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32nd International North Sea Flow Measurement Workshop
21-24 October 2014

Technical Paper

Field Trials and Pragmatic Development of SONAR Flow Meter Technology

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1 Introduction

This paper describes a collaboration between BP Azerbaijan - Georgia - Turkey (AGT) Region and Expro Meters Inc, a wholly owned subsidiary of Expro Group. The collaboration was in the pragmatic application of SONAR flow measurement technology to meet an Operational requirement for retrospective, non-intrusive flow measurement in a number of 'allocation' type metering applications. An account of clamp-on SONAR flow meter development, based on field trials, for two of those applications, is described in this paper.

Applications of SONAR technology described in this paper include its use on a crude oil reception line at the Sangachal terminal, and its use, on the Shah Deniz 'A' platform, as a secondary measurement tool to verify an ex-test separator gas measurement device, providing additional measurements during critical well testing operations.

Through the use of SONAR technology meter diagnostics interface, in the event that meter performance becomes sub-optimal, remote expert support can be sought. Where necessary, the clamp-on meter components can be readily changed under permit to work without the need for shutdown and dependence on isolations for workforce safety.

2 Requirement for non-intrusive, retrospective measurement techniques

Operating experience has shown that the presence of particulate matter has impacted installed technologies such as time of flight ultrasonic meters, requiring retrofit of updgraded electronics with higher gain / higher signal levels.

The presence of particulate matter, and proximity of wax appearance temperature, stretches the 'tradional' assumptions around Newtonian fluid behaviour.

The design of 'allocation' meter installations makes no provision for line isolations e.g. to change out or upgrade installed 'primary elements' of differential pressure producer meters. Considering the cases presented here, change out of in-line elements would require full isolation, depressurisation or partial draining, and purging of a Test Separator and 10" gas line, or a 24" crude oil reception line.

Whilst these may seem straightforward Operations, at a marked up P&ID level, in a risk averse Operation these are signficant, complex ISSOW events unlikely to be undertaken for meter maintenance. The cost-benefit of potential deferred production does not support maintenance or instrument remediation through intrusive intervention.

3 SONAR Meter Technology

3.1 Brief History of SONAR Technlogy Meter Development

Sonar-based flow measurement technology was first introduced to the oil and gas industry with the deployment of the first down-hole, fiber-optic-strain, multiphase flow meter from the Shell Mars Platform in October, 2000 [1]. The fiber-optic-strain sonar meter used sonar-based passive-listening techniques to provide flow rate and compositional information for downhole oil, water, and gas mixtures.

The PassiveSONAR™ flow meter was introduced in 2003 as the first generation clamp-on sonar meter. PassiveSONAR employs piezo-strain sensors to replace the fiber optic strain sensors in the first generation, downhole SONAR flow meter. PassiveSONAR is well suited for high liquid loading multiphase flows typical of black oil wells and low pressure gas wells.

In 2009, the ActiveSONAR™ flow meter was introduced as the second generation Clamp-on sonar meter. The ActiveSONAR flow meter employs active pulsed-array sensors clamped to the outside of the pipe to track the velocity of the turbulent eddies in the fluid flow. The ActiveSONAR meter is generally applied to dry gas and wet gas flows in heavy schedule pipes and liquid continuous flows where the flow rate is below the measurement threshold for the PassiveSONAR meter.

Expro Meters, Inc. (a wholly owned subsidiary of Expro Group) currently owns patents and holds certain licenses to sonar flow measurement technology for topside oil and gas fields of use. BP America's E&P Technology Group participated in and funded certain early pilot technology development programs related to sonar flow technology.

3.2 Principle of Operation

Clamp-on SONAR-based flow meters utilize sonar processing techniques to determine the speed at which naturally occurring, coherent flow structures convect past an array of sensors clamped-on to the outside of the pipe.

Figure 1 illustrates the naturally occurring, self-generated, coherent structures present within turbulent pipe flows. Naturally occurring, self-generating, turbulent eddies are superimposed over the time-averaged velocity profiles. These coherent structures contain fluctuations with magnitudes on the order of 10 percent of the mean flow velocity and are carried along with the mean flow. These eddies remain coherent for many pipe diameters and convect at, or near, the volumetrically-averaged flow rate in the pipe.

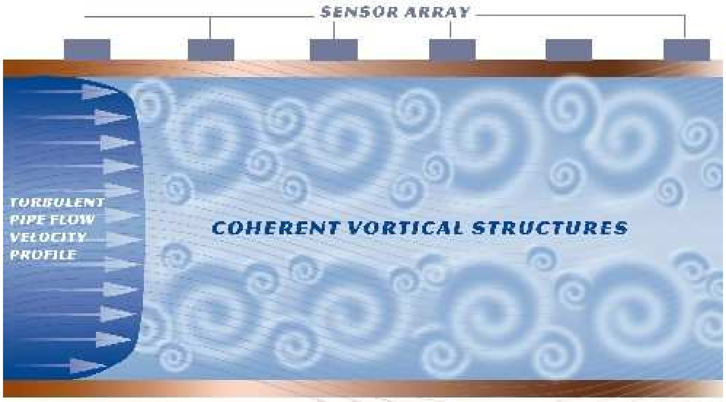

Figure 1 : Sonar-based Flow Meters with Coherent Structures within Pipe Flows

In sonar array processing, the spatial / temporal frequency content of sound fields are often displayed using "k-ω"plots. k-ω plots are presented as surface plots in which the power of a sound field is allocated to bins corresponding to specific spatial wave numbers and temporal frequencies. On a k-ω plot, the power associated with coherent structures convecting along with the flow is distributed along "the convective ridge". The slope of this ridge indicates the speed of the turbulent eddies. Thus, identifying the slope of the convective ridge determines volumetric flow rate.

