NORTH SEA FLOW MEASUREMENT WORKSHOP
measuring for the energy transition

Gas USMs: A Guide to Creating a Condition-Based Monitoring System

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1. INTRODUCTION

Ultrasonic flowmeters (USMs) have been used within the fiscal side of the oil & gas industry for at least 25 years. During this time a wealth of experience and understanding of the capabilities of this technology has been documented in journal articles and in numerous papers from various conferences around the world.

USMs were identified early on as having potential for condition-based monitoring (CBM), where the user makes use of the diagnostic data provided by the USM to target manual interventions where required. Once collected and analysed, the data can be used to determine when flow calibration should be scheduled (condition-based calibration).

USMs vary widely in design which creates complexity in understanding design characteristics and interpreting certain diagnostic parameters. Whilst the information is available in literature, it could be a lengthy task for the metering engineer to find and review all this information.

The purpose of this document is to bring together and briefly describe the salient points pertaining to the use of gas USMs in CBM applications, referencing the source in literature where available. This also gives everyone using this technology the benefit of the experience of the many measurement professionals who use or have experience of this approach.

This is still an active research area and it is anticipated this will be a live document which will be periodically updated as understanding develops.

This guide is split into 4 sections, all of which have relevance to use of USMs in CBM applications. These are USM Selection, Meter Station Design, USM Calibration and USM Operation.

2. USM SELECTION

When selecting a USM for CBM applications users need to be aware of the advantages offered by various designs. Certain choices in specification may affect the suitability of the USM for CBM applications and fiscal measurement in general. This section explains the main points with references to various papers to help users understand these advantages and the capabilities of present designs. Firstly, the main velocity profile effects are described, followed by a brief overview of common designs and how these can be supplemented by diagnostic paths. A brief description of considerations regarding choice of spool material and recent transducer design improvements are also given.

2.1. Non-axial flow and axial distortion

Before describing the principles of USMs and considerations to be made when choosing a design for a CBM application, it is necessary to explain the two main velocity profile effects which can impact performance, these being non-axial flow and axial distortion.

The flow of fluid in a pipe is inherently 3 dimensional and may not be travelling parallel to the pipe's axis. In many applications it is also turbulent with numerous small independent vortices in the flow and the motion appears chaotic whilst still travelling in a certain direction. This is not what is typically meant when describing non-axial flow. The consensus at present seems to be that turbulence and changes in its intensity do not cause systematic measurement errors [1], [2], [3] although this is disputed in some papers [4], [5]. The belief at present is that because the USM is sampling the path velocities many times per second and averaging them, and that the turbulence itself is random in nature, the effect averages out over a relatively short period of time but appears as noise in the path velocity measurements.

Ignoring the effects of turbulence allows one to concentrate on the main movement of flow. The non-axial flow, or non-axial velocity components refers to the individual components of velocity in 2 of the 3 dimensions which make up the velocity vector at any point. The axial velocity component is that which is parallel with the pipe axis. Fig. 1 is shown to help illustrate the point.

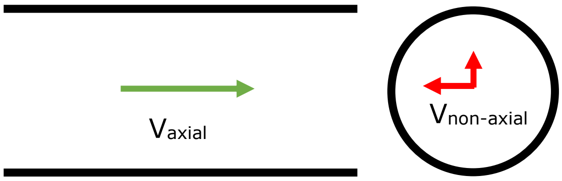


Fig. 1 – Illustration of axial (green) and non-axial (red) velocity components

Purely axial flow (green arrow) only has component z which is non-zero, the non-axial components x and y are 0. Swirling flow will typically have non-zero values for all 3 velocity components.

Non-axial flow is often in the form of single or counter rotating vortices which can be caused by certain combinations of pipework upstream and is discussed further in section 3.

The basics of USM measurement principles are explained in many papers, e.g. [6]. It is important to realise that USMs measure the transit time and *infer* axial velocity on the path. They then use these path measurements to approximate bulk mean velocity using an 'integration technique'.

For many designs the inference assumes that the flow is purely axial (no bulk rotation of the fluid). If this rotation is present in certain designs, it will create systematic measurement errors. The only designs which do not rely on this assumption are swirl cancellation designs which are discussed shortly.

Changes in the axial distribution from that seen at calibration can also affect USMs. At the calibration facility a typical axial profile may be something close to Fig. 2a whereas in service it may be closer to Fig. 2b.

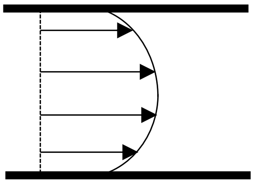


Fig. 2a - Example distribution of axial velocity components in fully developed flow

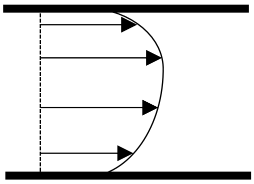


Fig. 2b - Example distribution of axial velocity components in distorted flow

All USMs are affected by this change to varying degrees and sensitivity is typically dependant on the number of paths. The integration technique will also affect sensitivity.

Many designs do not measure swirl components. The only designs which do are the in-plane crossed chord designs discussed shortly. Some do report an estimated swirl making certain assumptions and may report genuine axial distribution changes as swirl. For any non-swirl cancellation design, a change in the apparent velocity profile indicated by the path velocities could be caused by a change in the axial distribution, or they could be caused non-axial flow. Flow conditioners are commonly used to reduce non-axial velocity components present in the USM. Non-axial flow can result in large measurement errors in non-swirl cancellation designs.

2.2.Chordal Designs

Individual manufacturers vary in how they define a 'chord' which is discussed in detail in [7]. A simple way to understand chord is to define it as a straight line touching two points on the edge of a circle. All chordal USMs have chords which are parallel to one another in the cross-sectional plane. Two common chordal designs are shown in Fig. 3a and Fig. 3b.

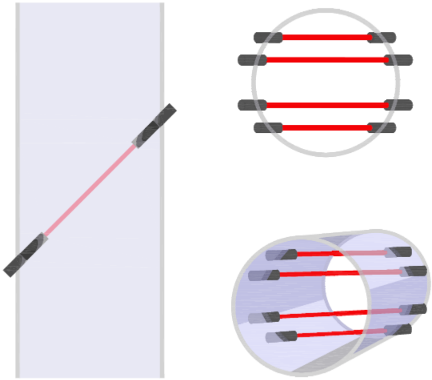


Fig. 3a - Multi-path parallel chord [8]

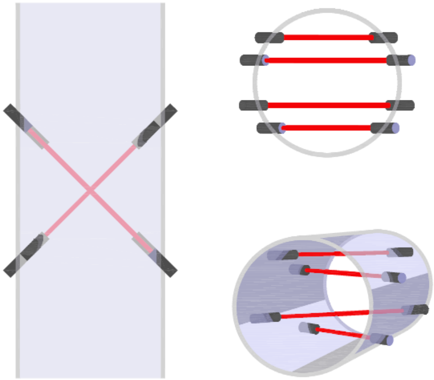


Fig. 3b – Multi-path parallel crossed chord [8]

Cameron in [7] define chordal path to be the path which lines up with a chord in a cross-sectional view of the meter. Some USMs have multiple chordal paths in a single chordal plane, such an example are swirl cancellation designs of which there are two main types; those which use two chordal paths per chord, and those which use a single chordal path on each chord and use reflection to achieve swirl cancellation. These are shown in Fig. 4a and Fig. 4b.

