typical expected values 2-4%)
- The Turbulence for the inner (B & C) chords was between 1.9 and 2.9% (typical expected values 1-2 %)
- No swirl was detected

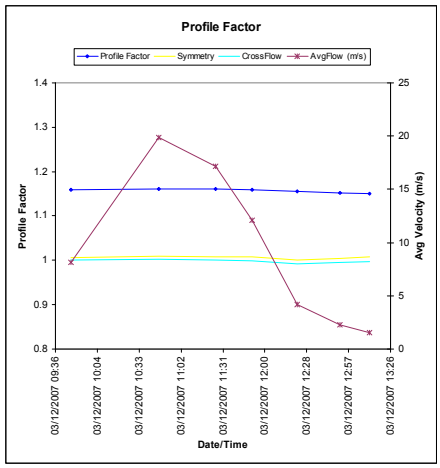


Fig 17. Process Condition Diagnostics at Flow Calibration

These Process Condition Diagnostics confirmed that the test line used provided a fully developed, symmetrical, non-swirling flow profile for the GUSM, and confirmed the low turbulence levels expected when there are no upstream blockages.

6.3 Measurement Integrity Diagnostic

- A manual AGA-10 SOS comparison was done by comparing the measured SOS with a calculated SOS derived from the calibration facility gas composition, temperature and pressure. The percentage deviations varied between -0.44 % and -0.50 %.

From a diagnostics perspective, the calibrations proved very successful, and provided an excellent database from which to “footprint” the GUSM.

Critically, from a measurement uncertainty perspective the GUSM also performed as expected. In line with recent re-calibration history the GUSM showed a small shift in FWME (-0.055 %). The GUSM has not shown a shift in FWME of more than 0.16% since February 2003 (7 re-calibrations).

This clearly demonstrated the negligible impact of upgrading the electronics and transducers, and gave confidence that the long-term stability of the GUSM was unaffected by the upgrade work.

7 ON SITE DATA ANALYSED

As mentioned, the data analysis methodology was primarily defined by the operational conditions on site.

The table below details the dates on which the flow was analysed, and the flow conditions at that time. (Table 1)

Table 1. Summary of data collection period process

Date	Flow conditions
15/12/07	Single stream steady high flow velocity (16ms^{-1})
27/12/07	Single stream steady high flow velocity (16ms^{-1})
02/01/08	Offline
06/01/08	Single stream steady high flow velocity (12 ms^{-1})
13/01/08	Single Stream non-steady flow conditions (13 ms^{-1} falling to 6ms^{-1})
19/03/08	Dual stream parallel flow (9 ms^{-1})
31/03/08	Dual stream parallel flow (9 ms^{-1})
22/04/08	Dual stream parallel flow (9 ms^{-1})
28/04/08	Offline
27/05/08	Single stream steady high flow velocity (18 ms^{-1})
27/06/08	Single stream steady high flow velocity (18 ms^{-1})
09/07/08	Offline
02/08/08	Offline
10/08/08	Single Stream non-steady flow conditions (variable - 4ms^{-1} and 6ms^{-1})

8 DATA ANALYSIS – ONSITE RESULTS

8.1 Functional Checks

In order to establish if there had been any deterioration in the performance of the GUSM components the gain levels, at similar process conditions, were compared over a period of 8 months. (Table 2)

Table 2. Gain levels over time – Flowing

	Temp (C)	Press (KPag)	Avg V (m/s)	GainA1	GainA2	GainB1	GainB2	GainC1	GainC2	GainD1	GainD2
15/12/07	9.96	7412.04	16.02	52	46	49	50	46	46	45	45
27/12/07	9.66	7414.79	15.98	52	46	49	50	46	46	45	45
06/01/08	12.80	7443.82	12.18	49	44	48	49	44	45	42	43
27/05/07	12.30	7410	17.65	52	46	49	50	45	46	44	45
27/06/08	13.09	7378.38	17.64	52	46	49	50	45	46	44	45

When we observed almost identical gain values being applied, at very similar process conditions, after 8 months of almost continuous operation, it was clear that no degradation in signal generation, reception or processing had occurred over the time period.

The SN ratios, performance levels and gains were also checked during offline periods when the FCV had no effect on the ultrasonic signals. (Tables 3, 4 and 5)

Table 3 Gain levels over time – Offline

	Temp (C)	Press (KPag)	Avg V (m/s)	GainA1	GainA2	GainB1	GainB2	GainC1	GainC2	GainD1	GainD2
Jan 08	9.31	7175.73	0	44	44	48	47	44	44	40	40
April 08	15.29	7722.41	0	44	43	47	48	44	44	39	40
July 08	14.52	7415.20	0	44	44	47	47	44	44	39	40
Aug 08	16.11	6430.98	0	46	46	50	50	46	46	41	41

Table 4 Signal to Noise Ratio levels over time – Offline

	Temp (C)	Press (KPag)	Avg V (m/s)	SNR A1	SNRA2	SNRB1	SNRB2	SNRC1	SNRC2	SNRD1	SNRD2
Jan 2008	9.31	7175.73	0	7290	7074	5883	5598	5931	5660	6661	6470
April 2008	15.29	7722.41	0	6339	6203	5385	6242	5861	5927	6299	6778
July 2008	14.52	7415.20	0	6962	6834	4866	4332	5861	5309	5589	6249
Aug 08	16.11	6430.98	0	7215	7229	6038	6002	6297	6154	6257	6129

Table 5 Performance levels over time – Offline

	Temp (C)	Press (KPag)	Avg V (m/s)	Perf A1 (%)	Perf A2 (%)	Perf B1 (%)	Perf B2 (%)	Perf C1 (%)	Perf C2 (%)	Perf D1 (%)	Perf D2 (%)
Jan 2008	9.31	7175.73	0	100	100	100	100	100	100	100	100
April 2008	15.29	7722.41	0	100	100	100	100	100	100	100	100
July 2008	14.52	7415.20	0	100	100	100	100	100	100	100	100
Aug 08	16.11	6430.98	0	100	100	100	100	100	100	100	100

Again, it could be clearly seen that no significant changes in the GUSM performance had occurred, and there was no information to suggest that GUSM is degrading or failing in any way.

8.2 Measurement Integrity Diagnostic Checks

For a typical gas pipeline, operating at less than 10200 KPag, we can expect the AGA-10 deviation on a well designed, correctly operated metering system to be around 0.21% [Ref. 5].

Consistently achieving deviations less than this are indicative that the metering system is performing as designed, with accurate temperature and pressure measurements, an accurate gas composition, correctly functioning sample and pressure let down systems and an accurate GUSM.

By independently checking and comparing data from the secondary instruments it is also possible to independently verify the calculated SOS. This gives the operator more information when checking the GUSM measured SOS

In a system where this independent checking is routinely carried out, a continuing low and stable AGA-10 deviation is an extremely strong indication of stable GUSM performance as it confirms a lack of transducer face contamination and verifies correct signal measurement.

The independent checks employed by this metering system include:

- Dual GCs that calibrate daily and are independently checked to ISO-10723 every 2 years. The two GCs are also subjected to a composition discrepancy check to alert the operator in the event of any deviation between measured un-normalised compositions
- The Pressure and Temperature transmitters are checked and calibrated every 3 months
- There are dual Densitometers, which are vacuum checked every 3 months and subjected to a discrepancy check. The measured density is compared to the calculated density and checked for discrepancies

The AGA-10 data, from the same single stream flows, referenced in 8.1 was analysed to check for stability. (Table 6)

Table 6 AGA-10 deviations over time

	Temp (C)	Press (KPag)	Avg V (m/s)	Mean AGA-10 SOS Deviation (%)
15/12/2007	9.96	7412.04	16.02	-0.093
27/12/2007	9.66	7414.79	15.98	-0.071
06/01/2008	12.80	7443.82	12.18	-0.093
27/06/2008	13.09	7378.38	17.64	-0.030

In addition to calculating the mean, the data was further analysed to check the distribution of the data. The results were very consistent throughout the 8 months, and the data is shown below. (Fig. 18 to 21)

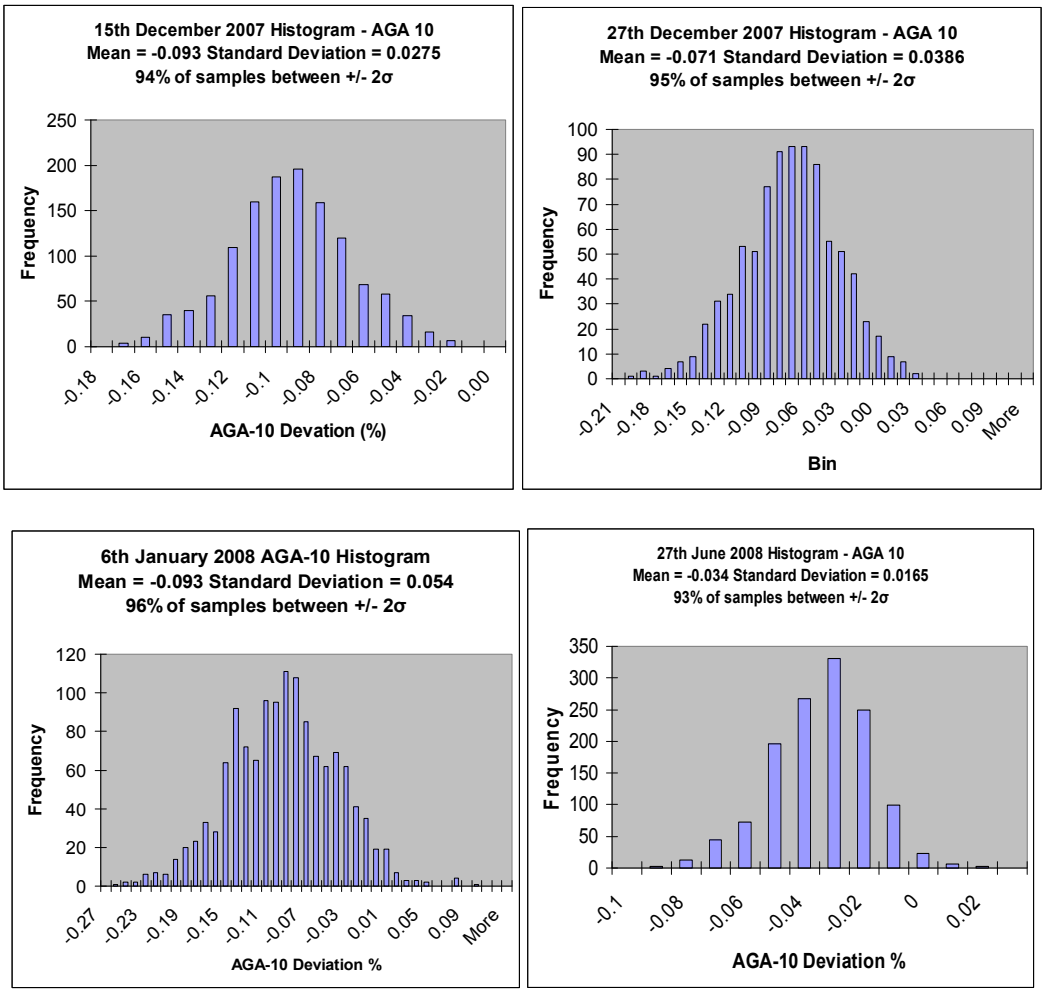


Fig 18 to 21. AGA-10 Deviation Distributions

After analysing the data at similar, single stream flow conditions throughout the 8 months, it was not possible to find any indication that the AGA-10 comparison was showing any signs of drift or bias.

The data confirms that the control limit of ±0.21% [Ref. 5] is reasonable, and achievable for this site.

8.3 Process Condition Diagnostic Checks

8.3.1 Validity of Calibration Transfer / Suitability of Metering Stream

It was first of all necessary to confirm that the uncertainty data from the calibration would be valid when the GUSM was placed in service.

It is obvious that the metering skid has a very different inlet pipe configuration from the calibration facility. (Fig. 22) With a complex series of bends, “Tees”, and the symmetrical inlet header, the concern is: does the upstream configuration (Inlet Header - 2X Full Bore MOV’s – 2D – Conditioner Plate – 10D – USM) come close to replicating the flow profile generated at the flow facility?

Fig 22. Inlet Header Geometry

A comparison of the Process Condition Diagnostic data can be seen below. (Table 7)

Table 7 Site Start-Up Process Condition

	Location	Avg. Flow Velocity ms^{-1}	Avg. Profile Factor	Avg. Symmetry	Avg. CrossFlow
03/12/2007	Flow Facility	17.0	1.159	1.007	1.001
15/12/2007	Start Up	16.1	1.129	1.014	1.001
% Change			**-2.7**	**0.7**	**0.0**
Ideal Value			1.171	1.000	1.000
% from Ideal			**-3.6**	**1.4**	**0.1**

The relatively low differences in Symmetry and Crossflow were very reassuring. The fact that these parameters had shifted by less than 1% suggested a very close approximation to the flow facility conditions, and indeed close to the ideal values of 1.0.

It is not surprising, given the complex inlet geometry, that the flow is not completely symmetrical. The small deviations suggest that the 10D upstream spool and conditioning plate are very effective in removing any undesirable asymmetries.

When the Profile Factor was studied, the larger deviation was initially a concern. In 1998, during flow testing prior to start-up, the first flows of gas showed an "inverted profile" highly indicative of a large degree of swirl. [Ref. 2] (Fig. 23) This was subsequently confirmed when a visual inspection of the upstream pipe work showed "rifling" in the upstream spool (formed by oil and grease residues upon start-up). This severe swirl was deemed unacceptable, so conditioning plates were obtained and the GUSMs re-calibrated and re-installed.

Included in the diagnostic monitoring and logging software is a check on Swirl Angle. Based on calculations used in "Diagnostics of the Daniel USM, South East Asia Workshop, 2003" [Ref. 2] it was possible to estimate and log the magnitude of the swirl being experienced at the GUSM. Whilst there was never a non-zero reading during the flow calibration, on site there was a small, consistent swirl -predominantly 1 or 2 Degrees (Fig. 24 and 25). Referring back to the data in [Ref. 2] (Fig. 26), a small swirl between 1 and 2 degrees would show as a "flattening" of the profile to between 1.146 to 1.123.

The value of 1.129 measured on start-up can be seen to be reasonable. There was no evidence to doubt the validity of the calibration transfer, or the suitability of the metering stream for good measurement.

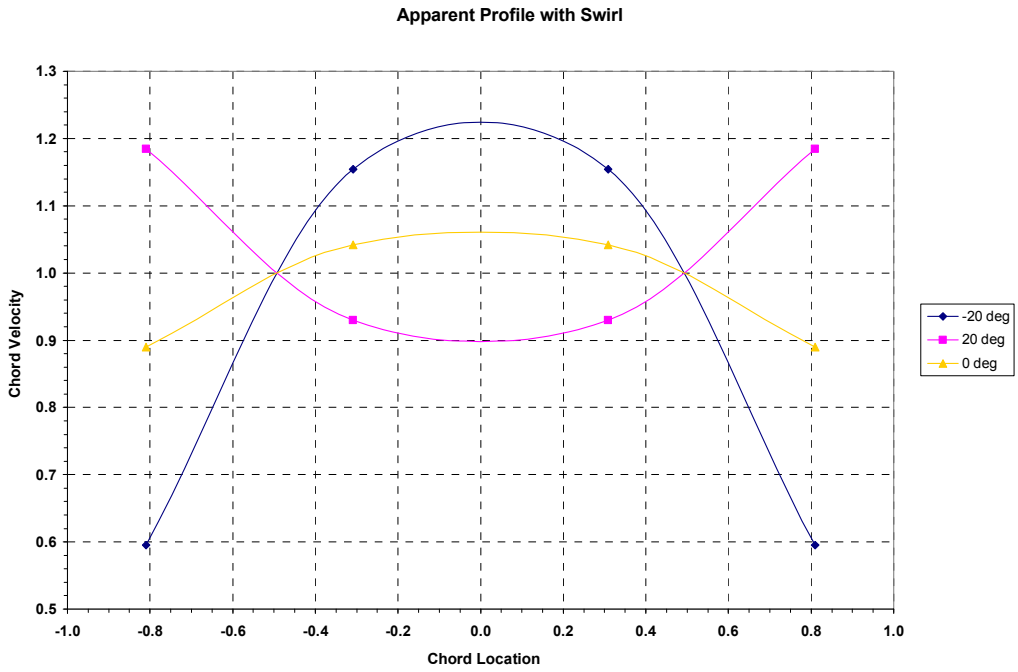


Fig. 23 – Swirl / Profile Data

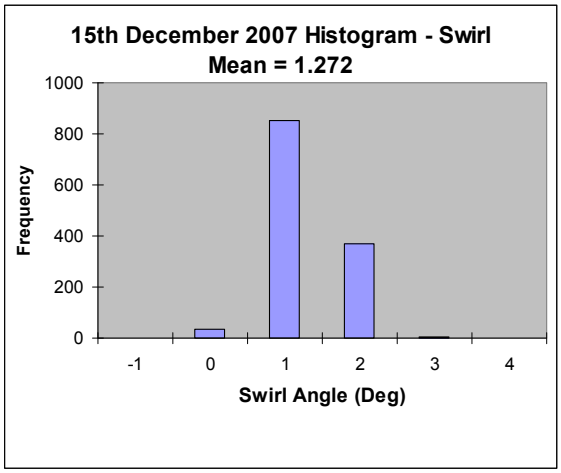


Fig. 24 Measured Swirl Data 15th December 2007

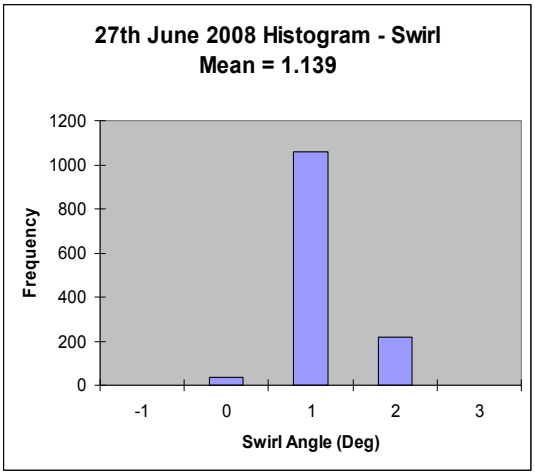


Fig. 2 Measured Swirl Data 27th June 2008

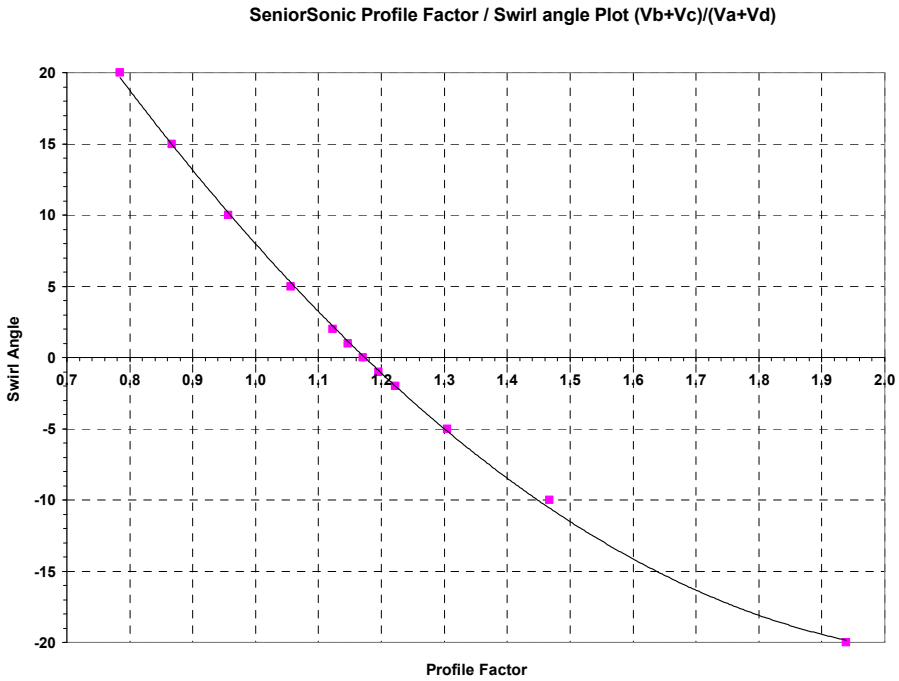


Fig. 26 Profile Factor Vs. Swirl Angle Plot

8.3.2 Stability of Process Condition Diagnostics

Having concluded that the transfer of the flow facility calibration to site appeared valid, it remained to establish that the conditions in the stream were stable over time using the same Process Condition Diagnostics.