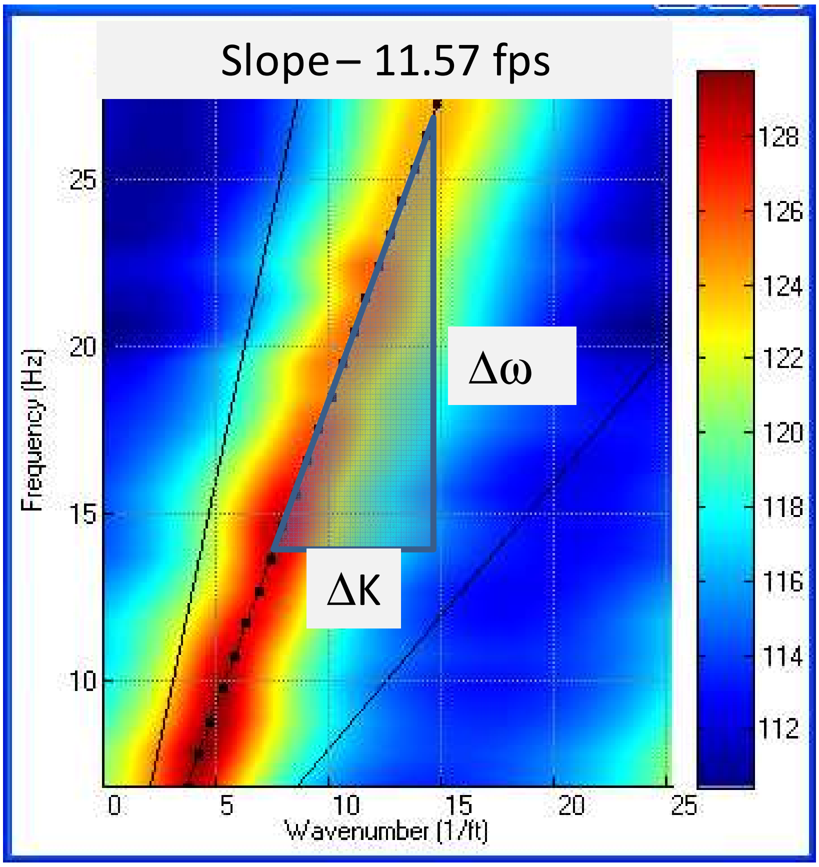

Figure 2: K- ω plot from a Clamp-on, SONAR meter

Figure 2 shows an example of a k- ω plot generated from the diagnostic output of a sonar flow meter clamped on to an 8-inch, schedule 120 pipe operating with ~3 mmscfd of methane gas flowing at 5 barg. As shown, the k- ω plot exhibits a well-defined convective ridge. The slope of the convective ridge was determined to be 11.57 feet/sec by the SONAR flow meter.

Both the PassiveSONAR and the ActiveSONAR meter operate on the Sonar principles of operation described above. However, the PassiveSONAR meter employs an array of strain based sensors which are wrapped circumferentially around the pipe. ActiveSONAR meters utilize an array of transmitting sensors arranged along one side of the pipe and a corresponding array of receiving sensors on the opposing side of the pipe.

3.3 SONAR Technology screening

PassiveSONAR is generally applicable to highly liquid loaded, multiphase flows typical of black oil wells and low pressure gas wells. The passive, strain-based sensing technique tends to be tolerant of multiphase conditions. The primary limitation of the PassiveSONAR meter tends to be low velocity flows in thick walled pipes.

The ActiveSONAR meter, because it introduces a noise source into the fluid medium to "insonify" the vortical structures in the flow, is capable of measuring flows with less energy and has a lower velocity threshold therefore can be applied to lower rate gas, wet gas and liquid flows.

Specifically, the primary parameter used to screen applications for suitability of clamp-on sonar and then to select the type of sonar meter to be applied is dynamic pressure. Dynamic pressure is expressed as:

$$\text{Mixture Density x Velocity}^2$$

Generally, higher dynamic pressures are favorable for both Active and Passive SONAR, with Active SONAR being more tolerant to lower dynamic pressures.

Application screening is a multi-parameter space, including variables such as pipe wall thickness, fluid density and expected gas volume fraction.

3.4 Previous trials in BP AGT Region

Trials were undertaken in 2009 using PassiveSONAR for gas measurement during a gas debottlenecking study on the Shah Deniz 'A' Platform. For the purpose of trial evaluation, verification of reference measurement performance was undertaken using cfd techniques, [2]. The cfd report concluded that the reference meter installation would likely read flow rates low, by around 1%, due to installation geometry effects.

The same reference meter was used in this gas meter trial, as described in Section 5, as a comparison meter against the SONAR meter.

4 Application of Active SONAR Technology on a Liquid Crude Oil Reception Line

4.1 SONAR meter trial installation

An ActiveSONAR meter was screened to monitor pipeline flow, alongside a two beam, in-line ultrasonic 'time of flight' meter (usm). The reliability of the in-line usm appeared to be affected by certain flowing regimes, potentially waxing and gas breakout.

The SONAR meter, model QEX1000AB was fitted on a 24" oil reception line in Sangachal Terminal, onshore in Azerbaijan. The SONAR meter was fitted downstream of the existing in line ultrasonic meter as represented in Figure 3.

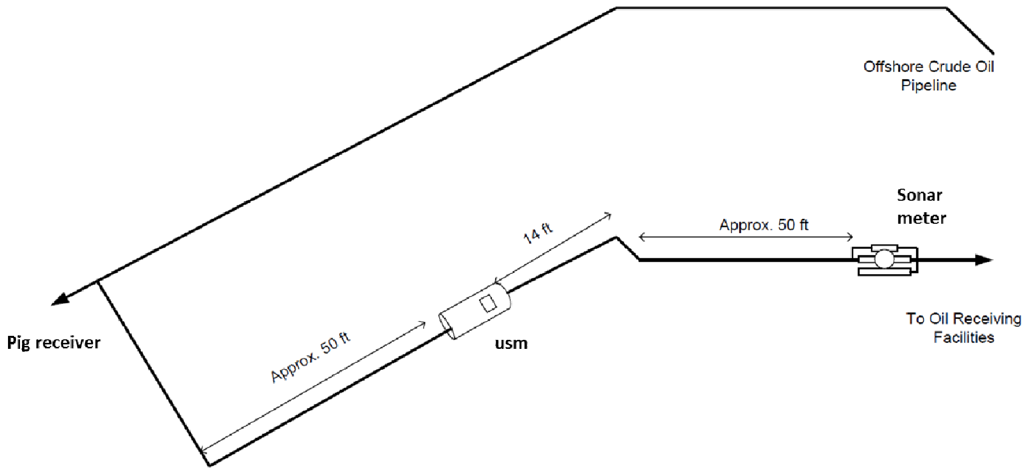

Figure 3 - SONAR meter trial schematic

The 24" line material is API 5L carbon steel with a nominal wall thickness of 34mm, flange rated at 900# RTJ. Hazardous area rating of the unit is for Zone 2 operation.

Surface preparation of the pipework was undertaken by BP AGT Operations personnel and the meter was installed by Expro Meter Service personnel with site support as required. Meter installation conforms to the requirements described in [3].