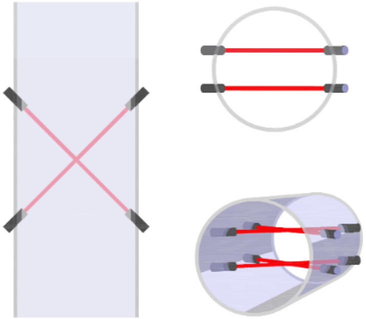


Fig. 4a – In-plane crossed chord swirl cancellation design [8]

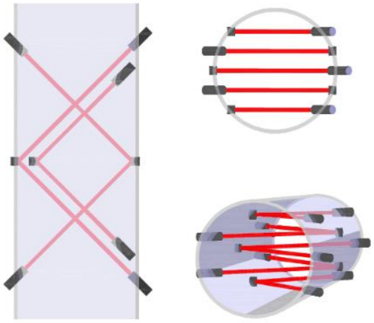


Fig. 4b – Parallel chord reflective swirl cancellation design [8]

The in-plane crossed chord design is shown above with only 2 chords but is typically sold with at least 4. This design is discussed in [9], the parallel chord reflective design is discussed in [10]. The parallel chord reflective design shown in Fig. 4b has 5 chords according to the definition of chord in this document.

A similar principle is used in both to achieve swirl cancellation; because the paths on the same chord have an angle with respect to the pipe axis which is equal in magnitude but opposite in sign, the swirl components cancel when the two paths are averaged and allow a measurement of true axial velocity. This is also discussed by the author in [11]. The in-plane crossed chord allows measurement of the average non-axial velocity component in the x direction across the path (the y component does not affect the measurement in the chordal design). The parallel chord reflective design has an advantage in that it can identify contaminants which occur at the point of reflection.

Swirl cancellation designs have advantages in terms of minimal upstream straight length requirements whilst maintaining OIML R137-1&2:2012 [12] class 0.5 compliance (the highest rating in tests of resilience to installation effects), no requirement for flow conditioner which eliminates this as a potential source of blockage and simplifies diagnostic interpretation. Given the extra hardware required, these designs are more expensive, but this should also be considered alongside cost reductions in terms of footprint of the metering skid, reduced risk of mismeasurement and removal costs if the flow conditioner becomes blocked.

In swirl cancellation designs a change in the measured profile can be understood to be a change in the axial distribution, whereas in non-swirl cancellation designs this is not the case and diagnostic interpretation requires knowledge of the path configuration and transducer angles to ascertain what swirl would look like. This is discussed in [13] and [11]. Given a change in velocity profile, perhaps caused by some unknown disturbance introduced upstream, it is advantageous to differentiate the effects of non-axial flow from just a change in the axial distribution because the error caused by non-axial flow is likely to be larger [11].

Chordal designs typically use integration techniques based on an interpolation polynomial which when integrated takes the form of a weighted sum whereby each velocity is multiplied by a weighting factor for that path, these results are then summed to calculate mean velocity. This is more generally known as quadrature, and typically designs use Gauss-Legendre or Gauss-Chebyshev 2nd type [14] (also commonly referred to as Gauss-Jacobi) forms of this technique with OWICS being another technique mentioned in literature [15], [16]. The function being interpolated is referred to in literature as the area flow function [16], which represents the product of mean velocity across the chord and the chord length at any given height. This is illustrated in Fig. 5.

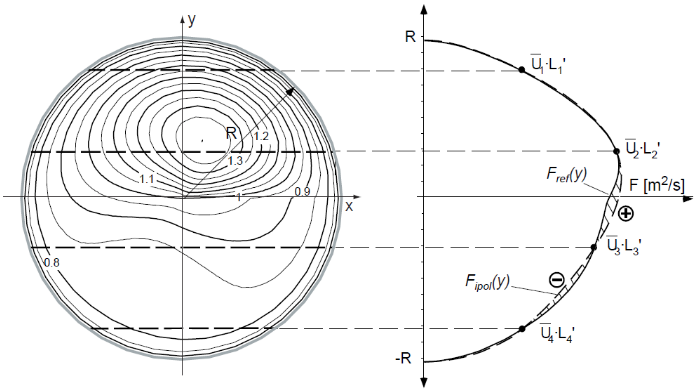


Fig. 5 - Illustration of a distorted axial velocity profile, the associated area flow function and interpolation polynomial [15, Fig. 1]

Because the integration scheme is based on an interpolation polynomial, in the event the axial profile changes, the integration scheme can adapt and effectively remodels the axial profile. However, given that most chordal USMs are presently only available with 4 or 5 chords (these chords can now be thought of as samples for the interpolation polynomial), it is possible that integration errors can remain.

Integration scheme design can be commercially sensitive. Some papers in literature discuss these techniques in more detail, for example [16] and [11].

2.3.Diametric-Reflective Designs

These designs include measurement paths which lie across the meter diameter when viewed in the cross-sectional plane. A common design also includes bounce paths which prescribe a triangle in this plane. This is shown in Fig. 6.

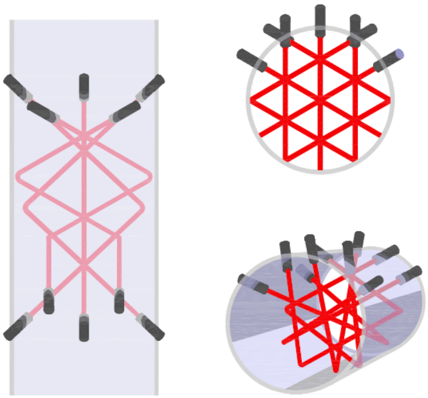


Fig. 6 - multi-path mid-radius and diametric [8]

This design uses 3 single reflection paths, which provide an axial velocity estimate unaffected by swirl. It also uses two twin double bounce paths which are designed to measure swirl. A more recent evolution of this design is described in [17].

The integration technique of this style of design is described in [18]. Whilst it uses a weighted sum and has the appearance of quadrature it is not based on the integration of interpolation polynomials. In [18] it is mentioned this design employs a velocity-based correction which is consistent with the work of [19], which describes diametric-reflective designs more generally noting that in more simplistic designs averaging can be used along with a Reynolds based correction. Such corrections can assume a velocity profile of a certain shape and manufacturers should be consulted to understand any corrections being used. This may necessitate extra care in ensuring the velocity profile in service matches that seen during calibration.

Diametric-reflective designs can be more simplistic twin or single path designs, but these are not discussed further as they are generally not used in fiscal applications.

2.4.Diagnostic Paths

Modern chordal designs may be supplemented by additional diagnostic paths and are typically not used in the calculation of meter velocity. These can take the form of a single direct or reflective path (e.g. 4+1) or an entire duplicate meter in the same body (e.g. 4+4). Some manufacturers offer both reflective and direct diagnostic paths (4+2). The reflective path [10] allows for detection of contaminants at the pipe wall when the contaminant is at the point of reflection. A single direct path [20], [25] relies on the difference between the single and main measurement path mean velocity predictions being heavily flow profile dependant. This requires the user to monitor the difference between the two velocity predictions. In [25] the authors recommend use of a flow conditioner to improve the ability to detect a disturbance by reducing the variation in the velocity profile. A duplicate USM in the same body such as a 4+4 is designed for redundancy and diagnostic purposes.

There seems little in literature which examines the sensitivity of these techniques across a wide range of meter sizes. Users are encouraged to seek manufacturers guidance regarding sensitivity of any method and manufacturers are encouraged to publish data describing testing of these techniques across a variety of sizes.