Using the same methodology of comparing data from periods of similar, steady, single stream conditions it was possible to look at the condition of the stream over time. (Table 8)

Table 8 Process Condition Diagnostics over 8 months

	Temp (C)	Press (KPag)	Avg V (m/s)	Avg. Profile Factor	Avg. Symmetry	Avg. CrossFlow	TurbA (%)	TurbB (%)	TurbC (%)	TurbD (%)
15/12/07	9.96	7412.04	16.02	1.129	1.014	1.001	3.46	2.05	2.12	3.14
27/12/07	9.66	7414.79	15.98	1.130	1.014	1.001	3.61	2.05	2.10	3.10
06/01/08	12.80	7443.82	12.18	1.129	1.014	0.999	3.37	2.03	2.07	3.13
27/05/07	12.30	7410	17.65	1.129	1.017	1.001	2.27	1.31	1.37	2.17
27/06/08	13.09	7378.38	17.64	1.130	1.017	1.000	2.25	1.30	1.35	2.15
% Variation				0.09	0.29	0.20				

The first obvious conclusion to be drawn is taken from the Turbulence data. We know that the Turbulence values for the GUSM are typically 1-2% for the inner (B and C) Chords and 2-4% for the outer (A&D). It is important to note that these values increase by a factor of three or more when a partial blockage of the flow conditioner occurs. [Ref. 4]

The stability of the values measured here (and the low number of Turbulence alarms during the 8 months of logging) clearly demonstrates that there has been no blockage of the conditioner.

When we consider the Crossflow and Symmetry variations it is very difficult to draw any conclusions as very little reference data exists. The Crossflow reading appears very stable, varying either side of the ideal value by 0.1%. The 0.29% variation in the Symmetry reading should be monitored to see if the upward trend continues, or if the data is simply random variation. There is no reason to suspect that the GUSM's integration technique cannot measure, accurately, in a flow that is still almost perfectly symmetrical.

As the GUSM body and spools have been in use for 10 years it is reasonable to assume that they are "conditioned" [Ref. 6], and, assuming there are no future gas quality issues, unlikely to change wall roughness.

The mean Profile Factor appears very stable, giving an excellent indication that the wall roughness is indeed constant.

To further check this apparent stability, the distribution of the data as time progressed was analysed to check for skews or biases. (Fig. 27 to 30)

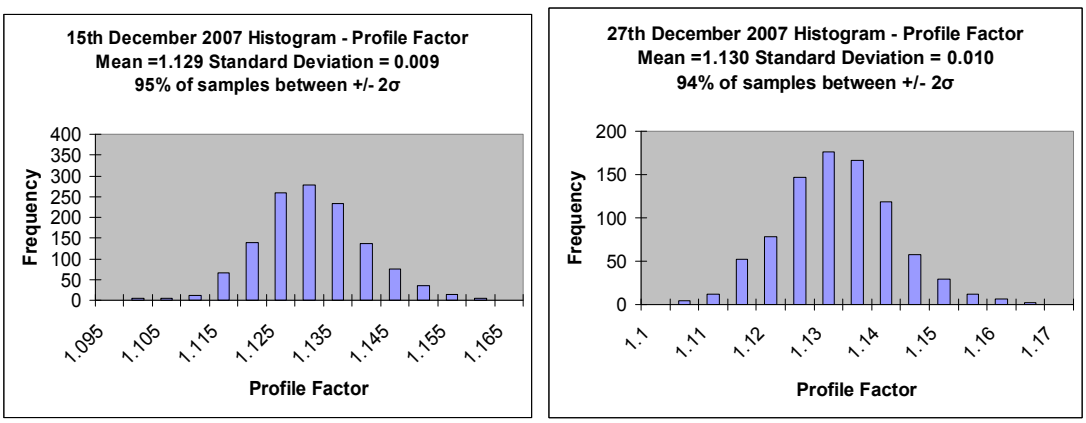
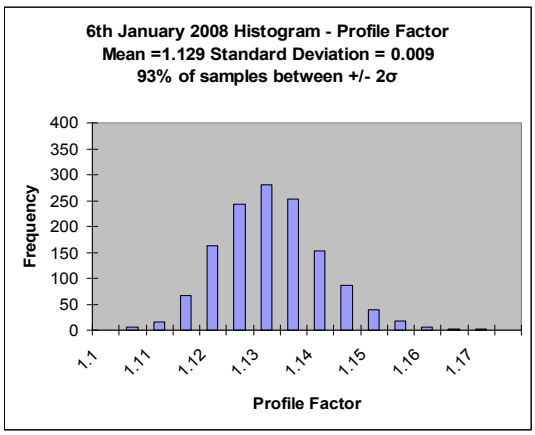


Fig. 27 and 28 Profile Factor Distributions



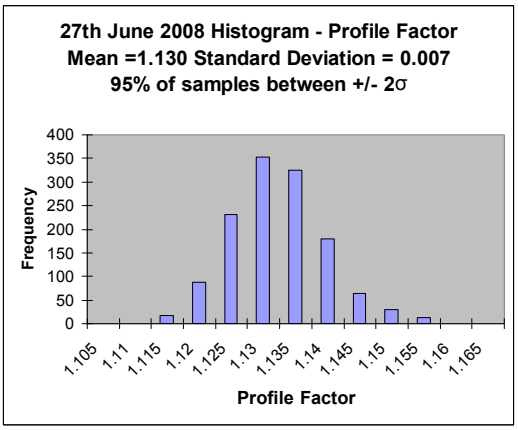


Fig. 29 and 30 Profile Factor Distributions

After analysing the data at similar, single stream flow conditions throughout the 8 months it was not possible to find any indication that the Profile Factor was showing any signs of drift or bias.

The lack of reference data makes it difficult to make a definitive statement on control limit values. There is limited data which looked at relating Profile Factor change to GUSM uncertainty for a 10" GUSM. [Ref. 7]

- For the 10" GUSM a 4.9% change in Profile Factor produced a change in uncertainty (FWME) of -0.36%

The same data also suggested that larger GUSMs are less affected by changes in Profile Factor than smaller sizes.

When we consider that the GUSM studied here (4 times larger cross sectional area), showed a shift in Profile Factor of less than 0.1% over the 8 months, it seems reasonable to assume that the magnitude of any subsequent shift is likely to be insignificant.

Consequently, it would appear sensible to set the control limits as 1.129 (the mean measured Profile Factor) ±0.5%. This should accommodate the single stream, steady flows as well as parallel and non-steady flows (see Section 9)

When we further consider the stated uncertainty of the accredited calibration facilities, we must ask if they are likely to identify a shift of this magnitude?

9. NON-STEADY AND PARALLEL FLOWS

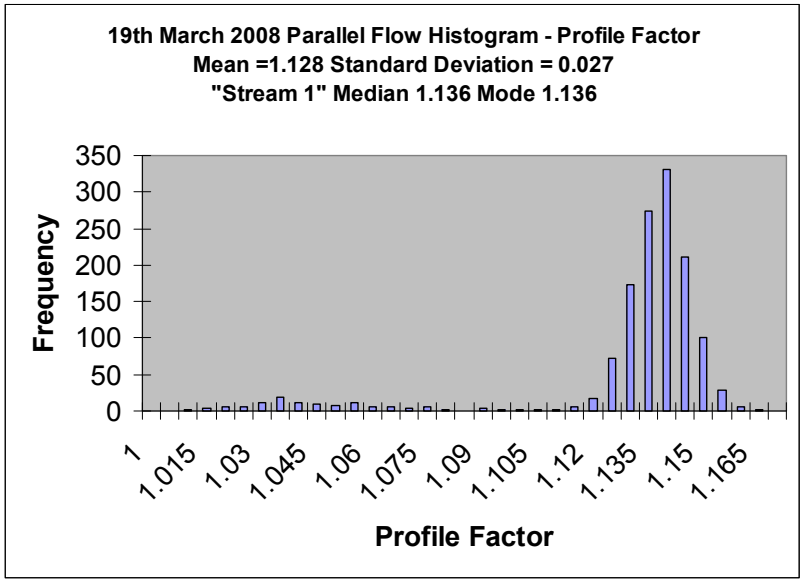
The data studied so far is mainly from single stream, steady flows. Not all sites will have the "luxury" of these repeating conditions, so it was decided to look at data from steady, parallel stream flow periods, and ***non***-steady single stream flow periods to investigate how the data would change. (Table 1) It was immediately clear that there was no impact on GUSM functionality i.e. gains, SN ratio, performance, so attention was focused the AGA-10 comparison and Profile Factor.

9.1 Profile Factor and AGA-10 Distributions At Parallel Flows

Table 9 Parallel Flow Periods

Parallel Flows	Temp (C)	Press (KPag)	Avg V (m/s)	Avg. Profile Factor	Mean AGA-10 SOS Deviation (%)
19/03/2008	10.99	7418.29	8.73	1.128	0.017
31/03/2008	10.83	7417.70	8.64	1.125	-0.032
22/04/2008	11.74	7461.99	8.34	1.125	-0.055

At first glance, when inspecting the means on the Profile Factor (Table 9), and comparing to the single stream values (Table 6), nothing appears to have significantly changed. However, the sample distribution reveals some interesting results. (Figs. 31 and 32)



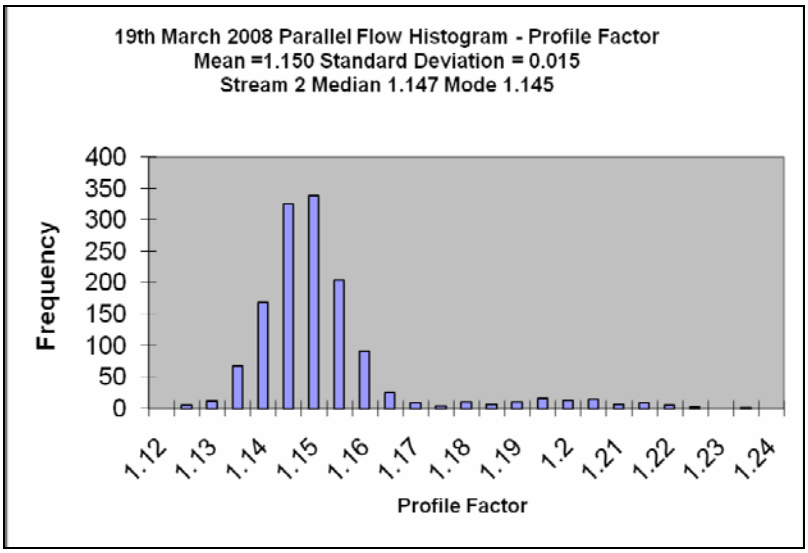


Fig. 31 and 32 Profile Factor Distribution, Parallel Flows

Although, on Stream1, the mean is very close to that for a single stream flow, the median and mode are both much higher (1.136), and there are a significant number of lower value samples. In addition, a similar phenomenon can be seen on stream 2. Here there are a significant number of higher value samples. It can be seen from the charts below that only the Profile Factor seems affected, with the Crossflow and Symmetry values showing no sign of this bias, either in mean value or distribution. (Figs. 33 and 34)

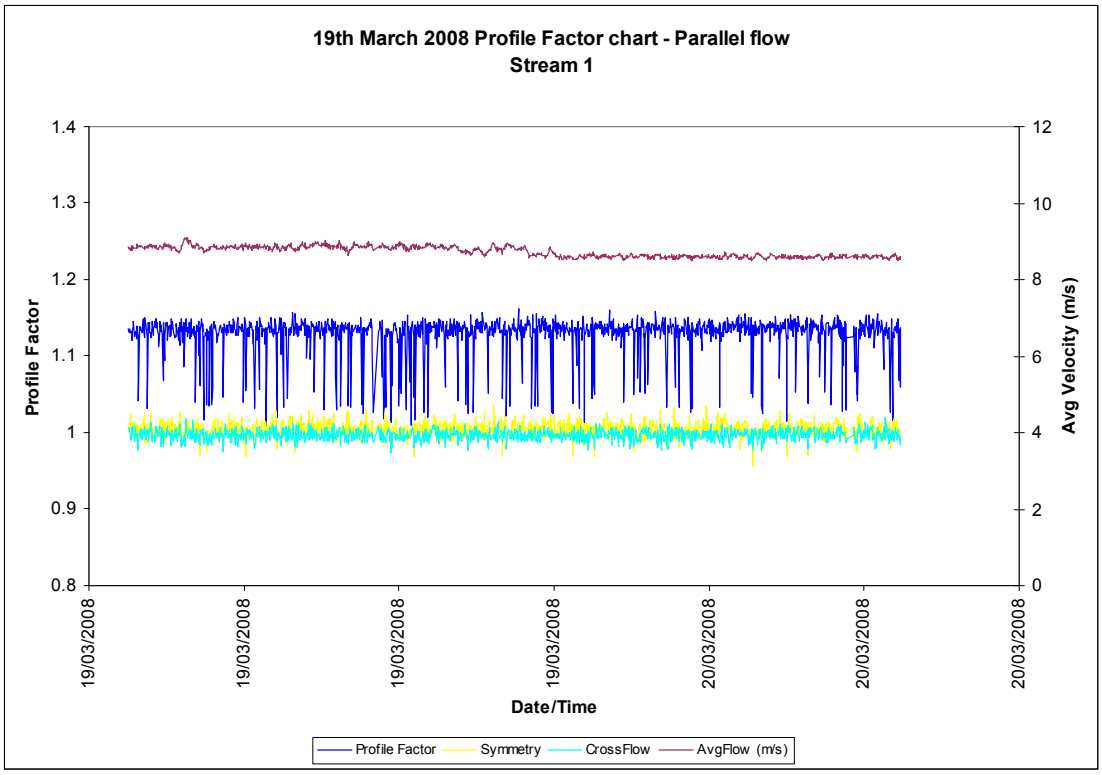


Fig. 33 Profile Factor Charts, Parallel Flows, Stream 1

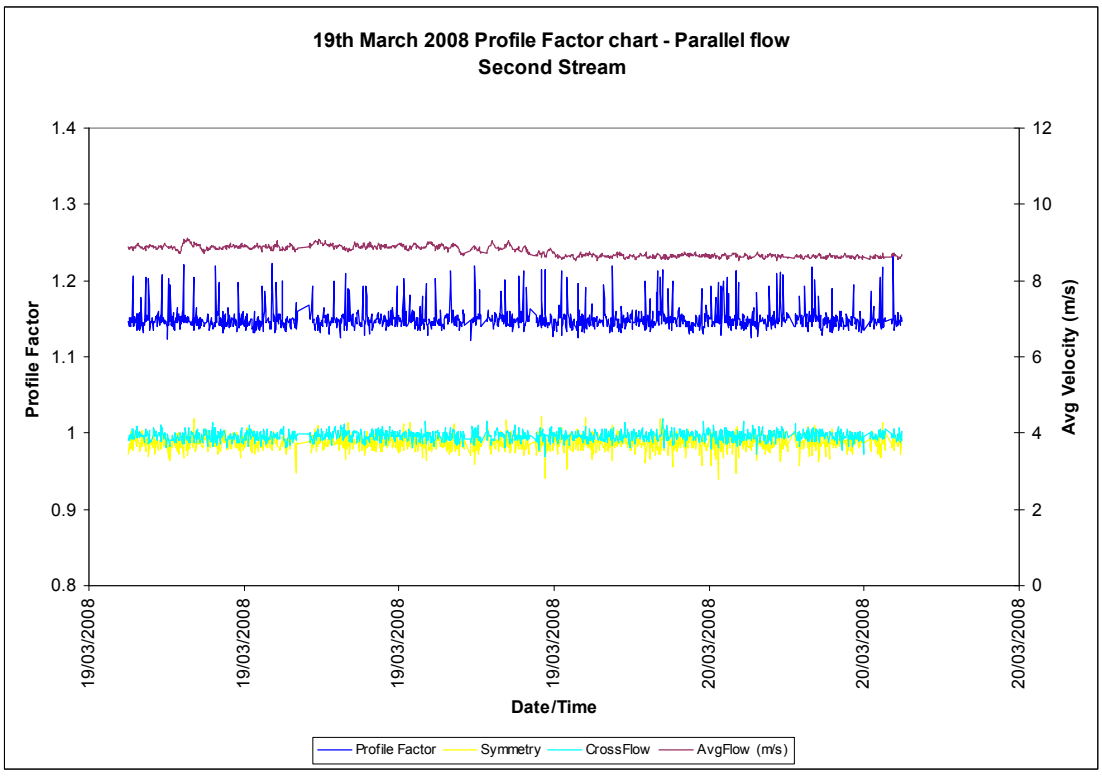


Fig. 34 Profile Factor Charts, Parallel Flows, second Stream

There is sporadic “flattening” of flow profile (and accompanying “sharpening” on the second stream). Is this a result of FCV’s continually being continually adjusted? This needs to be investigated.