Typical operating parameters of this line are flow rates of around 350 mbod, operating temperature between 10 - 30 °C (subject to season) and operating pressure around 25 barg.

The SONAR meter modbus was connected to the ICSS via a converter unit to convert from Modbus ASCII format to actual volume flow rate analog signal, [4]

4.2 Field Trial Events

A temporary installation of the ActiveSONAR meter was undertaken in January 2013 to assess the suitability of the technology. The ActiveSONAR Flow Meter was installed at a low point, downstream of the existing in-line ultrasonic flow meter (USM). Review of the meter diagnostic data showed that the ActiveSONAR Flow Meter was properly functioning and reporting a stable volumetric flow rate of around 2,700 m^3/h, see Figure 4 and reference [5]. Following 'proving' of the technology, against the in-line USM, the meter was 'mothballed' pending permanent installation i.e. specification, procurement and installation of permanent power and signal cables, and ICSS input allocation.

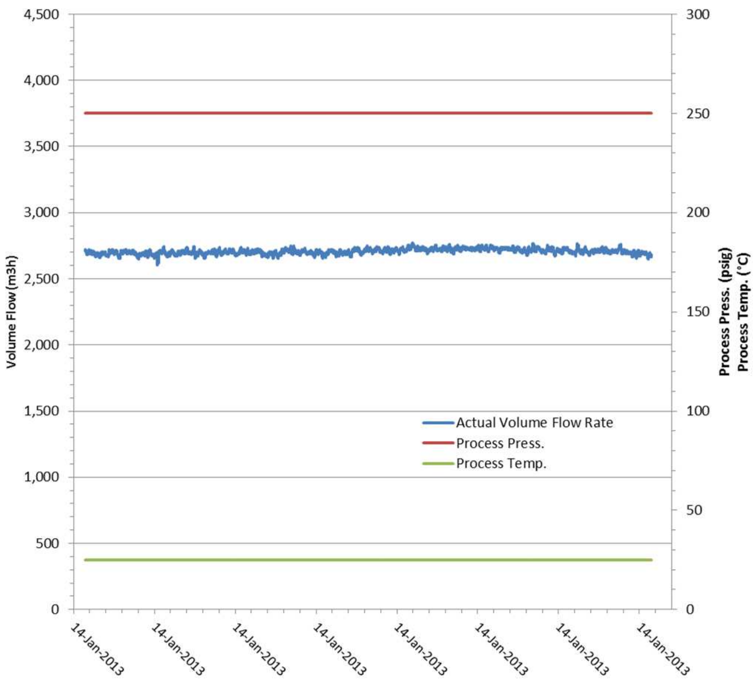

Figure 4 - ActiveSONAR technology 'proof' trend

Following hookup to the ICSS, in October 2013, it was noted that a high incidence of 'drop-out' was evident on the meter trend, see Figure 5.

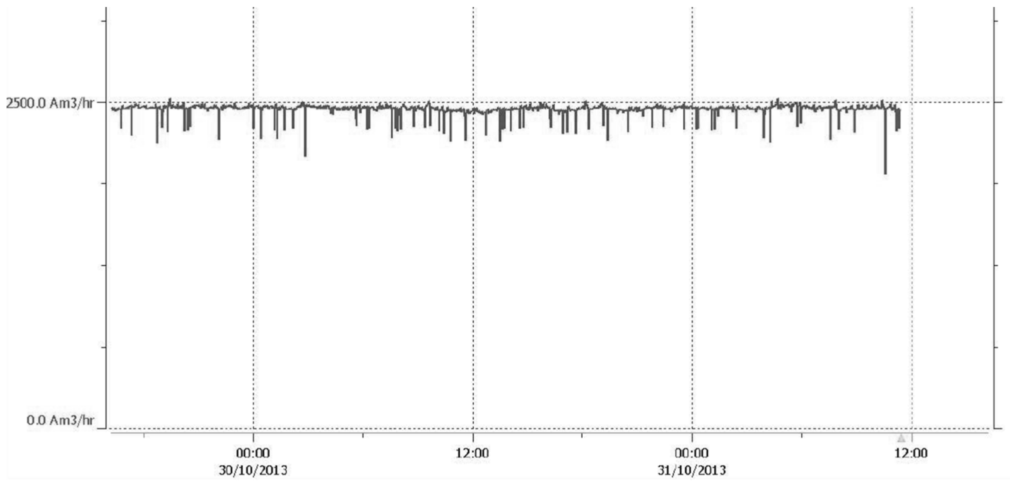

Figure 5 - initial ICSS ActiveSONAR meter trend

The January 2013 site visit data had been taken from a diagnostic COM port on the meter itself whilst the October 2013 data came from the ICSS monitor via a converter unit. It was noted that the meter communications required reconfiguration when power to the meter was cycled. The decision was made to call out Expro Meter Field Service support to investigate both issues.

A detailed trial history, from November 2013, in part, reflecting the trial and development work is aggregated in [6]. This section addresses notable events, in chronological order, arising throughout the trial period.

November 2013

The meter firmware was upgraded to v1.7.0.0 during this visit. The communications configuration issue was remediated to support external configuration. Historical data / data logging confirmed the presence of dropout and 'spikes', shown in Figure 6. During data logging periods the meter input to the ICSS was disconnected. Typically these were about 4 hours of data logged by the Field Service Technician laptop using the meter COM port. The data was sent back to the SONAR meter development team for analysis.