2.5.Choice of Spool Material

Experience has shown that the choice of USM spool material is an important consideration, especially so when they may be left in service for considerable periods. The flowmeter bore can corrode in service in certain applications, but they can also corrode in transit to/from the calibration facility. If this happens in service the experience shows that the change in diagnostics in common 4 chord designs is minimal [20] so it may escape detection, but the change in performance and therefore resulting mismeasurement can be considerable.

If this happens en route to calibration it will likely become evident in the following investigation into the cause of the shift. At this point the measurement during the previous service period will be in question and may only be saved by documented evidence (photographs) of the bore condition upon removal at site and good CBM records whilst the meter was installed. If this happens following calibration, then the calibration results may no longer reflect meter performance and it would be advisable to have it recalibrated with obvious cost consequences.

Bearing in mind the above discussion and cost of investigations, mismeasurements and extra calibration runs, users are strongly encouraged to specify the best quality steel which they can afford whilst ensuring all precautions are taken to prevent dissimilar metal corrosion. USMs are typically offered with a choice of carbon steel, coated carbon steel, stainless or duplex steel. Users should seek guidance from the manufacturer regarding expected life span of any coatings and follow any recommendations for preserving bore condition in transit.

Should internal corrosion be identified during flow calibrations then a periodic inspection programme should be implemented. This need not entail removal of the USM, and for ease of access, borescope inspection ports should be considered as part of the system design.

2.6.Transducer Design

The purpose of this section is to highlight the more recent improvements in USM transducer design. The 2000 GERG project investigated ultrasonic gas flow meters and included testing of various transducer designs [21]. It was found that some were prone to failure due to bonding defects which the authors suspected was due to changes in pressure and temperature during testing over several months. Bonding defects resulting from the impedance matching layer have been mentioned by others in literature as a source of measurement errors [22].

In [23] the authors explain debonding occurs due to the difference in thermal expansion coefficients of the piezoelectric crystal and the epoxy, which can cause the epoxy to crack with high or varying temperatures or high pressures and propose a mini horn array to replace the epoxy which is not subject to failure under these conditions. Another solution to avoid a matching layer was proposed in [24] which uses stacked ultrasonic transducers, which are also discussed in [53].

It appears that later transducers are more suited for CBM applications where longer service periods are the norm. Users are encouraged to seek guidance from the manufacturer regarding statistics relating to long-term stability of the transducers and associated hardware. Occasionally users wish to use older USMs for CBM applications; in these cases, users are encouraged to seek guidance from the manufacturer regarding the model of transducers presently installed and any potential benefits of replacing them with the latest design.

3. METER STATION DESIGN

This section highlights some of the considerations regarding the design of USM meter stations for general good metrology and CBM applications. Some issues surrounding upstream geometry are briefly discussed followed by some discussion of the advantages and disadvantages of flow conditioners. The importance of quality valves is also highlighted.

Ultrasonic noise generated by flow control valves or other elements within the process is also an important design consideration but is not discussed here (see for example [8], [26]).

3.1.Upstream Configuration

Metering stations are periodically encountered with less than ideal upstream configurations. Measurement engineers should ideally be involved and comment on the upstream piping arrangement, selection of meter design and flow conditioner at a point in the project which is early enough to change the design if necessary.

The effects of upstream disturbances (commonly referred to as installation effects), for example non-axial flow or axial distortion, will likely be systematic and are generally unknown. However, disturbance testing, such as that described in OIML R137-1&2:2012 [12], seeks to ensure the effect is not beyond a certain limit, depending on the accuracy class. Every effort should be made to minimise these effects at source.

The relevant standards provide detail regarding the issues caused by poor upstream geometry. For example, ISO-17089:2019 [26] and BS-7965:2013 [8] both highlight that axial distortion can persist for 50D or more and that swirl can persist for 200D or more, both citing issues with out of plane and in plane bends. It is also reported in [27] that double out of plane bends produces asymmetric swirl (swirl with a vortex which is not on the pipe centreline). These piping configurations are rightly included as part of the OIML R137-1&2:2012 disturbance tests.

ISO-17089:2019 also mentions blank tees and headers as a potential disturbance. BS-7965:2013 mentions 'various combinations of upstream fittings' including tees as an example. These have been described in literature as causing various issues in ultrasonic metering stations but are not included in the OIML R137 disturbance tests. For example, these were cited as causing issues with swirl and axial distortion in [28] and the modelling is described in detail in [29]. Furthermore, the modelling and experience suggested that the flow conditioner may not be able to deliver a suitable profile downstream of this disturbance. A further example is detailed in [30] whereby a tee connection on the inlet to a master stream (effectively forming a blind tee) was found to introduce a significant flow disturbance and that axial distortion persisted downstream of the subsequent flow conditioning plate. This paper also highlights the benefits of performing CFD analysis during the design phase, rather than after the metering skid has been delivered. However, CFD models involve assumptions and should not be considered the panacea for poor upstream geometry. They can have high uncertainty and may not be traceable. They are however valuable as a tool to ascertain which components are creating a problem and establishing how to modify the pipework to lessen or remove the issue.

There has been some testing of various blind tees and headers. Some work is described in [31] with a selection of USMs tested, both chordal and diametric-reflective, with errors being up to ~0.2%.

3.2.Flow Conditioners

There are a variety of flow conditioner designs available. The principal role of this device is to destroy non-axial flow however they may not always deliver a developed profile (as described in 3.1) which may cause subsequent investigations into any potential installation effect upon introduction into service, since this may cause a persistent difference between the profile at calibration and that in service. Depending on the distance from the disturbance they may not remove all non-axial flow and CFD modelling may be required to inform the best position during the design phase.

Flow conditioners are often used with non-swirl cancellation designs for good reason. The upstream geometry at site is often very different to that at the calibration facility and the flow conditioner generally offers the best way to use such USMs and limit installation effects. With such USMs, flow conditioners also allow users to confirm that installation effects remain within certain limits by use of velocity profile diagnostics, as described in [9]. They do however create a pressure drop, the absence of which was one of the original claimed advantages of USMs [39]. The additional pressure drop leads to extra energy consumption which is undesirable when trying to minimise emissions. The costs of multiple flow conditioners can also accumulate and be significant over time [13].

Flow conditioners can also be prone to blockages which is undesirable in CBM applications, given the objective is to minimise maintenance. When such events occur, this may also cause a mismeasurement which may not be immediately identified, depending on the level of scrutiny of the USM diagnostics. Care is also required in their installation with measurement errors due to rotation of the flow conditioner reported in [32] and [33]. They must also be present at calibration. Flow conditioners should be marked in such a way that allows the user to confirm the orientation when installed.

One of the advantages of swirl cancellation designs is that they can be used without flow conditioners. Given the above discussion this may be preferable, especially in CBM applications where one is aiming to minimise maintenance.

Users are encouraged to consider this option and the longer-term costs associated with the use of flow conditioners.

3.3.Meter Isolation Valving

A common problem in general with meter stations is passing valves which can prevent key maintenance from taking place and can be expensive and time consuming to resolve. Users are encouraged to source valves which are known to have a sufficient operational life rather than accepting cheaper valves which may not last. Caution should also be taken to ensure valves are not operated with a high differential pressure across them. It is recommended that isolation and de-isolation procedures are created.

Fully operational valves are key in CBM applications; the USM must be able to be safely isolated (incorporating double-block and bleed valve arrangements on inlet and outlet where necessary) and removed for investigation if the diagnostics indicate this is required. Passing valves can force the user into continuing production with an ongoing mismeasurement, which may or may not be retrospectively quantifiable. For this reason, dual streams should also be considered. A further important point, which is explained in the standards, is that valves should be full bore. Users are encouraged to confirm that any valves supplied for their system are indeed full bore.