The mean AGA-10 comparison data also appears, from studying the mean deviations, to be unaffected by the parallel flows (Table 9). Again, however, differences are to be found when the distribution of the results is inspected. (Figs. 35 and 36)

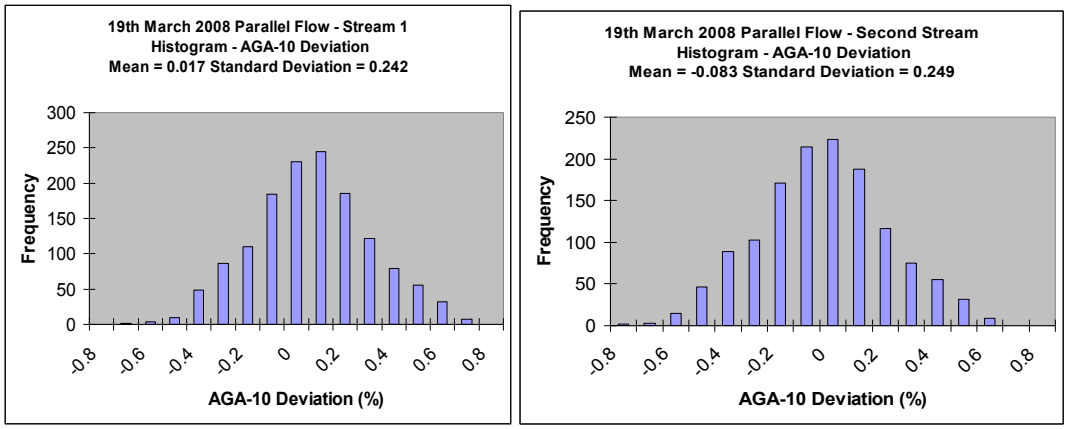


Fig. 35 and 36 AGA-10 Distribution, Parallel Flows

The samples are spread over a range of around 1.4% to 1.6%. This is far larger then the distributions for a single stream flow, where the samples were spread over a range of 0.1% to 0.3%.

9.2 Profile Factor And Aga-10 Distributions At Non-Steady Flows

The Flow Velocity Charts for the days studied are shown below. (Figs. 37 and 38)

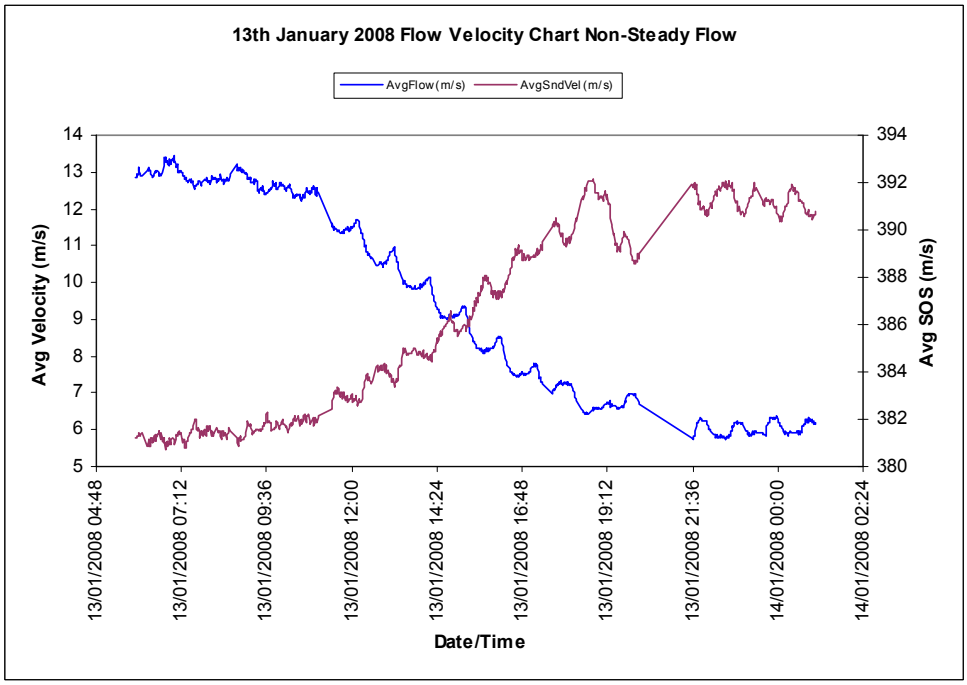


Fig. 37 Flow velocity charts, Non-Steady Flows

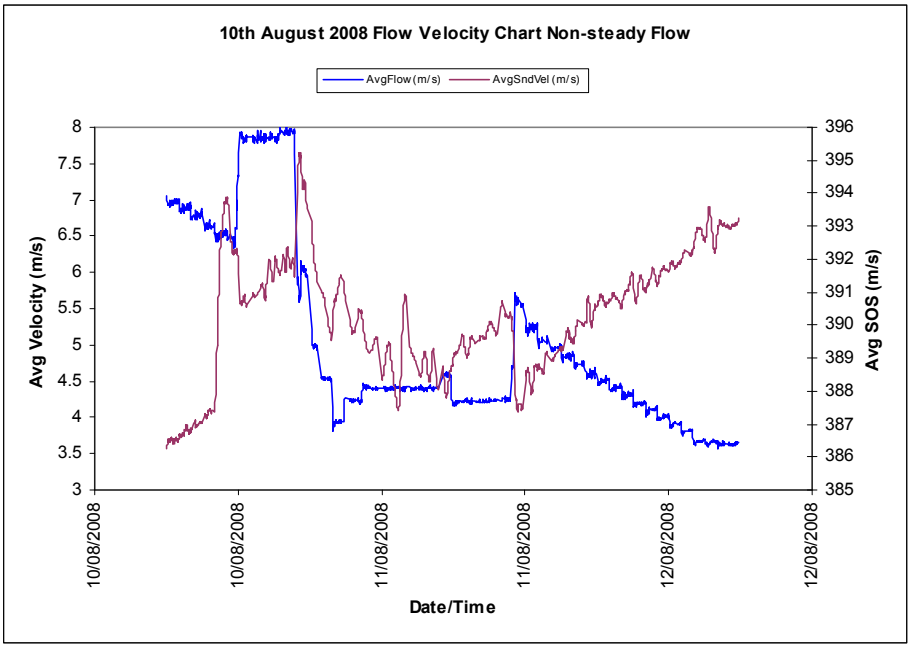


Fig. 38 Flow velocity charts, Non-Steady Flows

It is clear that, for operational reasons, the flow is far from steady state. What effect would this have on the AGA-10 comparison and Profile Factor?

A stark contrast in the spread of the data is obvious. On the 13th January 2007, when the flow drops relatively steadily (Fig. 37), the AGA-10 comparisons are very similar to those for the single stream steady flows. The more pronounced flow velocity variations experienced on the 10th August 2008 (Fig. 38) have resulted in data with a very much larger spread. The mean appears relatively unaffected. (Figs. 39 and 40)

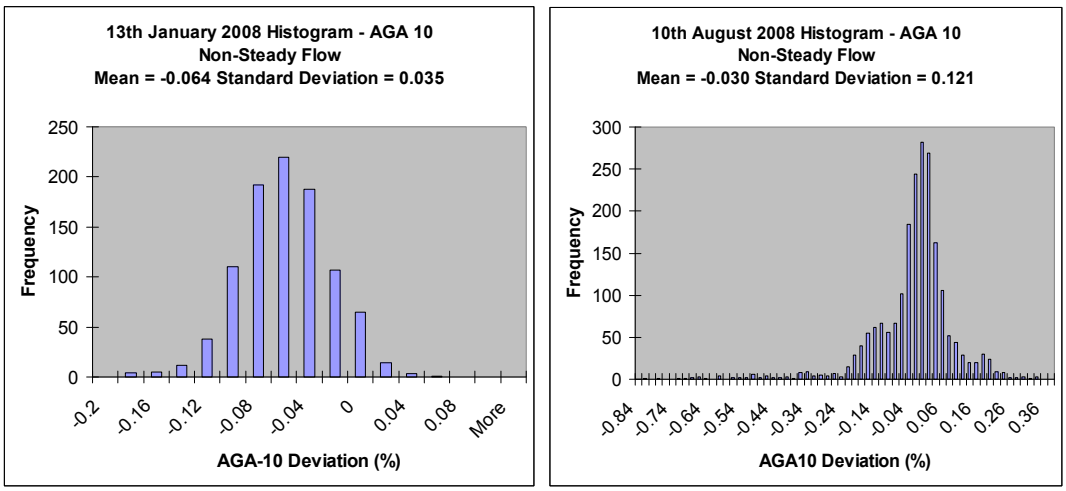


Fig. 39 and 40 AGA-10 Distribution, Non-Steady Flows

The Profile Factor data is very similar, in both mean and distribution, on both days, to that for the single stream steady flow data. (Figs 41 & 42)

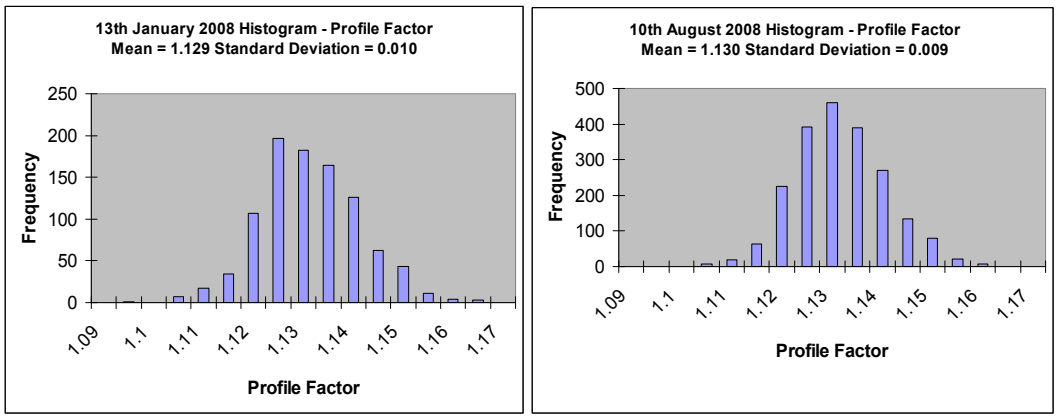


Fig. 41 and 42 Profile Factor Distribution, Non-Steady Flows

10 CONCLUSIONS

It is possible to gain a qualitative indication that a meter has not shown any drift in its operating characteristics, allowing consideration to be given to extending the interval between meter calibrations beyond the current 12-month horizon. Ultimately continuous 'health-checking' has the potential to complement or replace the current strategy of regular, calendar-based recalibration.

To achieve the confidence level of the performance of the GUSM it is important to focus on data that can reliably demonstrate meter stability, system accuracy and upstream internal pipe condition. This relies on datum sets being established at calibration facilities and a period of "benchmarking" of the onsite performance of the meter and system before effective investigation / action limits can be established.

In support of the above statements we believe that:

- The diagnostic data collected on start up demonstrates that the transfer of the calibration is valid. The Profile Factor, Symmetry and Crossflow have a flow profile that is very close to, if not perfectly, developed and symmetrical.
- There has been no degradation in GUSM functionality since the data logging began
- The process condition diagnostics show no evidence of blockage, contamination or wall roughness changes over the period of data collection.
- The calculated SOS was independently verified by means of the GC, PT, TT and densitometer checks and calibrations. The GC, pressure and temperature transmitters, and densitometers have all performed to well within their expected tolerances.
- The very low, and very stable AGA-10 deviations (bearing in mind the independent verification of calculated SOS) give confidence that:
  - The metering system is performing as designed *(i.e.)* with a very low uncertainty
  - The GUSM transducers remain free from contamination
- The stability of the Profile Factor data over time, when combined with the strong AGA-10 correlation, the functional diagnostic stability, and the long history of flow calibration stability, strongly suggests that the metering system is performing exceptionally well and that the GUSM has not shown any shift in its operating characteristics.
- The data collected from the single stream steady flow conditions, which were regularly repeated provided an excellent platform from which to look for GUSM stability and measurement integrity.
- The upgrade of transducers and electronics had a negligible impact on the GUSMs performance (FWME shift of -0.055 %).

11 LOOKING TO THE FUTURE

- The data analysis, which took place for this paper still required a fair amount of manual manipulation. There is a need for USM manufacturers to make the collection and analysis of data more user friendly and intuitive, and to further automate the software to reduce the man-hours required to draw a meaningful conclusion from the data.
- The proposed new international standards for GUSM measurement actively encourage the collection of diagnostics as a way to reduce maintenance and re-calibration, but do not provide a detailed methodology. This paper represents a step towards producing a practical methodology and demonstrates that co-operation between vendors, operators and measurement authorities can produce tangible benefits for all parties.
- It may be possible to address the incongruity, which exists between the specifications of modern pressure and temperature instrumentation, and the maintenance regime for fiscal operators. Many operators are required to carry out checks every few months on transmitters, which come with a stability guarantee of 5 years or more. Condition Based Monitoring offers an opportunity to reduce this burden.
- The data shown in this paper is from an established, conditioned, proven stable system. When new systems, which have the Condition Based Monitoring package, come on-line it will be possible to start building a large enough database to perhaps allow correlating shifts in diagnostics with shifts in GUSM uncertainty.
- The remote access capability of the software provides the potential for operators to establish centralised monitoring centres to watch over GUSMs in geographically separate locations. This could significantly reduce the cost of metering by, for example, replacing dedicated on-site metering teams with mobile metering teams who use Condition Based Monitoring to better direct their efforts. Where local metering expertise does not exist it provides a huge potential for third party metering maintenance contracts.

12 REFERENCES

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North Sea FLOW Measurement Workshop

Paper 2.2

Characterizing Ultrasonic Meter Performance Using A Very Large Database

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Characterizing Ultrasonic Meter Performance Using A Very Large Database

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1 INTRODUCTION

Ultrasonic meter calibration results are often the basis for gas volume uncertainty estimates. Current ultrasonic meter calibration processes do not completely identify many characteristics of ultrasonic flowmeters:

- short term random effects are not well identified due to limitations in the number of data points that make up a calibration
- long term random effects are not identified because a typical calibration only lasts a few hours
- performance characteristics correlated with line size are largely unknown if a user does not calibrate a range of meter sizes

This paper summarizes some analyses of a very large database of ultrasonic meter calibration results. The database has been populated during eight years of operation of an ultrasonic meter calibration facility. The analyses result in the quantification of meter performance separated into four categories:

1. Short term random effects expressed as a function of velocity of several “typical” ultrasonic meters. The time frame associated with “short term” is on the order of many minutes up to one hour.
2. Long term random effects expressed as a function of velocity of several “typical” ultrasonic meters. The time frame associated with “long term” is on the order of several years.
3. Random effects expressed as a function of velocity present in the “as found” data of multiple meters of the same size. These data are presented for a range of meters sizes.
4. Diagnostic parameters that relate to the development of initial calibration fingerprint curves and assist in monitoring long term meter performance.

The CEESIowa test facility went into operation in March 1999. During the intervening years a large calibration database has been assembled, much of the information is unique in the world. This paper discusses some results from “mining” that large dataset for information that is useful to the industry.

Two definitions of “data mining” can be found in [1]:

1. "The nontrivial extraction of implicit, previously unknown, and potentially useful information from data“
2. "The science of extracting useful information from large data sets or databases"

The data mining task is not complete, this paper organizes some of the results obtained thus far.

2 STATISTICAL PROCESS CONTROL

Much of the data discussed in this paper were obtained from three chordal path ultrasonic meters that are used as check meters in the Iowa facility. The nominal diameters are DN300 (12 inches), DN500 (20 inches) and DN600 (24 inches). Within this paper the meters are identified as SPC12A, SPC20 and SPC24.

Control charts based on a variety of check meters have been maintained on a regular basis since September 1999. This section provides a brief review of the process currently in place to organize and interpret data from these meters [2,3]. Figures 1, 2 and 3 of the paper are reproduced from [3] to aid in the discussion.

The development of the control charts begins with a curve fit of meter error and velocity. The conventional (AGA9 [4]) definition of meter error is the difference between flowrate values reported by the meter and the laboratory standard. In the Iowa facility nine twelve inch turbine meters are used as standards. While the AGA 9 definition is used in this paper, it is noted that the ISO VIM [5] states:

> "The error concept can be used when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of measurement standard of negligible measurement uncertainty."

Current day ultrasonic meter calibration processes are characterized by meters exhibiting long term random effects that are smaller than the uncertainties of the laboratories. It is suggested that the use of the term "error" does not meet the ISO VIM definition.