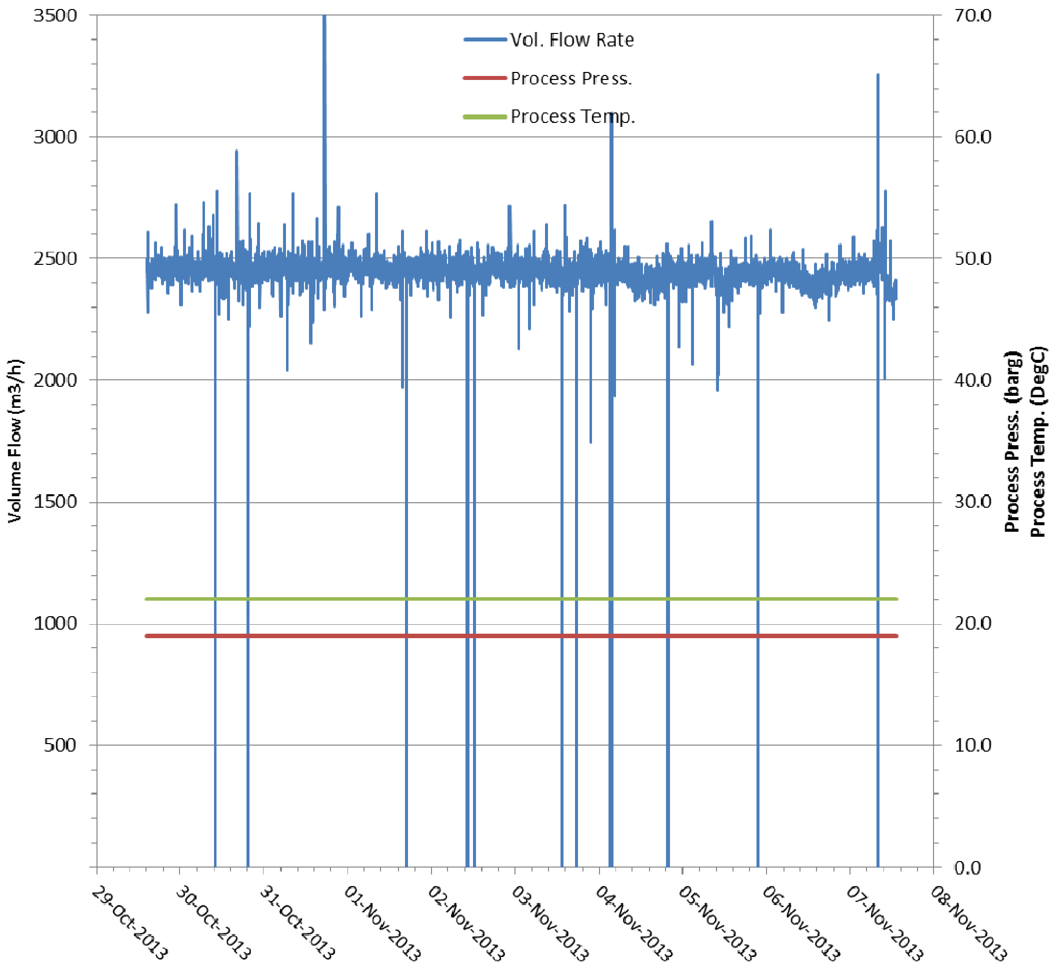

Figure 6 - example of meter dropout from November 2013

January 2014

Permanent meter installation was finalised in early January. As the Expro Field Service Technician was 'in Region' on other work (the Offshore ActiveSONAR wet gas meter installation), two site visits to Sangachal were undertaken in early January and late January.

Following analysis of the November data, revised firmware was developed by Expro, v1.7.0.1, and installed in the meter during the early January visit. The revised firmware was implemented to support external communications configuration and to modify signal processing parameters, reducing the meter sensitivity to changes in flow regime. During this visit the second COM port was also hooked-up to 'back of panel' to support simultaneous flow rate montioring and data logging. When re-connected the ICSS heavy drop out was apparent on the meter trend.

In late January the Expro Field Service Technician returned to Sangachal Terminal. The source of heavy drop out was traced to incorrect data type handling, as a result of changed communications configuration, in the ICSS input configuration. This was modified by the BP Operations Technician and the heavy drop out issue was resolved, although intermittent drop out remained. Further data was collected for analysis by Expro developments team.

May 2013

Although 'drop out' had been managed, 'spiking' was till an issue so a site visit was undertaken to load revised firmware to the meter, v1.7.1.0, which incorporated a 'spike' filter.

During this visit, the Field Service Technician noted 'inconsistent' readings from a transducer pair, channel 2. The sensor array was removed, coupling paste re-applied and the array re-fitted. No improvement was noted in the readings. It was concluded that the transducer pair had become faulty and channel 2 was disabled leaving the meter with 2 functional channels. The meter was confirmed as fully operational with 2 transducer pairs.

4.3 Oil application post trial monitoring

Longer term operation of the meter has been monitored by BP AGT Operations. The longer term performance indicates the SONAR meter technology is robust, see Figure 7, and fault tolerant to a transducer pair failure in the application described.

The SONAR meter appears to show an increased variability in flow rate corresponding to increaes in flow temperature. Further investigation would be required to determine if this observation is due to process changes or flow meter behaviour.

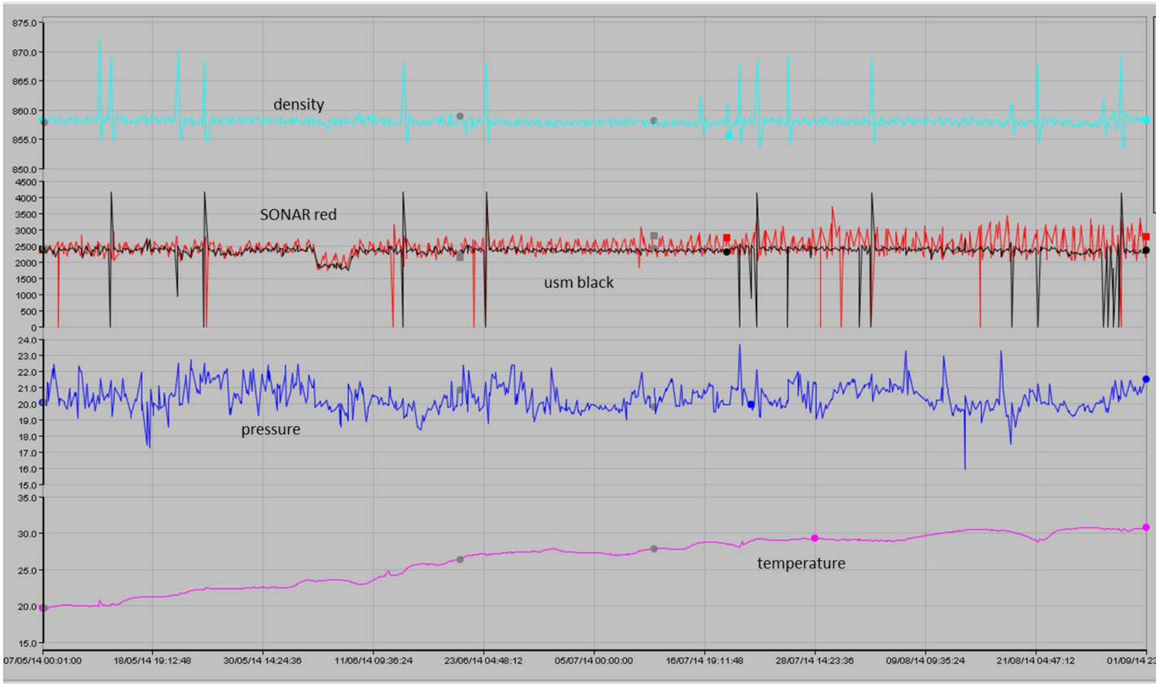

Figure 7 - longer term oil meter monitoring

5 Application of Active SONAR Technology on a Test Separator Gas line

Planned introduction of a new well gave rise to anticipated gas flow rates of between 8 -30 mmscfd. These rates would generate a few mbar, very low pressure drop across the annubar (the reference meter which was modelled in [1]) hence a supplemental, assurance method of metering low gas flow rates was investigated. Alternative configurations of differential pressure transmitters were considered, and eventually fitted, but the decision was also taken to fit an ActiveSONAR meter as a contingency measurement.