4. USM CALIBRATION

This section describes good practice which should be followed in the days leading up to flow calibration, during calibration and following reintroduction into service.

4.1.Removal from Service and Transport to/from the Calibration Facility

Prior to removal from service, ensure that diagnostic data is recorded which shows the USM in operation in its last few days service. A copy of the configuration in the meter electronics should also be taken. These two elements can be used to demonstrate satisfactory measurement over the service period if necessary and that any change in performance occurred during or after removal for calibration.

The USM condition following its service period must be maintained to ensure a representative flow calibration. Often removal from service goes without incident but there have been issues caused by contamination with valve grease due to passing valves, or through use of dirty hoses to purge the system. Ensure all purging operations are carried out with clean equipment, dedicated hoses are recommended.

The USM internals and exterior should be photographed upon removal prior to shipping to the calibration facility. This serves as a reference of the condition in case of corrosion or damage during transit.

The manufacturer should be consulted regarding how best to transport the USM and preserve the bore condition. As a minimum, blanking plates designed to prevent moisture ingress should be installed.

It is recommended that further photographs are taken of the USM and bore condition immediately prior to installation at the calibration facility. Photographs of the USM installed in the test lines and the test lines themselves should also be taken.

A drawing of the USM piping configuration should be created to ensure consistency of installation during future calibration.

4.2.Best Practice to Ensure Representative Flow Calibration

Calibrations should be witnessed by the operator. Consideration should be given to having a representative from the manufacturer present to assist with verifying meter performance and with any investigations as required.

Ideally the USM should be calibrated with the upstream spool piece and any flow conditioner used in service. Some operators use dedicated calibration spools which are kept onshore to minimise work offshore. In these cases, the spools should be kept in a suitable environment and protected from corrosion of the bore.

There has been some published work which examines the effects of a corroded upstream spool on the measurement, see [20] and [34]. It seems further research is required in this area; both papers report the error to be ~0.2% or less, but the work in [20] seems to show the effect decreasing as operating pressure increases. However, this may be a residual pressure dependency on the USM because the tests with non-corroded pipe resulted in a performance change of a similar magnitude as operating pressure increased. It is possible that this effect will also depend on the integration scheme design, as suggested in [34]. This suggests caution should be applied when transferring learnings in this area from one USM design to another.

USMs offer a wide range of outputs, e.g. 4-20ma, pulse output and digital (usually serial MODBUS) with the latter two being common in fiscal USM systems. Every effort should be made to calibrate the USM using the output that will be used in the field. The calibration facility may offer a choice; if they do not then comparisons should be made and recorded during calibration (using the manufacturers software if required) to demonstrate there is no change in performance between outputs. There has been at least one instance where a significant difference has been found between analogue and digital outputs, but it is typically negligible.

A further complication can arise with digital outputs. Experience has shown that in some USMs, internal corrections (for example piece-wise linearization correction factors) can be applied to the gross volumetric rate but not the mean velocity. This is particularly important where linearization is performed in the USM electronics rather than the flow computer. A test of the linearization is typically performed at the end of the calibration during verification runs. If a comparison between outputs used at the test facility and in service is not made at this point this can be overlooked leading to significant mismeasurements. For this reason, where a difference in outputs between calibration and service exists and linearization is performed by the USM, a comparison of the outputs should be made during verification runs to confirm any corrections are being properly applied to the output used in service.

The flow rates used for calibration should be representative of the rates which could reasonably be expected over the anticipated service period. Use of a small number of points across the entire meter operating range should be carefully justified. Consideration should be given to choosing a greater number of points around the typical operating flow rate. When determining the minimum and maximum flow rates it is suggested that once the typical operating range is determined, an additional allowance should be made to account for any optimisation of plant or additional wells which are expected over the anticipated service period.

Flow calibration should be at operating conditions seen in service. However, this is not always possible in high pressure applications. Detail of the effects caused by calibrating at different temperatures and pressures to those seen in service is discussed in [35]. In these cases, corrections (for example those detailed in ISO-17089:2019 [26]) can be used. Manufacturers published corrections should only be used if evidence can be provided which demonstrates their effectiveness at the operating conditions required.

Some USMs implement a Reynolds correction and the user has no choice whether to apply it or not. Based on one such correction, the effect can be negligible or more material, depending on meter size. Manufacturer’s guidance should be sought to ascertain whether the correction is material, accounting for the difference between calibration and operating pressure. Some such corrections use pressure which can be fixed in the USM electronics or can be supplied dynamically. With such corrections the preference is to have live measurement supplied to the USM electronics. However, in the case where the pressure is fixed and the correction is material, the pressure needs to be set at the calibration conditions during calibration, and then changed to operating conditions when in service. This avoids a mismeasurement.

However, some USMs perform their own spool geometry corrections, sometimes using fixed pressure and temperature in the USM electronics. It is recognised that this can conflict with the correct settings for the Reynolds correction, and it is considered good practice for the spool corrections to be disabled and for the associated corrections to be performed in the flow computer. Where they are not disabled, if the Reynolds correction has a negligible effect the fixed conditions should be left at their original values. In such cases it is considered poor practice to change the fixed conditions in the USM immediately prior to each calibration because this changes the meter response, with changes in temperature being more significant. If the Reynolds correction is material it may be preferable to disable the USM body corrections and the manufacturer should be consulted.

Diagnostics should be recorded during calibration, ideally a sample at each flow point but as a minimum the diagnostics at the typical operating flow rate should be recorded. This is then used as a comparison with the diagnostics seen in service. This can be manually recorded, but ideally should be recorded through use of manufacturers software to record the data in the form of a continuous log file. Alternatively, a diagnostic report based on several minutes of data can usually be created.

If this is a recalibration a comparison of velocity profile diagnostics against those seen at the previous calibration can be performed with a suggested maximum difference of 1%. This further confirms the test setup is the same, that no profile effects are resulting from the configuration of the test lines or any installation issues at the calibration facility and that no significant deterioration of the internal bore condition or upstream pipework has occurred.

During calibrations of gas USMs the theoretical velocity of sound (VOS) in the test lines can usually be calculated by use of AGA 10 [36] or using GERG as included in AGA-8:2017 [51], using the calibration facilities measured composition, pressure and temperature. This can then be compared with the VOS measured by the USM and allows the user to confirm that the calibration facilities instrumentation and the USM is performing as expected. Since calibration is usually performed on gross volume, calibration facilities can correct the reference meter quantities to the conditions at the USM by use of calculated densities at these conditions. Thus, such a check gives further confidence this correction is accurate.

4.3.Acceptance of Calibration Results

Each test point should have a minimum of 5 repeats with more if results dictate. Dixons Q test or Grubbs tests can be used to detect outliers. A further method is to define acceptable results as 5 consecutive runs which all lie within +/- 0.1% of the mean. For example, if the mean error is 0.2%, any runs within 0.3% and 0.1% are considered acceptable. This is consistent with assuming +/-0.1% repeatability for the USM.

Occasionally the results follow a trend and deviate from this trend when the reference meters are changed, for example at lower flow rates. Such instances could be genuine or could suggest an issue at the calibration facility. One method to eliminate the test facility is to repeat the runs for the previous higher flowrate on the new reference meter and check the results are consistent. If they are then the lower runs should be repeated, and the results compared. If this cannot be done, an alternative method is to simply request the suspect runs are repeated with a different reference meter and compare results.