Having defined a curve relating error and velocity; a residual is defined as the percent difference between a data point and the curve fit value. The standard deviation of the residuals defines a statistical interval that contains 95% of the data. Figure 1 shows a plot of residual vs. velocity for SPC24. Most measurement processes exhibit random effects that increase in magnitude for lower operating range values, the measurement of differential pressure represents a familiar example. The data of Figure 1 confirm such behavior for this ultrasonic meter based flow measurement process.

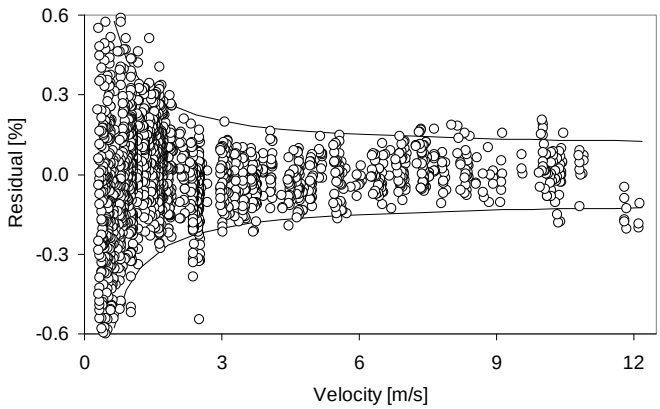

Fig. 1 – SPC24, Curve Fit Residuals

The statistical interval width is $\pm 2s$ where s is a standard deviation expressed in percent. Frequently s can be defined by an equation of the form:

$$s = a + (b/v) \times 100\% \qquad \text{[Eq 1]}$$

where v is velocity. Traditionally the coefficients a and b are selected until the interval appears to contain 95% of the data, a methodology is more qualitative than quantitative. One objective of current analyses is to better quantify the velocity dependence, a new approach is applied to data from Meter SPC24 in the next section.

The next step is the creation of the control charts. The residuals determined from calibration data obtained in a single day are compiled and the mean and standard deviation are calculated. Two control charts containing daily values of mean and standard deviation plotted against time are contained in Figures 2 and 3.

The dependence of meter error on velocity prevents directly comparing results obtained at different velocities on a percent basis. For example, a residual of 0.3% is acceptable at 1 m/s but not at 10 m/s. The data are normalized based on the confidence interval prior to creation of control charts therefore the ordinate values in the control charts of Figures 2 and 3 are presented as multiples of s.

The solid lines in Figure 2 are control limits calculated based on 95% confidence. The process can be stated to be operating in a state of statistical control if 95% of the data lie between the control limits. The control chart in Figure 3 has only one control limit because the standard deviation cannot have a negative value. Statistical control is demonstrated if 95% of the data points lie below the single control limit.

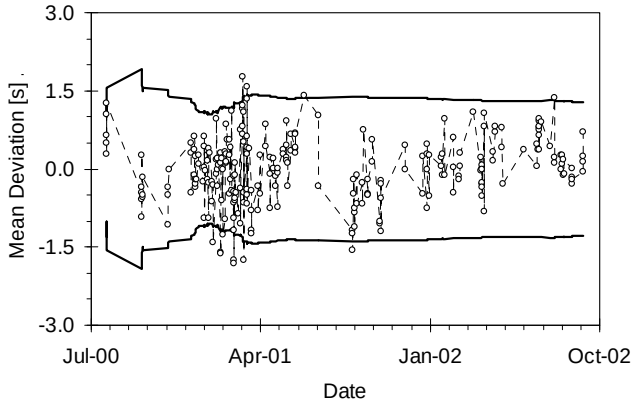

Fig. 2 – SPC24 Control Chart

The process of determining control limits requires the calculation of two standard deviation values [2]. The "within" standard deviation accounts for random effects observed during a single calibration day. The "between" standard deviation accounts for random effects observed between calibration days. These values can be interpreted to represent the short and long term random effects associated with the calibration process.

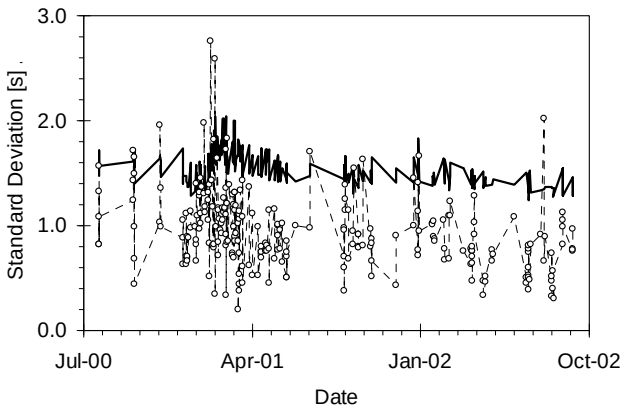

Fig. 3 – SPC24, Control Chart

Control charts are valuable in summarizing large data sets. Multiple data points obtained during one day are represented by two values. The control charts allow for a quick check of how consistent the current calibration is when compared to the accumulated history. The original application of control charts at CEESI was to allow a quick check of pressure transducer calibration results

Summarizing historical performance with a control chart is not as valuable in providing detailed meter performance information. One of the objectives of the data mining project is to investigate alternative analytical techniques to evaluate ultrasonic meter performance.

3 METER 1 – SPC24

The first meter under discussion, SPC24, was put into service in September 1999 as a check standard. This meter is permanently installed upstream of the test section and therefore subject to unchanging inlet conditions. No flow conditioner is installed. In January 2007 the transducers were replaced. The electronics remain unchanged except for some minor adjustments in December 2003.

Meter SPC24 is installed in series with every meter under test (MUT) calibrated in the DN600 (24 inch) test section. The data being analyzed consist of 7246 data points obtained between August 2000 and May 2006 over the velocity range of 0.5 to 24 m/s. It is noted that the velocity through SPC24 is defined by the MUT test plan. The data distribution is skewed towards lower values because the MUT is generally smaller than or equal to the check standard. This distribution is fortunate because more data are available to quantify the larger random effects present at lower velocity values.

The present analysis began by sorting the based on velocity. The sorted data were divided into 64 groups of approximately 100 data points each, each group of data represents a nominally constant velocity. The magnitude of random variations in meter error is dependent on both velocity and time. The analysis of a group of data points obtained at the same velocity allows for the isolation of time dependent effects. Typical results associated with a single group show in Figure 4, these data were determined over the 7.2 to 7.6 m/s velocity range. The ordinate is meter error while the abscissa is time, the symbols on the graph represent individual data points.

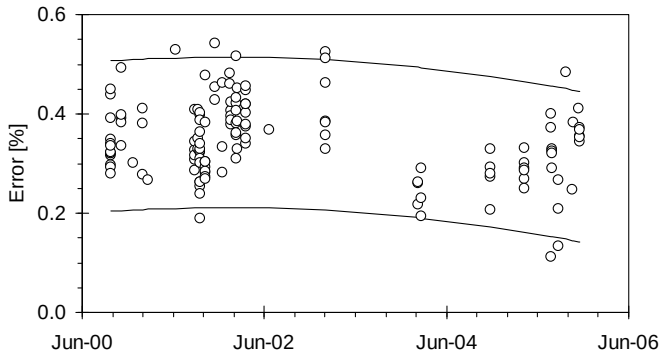

Fig. 4 – SPC24, Variation of Meter Error Over Time, Velocity = 7.2 – 7.6 m/s

The analysis continued with the fitting of a quadratic equation relating meter error and time and the determination of a residual for each data point. The standard deviation of the residuals is called standard error of estimate (SEE) [6]; for the present data SEE = 0.076%. The solid lines in the graph represent an interval of width ±2×SEE centered about the quadratic fit that contains 95% of the data points.

The data points in Figure 4 are uniformly distributed within the interval which indicates that the meter performance is reasonably consistent. A non-uniform distribution might indicate a second order effect requiring additional analyses.

The quadratic fit suggests a slight downward drift over time. A maximum error value of 0.363% is observed in early 2002 while a minimum value of 0.294% is observed in early 2005. The difference of 0.069% represents a potential drift rate of 0.023% per year.

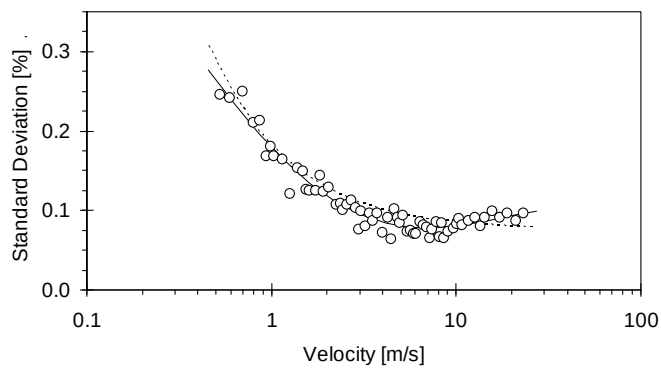

Fig. 5 – SPC24, Magnitude of Random Effects

Several conclusions can be drawn at this point. First, a potential drift or 0.023% per year represents a very small effect. Second, it is demonstrates that the analytical process is very sensitive. The interval width can be interpreted to represent a component of uncertainty. It is observed that a constant error value, a straight line with zero slope, could fit within the interval, the data could be interpreted to predict zero drift.

The analysis of Figure 4 was repeated at each velocity interval. The results are contained in Figure 5, the ordinate is standard deviation expressed as a percent of reading, the abscissa is velocity. The solid line is a fourth order polynomial fit of the data. The "best" performance, corresponding to the lowest standard deviation, is observed near the middle of the velocity range. The curve fit values over the 5.2 to 9.1 m/s range, for example, lie below 0.08%.

The dashed line in Figure 5 represents Equation 1 with a = 0.075 % and b = 1.05 [mm/s]. The term a in Equation 1 accounts for random effects that are consistent with velocity, sometimes called "percent of reading" effects. The term b accounts for the additional "percent full scale" effects that are commonly observed in most measurement processes. The result is the increase in standard deviation with decreasing velocity.

An alternative coefficient, b', can be defined as:

$$b' = b/L \qquad \text{[Eq 2]}$$

where L represents the effective spacing between transducer faces. While the determination of L is complex, the value is primarily dependent on meter geometry and can therefore be assumed constant. Equation 1 can be realized using b' with units of time illustrating that full scale effects arise from limitations in the measurement of time and effective transducer spacing**.**

The results of Figure 5 indicate a slight increase in standard deviation at high velocity. The magnitude of this change is approximately 0.02% between 10 and 30 m/s. This slight increase is the major contributing factor to Equation 1 not fitting the data as well as possible. A physical explanation for this observation is not currently proposed.

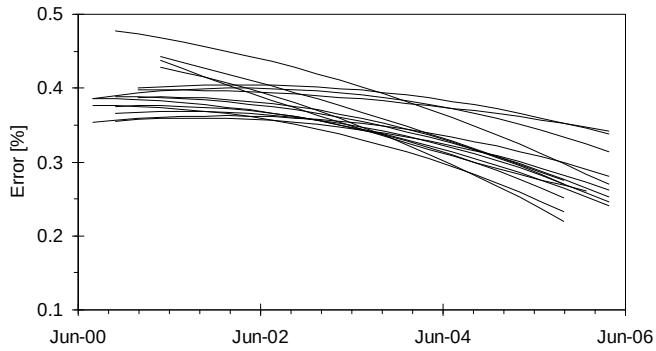

Fig. 6 – SPC24, Variation of Error With Time
Constant Velocity Curve Fits With Similar Shapes

The results of Figure 5 are useful to CEESI in precisely quantifying the random effects required to normalize control chart data. The results are useful to the industry because the random effects represent an important uncertainty component associated with a "typical" ultrasonic meter. What is typical? Comparable results could be reasonably expected from another similar meter of the same size, perhaps a similar meter of a different size. One objective of the data mining effort is to determine the effect of diameter on the distribution and magnitude of random effects.

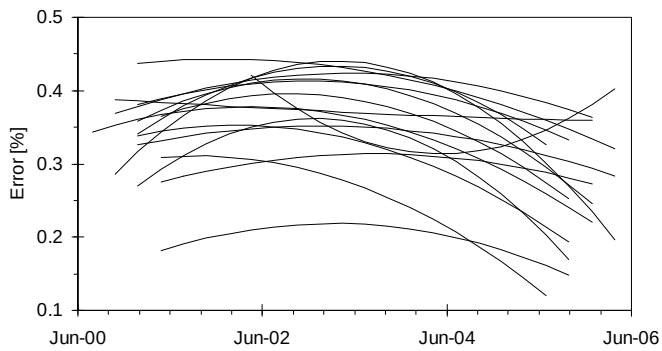

Fig. 7 – SPC24, Variation of Error With Time
Constant Velocity Curve Fits With Dissimilar Shapes

The quadratic fit of the data in Figure 4 predicts meter changes over time. Similar curve fits have been determined for data from a number of the velocity ranges, some of the results are summarized in Figure 6**.** The ordinate is meter error and the

abscissa is time, each solid line represents the quadratic fit associated with a velocity range. The data shown represent 16 curves with similar shapes, similarity having been judged by eye. Figure 7 contains the remaining curves, the shapes exhibit a greater range of variation. All but two of the curves in Figure 6 fall in the 7 to 15 m/s range. All but four of the curves in Figure 7 fall in the 4 to 7 m/s and 15 to 23 m/s ranges. It appears that the meter exhibits more consistent long term behaviour in the middle of the velocity range than at either higher or lower velocities. A similar general trend has also been noted in Figure 5.

How are these results useful? Figures 6 and 7 quantify long term effects associated with this meter. These effects may be identified as drift, stability, or reproducibility; they may be considered random in nature. From the user's perspective, this information can help select a recalibration interval that balances cost and performance. The results provide CEESI an alternative tool to monitor consistency of the facility with greater detail than a control chart. Repeating from above, comparable results could be reasonably expected with another similar meter of the same size, perhaps a similar meter of a different size.

Historical analyses of meter SPC24 have included control charts of various diagnostic parameters, a detailed discussion including several examples are contained in [7]. That discussion included a case where meter SPC24 was installed downstream of an orifice meter and the resulting diagnostic (profile factor) clearly indicated abnormal conditions. The data mining effort includes available diagnostic data, currently the analyses have not resulted in additional conclusions concerning meter SPC24.

4 METER 2 – SPC20

The second meter under discussion, SPC20, was also put into service in September 1999 as a check standard. In October 2002 the electronics failed and a component was replaced. In February 2005 the transducers and electronics were replaced. This meter is permanently installed upstream of the test section and therefore subject to unchanging inlet conditions. No flow conditioner is installed.

Meter SPC20 is installed in series with every MUT calibrated in the DN500 (20 inch) test section. The data available for analysis consist of 15,250 data points obtained between April 2000 and July 2008 over the velocity range of 0.3 to 30 m/s. The present discussion is limited to the analysis of data obtained after the replacement of electronics and transducers in February 2005.

The present analysis parallels that underway for SPC24. The velocity sorted data were divided into 65 constant velocity groups each containing approximately 235 data points. The analysis to date consists of 14 velocity groups, the results are summarized in Figure 8. The ordinate is SEE associated with a constant velocity group while the abscissa is average group velocity.

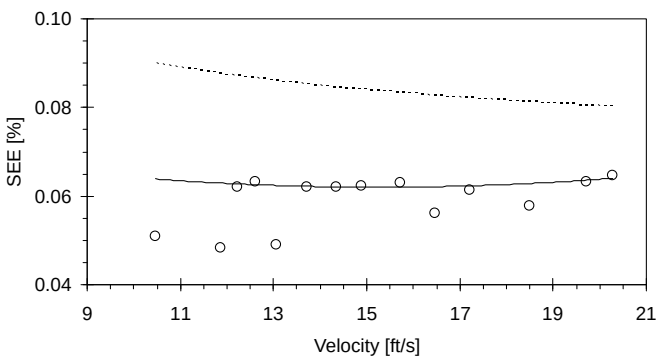

Fig. 8 – SPC20, Magnitude of Random Effects

Nine of the data points appear to follow a trend, a curve fitted to these data is shown as a solid line. The five data points with lower SEE values are not used in the curve fit.

The dashed line in Figure 8 indicates typical values in use immediately prior to failure of the electronics in October 2002. The difference between dashed and solid lines is the current vs. older electronics and transducers; clearly there is improvement as a result of the upgrade.

Meter SPC20 was subject to two historical events; failure of the electronics in October 2002 and full replacement of electronics and transducers in February 2005. Analyses of detailed data obtained in conjunction with these events would prove of value to the industry. A summary of older analyses concluded [8] that the control charts may have provided advanced warning of the electronic failure of 2002. The current results have not contributed new information to support this conclusion. The Iowa data acquisition system began collecting diagnostic data in September 2002, such data are therefore unavailable for the period preceding the electronics failure.

Meter SPC20 indicated a shift in performance with the new electronics and transducers in February 2005. At present that shift represents a single data point and will not be discussed in this paper. One of the future data mining activities involves collecting data from many re-calibrations that would better quantify the shift of a "typical" meter in response to changing transducers and/or electronics; data from SPC20 would be part of that study.

5 METER 3 – SPC12A

The third meter under discussion, SPC12A was first put into service in January 2003. It was primarily used by the manufacturer for research and development testing and the resulting data are proprietary. In March 2005 the electronics and transducers were replaced and the meter was put into service as a check meter.

Meter SPC12A was installed in series with most MUT calibrated in the DN400 (16 inch) test section between May 2005 and August 2006. A different check meter, SPC12B was installed for most of the calibrations completed between September 2006 and September 2007. The performance SPC12B will be the subject of future analyses. Meter SPC12A was returned to more continuous service as a check meter in October 2007. The present analyses are based on data obtained between May 2005 and August 2006.

As compared to SPC20 and SPC24, meter SPC12A is installed downstream of the test section. The pipe layout upstream of the meter therefore varies from one calibration to another. During the time interval of interest numerous calibrations were completed on DN150 (6 inch), DN200 (8 inch), DN250 (10 inch) and DN300 (12 inch) MUT, a few calibrations were completed on DN350 (14 inch) and DN 400 (16 inch) MUT.