5.1 SONAR meter trial installation

A Sonar flow meter, model QEX1000AB, was installed on Shah Deniz 'A' platform, test separator, 10" gas outlet bypass flow line, upstream of the in-line 'annubar' (differential pressure producer) mass flow meter, configured for standard volumetric flow measurement.

The line rating is Schedule 120, nominal wall thickness of 22.25 mm. Actual volume flow rate were reported to the platform ICSS report volumetric flow rates to the platform DCS at actual conditions.

A schematic represention of the trial installation is shown in Figure 8.

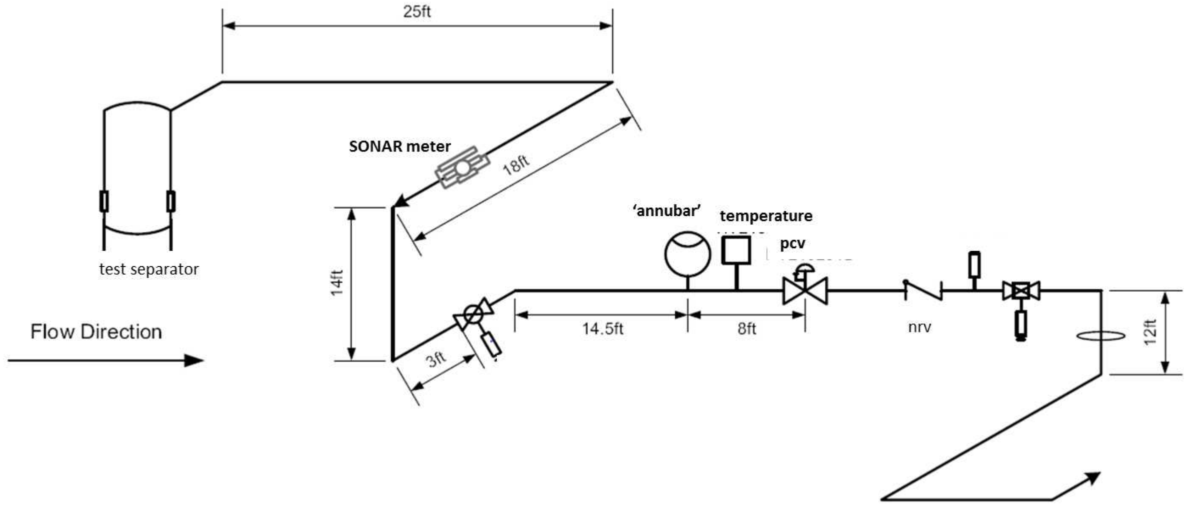

Figure 8 - Trial gas SONAR meter installation

Surface preparation of the pipework was undertaken by BP AGT Operations personnel and the meter was installed by Expro Meter Service personnel with site support as required. Meter installation conforms to the requirements described in [3].

The annubar is sized for a flow range of 0 - 230mmscfd, with typical operating temperature around 50 °C and operating pressure around 150 barg.

The Modbus communication cable from the flow meter was routed to a Modbus to 4-20mA Converter unit [4], wired to the platform ICSS (Integrated Control and Safety System).

5.2 Field Trial Events

June 2013

At the request of BP AGT Region, Expro Meters mobilized a field surveillance technician (FST) to the Shah Deniz 'A' platform in the Caspian Sea to install a 10-inch ActiveSONAR Flow Meter on the 10-inch bypass flow line of the test separator gas line meter run.

The Expro FST commissioned the flow meter with flow through the test separator [7]. Review of the flow meter diagnostic data confirmed that the flow meter was properly operating and reporting valid flow rates at between 150 and 200mmscfd.

The Modbus to 4-20mA Converter unit was also configured and scaled to report flow velocities between 0 and 16 m/s. BP AGT Operations personnel confirmed that the flow readings from the ActiveSONAR Flow Meter were being correctly reported to the ICSS.

November 2013

Expro was mobilised to support low flow gas flow rate trials, [7]. With data taken from the meter diagnostic port, the performance of the ActiveSONAR meter installation is summarised in Figure 9.