The calibration results should be compared with the previous calibration to identify if an excessive change in performance has occurred. The results can be compared in terms of change in the single FWME [26]. Alternatively, the change in the performance at the rates which are typically seen in service can also be used. The difference (D) between two calibrations performed on gross volume should be within the combined uncertainty of the test facility uncertainty and the USM repeatability across two calibrations as per Eq. 1.

$$D = \sqrt{{u_{test\_facility}}^2 + {u_{test\_facility}}^2 + {u_{usm\_repeatability}}^2 + {u_{usm\_repeatability}}^2} \qquad (1)$$

Eq. 1 assumes that any other factors affecting the uncertainty are either negligible or are the same between two different calibrations and have a systematic effect on the measurement. In this way the systematic effect will be the same on both calibrations and not affect the difference between them. Application of this formula typically results in values of D ~ 0.3%.

If the USM performance changes from one calibration to another in excess of the calculated D value an investigation into the reasons for the shift should begin. The following is a non-exhaustive list of elements which can be checked:

- Confirm s/n of USM & transducers matches expectation.
- Confirm the previous calibration is representative by using results from an earlier calibration or the factory calibration.
- Compare USM configuration report against that used at the previous calibration.
- Confirm diagnostics are aligned with expectation, e.g., gains & SNR are not largely different to expected values and that paths are in close agreement. Confirm velocity profile diagnostics are within 1% of those seen at the previous calibration. The manufacturer should be consulted regarding diagnostic interpretation if necessary.
- Perform measured vs calculated VOS check to confirm correct operation of USM and of test facility instrumentation. Tolerance typically used is 0.21% [39] however typical differences can be much less. The path VOS measurements can also be compared relative to each other and compared with a previous calibration.
- Check orientation of flow conditioner. Remove USM from the test lines and check bore condition (compare with photographs at the previous calibration), spool alignment and that correct gaskets have been fitted which do not protrude into the bore.
- Check that no changes have been made to the piping configuration at the test facility, either upstream or downstream of the meter under test since the previous calibration.
- Check which reference meters are in use and confirm the test facility configuration of the associated calibration data for these meters is correctly entered and applied.
- Confirm pressure and temperature instrumentation is updating and that pressure transmitters have not been accidentally isolated from the process.

- Perform a sense check of the values between the USM under test and the reference meters and ensure changes in these values are in the correct direction, making some allowance for ambient conditions.
- Review configuration of the test lines and identify any valves which if passing may cause product to be missed either by the reference meters or the USM. Ask the test facility to perform cavity checks or close additional valves as required. The direction of the shift can be used to inform where efforts should be focussed.
- The transducer waveforms can often be reviewed using manufacturers software to interrogate the USM. This may require specialist training to correctly interpret, and the manufacturer should be consulted if necessary.

If the above process does not suggest any cause the USM should be sent to a different test facility to confirm the change in performance. If confirmed the manufacturer should then be consulted.

4.4.Application of Calibration Results

It is advisable to correct the raw USM output in the flow computer where interpolation can be routinely checked, and it can be demonstrated it operates as intended across the range (for example when extrapolating the meter factor of the first/last calibration point is returned). It is acknowledged however that there are advantages to implementing the correction in the meter head, for example there is arguably less chance of incorrectly configuring the correction in the flow computer.

The meter response is commonly corrected by use of linear point to point interpolation, but other methods do exist and are mentioned in BS-7965:2013 and ISO-17089:2019, these being a single flow weighted mean error (FWME) and 'polynomial algorithms'. There is some discussion of the issues surrounding implementation of calibration results and data fitting in general in [37].

Use of a single calibration factor is not recommended in fiscal applications. Some USMs can display non-linearity across the range and without exact knowledge of future production rates the correction factor which minimises the uncertainty cannot be known. Some USMs can be fairly linear across the working range, but sometimes display non-linearity towards the bottom of the range. Given the fiscal quantities involved with typical USM metering stations, it is usually worth the effort to correct the flowrate properly across the range and obtain maximum value from flow calibration.

It is noted that in both ISO-17089:2019 and in [37] that polynomial interpolation can be unstable at the extremes and it is felt it is the least preferable option. This issue can be overcome and is described in detail in [38]. However, to correct the issue requires a specific distribution of flow rates to be used and may not provide the operator with flexibility to use more points around the typical operating flow rate. Flow computer software would also require modification to use such methods. Therefore, at present, it is felt this is still the least preferable option.

5. USM OPERATION

This section describes a selection of monitoring techniques from literature. Some familiarity with USM diagnostics is assumed. Useful background to this section is provided in a variety of papers, for example [40 – 43, 48].

The USM is affected by changes in the condition of its components (e.g., transducers/electronics internal bore) and operating environment (e.g., velocity profile, fluid properties, ultrasonic noise). Many such changes can be identified through use of internal diagnostics although these presently provide a qualitative view of meter performance, the resultant measurement error cannot usually be determined. Internal diagnostics are the main subject of this section, however Cousins and Steven [44] describe other diagnostic methods which can in principle be used alongside internal diagnostics such as mass balance checks and two meters in series. Mass balance checks do lack sensitivity [44] and users should expect noise, but they can be of value if analysed over a long period. The below sections give a short summary of use of two meters in series and master meter verification before describing techniques for monitoring using internal diagnostics.

5.1.Two Meters in Series

A further monitoring method is to use two meters in series. It is noted in [44] the difference in theory cannot be better than the combined uncertainties of the two meters used. However, some components of USM measurement uncertainty are systematic and would be eliminated from the difference if the two meters in series were calibrated as a package, as recommended in [45] which specifies methodology for comparing USMs of different designs in series which originate from German guidelines designed specifically for this purpose. [45] recommends a maximum difference of 0.5% based on standard volume and a maximum change of 0.3% in the difference of each path VOS from the mean compared to that seen during the commissioning period. From the data presented it does appear that some installations can achieve a tighter difference between the standard volume flow of the two USMs and the authors suggest considering use of a 0.3% limit where 1% uncertainty is required. The reason for the limit of 0.3% difference in path VOS to the mean is not clear but it appears a coarse limit. Simple analytical models suggest that even in smaller sizes, a significant systematic measurement error in transit time will not be apparent from this check but should present itself in the difference between the two USMs. It is recommended to set both the VOS limit, and the permissible difference between the two USMs, as tight as possible according to site experience.

[45] also recommends use of additional USM diagnostics to help identify common mode errors, for example caused by contamination or noise and suggests also comparing with theoretical VOS alongside the difference from the mean. This is important, for example in the case of uniform contamination, where the mean VOS across all transducers may be elevated and a comparison against the mean alone may not identify the error. Common mode error detection can be improved by careful selection of the two meters in series. For example, if one employs reflection and the other is direct path, then the contamination will have a larger effect on the reflective path design because of the larger effect on measured path velocity and thus present itself in the difference. This does not mean it will be sufficiently sensitive and the operator is encouraged to model these scenarios to ascertain sensitivity of the method for the chosen designs and size. [45] also recommends use of different transducer operating frequencies (differing by at least 50 kHz) for each USM which should result in a different sensitivity to noise. However, common mode error may be difficult to eliminate and as such the difference being within appropriate limits only makes it probable that the meters are operating correctly [44].

[44] also raises the possibility of using meters with different design principles in series. For example, one could be a USM and the other could be a DP meter (downstream of the USM). This could be calibrated as a single package and in principle could, as the authors explain, further reduce the likelihood of common mode error although experience with this approach appears limited at present. Such a symbiotic approach is also suggested along with examples of how to interpret the ultrasonic and venturi meters diagnostic systems in [46].