Meter SPC12A inlet conditions vary depending on the MUT requirements. Some calibrations, for example, include two MUT installed in series, a configuration that would require additional space when compared to a single meter calibration. Other calibrations include the effect of elbows, tees and other pipeline fittings, such tests would potential introduce distorted or swirling profiles upstream of SPC12A. While the use of sufficient straight pipe plus a flow conditioner was always a goal, they would only be included if the test requirements were not

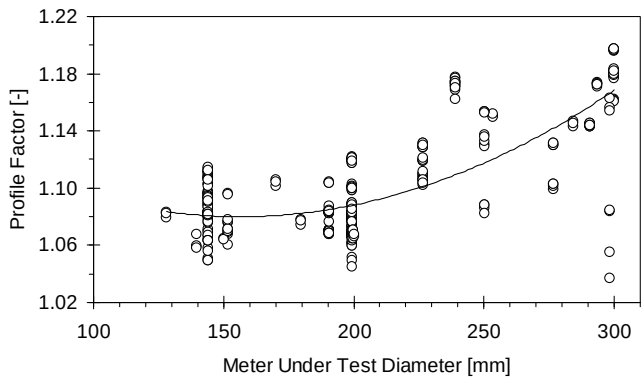

Fig. 9 – SPC12A, Profile Factor Variation with MUT Diameter Velocity = 6.7 – 7.6 m/s

compromised. The database for SPC12A provides a unique opportunity to gain insight into installation effects. For every calibration, the installed fittings have been recorded, these data have not yet been integrated into the database.

The mining of meter SPC12A data has included investigation of the profile factor, a commonly applied diagnostic parameter [7]. Results obtained over the 6.7 to 7.6 m/s velocity range are shown in Figure 9, the ordinate is profile factor while the abscissa is MUT diameter. The numerical value of profile factor is frequently interpreted to represent the velocity profile; a larger value corresponding to a more pointed profile, a smaller value indicating a flatter profile.

While random effects are clearly present, the data in Figure 9 appear to indicate a change in profile factor with upstream pipe configurations. The flow from a smaller to larger diameter in a commercial pipe reducer will result in a jet because the flow does not remain attached to the wall. The result, illustrated in Figure 10, will be a velocity profile that is more pointed than the fully developed profile associated with the Reynolds number and surface roughness. An ultrasonic meter exposed to the velocity profile of Figure 10 would be expected to exhibit a increase in profile factor. The trend in Figure 9 indicates the opposite effect, the profile factor decreases with MUT diameter.

Fig. 10 – Proposed Distorted Flow Profile

When a curve is fitted to a set of data the square of the correlation coefficient, R^2, indicates the degree to which the variation in the abscissa values is correlated with the ordinate values. The curve fit of Figure 9 is characterized by $R^2 = 0.56$ which means that 56% of the variation in profile factor is correlated with MUT diameter. The remaining 44% of the variation is either random or correlated with a different parameter. Identifying additional correlations remains an objective of future investigations.

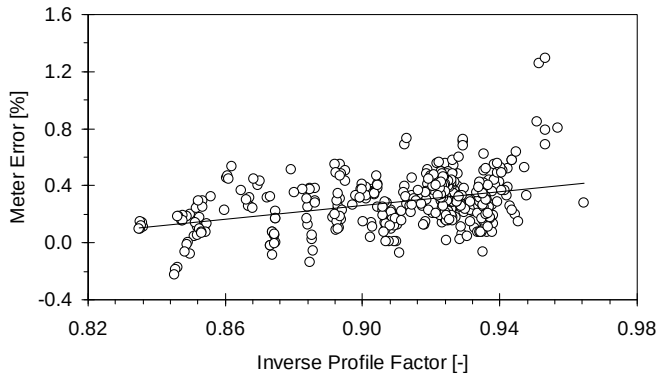

Fig. 11 – SPC12A, Meter Error Variation With Inverse Profile Factor
Velocity = 6.7 – 7.6 m/s

If the profile factor changes in response to upstream conditions, what impact does this have on meter error? Figure 11 shows a plot of the meter error and inverse profile factor. The solid line is a linear fit of the data characterized by $R^2 = 0.15$. It appears as if there is an effect, however small, of profile factor on meter error. The difference in correlation coefficient values (between Figures 9 and 11) indicates that the multipath velocity averaging is reducing the impact on meter error. The abscissa data are presented as the inverse of profile factor, as the data analysis proceeded the emerging data patterns seemed to indicate slightly better linearity with the inverse.

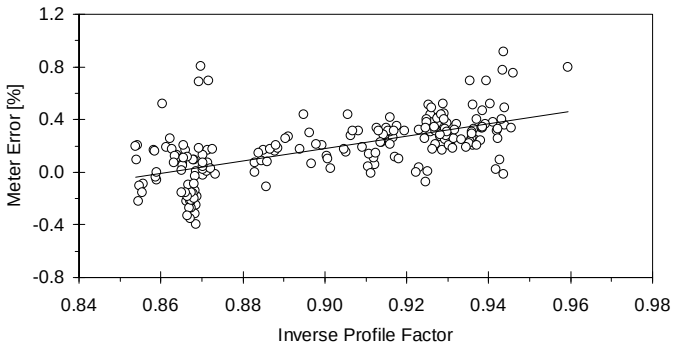

Fig. 12 – SPC12A, Meter Error Variation With Inverse Profile Factor
Velocity = 5.0 – 5.2 m/s

A similar plot is contained in Figure 12. The velocity range is 5.0 to 5.2 m/s and the linear fit is characterized by R^2 = 0.38. This plot, the result of a quick survey of the database, indicates the presence of data ranges that exhibit stronger correlation with profile factor.

The mining of meter SPC12A data needs deeper drilling. The analysis has not yet included complete descriptions of the pipe and fittings installed between SPC12A and the MUT. Including these data is expected to provide additional insight into the underlying fluid dynamics.

As with SPC20 and SPC24, the velocity through meter SPC12A is dependent on MUT size. This effect is more pronounced with SPC12A, a DN150 (6 inch) MUT will result in a velocity ratio 0.25. The smallest typical MUT size in the DN500 (20 inch) is DN350 (14 inch) which results in a velocity ratio of 0.70. The smallest typical MUT size in the DN600 (24 inch) test section is DN550 (22 inch) which results in a velocity ratio of 0.92. The variable velocity ratio imposes an additional constraint on the analyses.

6 INVESTIGATION OF METERS UNDER TEST

Analyses of meters SPC12A, SPC20, and SPC24 are based on large quantities of data obtained with single meters. The analyses described in this section are intended to represent smaller quantities of data obtained from multiple similar meters.

The first results under discussion were obtained from as ensemble of 23 chordal design DN250 (10 inch) MUT. The analysis began with a curve fit of meter error and velocity for each MUT, the curve fit residuals for all 23 MUT are shown in Figure 13. The solid lines represent a statistical interval of ±2*s* in width where s is defined by Equation 1 with *a* = 0.048% and *b* = 1.06 [mm/s]. When these results are compared to Meter SPC 24, the same value for *b* is observed. It appears that the basic relationship between random effects and velocity is the same for both meter sizes.

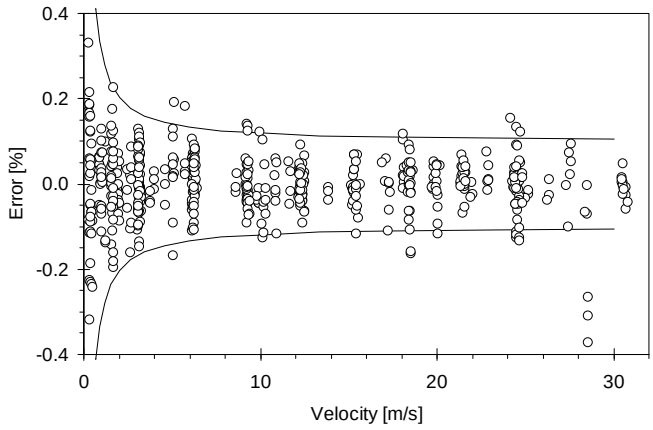

Fig. 13 – DN250 MUT Ensemble Meter Error Curve Fit Residuals

The *a* value for the meter ensemble (*a* = 0.048%) is significantly less than that for Meter SPC24 (*a* = 0.075%). One natural conclusion might be that the DN250 design is more repeatable than the DN600 design because the *a* values represent short term random effects. The difference between the meters is that a new curve fit is developed for each new set of ensemble data, while a single curve fit is applied to the data

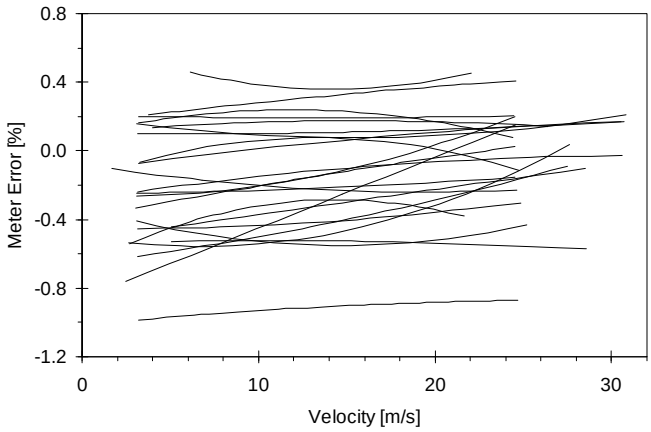

Fig. 14 – DN250 MUT Ensemble Meter Error Curve Fit Values

from Meter SPC24. Comparable performance from the large meter might be observed if the data were fit to a new curve every day.

The curve fits relating meter error and velocity are shown in Figure 14, each line represents one MUT. The data all lie within +0.46% and -1.0%; this range of values combined with values from Figure 13 provides one method for estimating the uncertainty of an un-calibrated ultrasonic meter. The uncertainty in a calibrated meter combines the values from Figure 13 with an uncertainty associated with calibration process. The uncertainty of a calibrated meter is always less than an un-calibrated meter. One of the curves of Figure 13 appears to be an outlier; in addition to generally reducing uncertainty, the calibration process will identify outliers.

A similar graph appears in Figure 15 where the curves fit profile factor data. These data illustrate that a curve relating profile factor and meter error is unique to each meter [7]. It has been proposed that diagnostic parameters can form a potential fingerprint to be monitored as an indicator of meter performance. A suggested application would be to record a fingerprint during calibration and then immediately upon installation in the field. Differences between fingerprints would identify potential changes to meter performance resulting from initial installation. Continuous monitoring of the fingerprint over time could provide indication of future meter problems.

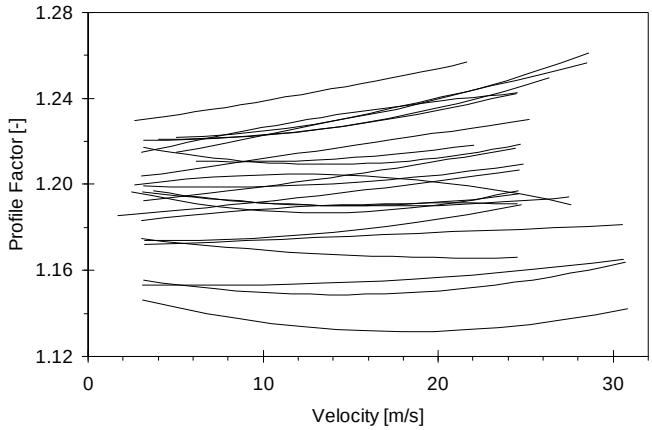

Fig. 15 – DN250 MUT Ensemble
Profile Factor Curve Fit Values

While identifying a relationship between profile factor and meter error is valuable; it does not provide a useful fingerprint because meter error is unknown in the field. Diagnostic data from individual meters in the ensemble are being evaluated for potential "field useable" fingerprints. One potential example is illustrated in Figure 16, the ordinate is the difference between measured and calculated speed of sound values. The calculated value is based on gas composition measured by a chromatograph and an equation of state [9]. The data were obtained over a range of velocities between 3 and 25 m/s. The solid line is a quadratic fit of the data characterized by $R^2 = 0.77$. Once installed, it would be a simple matter to periodically obtain data points and evaluate how well they fit the curve fit. One objective in continuing this investigation will be to evaluate how common this, or other, fingerprints are among similar meters. A second objective will be to evaluate the typical uncertainty associated with a fingerprint curve.

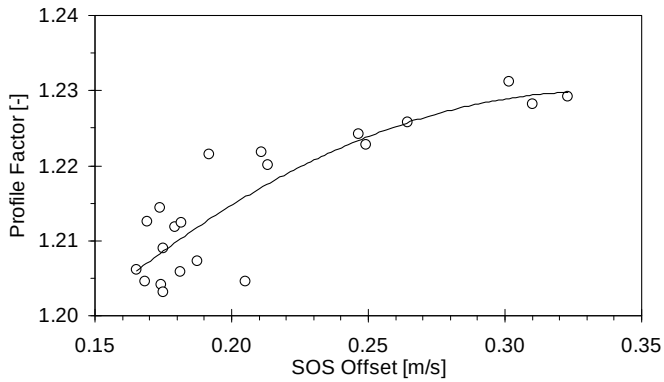

Fig. 16 – Selected DN250 MUT
Profile Factor vs. Sound Speed Fingerprint

7 SUMMARY AND FUTURE WORK

This paper has presented some results from an ongoing project to mine the CEESIowa calibration database. A summary of the results presented includes:

1. The process of characterizing two large meters (DN500, DN600) is well underway. Short and long term random effects have been defined, the long term values cover a period of several years. One of the meters shows an improvement in performance as a result of new electronics.

2. A third smaller meter (DN300) is exposed to a broader range of installation conditions. The analyses are more complex but the potential value of the results is high. The analyses thus far have identified meter sensitivity to installation conditions, additional detailed data have not yet been included.

3. Analysis has begun in the investigation of ensembles of similar meters under test. The discussion is based on a limited number (23) of DN250 meters. The effect of calibration has been demonstrated and some promising diagnostic tools identified.

As the project continues, the following activities are planned:

- Continue to the analyses already described, most are incomplete.
- Integrate additional diagnostic parameters into the database for the check meters. The speed of sound, in particular might yield some promising results.
- For the DN300 meter provide a summary of random effects as they vary with velocity and time.
- Begin analysis of a second DN300 check meter, a chordal design meter from a different manufacturer.
- Expand the ensemble MUT analysis to other meter sizes.
- Expand the MUT analysis to investigate meters returned for re-calibration.

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North Sea FLOW Measurement Workshop

Paper 2.3

Practical Experiences of Operating Small Bore (4”) Gas Ultrasonic Meters for Fiscal Measurement on a FPSO

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TÜV SÜD

nel technology for life

Practical Experiences Of Operating Small Bore (4”) Gas Ultrasonic Meters for Fiscal Measurement on a FPSO

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Jason Laidlaw, METCO Services Ltd

1 INTRODUCTION

CNR International (UK) Ltd (CNRI) have operated the Banff oil field in Blocks 22/27a and 29/2a of the North Sea UK Continental shelf since 2003 by producing the hydrocarbons over the Teekay operated Banff FPSO. In 2004, CNRI tied back its Kyle oil field in block 29/2c to the Teekay Banff FPSO which resulted in a number of required changes and additions to the measurement systems on board. One of these modifications was the installation of a new ‘fiscal’ quality gas measurement system to replace the previous four stream 4”nb orifice plate gas export skid. The new skid was required due to the increased overall gas flowrates from the additional Kyle field production, plus CNRI wished to give itself options regarding how its produced gas could be utilised. As well as the option to continue exporting gas to the BP operated CATS gas pipeline, there was also a requirement to introduce a route for gas re-injection into the Banff field and the provision of gas lift for a number of key wells. This paper describes this new system methodology for operation and field experience with these small bore ultrasonic meters used in a high accuracy application.

2 METERING STATION DESIGN AND OPERATION

The new system features two 4”nb Instromet Q-Sonic 3S flowmeters constructed from duplex stainless steel. The meters are installed in a ‘Z-arrangement’ which has been utilised in other geographic sectors [1], while it is relatively uncommon in the UK offshore sector with the Dawn system previously reported at the NSFMW being an exception [2].

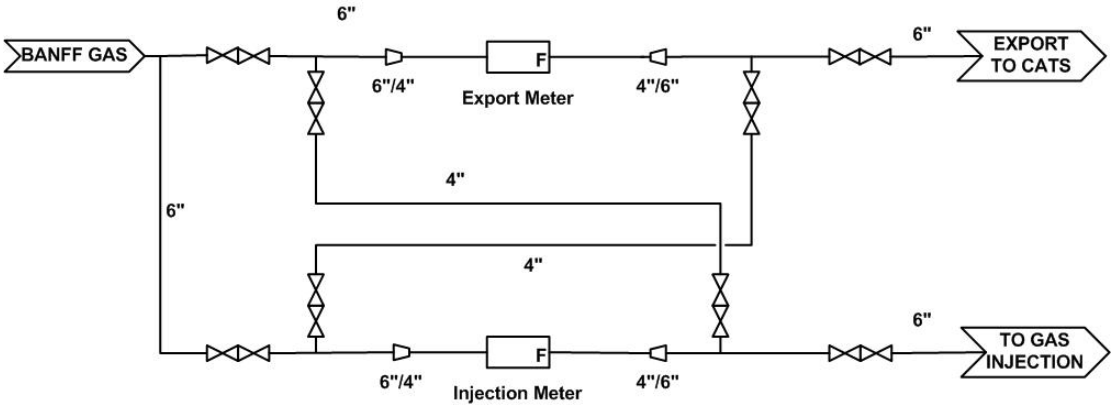

Figure 1 Banff Export / Injection Metering Schematic Diagram

The system allows the gas to be routed to export, re-injection (including gas lift) or both whilst also offering the possibility of placing the two meters ‘in-series’ to allow in situ verification.