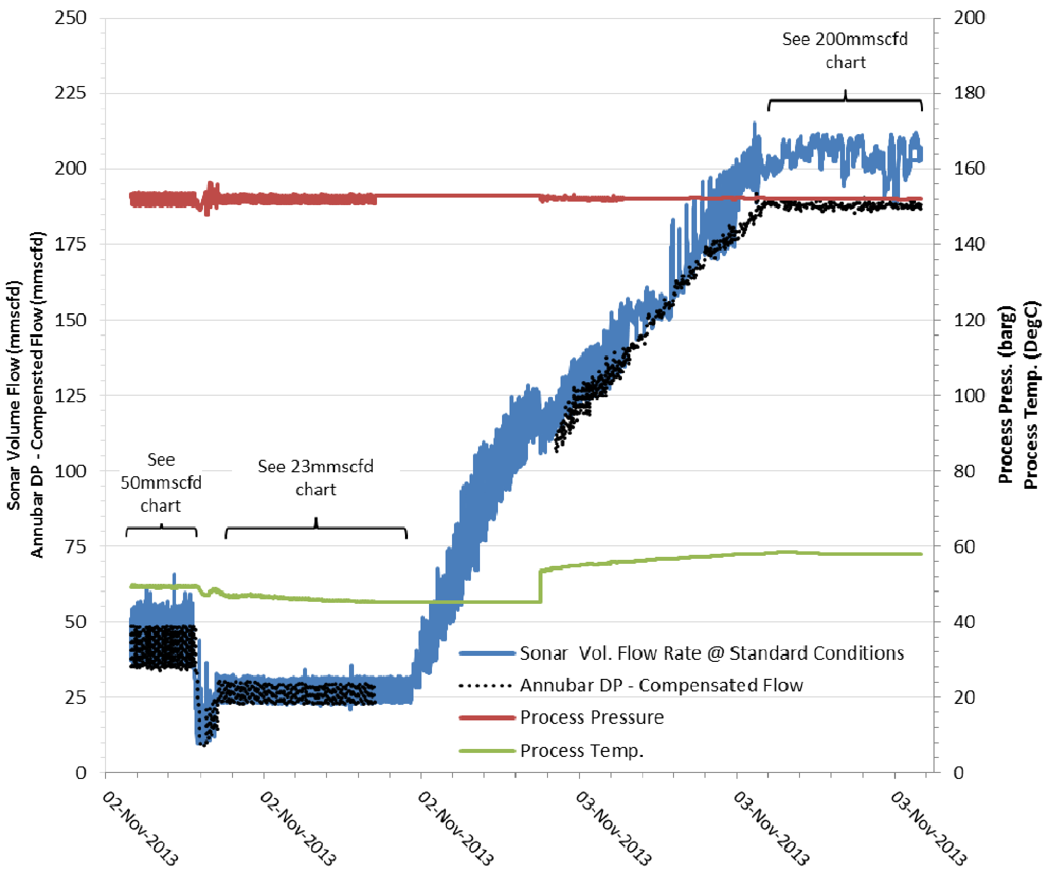

Figure 9 - low gas flow rate trial

It can be seen that the SONAR meter performs closely to the annubar but the annubar 'clips' at around 190 mmscfd, believed to be due to differential pressure transmitter re-ranging.

From the same trial, review of 'discrete' periods revealed signficant incidence of drop out, Figure 10 **- SONAR gas meter dropout**

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Figure 10 - SONAR gas meter dropout

Following the low flow trial BP AGT Operations monitoring of meter performance noted excessive noise when the meter was shut in.

<u>May 2014</u>

Expro was called out and installed v1.7.1.0 firmware, [8].

In addition to the newly developed spike filter, proven on the oil application, the flow meter was configured with "zero flow" settings to reduce the probability of false reporting of flow velocity to the ICSS when the bypass line is shut in.

5.3 Gas application post trial monitoring

Longer term operation of the meter has been monitored by BP AGT Operations.

Since the low flow trial the 10" line has not been in use to assess the operational performance of the spike filter on the gas meter, although it has been proven on historical data sets. It is clear however that the 'zero flow' settings need to be revisited, see Figure 18.

6 Trial based Development

The Expro Meter development team strategy, in addressing the issues of drop out, spike filter and zero flow cut-off, are summarised as follows.

The SONAR flow meter algorithms follow a series of discrete modules to report a valid flow rate to the client's data system, Figure 11. Two of these modules were modified to meet the requirements of the Sangachal metering application. The modifications made to the flow meter are not client specific.

1. Sensor Signal Processing
2. External Communication Protocols

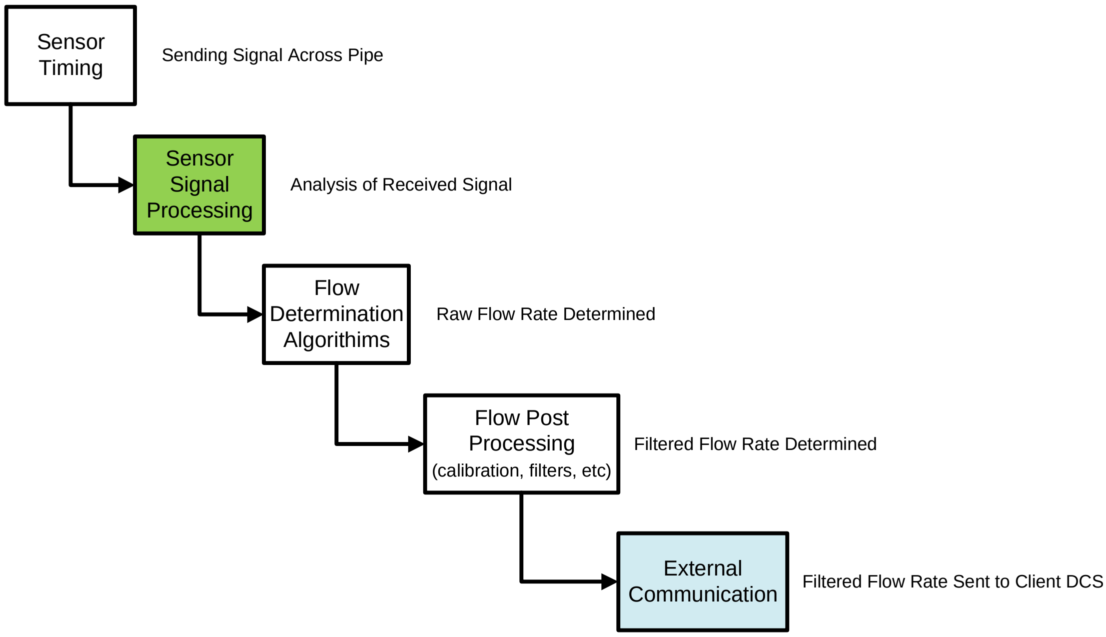

Figure 11 - Block Diagram Depicting Firmware Modules

6.1 Addressing 'drop out' (zero flow readings)

From analysis of the early January data, for the oil application meter, the Expro development team, indicated that genuine 'flow disruptions' and intermittent pipeborne vibration were picked up by the sensor array and gave rise to spurious data points entering the meter input data buffer. When a 'bad' data point was received into the buffer, flow signal processing was 'corrupted' until the bad point exited the buffer. This gave rise to periods of between 7 and 20 seconds of apparent meter drop out.

The firmware was modified to reduce meter sensitivity to flow distortions, depicted in Figure 12 and Figure 13 below.