5.2.Master Meter Verification

As explained in [44] proving is only applicable on liquid systems. Some use an indirect master meter approach which has been applied for both liquid and gas applications [30]. Ideally the master meter should be a design which is as robust as possible to installation effects. The master meter should be kept isolated from the process to minimise the likelihood of common mode error. It should be noted that use of a blind tee in a z-configuration has been found to introduce a significant flow disturbance [30] and could lead to systematic differences between stream and master meters. A further issue which can occur is changes in both stream meter factors when the master meter is changed out for a calibrated spare. This can be due to the calibration facility being a 'floating reference', floating according to its stated uncertainty. A calibration could catch the calibration facility on a 'good' day, in which the reference meters are reading very close to the unknown true value, or they could catch it on a less good day when the reference meters are further away from the unknown true value, which then presents itself as a change in the meter factors of the stream meters. This would depend on the uncertainty of the facility and is more likely to be visible in gas master meter systems than liquid systems because of the higher uncertainty in typical gas flow calibration facilities. Where multiple master meters are present to facilitate routine recalibration and replacement, they should both be of the same type and same version of internal software. This is because the capability of USMs to cope with changes in the flow profile between the calibration facility and the field is dependent on the design and any internal commercially sensitive corrections. Use of different models or even different versions of the same model could lead to differences appearing in the stream meter factors when a newly calibrated master meter is installed.

The master meter arrangement can in principle be used to monitor if the performance of stream meters has changed with any resultant meter factors not downloaded to the stream meters. The performance during comparisons with the master meter can be monitored and used to supplement monitoring using internal diagnostics to determine if flow calibration of stream meters is necessary. A difference should be expected, and the typical difference can be assessed during the footprint period (see 5.3.2) with changes out with determined limits investigated. However, the repeatability of such a system may mask smaller changes in performance of the stream meters. An examination of the sensitivity of this technique has not been seen in literature.

5.3.Internal Diagnostics

Use of internal diagnostics to verify flowmeter performance should be considered a required task when using USMs in fiscal applications, not an optional extra required only for CBM applications. [44] makes the point that the flowmeters uncertainty is only valid when it is operating correctly, which is itself commonly determined through use of internal diagnostics, and therefore the flowmeters uncertainty is dependent on the capability of the diagnostic system. A further role of the CBM system is to verify the whole measurement system. Certain tests can cross check other instruments with a fiscal impact and provide further assurance that any errors are within certain limits. Such checks were termed "Measurement integrity diagnostics" in [43].

The diagnostic system must obviously be used to be of any benefit, merely having it is not enough. This issue is also discussed in [44]. The review of the diagnostic system must be included in procedures and time allotted for its review in maintenance management systems.

Footprinting USMs was described in [43] and is a good technique for monitoring internal diagnostics. In the following sections each diagnostic will be explained and a method for monitoring will be suggested. A revised method for defining limits is suggested in 5.3.2. Suggested limits are provided where appropriate but are intended only as a guide and they may not be applicable for all meters and installations. Any limits used should be based on site experience, as per 5.3.2.

Caution should also be applied when transferring learnings from one USM design to another. Even some which are similar in terms of chordal positions can have different characteristics. For example, [52] and [20] examine the velocity profile effect resulting from roughness changes due to contamination or corrosion. With the iD change removed from the error, the remaining velocity profile effect was found to cause a positive error in one, and negative error in the other.

This section first discusses data requirements for internal diagnostics followed by guidance for implementing CBM in practice, methods to monitor changes in component condition and the operating environment and measurement integrity checks.

5.3.1. Data Requirements

Diagnostics were originally obtained in the form of short duration logfiles, sometimes requiring the user to periodically connect to the USM in the field. This was described as an early technique in a paper from 2011 [18]. Modern systems retrieve and record the diagnostic data via the flow computer or direct from the USM continuously and allow users to trend diagnostic parameters over time and permit retrospective analysis and learning. Use of periodic log files have some disadvantages, a significant one being that if an event occurs which changes the meter performance it may not be identified until sometime later with potential financial consequences. Furthermore, it could be very difficult to ascertain when the issue started for mismeasurement purposes. Analysis is made more time consuming by having to merge individual files into one for analysis. Another issue relates to the safety of using non intrinsically safe equipment in the field to connect to the USM. For these reasons, an intermittent logfile based approach is not recommended and consideration should be given real time recording of diagnostics. The diagnostic data path should also be given consideration during design and commissioning of a new system. If it is decided that a logfile approach is to be used the rationale for this should be carefully documented.

Diagnostic data should be provided synchronously. A large time delay between elements of diagnostic data can give a false impression of a problem. Diagnostic data should also be provided at a sufficient frequency. In the authors experience, large amounts of averaging can also mask a problem. For example, experience has suggested that design problems upstream can create noisy velocity profiles with a variance in profile factor larger than the typical tolerance. Such a problem was masked by use of hourly averages. A further issue seen was a cyclic USM VOS caused by hunting control valves blending gases with different CVs which highlighted an unknown element of uncertainty. This was subsequently eliminated but was spotted through use of high frequency data. However, such data must be correctly interpreted. With process upsets on live plant and certain instruments containing some inherent lag (e.g., sample lag time and cycle time with GCs or response time for RTDs) these could result in the usual checks failing for a proportion of the time. This proportion should be monitored, but the user should not expect 100% compliance. For example, if over 3 months or 93 days there were 12 hours which were out with usual limits, that was within limits 99.5% of the time, which, given our uncertainties are the target for 95% of the time, is still well within limits.

5.3.2. CBM in Practice

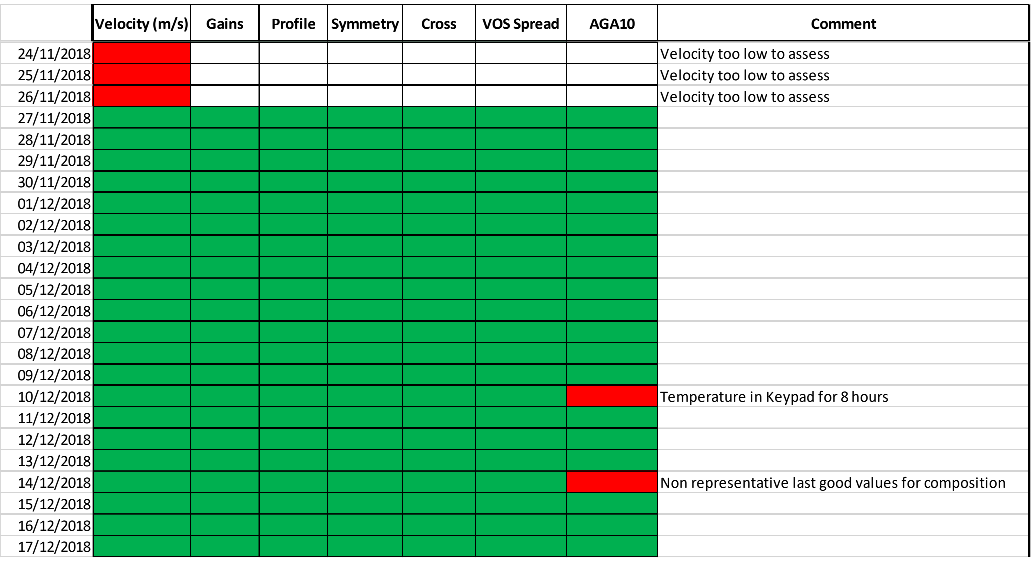
Before moving to a CBM philosophy, agreement should be sought from partners and the regulator (where necessary) and justification provided which demonstrates sufficient stability in the USM and the system.