The flow meters are installed in the field with 21.8D of straight upstream pipework and 5.8D downstream, in keeping with the recommendations of BS 7965:2000 [3]. The option of utilising a flow conditioner with shorter upstream lengths was discounted to maximise the effect of the compression system. Ultrasonic flowmeters were selected for this application for two main reasons. Firstly the negligible pressure loss through the meter allows the complete range of expected flow rates to be covered by the two stream system at 4”nb. This was a key parameter as the Banff FPSO is much smaller than most FPSO vessels and the only place that the new system could be located was on its turret. A system requiring additional metering streams could not be accommodated in the limited available space. The design flowrates were 0.1427 to 2.41 MSm3/day at between 160 and 200 barg. Actual volumetric flowrates

are between 550 and 600 m3/hr compared to the nominal meter maximum of 650m3/hr. Secondly, CNRI had to gain permission from BP to allow the installation of a new meter type other than orifice plates for export into the pipeline. The BP CATS pipeline entrant requirements had up to this point in time required orifice plate flowmeters due to their wide ranging standard acceptance in the industry. Unfortunately the flow rate scenarios expected during future production could not be accommodated with orifice plate meters owing to the space required for a suitable system not being available. Other meter options were considered for example Venturi meters and Coriolis meters but the ultrasonic meter was overwhelmingly the best option. For example Venturi meters can be unpredictable in their response as has been reported at the NSFMW before [4] and Coriolis type flowmeters for high accuracy gas applications were only just emerging as an accepted technology at that point in time. Ultrasonic flowmeters had, by 2004, been installed successfully in a number of locations offshore in many international sectors and were therefore the logical choice for this application.

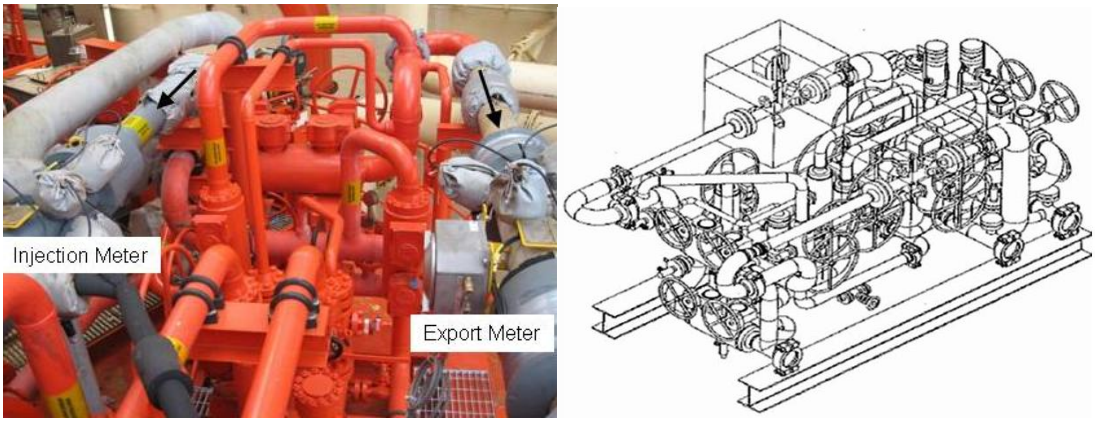

Figure 2 Turret Metering Station

One aspect that CNRI were required to demonstrate was that the meters could be verified adequately. This was key for the acceptance of the system. So as well as the provision of verification in the field by routing the two meters in series, a complete spare meter stream was also provided to allow either the export stream or the re-injection stream to be removed and sent for re-calibration. Each meter stream comes complete with dedicated upstream and downstream pipe work spools so that the streams can be calibrated as one unit to remove additional measurement uncertainty from the removal and re-application of the meter spools at installation. The meters have been periodically calibrated at PIGSAR in Germany since July 2004. Finally monitoring through the analysis of the diagnostic capability of the Instromet meters gives added confidence and also helps to identify early any problems that may occur.

As any of the three meters can be installed in either the export or injection lines, the meters are identified by serial number in this paper. The meter serial numbers are 2901, 2902 and 2903.

3 METER VERIFICATION PROCEDURES

Banff was the first producer to use ultrasonic meters for fiscal export measurement to the CAT's pipeline. It was therefore to be expected that CAT's would require tight verification procedures to ensure that the measurement uncertainty was maintained at the required level. The verification procedures are based on regular laboratory calibration, in-service series line checks and monitoring of the meters diagnostics. The following describes in detail the verification procedures employed.

3.1 Laboratory Calibration

Prior to start-up and at regular intervals during their operation the Banff export and injection meters have been flow calibrated at PIGSAR in Germany. Three meters were purchased to allow onshore calibrations whilst still maintaining full operational capability. Initially CAT's

required re-calibrations on a 3 monthly basis. Hence a major effort was launched to calibrate the meters as often as possible with the result that each meter has now been calibrated 4 times (12 calibrations in total) in 4 years. Achieving this level of re-calibration has not been easy due to the basic logistics of transporting the meters, and the availability of the calibration facility. Transport to and from the FPSO in bad weather can easily delay transport schedules resulting in the meter missing its calibration slot which often have to be booked three to four months in advance. In winter, bad weather can stop transport for several weeks and when weather windows do appear these may only last for a few hours. With transportation there is also a risk of damage to the meter which leads to delays whilst repairs are carried out.

Following the presentation of satisfactory meter verification data including laboratory calibration results, series line checks and diagnostic data, CAT's relaxed the re-calibration period from 3 to 6 months in September 2007.

Figure 3 Meter with Spools

Due to the small size of the meters there was a concern over the potential effect of misalignment between the meter and its upstream and downstream spools. Any mis-alignment at the upstream spool creates a discontinuity in the pipe wall which will disturb the flow profile within the meter. The effect of misalignment would be greater than normal due to the relatively small nominal bore of the meters. As the intention was to calibrate the meters on a regular basis this would require the regular removal and re-installation of upstream and downstream spools thus increasing the risk of misalignment. For this reason it was decided that the upstream and downstream spools should remain permanently attached to the meter. This made transportation of the meter more difficult as the meter with spools attached measured over 3 metres. However it was felt that the measurement risk justified the transport difficulties.

Calibrations are performed using natural gas at a nominal pressure of about 50 barg. The meters are calibrated at 6 nominal flowrates over a 30:1 turndown ratio. Each flow point comprised of the average of at least three test runs.

Meter diagnostics are recorded during the calibration, these are used to confirm the health of the meter and as a reference with which to check the meter when operating in-service (see Section 3.3 for more details).

The calibration results are entered into the metering station flowcomputers (Instromet 2000) where a correction is applied using linear interpolation between the calibration points. No correction is applied to the meter head electronics. This simplifies the process and makes the meter setup easier to audit.

3.2 Series Line Checks

The metering station has been designed to allow the injection and export meters to be lined up in-series. This enables the relative performance of the meters to be assessed during operation.

The meters can be either lined up in-series for export to the CATS pipeline or for gas Injection /Lift on Banff and Kyle fields depending on operational requirements. Since start-up of this system gas has mostly been fed to the Injection stream. In order to reduce the potential for common mode errors the export stream has remained offline and isolated in between series line checks. At most these checks take three or four hours per week. In effect the export meter has operated, so far, very much like a master meter, with and the injection meter as the duty meter. However, owing to the stringent requirements of the CATS pipeline, and the potential requirement for gas export at short notice should there be an issue with the re-injection system, the export meter was given priority in terms of the hierarchy of the two meters.

The series line check procedure begins with altering the valving so that the meters are in series. The station is then left for a period to allow the temperatures to stabilise. The test period then begins at the start of the hour and lasts for one reporting hour. At the end of this period the accumulated mass flow totals for that hour are recorded and the discrepancy is calculated as follows:

$$E=\frac{Total_{inj}-Total_{exp}}{Total_{inj}}.100\%$$

Where

E	Discrepancy between injection and export meters (%)
$Total_{inj}$	Injection Meter accumulated 1 hour mass total (tonnes)
$Total_{exp}$	Export Meter accumulated 1 hour mass total (tonnes)

The checks use mass totals because the pressure drop between the meters is too great to use gross observed volume. Hence the check not only compares the performance of the two meters but also includes the pressure and temperature measurements, and the flowcomputer calculations. The only equipment which is common to the metering streams and hence is not monitored by this check are the gas chromatographs.

Series line checks are normally performed once a week, also just prior to and just after a meter change-out. The results are trended and limits which trigger further investigation have been set. The limits are as follows; any discrepancy greater than ±1% or any change in discrepancy greater than 0.3% which is not related to a change-out of the meters.

3.3 Diagnostics Monitoring

The final verification technique is the monitoring of the meter diagnostics. The meters can report various diagnostic parameters which can assist in the early detection of meter faults. The export and injection meter diagnostics are normally logged on a weekly basis during the series line checks using Instromet's utility / diagnostic software application UNIFORM. The logged data is averaged and then trended on a specifically developed health check spreadsheet. The spreadsheet incorporates the health care limits as defined by Instromet [5]. Any deviation out with these limits triggers further investigation. Table 1 details the monitored diagnostics and the action limits set.

The overall velocity of sound as measured by the meter is compared to the value calculated using the live gas chromatograph composition and the AGA8 equation of state. An action limit of ±0.25% has been defined as this is the typical tolerance recommended [5].

Table 1 – Action Limits for Meter Diagnostics

Diagnostic	Action Limits ref [5]
Velocity of Sound (AGA-8 comparison)	±0.25 %
Velocity of Sound (VOS) Footprint	> 0.1% shift
VOS Footprint – (shift from Cal.)	> ±0.1%
Path Velocity Ratio (PVR)	<0.97 or > 1.07
Performance Level (all paths)	< 60% *1
AGC_{ratio}	< 1
Swirl Angle	> ± 20 deg

*1 for high flowrate operation

The velocity of sound (VOS) ratios are monitored, the ratio of one path's VOS to another, and one path to the average VOS are trended. A full set of ratios is known as the meter's VOS footprint. The footprints are trended in two ways on the health check spreadsheet, Figure 4 shows the trends for one meter. The trend on the left details all of the meters' VOS footprints, this is used to monitor long term trends, [5] recommends that individual ratios should not shift by more than 0.1% over time. The trend on the right monitors the shift in VOS footprint from the meters' most recent calibration. A limit of ±0.1% is applied to this check. As the VOS footprint does vary slightly with flowrate, the calibration footprint used in this check is taken from the test point closest to the expected operational flowrate.

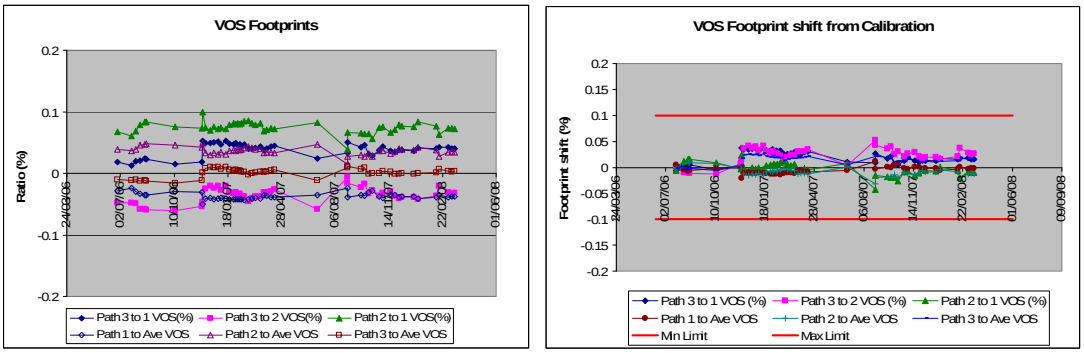

Figure 4 VOS Footprint Monitoring

The path velocity ratio is the name given to the ratio of the gas velocities measured on the axial path (2) to the average of the swirl paths (1 and 3). [5] states that the ratio can vary with flow velocity, however it recommends that in general the ratio should remain within the range 0.99 to 1.07.

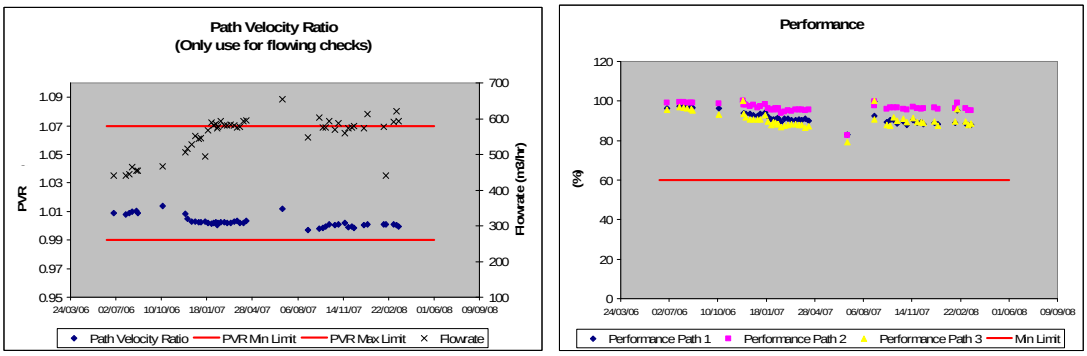

Figure 5 Path Velocity Ratio and Path Performance Monitoring

The performance level is the percentage of ultrasonic pulses which are accepted by the meter's electronics. The performance level for each path is monitored. [5] states that under normal circumstances the performance level should be greater than 90% however 60% is acceptable at higher flowrates. Higher flowrates are not defined but seeing as the meters are operated close to the meters' maximum flowrate for most of the time the 60% limit has been adopted.

The meter reports two parameters which are related to the automatic gain control (AGC) for each transducer, the AGC_{limit} and the AGC_{level}. As stated in [6], AGC_{level} is the pulse amplification factor, and AGC_{limit} relates to the maximum amplification of the background noise. The ratio of the two AGC_{ratio} correlates with the signal to noise ratio. The minimum limit for AGC_{ratio} has been set to 1 as it is at this level at which [6] states that meters start to fail due to ultrasonic noise.

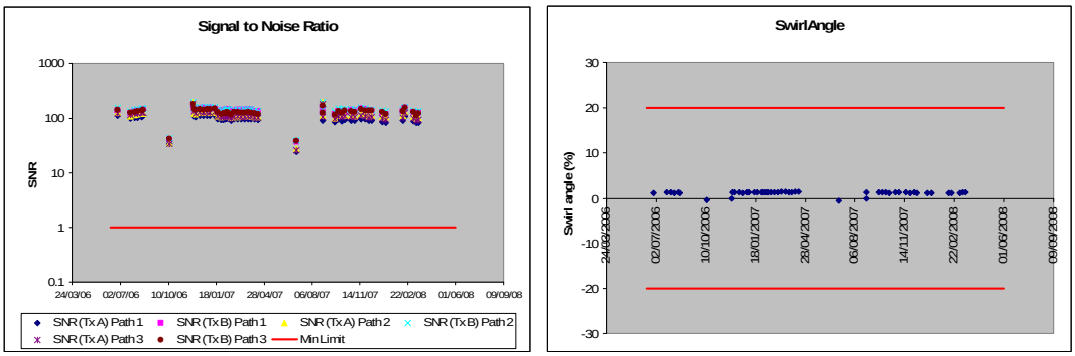

Figure 6 Signal to Noise Ratio and Swirl angle Monitoring

Finally the swirl angle diagnostic monitors the difference in the gas velocities measured on the swirl paths (1 and 3), and converts this to an angle measurement. As the name suggests a larger swirl angle indicates a greater amount of swirl in the flow profile. Instromet advised that a swirl angle of less than 10 degrees would have no impact on the measurement, and that up to 20 degrees of swirl can be tolerated, hence an action limit of 20 degrees was set.

4 INITIAL CALIBRATION ISSUES

This section discusses issues regarding the initial calibration of meter 2903.

In July 2004 prior to startup of the new metering system, the recently purchased meters were sent to PIGSAR for calibration. Each meter was calibrated in flowline 1, with its own 20 D upstream spool plus additional connections which gave a total upstream straight length of 22D, a CPA plate conditioned the flow at the entrance to the straight length. The calibration results as shown by the solid symbols in Figure 7 were accepted by CNR and CATS as per the discussion given in Section 5.4 of this paper.

Following the calibrations, during a pre-start-up audit it was noticed that the metrology certificate for meter 2903 implied its meter tube was tapered. The diameter measurements were outside the variation allowed by BS 7965:2000. This was an important issue because without conformance to the ultrasonic meter standards the meter would not meet the CATS requirements.

Hence the meter was returned to Instromet for a quality review where the meters internal diameter was re-measured. As a result Instromet confirmed that the meter was compliant with the standards and the certificate had been in error. A new metrology certificate was issued stating the correct diameter. The open symbols in Figure 7 show the meter 2903s July 2004 calibration results corrected for the revised internal diameter.

However in order to re-measure the meter's internal diameter the upstream and downstream pipework had to be removed. Instromet indicated that removal of the spools would not have a significant effect on the calibration curve. However the operators felt that due to the small bore, these meters would be more susceptible to mis-alignment than other larger meters. Hence, it was decided to re-calibrate the meter at PIGSAR.

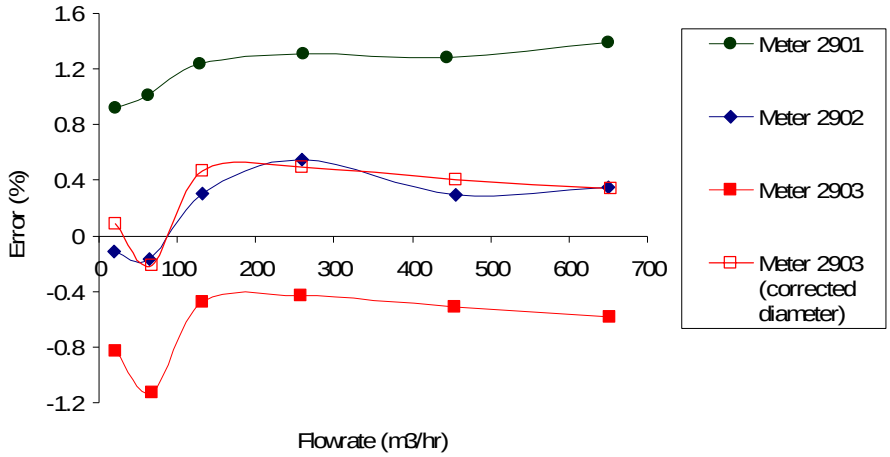

Figure 7 Initial Meter Calibrations (inc. 2903 with corrected diameter)

Meter 2903 was re-calibrated in May 2005 and surprisingly this calibration showed a shift of -0.5% when compared to its initial calibration of July 2004 (corrected for the internal diameter). Meter 2903 calibrations are shown in Figure 11. For the re-calibration the meter had been installed in the recently built line 5 instead of line 1 where it had been tested in July 2004. Line 5 had a significantly longer upstream straight length, 45D compared to 22D in line 1.