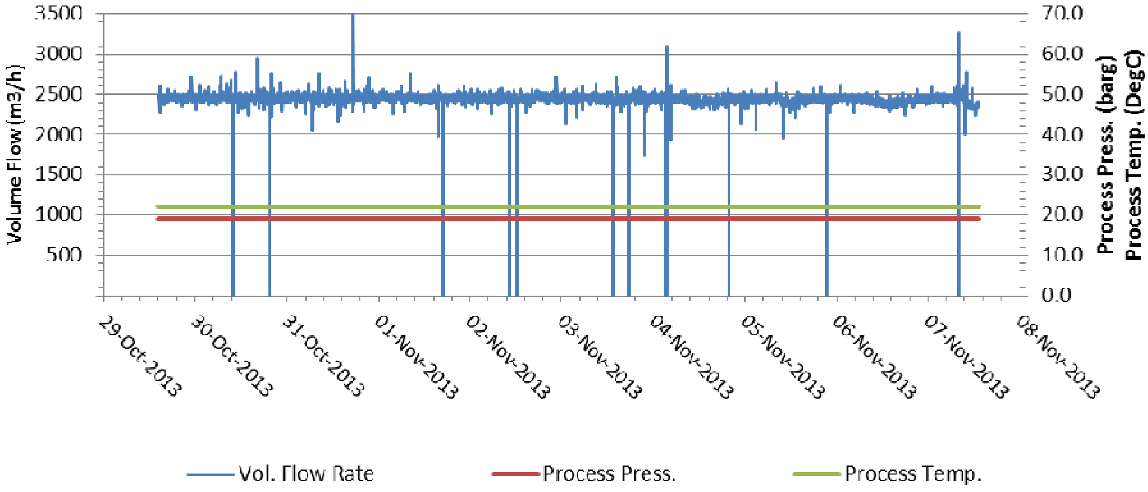

Figure 12 - signal 'drop out'firmware v1.7.0.0

Figure 13 - signal 'drop-out' firmware v1.7.0.1

Upon upgrading the firmware it was reported that the meter operation was much improved, however there continued to be occassional zero flow readings recorded by the ICSS, shown in Figure 14.

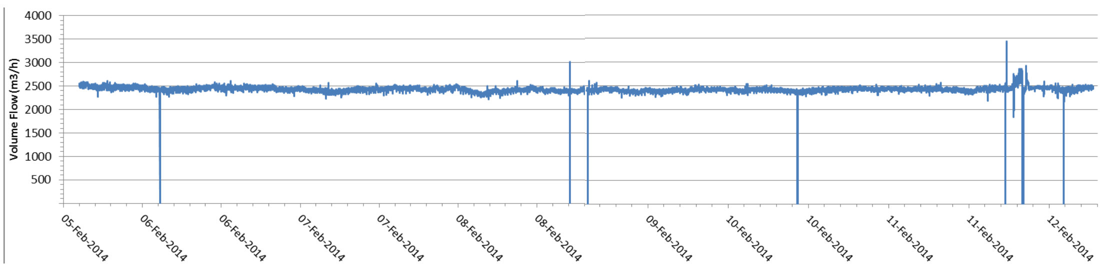

Figure 14 - Flow Data Showing Intermittent Zero Flow Readings

6.2 Addressing 'spiking'

The ActiveSONAR flow meter firmware was upgraded with a spike filter which eliminated the spurious zero flow readings, resulting in meter performance. Prior to configuring the ActiveSONAR flow meter with the spike filter, the effectiveness of the spike filter was tested using actual logged flow data and a flow simulator. The output of the simulator showed that the spike filter was effective at removing the spurious zero flow readings, as shown in Figure 15.

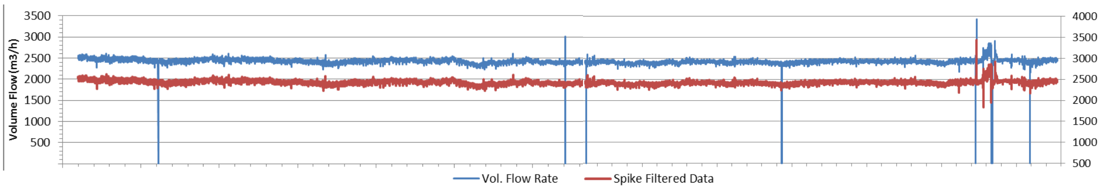

Figure 15: Flow Data Showing the Effect of the Spike Filter (Unfiltered (Blue) and Filtered (Red))

A 'before' and 'after' implementation of the spike filter is shown in Figure 16.