When attempting to create a condition-based monitoring system for a metering system, it is important to establish the possible diagnostics parameters which may be effective to the meter and installation. Not all meters offer the same level of diagnostic parameters and not all installations will allow for all parameters to be monitored and show meaningful information. Parameter selection is therefore critical in creating an effective monitoring strategy. For example, swirl measurement is only available on in plane crossed chord swirl cancellation designs or in designs employing clockwise and anti-clockwise swirl paths. Profile factor cannot be used on chordal USMs with paths in only 2 chordal planes. Certain installations may also prohibit use of signal-to-noise ratio because of high background noise.

Once the diagnostics parameters are selected, limits should be assigned based on a combination of manufacturer research and studying the meter in service immediately after being returned from external calibration. This period is conventionally referred to as the footprint period, where a meter's performance is studied during the first 2 to 4 weeks of installation. The results of this period should be reviewed in depth and filtered to discount process upsets to focus on normal operating conditions. The variance of each diagnostic parameter can then be reviewed to establish normal operating values. Limits can then be established which will trigger further investigation and potential action. Evidence supporting the choice of limits should be documented.

Equally important to the selection of the individual diagnostic parameters is the capability of any condition-based monitoring system to identify short-term deviations and longer term drift over time.

An example of a short-term monitoring strategy is shown in Fig. 8. In this example, parameters were monitored on a flow weighted daily basis with deviations highlighted through a simple traffic light system. Parameters which are not green are investigated and explained by the user to account for excursions.

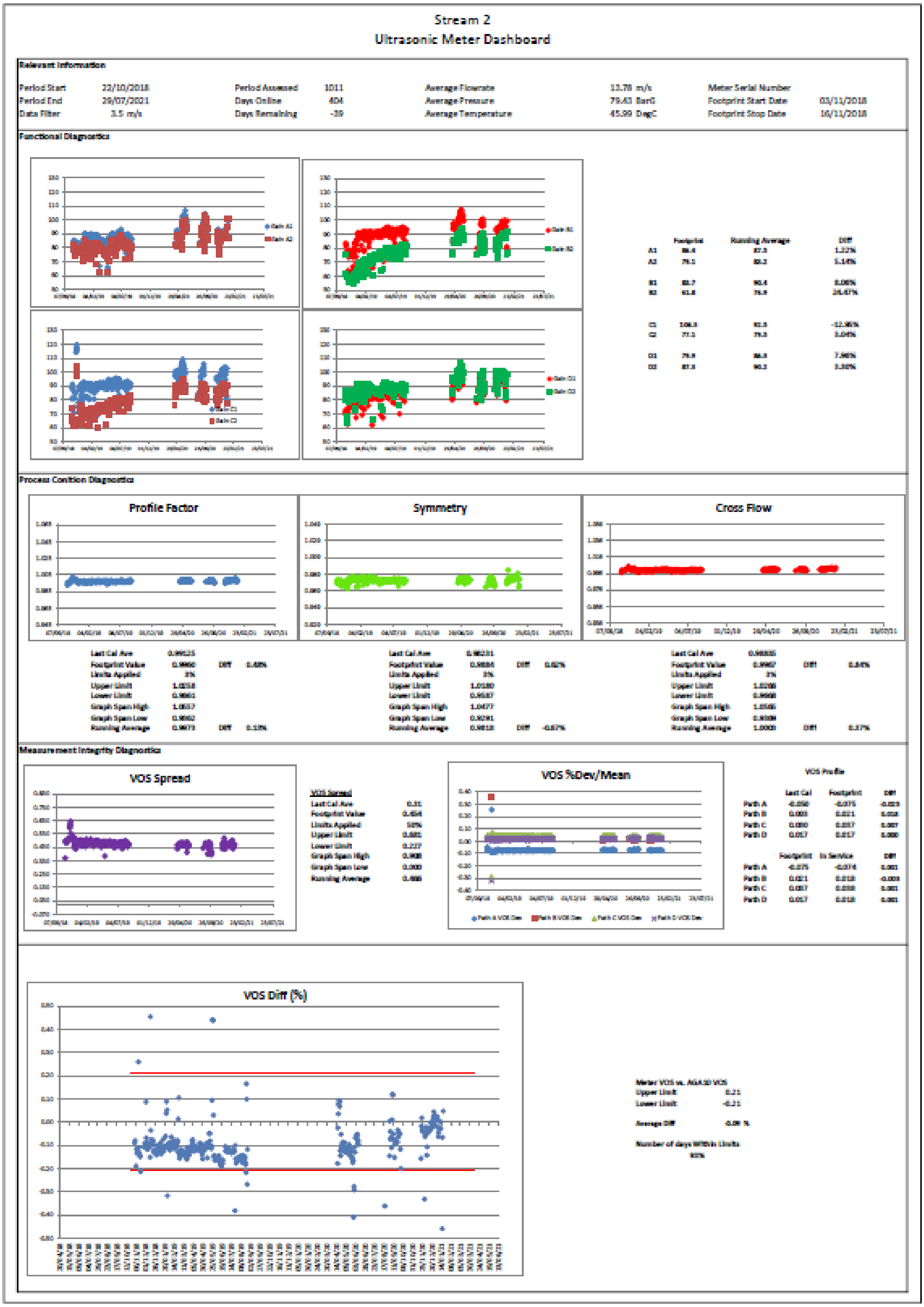


	Velocity (m/s)	Gains	Profile	Symmetry	Cross	VOS Spread	AGA10	Comment
24/11/2018	🟥							Velocity too low to assess
25/11/2018	🟥							Velocity too low to assess
26/11/2018	🟥							Velocity too low to assess
27/11/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
28/11/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
29/11/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
30/11/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
01/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
02/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
03/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
04/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
05/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
06/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
07/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
08/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
09/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
10/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟥	Temperature in Keypad for 8 hours
11/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
12/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
13/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
14/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟥	Non representative last good values for composition
15/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
16/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
17/12/2018	🟩	🟩	🟩	🟩	🟩	🟩	🟩	

Fig. 8 – Example of a short-term monitoring strategy

Interestingly, the more instrumentation that can be readily compared then the more effective and efficient the diagnostic tool becomes. In practice, it is not uncommon for the ultrasonic meter to identify problems with other instrumentation such as pressure, temperature and composition devices and show short-term process deviations such as liquid passing through the metering system.

An example of a long-term monitoring strategy can be found in Fig. 9. This shows the daily performance of each parameter graphically over time and can be used to demonstrate ongoing compliance with pre-agreed limit criteria.



Stream 2

Ultrasonic Meter Dashboard

Relevant Information

Period Start	22/10/2018	Period Assessed	1011	Average Flowrate	13.78 m/s	Meter Serial Number	
Period End	29/07/2021	Days Online	404	Average Pressure	79.43 BarG	Footprint Start Date	03/11/2018
Data Filter	3.5 m/s	Days Remaining	-39	Average Temperature	45.99 DegC	Footprint Stop Date	16/11/2018

Functional Diagnostics

Process Condition Diagnostics

Measurement Integrity Diagnostics

Fig. 9 – Example long-term monitoring strategy

5.3.3. Component Condition

The components of the USM which can lead to measurement errors upon change in their condition are transducers/associated IO and the internal bore. The relevant transducer diagnostics include:

- Gain - an indication of the amplification required to maintain signal strength. An increase means a weaker signal at the receiving transducer.