Discussion took place between CNRI, PIGSAR and Instromet as to whether the change in flow profile between the 2 lines had caused the shift. However, this seemed unlikely as both scenarios exceeded the 10D upstream straight length that was the manufacturer specification at that time. Indeed, all parties had been satisfied with the line set-ups prior to the calibrations.

If the profile was the issue then it would be reasonable to expect the same effect on the other meters as their initial calibrations were performed in identical manner to that of 2903 in line 1. However subsequent calibrations of the other meters (all subsequent calibration have been performed in line 5) did not show a similar shift and agreed well with the originals. Whether this was because the effect did not exist or because the effect had been cancelled out by operational effects (meters 2901 and 2902 had been in operation for some time before they were re-calibrated) it is difficult to determine. For example, the light coating seen on the meter internals could, in theory, have resulted in a positive shift which might have cancelled out the negative (profile) effect.

To conclude it was not possible to identify what had happened to cause the different calibration responses for meter 2903. There are too many variables and apparently conflicting evidence. For example there are at least 3 possible causes; a)The meter was affected by the removal and installation of the adjacent spools, b)The meter was affected by the different flow profiles in line 1 and 5, c)Meter configuration was changed somehow. However the CNRI representatives don't find any of these explanations satisfactory with the available information and evidence.

In November 2005 meter 2903 was installed on the Banff for the first time. It was installed in the injection line using its May 2005 (line 5) calibration. Figure 8 shows the almost 1% shift in series check results that corresponds to the installation of meter 2903. The positive discrepancy indicates that the injection meter (2903) was reading more than the export meter. This is a result of 2903 using its May 2005 calibration. Had the July 2004 calibration been used instead the shift would have been reduced by more than half, meaning that the series checks would have remained within the ±1% action limit.

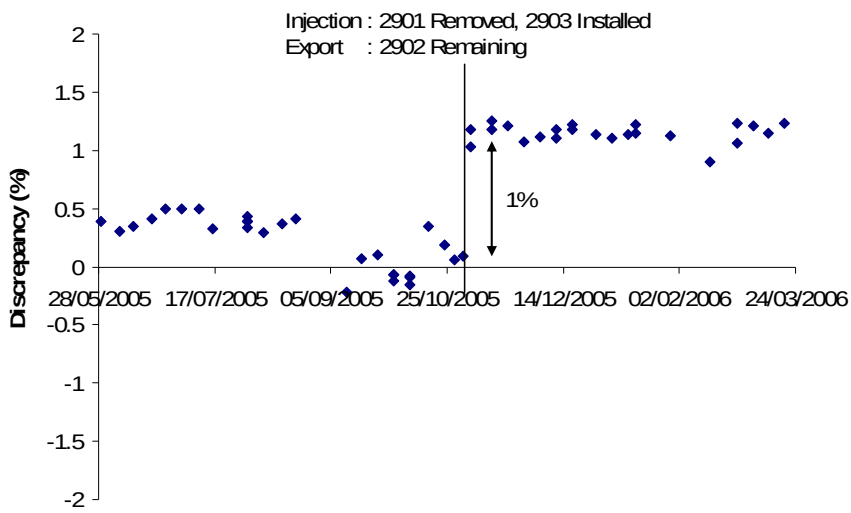

Figure 8 Series line check results showing shift on first installation of meter 2903

Since then 2903 has been successfully calibrated in line 5 at PIGSAR twice, each time the meter has returned to operation on the Banff FPSO with a minimal shift in series line check results.

To avoid and identify any future splitting of the adjacent spools from the meter, lead seals have been applied to all three meter streams. The experience also identified the requirement to witness calibrations in order to take action should unexplained calibration shifts occur.

5 METER CALIBRATION HISTORY

This section reviews the calibration history of the ultrasonic meters, as it developed after the initial calibration issues described in the previous section.

5.1 Meter 2901

At start-up of the turret metering system in 2004 meter 2901 was installed in the injection line, using its initial calibration (July 2004). All of the 2901's calibrations are shown in Figure 9. It operated in the injection line until November 2005 when it was removed for its first re-calibration (Nov. 2005). The re-calibration showed that the meter had retained its linear response and had only shifted slightly in the positive direction from its initial calibration. The shift in flow weighted average (FWA) was only just over 0.1%.

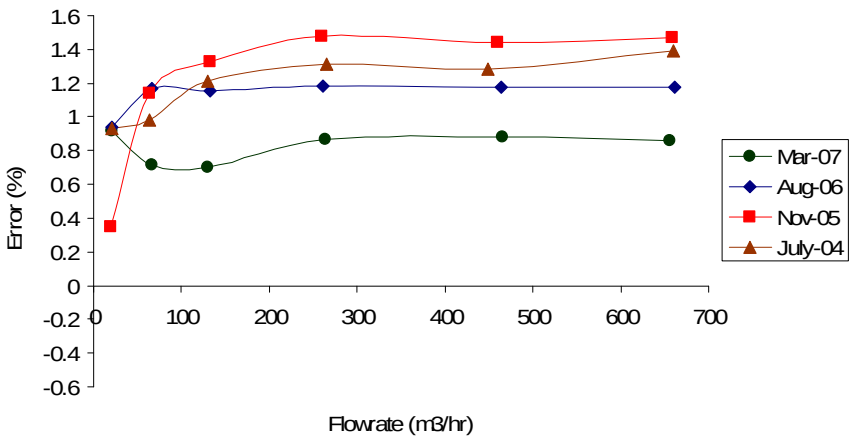

Figure 9 Meter Serial No. 2901 Calibrations

Following the calibration the meter was shipped to the Banff FPSO however it was not installed as it sustained some damage to one of its transducers connections in transit (see Section 8 for more details). Hence the meter was returned to Instromet for repair and then to PIGSAR for a further re-calibration. This re-calibration (Aug. 2006) showed the meters response to have shifted in the negative direction, the shift in FWA was -0.25%. The meter was then returned to Banff where it was installed in the export line.

After a short period in the export line a fault was diagnosed on path one of the meter (see Section 7). The meter was again returned to Instromet for inspection, where a transducer on path 1 was found to be faulty. Following replacement of the transducer pair the meter was once again returned for re-calibration (March 2007). This showed the meters response (FWA) to have shifted by -0.32% from the previous calibration (August 2006). The meter was then returned to the export line.

The calibrations of meter 2901 have shown the meter to have a very linear response, and reproducibility has been good considering the transducer replacements. It is interesting to note however that between the November 2005 and August 2006 calibrations the only change to the meter was the replacement of the path 1 transducers, the meter was not installed on the Banff. This indicates that the shift in FWA of -0.25% was due to the transducer replacement. This confirms that re-calibration following replacement of transducers IS required for the fiscal applications of these meters.

5.2 Meter 2902

At start-up meter 2902 was installed in the export line, using its initial calibration (July 2004). All of the 2902's calibrations are shown in Figure 10. It operated in the export line until August 2006 when it was removed for it first re-calibration (Oct. 2006). The re-calibration showed the meters response to have changed very little except at the 260 m3/hr test point , where a shift of 0.48% was recorded.

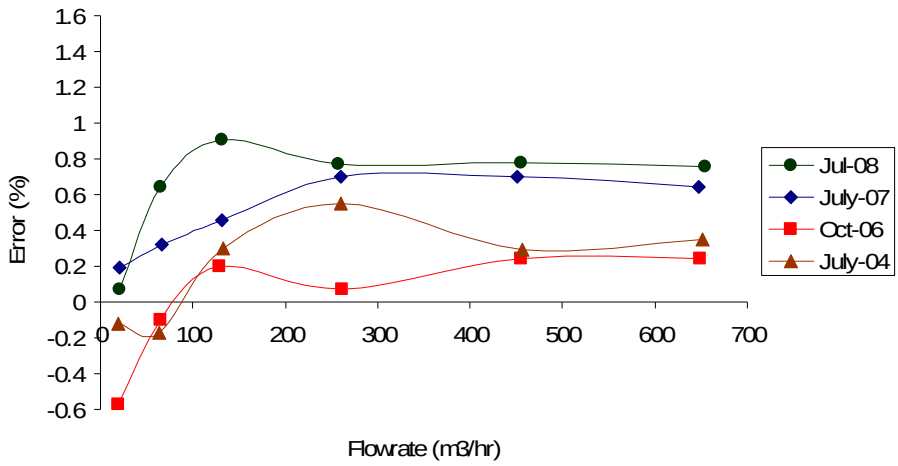

Figure 10 Meter Serial No. 2902 Calibrations

The meter was returned to the export line where it remained until April 2007 when it was removed for its second re-calibration (July 2007), following the calibration it was observed that the meter spool and its upstream and downstream straight lengths were slightly out of alignment (estimated at 1 - 2mm). It is not known how this misalignment occurred. It may explain the larger than expected shift in response seen in the July 2007 calibration. The shift in FWA was +0.45%. The meter was returned to the export line, where it remained until March 08 when it was sent for its third re-calibration (July 2008). This generated a very reproducible response from the previous calibration apart from the 130m3/hr test point, where a shift of 0.45% was noted. This result seems quite similar to that noted between the July 04 and Oct 06 calibrations at the 260 m3/hr test point.

Meter 2902 has been used exclusively in the export line, hence it has had minimal throughput whilst in-service. It has remained linear, with generally good reproducibility, the slightly larger than expected shift between 2nd and 3rd calibrations may be due to meter misalignment with its upstream spool.

5.3 Meter 2903

Meter 2903 was installed in the injection line in November 2005 using its May 2005 calibration. Since then it has been re-calibrated twice in January and December 2007 and until March 2008 the meter had been used exclusively in the injection stream. These 2007 re-calibrations have indicated a very similar response which are quite different (approx. 1% in FWA) from the May 2005 calibration.

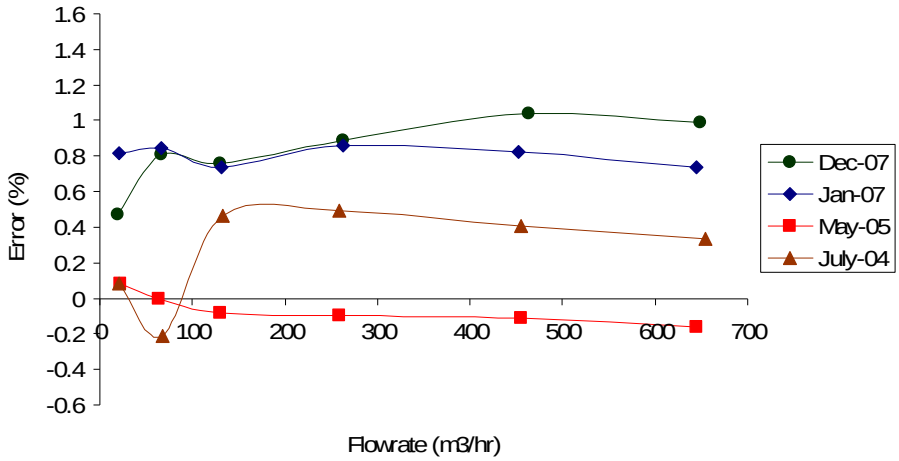

Figure 11 Meter Serial No. 2903 Calibrations

Meter 2903's last two calibrations have shown excellent reproducibility between which the meter has operated at near its maximum flowrate for a period of over 6 months.

5.4 General Calibration Observations

The criteria for acceptance of ultrasonic meters are contained within the standards AGA9 [7] and BS7965 [3]. In particular with reference to these meters the criteria state that

1 Small meter (< 12" NB) maximum error limit ±1% for flowrates of 10%max and above.

2 Maximum peak to peak error (difference between maximum error and minimum error) 0.7% for flowrates of 10% max and above.

Strict adherence to these criteria would have resulted in rejection of all meter 2901s calibrations apart from the latest as the calibration curves were above the 1% maximum limit. Also the initial calibrations of meters 2902 and 2903 just exceeded the maximum peak to peak error of 0.7% for flowrates of 10% of max and above.

However these meter calibrations were accepted by CNRI and CATS for the following reasons. Firstly while 2901 is out with the ±1% criterion, the linearity of the meter has been excellent and an application of suitable meter factors would provide a very accurate meter. For 2902 and 2903 the peak to peak failures were at the lower half of the flow range (i.e. out with the FPSO's normal operating range) and in the experience of the authors, peak to peaks in small bore ultrasonic flowmeters exceeding 0.7% by small amounts are not uncommon. It is interesting to note that over time these meters have actually improved in linearity, see Figure 12. Following the experience gained with these meters, it is the authors' opinion that strict application of the criteria in AGA 9 and BS 7965 may be too onerous for small bore

meters (4" nb for example) and a slight relaxation may be appropriate to avoid rejection of otherwise satisfactory and effective meters.

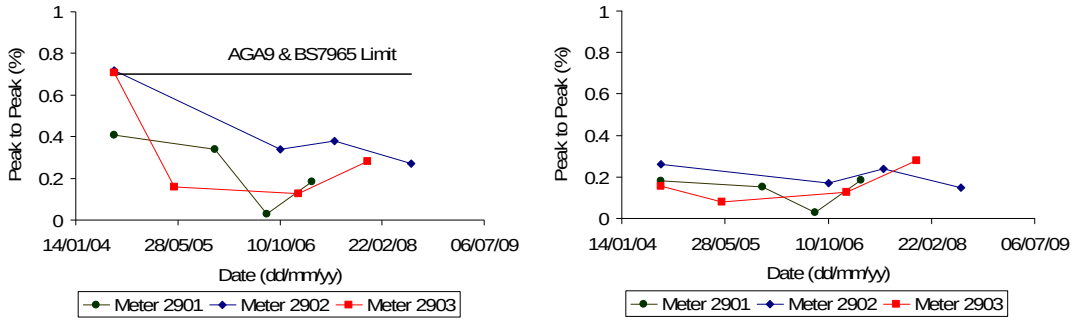

Figure 12 Meter peak to peak error (Left 10 to 100%, Right 20 to 100% of max flowrate)

Assessing meter reproducibility has been complicated by issues encountered throughout the operation of the metering station. Change out of transducers due to faults or transport damage invalidates the assessment of reproducibility because the physical meter has been modified. Mis-alignment of the upstream spool is again a physical change of the metering package and doubts over a calibration means that reproducibility is again queried.

Figure 13 shows the flow weighted average errors for all of the calibrations performed on all of the meters to date. Calibrations which are discounted for reproducibility are shown with open symbols and dashed connecting lines. The last two calibrations on meter 2901 are discounted as transducers were replaced prior to each calibration. The July 2007 calibration of meter 2902 is discounted as a mis-alignment in the upstream spool was noted at that calibration, and the first two calibrations of 2903 are discounted as there is doubt over the cause of the -0.5% shift between calibrations (see Section 4).

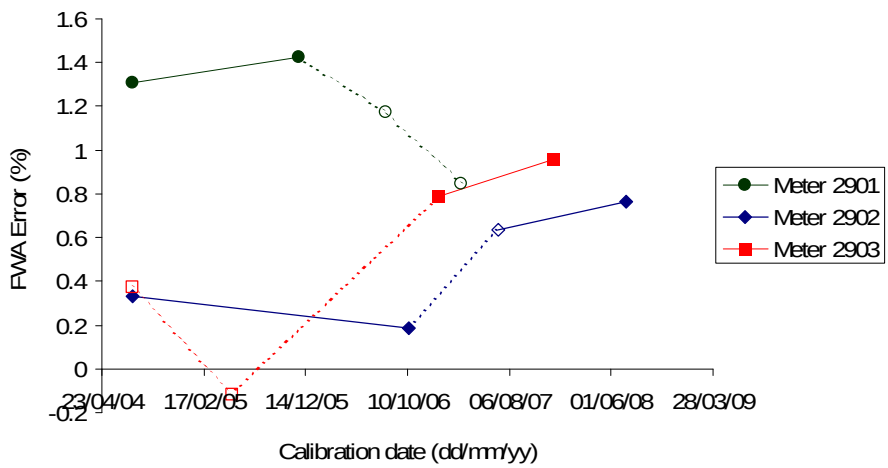

Figure 13 Calibration FWA Errors

That leaves three periods where meter reproducibility can be assessed. In the cases of meter 2901 and meter 2903 both these meters were installed in the injection line where they were operated on a near continuous basis. Both meters experienced a positive shift, 2901 recorded a FWA shift of 0.12% during a year of operation, while 2903 recorded a 0.17% shift in 6 months of operation. Meter 2902 was installed in the export line and hence was only operated for a few hours each week. It recorded a -0.15% shift in FWA during one and half years in-line.

This indicates that not withstanding meter faults etc the reproducibility of the meters is very good giving confidence in the meters long term response, and once a clear calibration history has been collected, potentially allowing an increase in time period between calibrations.

6 SERIES LINE CHECK HISTORY

Figures 14 and 15 show the full history of series line check results since start-up. Overall it shows the results are generally stable between meter change-outs, with distinct shifts in deviation at meter change-outs. It shows the majority of results to be within the ±1% action limits. Results out with the limit are nearly all in the period between the 4th Nov 2005 and the 27th Aug 2006. This corresponds to when meter 2903 was first installed. At the time the failures initiated a series of checks, including review of meter diagnostics, additional re-calibrations of pressure and temperature transmitters, and additional valve integrity checks, none of which identified a problem. The results returned to within limits at the following meter change-out.