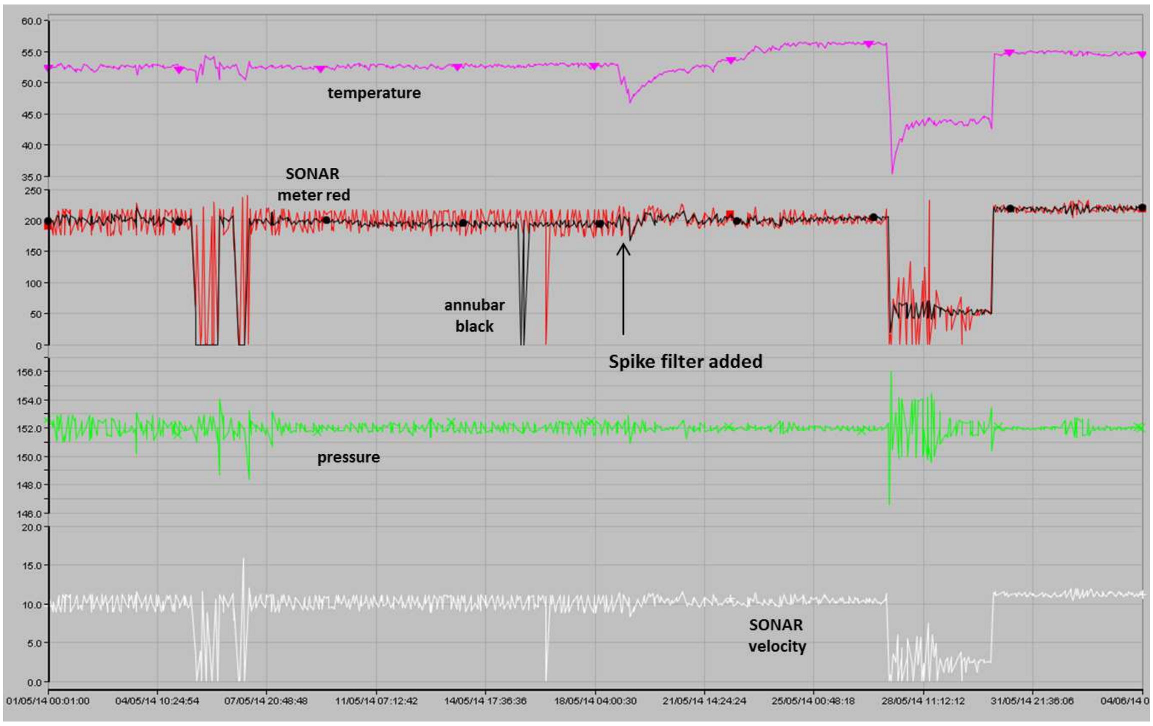

Figure 16 - Spike filter on gas application

The spike filter state diagram is shown in Figure 17

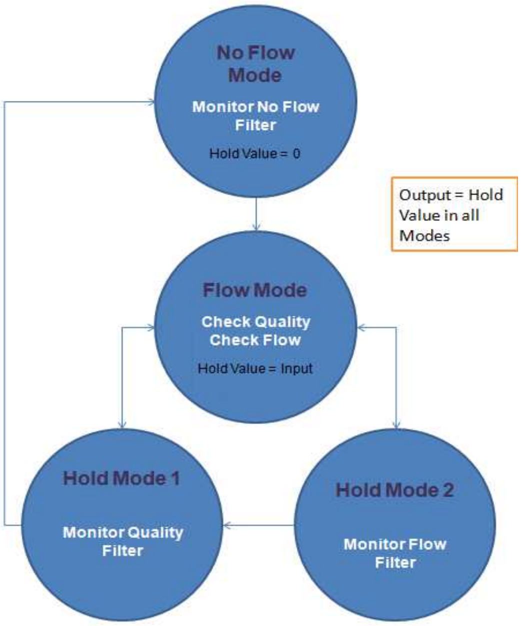

Figure 17 - Spike filter state diagram

6.3 Addressing zero flow cut

Longer term monitoring indicates the zero flow cut off for the gas application has not been effective as intended and requires further work, Figure 18. The reason that the 'zero flow' settings are not effective is that an opportunity was not availble to observe and optimize the configuration during shut in conditions. At the next platform visit, it is planned to modify the meter 'zero flow' settings whilst the flow line is shut in to eliminate false reporting during no flow conditions.

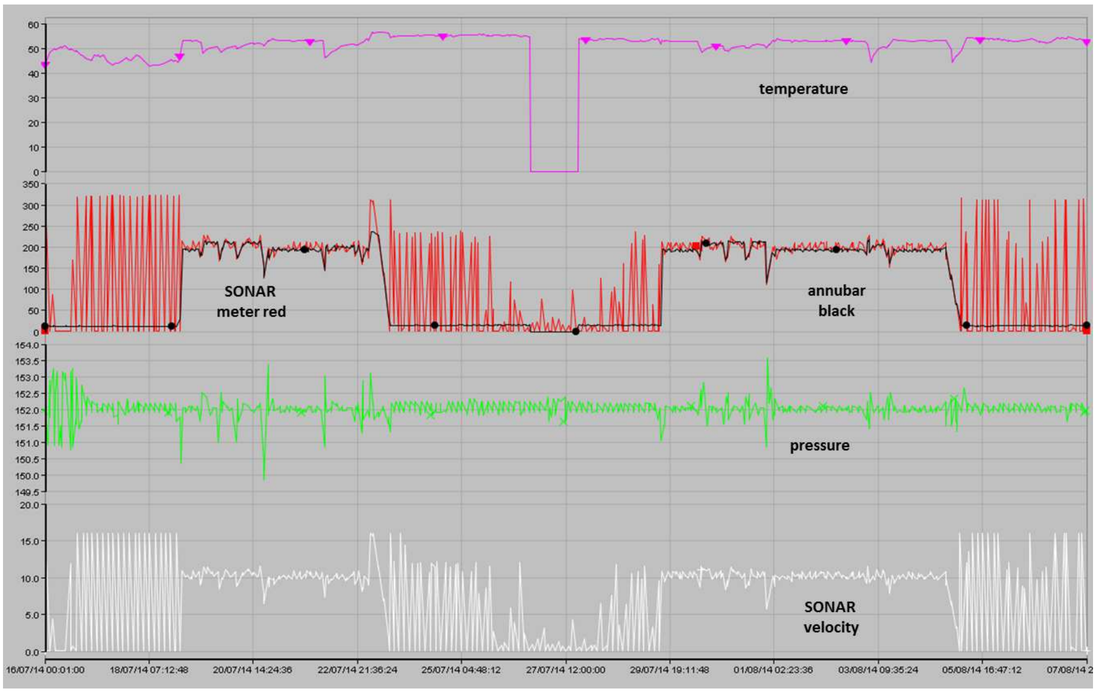

Figure 18 - Gas application post trial monitoring

7 SONAR meter technology Diagnostic interface

The SONAR meter technology has a diagnostic software suite, Flowstudio, used by Expro Field Technicians, which enables data streaming and critical parameter interrogation to support diagnostic tuning. The suite can also be used to 'benchmark' performance to provide some operational assurance around blackbox technology.

8 Conclusion - Discussion of Trial Results

The results indicate that the clamp-on SONAR technology, as a non-intrusive retrofit meter technology, is at least comparable with other type of technology such as ultrasound or differential pressure producer meters and in some cases is likely to exceed the performance of installed meters.

As with any type of black box technology, assurance around meter performance is implicit from key parameters or meter diagnostics. As is current industry practice, with e.g. ultrasonic meter technology, it is possible to benchmark key meter performance parameters during factory calibration / function tests and use these to establish a baseline for performance monitoring / verification in the field.

There is some future development required with the model used in the trials, specifically zero flow cutoff in gas applications.

9. NOTATION

ω Angular Frequency (shown on plots as frequency for clarity)
K Wavenumber (1/wavelength)

10 REFERENCES

[1] Kragas, T. K., et al., "Downhole, Fiber Optic Multiphase Flow Meter: Field Installation" Presented at the Society of Petroleum Engineers Annual Conference, SPE Paper #77654, September 2002.

[2] TUV-NEL, 'CFD-Based Estimates of Errors of Flowmeter on the Shah Deniz Gas Export Separators', Report Number 2008/104-Rev1

[3] Expro Meter Inc., 'ActiveSONAR QEX1000 Flow Meter Installation and Operations Manual ATEX and IECEx', EML00003, Rev 07.

[4] Expro Meter Inc., 'ActiveSONAR MODBUS to 4-20mA Converter Installation and Operations Manual', EML00005, Rev 03.

[5] Expro Meter Inc., Field Service Site Visit Report CTR00431, Rev01, January 2013. Proprietary Document.

[6] Expro Meter Inc., Field Service Site Visit Report CTR01113, Rev04, May 2014. Proprietary Document.

[7] Expro Meter Inc., Field Service Site Visit Report CTR00578, Rev01, June 2013. Proprietary Document.

[8] Expro Meter Inc., Field Service Site Visit Report CTR01091, Rev02, May 2014. Proprietary Document.