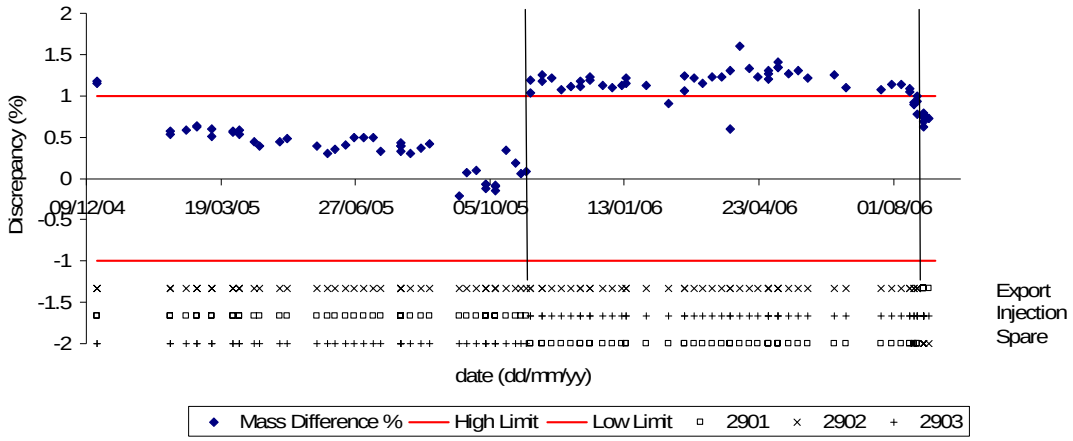

Figure 14 Series line check results (Dec 04 – Sept 06)

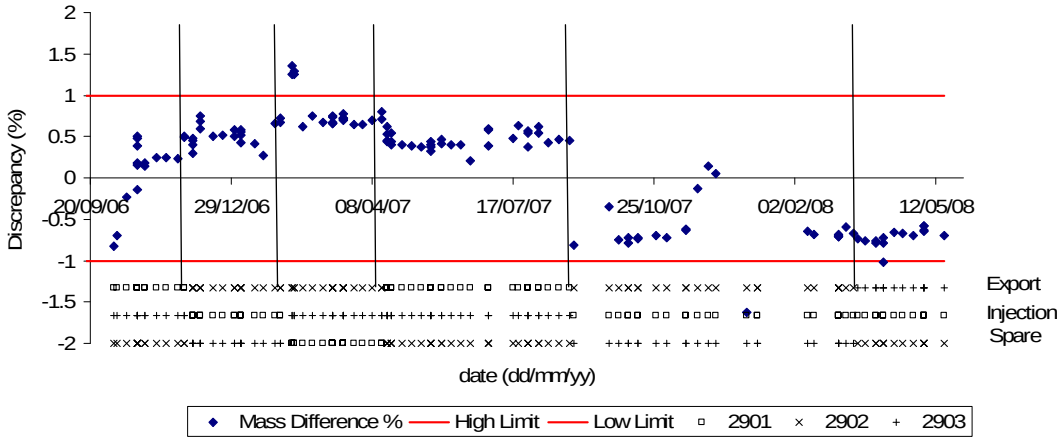

Figure 15 Series line check results (Sept 06 – May 08)

The results also show a tendency for increased scatter and/or temporary excursions from the stable result following meter change-outs or shutdowns. The reasons for this are unclear, it may be due to initial liquid drop-out, the results stabilising once the liquid has dried out, however there is no evidence of this from the meter diagnostics. The effect is observed after the meter change-out's of December 06, February 07 and April 07, and also after the shutdown of September 06.

7 METER FAULT DIAGNOSIS

It has already been discussed how the series line check and diagnostics monitoring procedures are designed to detect faults in the meters and as a result increase confidence in the metering performance. This section shows how a real metering fault was detected and rectified.

Following a six week maintenance shutdown the injection metering stream was brought back online without incident. Meter 2901 was in the export line and 2903 in the injection line. Immediately preceding the shut down the series checks had been returning discrepancies of about +0.7%, however following the shutdown the checks returned a -0.8% result. This 1.5% shift indicated that there may be a problem with one or both of the meters. A negative shift in series check results indicated that either the injection meter was under reading or export meter was over reading. Figure 16 shows the series line checks around that time.

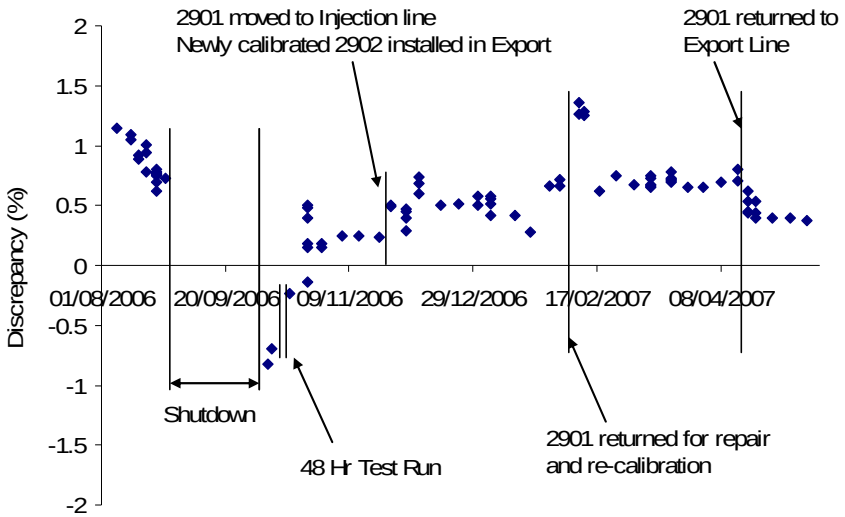

Figure 16 Series line Check results

As is normal during series line checks a log of the both meters diagnostics had been recorded. Figures 17 and 18 show the velocity of sound foot prints for both meters with series line check results overlaid. These show a significant change in the export meters velocity of sound (VOS) footprint (2901) whereas the injection meters footprint remained fairly constant. The alarm limit for changes in footprint recommended by [6] is 0.1%. The change in footprint registered by meter 2901 ranged from at worst 0.42% for the path 3 to 1 ratio to at best 0.04% for the path 3 to 2 ratio. It was this variation in the footprint that pointed to the fault. The only ratio which had not shifted out with the 0.1% limit was the 3 to 2 path ratio. This indicated that there was no fault on those paths, hence the fault seemed to lie with path 1.

None of the other monitored diagnostics for meter 2901 i.e. path velocity ratio, signal to noise ratio, or path performance were outside limits.

At this stage it was thought that the meter may have been affected by contamination. The export meter had been lying depressurised for some time during the shut down and as Banff had not exported to CAT's after the start-up it had only been run for a few hours during the series line checks. It seemed credible that there might be some liquid or debris in the line, which might affect path 1 particularly due to its transducers being in the bottom half of the pipe. Hence it was decided to run the export meter for a prolonged period (48hrs) to see if this would clear the contamination and the fault. (It has been observed that the repeatability of series line checks can be quite poor, for a short period after a meter change out). However although some improvement in the series checks was noticed; the shift in series checks reduced to about 0.5%, the change was still significant and meter 2901s VOS footprint remained very stable in its new state.

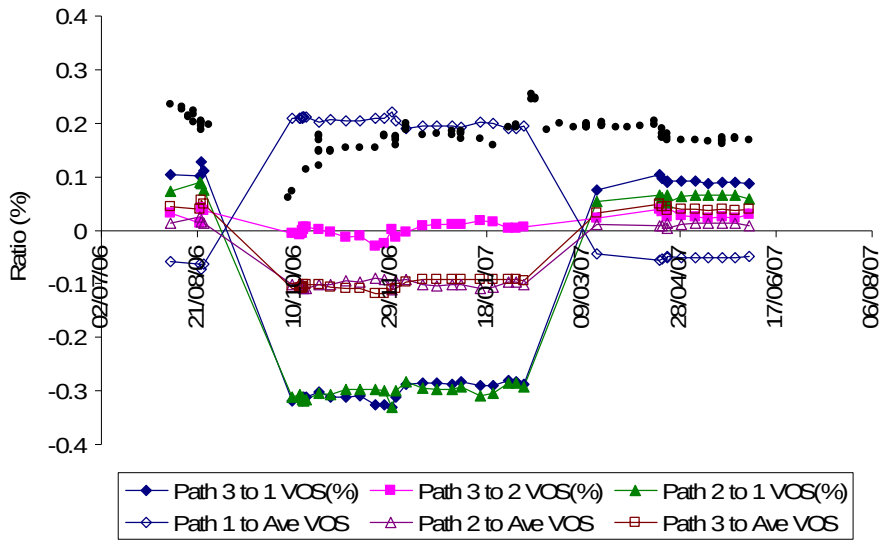

Figure 17 Meter 2901 VOS Footprint

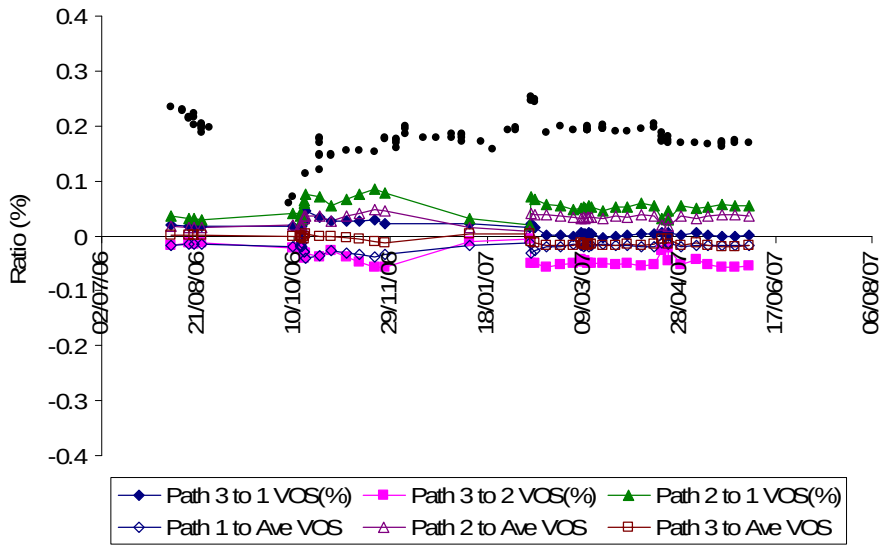

Figure 18 Meter 2903 VOS Footprint

It was decided that 2901 could not be relied upon to operate as a fiscal meter and that it should be transferred to the injection line allowing the recently calibrated 2902 to take the role of export meter. This was done at the end of December 2006.

After a period of operating in the injection line and with no change in the VOS footprint the meter was returned to Instromet's Essen facility for investigation and repair. The 'as found' test report showed that the measured velocity of sound on path 1 was just over 1m/s higher than on paths 2 or 3. The measured values were as shown in table 2:

Table 2 – 'As found' Test results (2901)

Path	VOS (m/s)
1	349.67
2	348.52
3	348.55

Instromet concluded that path 1 was faulty and should be removed for further investigation. Figure 19 shows both path 1 transducers, on the left is the damaged transducer, its face has been dislodged slightly from the holder. The movement was very small, no more than about 1mm, however this shortening of the path length, increased the measured flow velocity on path 1. The series check results suggest that this fault may have caused a +0.5% meter shift.

It was mentioned by Instromet that this sort of damage might have been caused by rapid depressurisation of the metering run.

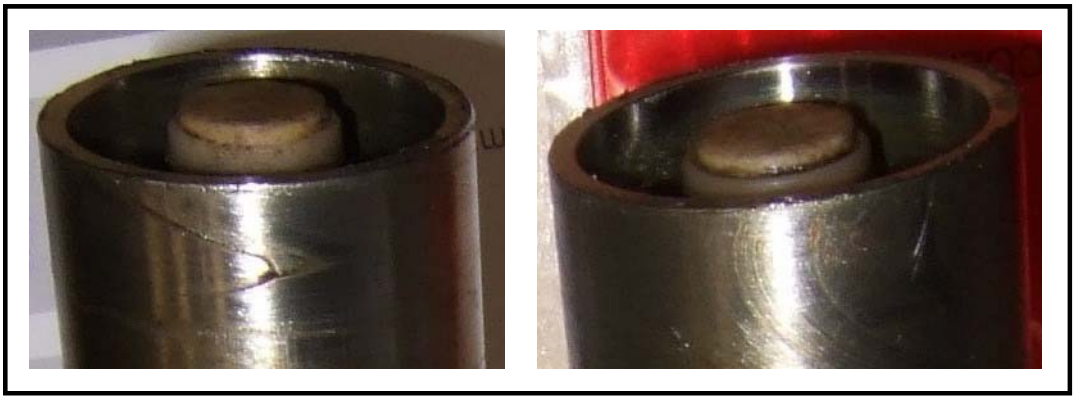

Figure 19 Meter 2901 Path 1 Transducers, damaged transducer on the left.

Both path 1 transducers were replaced and the meter re-verified at Essen. This showed the replacement had been successful as all paths now measured the velocity of sound to within 0.25 m/s.

The meter was then sent for re-calibration where it performed well, with a linearity of 0.22% across the full range and a shift in the flow weighted average from the previous calibration of -0.32%. Considering the change out of transducers this was considered to be a very good result.

This incident has shown how regular series line checks and diagnostics monitoring can quickly identify faulty meters, allowing remedial action to be taken to minimise any potential mis-measurement.

8 METER VUNERABILITY DURING TRANSPORTATION

The standard Q-sonic 3S meters purchased in 2004 are particularly vulnerable to damage of the transducer heads. The transducer design includes a connection which extends over 140mm from the head of the port casting. Due to concerns over transportation a specifically designed transport box was fabricated, this is shown in Figure 20.

Figure 20 Meter Boxed

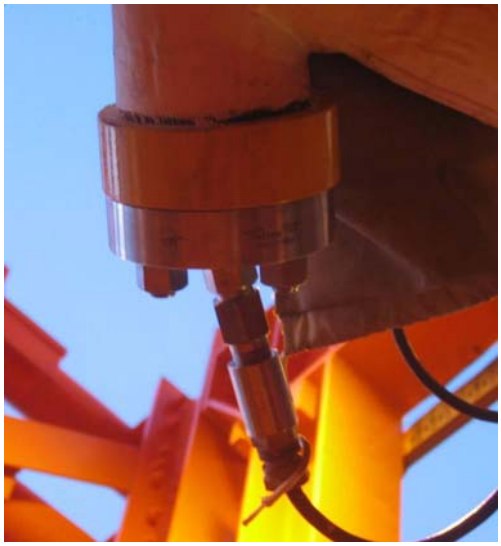

Figure 21 Damaged Transducer

However these precautions did not prevent damage to the transducers. In February 2006 during transport between the calibration facility in Germany and installation on the FPSO meter 2901 suffered damage to transducer 1B shown in Figure 21. It is not known where or how the damage was sustained, however the damage did compromise the integrity of the screw thread on the transducer. This meant the meter had to be returned to Instromet for replacement of the damaged transducer. Also because the transducers are supplied as matched pairs the 1A transducer also had to be replaced. And then because of the potential shifts due to the change out of the transducers the meter was re-calibrated before returning to the FPSO.

The repercussions of this damage were firstly the cost for repair and re-calibration, then the period during which no further meter calibrations could be performed because the spare meter was unavailable. The time between the damage being discovered and the meter being ready for installation was 6 months.

9 SUMMARY OF LESSONS LEARNT

This section summarises the main conclusions from operating these meters over the last four years.

9.1 Meters

Overall the meters are considered to have performed well, they have demonstrated a linear and reproducible response. This has been verified both in the calibration lab and in the field with the series verification checks. Several issues have occurred throughout their operation (e.g. initial calibration problems, transport damage etc) which have made assessing the long term performance of the meters more difficult, however when these issues are accounted for, it can be shown that the data backs up this conclusion.

The meters have been fairly reliable with only one transducer failure between all the meters in four years. It is interesting to note that the transducer failure occurred on path 1, which has its transducers on the underside of the pipe. The location of the path 1 transducer ports is not ideal, it would be better if they were self draining.

One problem with these particular meters has been the design of the transducer connectors as they are very vulnerable to damage. Significant effort has gone into minimising the risk of damage to these during transportation, including the provision of a purpose built transport box. However this is not a complete solution and it also adds additional issues, for example, ensuring the meter is installed correctly in the box etc. As damage in transit is a real risk, extending the period of time between calibrations is attractive bearing in mind the reproducibility of the meter calibrations when no ‘events’ have occurred.

9.2 Meter Verification

The meters have been subject to a rigorous verification process which has generated confidence in the meters performance. Periodic onshore calibration has been backed up with regular series checks and review of meter diagnostics. The verification process has been shown to be suitable for fiscal measurement. The fact that a meter fault was quickly highlighted by the series line checks, and then correctly diagnosed using the meter diagnostics, demonstrates the effectiveness of these checks between calibrations.

The experience of operating meters on the Banff FPSO has shown that the limits of AGA 9 and BS 7965 on peak to peak error and maximum error can be too restrictive for 4” meters, and if applied strictly might result in suitable meters being rejected. The meters have also been repeatable during calibration, which means the calibration error is inconsequential as the error is corrected by linear interpolation in the meter’s flowcomputer.

Regarding meter repairs, laboratory calibration has shown a shift in FWA of -0.25% following the replacement of one pair of transducers. This shift was seen in a meter which did not return to service between calibrations because it was damaged in transit. This was considered to be a very good result for such a small meter however it does not change the author's view that transducer change-outs on this size of meter at any rate require a re-calibration for fiscal measurement.

Meter shifts observed during the initial calibrations may have been due to several reasons, the following procedures adopted by the Banff FPSO are recommended to minimise calibration issues on small 4" meters.

- Leave Upstream and downstream spools attached at all times, to avoid risk of mis-alignment effects, use lead seals for verification.
- Maintain the same upstream pipework for laboratory calibration and subsequent re-calibrations.
- Witnessing of at least the initial meter calibrations and first re-calibrations is essential

The series line checks are a useful technique for monitoring the metering stations performance; however they should not be used as an alternative to calibration. On the Banff FPSO they have been used as an addition to calibration. They have been effective because they have been performed on a regular basis, also the trending of both series check data and diagnostics makes faults much easier to identify.

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