  Changes in gain can be caused by transducer problems, contamination of the transducer ports, liquids in the flowing stream for gas applications or operating pressure changes. The relationship between gain and velocity should be assessed during the footprint period for each transducer. If a gain-velocity relationship is evident and a correction deemed necessary, then a polynomial fit of the footprint data can then be used as the basis for comparisons with a batch of service data later in service. The present gain value should agree closely with that from the polynomial fit and analysis of the predicted and actual gain during the footprint period used to inform the limits.

- Performance - percentage of successfully received signals in a batch of a given size

  The performance tolerance should be set based on analysis of the data from the footprint period. Path performance should typically be above manufacturers guidance with any persistent reduction investigated. A suggested limit for this purpose is 10% change from the value observed in the footprint period. If the meter is operated above the designed maximum flowrate this can also cause performance to drop [39].

- Path VOS – mean speed of sound in the fluid across the measurement path

  These will be slightly different from each other and these differences represent a fingerprint for the USM. Individual path VOS can be checked as follows:
  1. The % difference between each path VOS and the meter measured mean VOS can be compared with a suggested limit being 0.05% [48]. This can be checked for suitability during the footprint period. It is also useful to compare measured VOS across paths of different lengths which also checks delay times [48] (offsets in time measurement due to delays in transmission through electronics).
  2. Relative VOS comparison in which the footprint is based on each path VOS relative to one another as described in ISO 17089-1:2010 para. 7.4.1.2 (mean VOS comparison with AGA10 is discussed in 5.3.5).
  3. Determine and trend VOS spread based on maximum and minimum values across all paths at any given instant.

Detection of a change in USM bore condition, for example contamination or corrosion does depend on the design. Direct path designs rely on the change in velocity profile whereas reflective path designs can in principle also detect this through measured VOS.

Experience suggests that in the case of corrosion the effect on the velocity profile on a chordal design is small relative to the error and can be missed if gradually changing with [20] reporting a change in profile factor of ~2% for a ~1.2% error. The same issue led to a 1% difference in the 4+1 design which should be detectable. Using the authors reported depth of contamination, the response of a reflective path design can be simulated which suggests the VOS would be significantly affected in the small size used (4”) and would also be easily detectable. Sensitivity of VOS to contamination decreases in larger sizes, as does the impact of a given reduction in iD, and users are encouraged to develop their own models of USMs based on the size and design chosen to satisfy themselves of their sensitivity and to assist with choosing limits. Additional guidance regarding use of the 4+1 to identify changes in velocity profile are given in 5.3.4.

5.3.4. Operating Environment

This section deals with changes in the operating environment which can occur in service and are considered common in fiscal applications. Below is an overview of the relevant diagnostics; the first five are profile diagnostics and monitoring techniques for these are discussed later in this section.

- Profile factor – sum of inner path velocities divided by sum of outer path velocities

  Note some manufacturers report profile flatness calculated as the reciprocal of profile factor. Changes in this can be due to change in the pointedness of the profile (e.g., due to corrosion / contamination). Changes can also be due to axial distortion or due to swirl in some designs [9, 11, 40].

- Symmetry ratio – sum of the upper divided by the sum of the lower chord velocities

  Changes can be due to deposition at the bottom of the meter or another disturbance (e.g., blocked flow conditioner) creating axial distortion. Changes can also be due to swirl in some designs [9, 11, 40].

- Cross-flow – sum of path velocities in one plane divided by sum of path velocities in the other plane

  This is typically associated with detecting presence of twin counter rotating vortices, for example those downstream of a single bend. Capability depends on how the vortices are positioned across the paths and whether the USM has paths in two separate planes [9, 40]. However, changes may also be apparent in other velocity profile diagnostics. The differences in this diagnostic between crossed and parallel chord designs are discussed in [40].

- Swirl – measured or inferred depending on design

  For example, swirl is measured directly for the in plane crossed chord design without interference from axial distortion. Some other designs report swirl but infer it by other means which may be susceptible to misinterpretation. Other designs use a pair of double bounce swirl paths which allow swirl to be inferred. Some designs cannot give any estimation of swirl.

- Turbulence - an indication of the variance in transit times over a batch

  Changes in transit time variance can in principle occur without changes in the flow (e.g., transducer / IO malfunctioning) but in practice it is common for this to be associated with changes in the turbulence levels in the flow. For example, in the event of a disturbance upstream the indicated turbulence for the path(s) most affected may increase from the usual value.

- Signal to Noise Ratio (SNR)

  An expression of the proportion of signal to background noise. Note this is often expressed on a logarithmic scale and therefore if the noise doubles the SNR will not half but will change by much less. Assuming the equation given in [40], a doubling of noise results in SNR reduction of ~6 dB. Reductions in SNR are typically associated with acoustic noise, for example from control valves. Depending on the capability of the signal processing some changes in noise may not affect the measurement and the manufacturer should be consulted regarding appropriate limits.

A common problem is a velocity profile disturbance, perhaps from blocked flow conditioner. This can change the profile in a systematic way, making it excessively different from that seen during calibration. All USMs are sensitive to changes in the velocity profile between calibration and service conditions to some degree and some will be more resilient than others. When reviewing the velocity profile presently being seen in service the following allowances should be made:

- The difference which is created by the upstream geometry differences between the calibration facility and offshore/onshore installation (geometry related difference)
- Gradual changes over the service period (service drift)

The geometry related difference should be assessed by comparing the profile diagnostics seen during calibration with that seen during the footprint period using established limits from disturbance tests for that diagnostic. Guidance should be sought from the manufacturer for these limits if they are not available in literature for the model of USM in use. See [9] for an example of such limits.

Thereafter the service drift should be closely monitored. The service drift allowance could have two levels, a warning limit (e.g., 1%) and an action limit (e.g., 2%). The limits used should be informed by analysis of the typical variance seen during the footprint period and should be carefully analysed with any step changes in diagnostics investigated. For example, if a flow conditioner is being used and it becomes blocked during the footprint period this could lead to a large service drift allowance and potentially a mismeasurement. It is recommended that the service drift allowance should not exceed the difference between the absolute value of the geometry related difference and the established limits from installation effect tests for that diagnostic.

The principle is illustrated in Fig. 10 and an example also follows: Following [9] the maximum difference between profile factor at calibration and that in service is 5%, similarly for symmetry ratio the maximum difference is 3%. When the USM is installed at site a comparison between the velocity profile diagnostics in service and those seen during calibration can be made to assess the geometry related difference. If a difference of 2% in profile factor and 1% in symmetry ratio is observed, that means that the allowance for service drift should not be larger than 3% of profile factor and 2% of symmetry ratio.

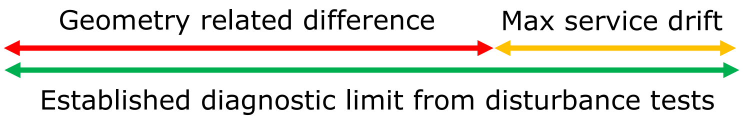


Fig. 10 – Illustration of the maximum limit for service drift

In practice there may be installations for which the geometry related difference is large and creates an unworkably small service drift allowance. In such instances the manufacturer and should be consulted regarding the impact of the geometry related difference on the measurement. If it is not economic to change the installation or USM design, then the cost benefit calculations should be documented, and a workable service drift allowance should be selected.

The above can be used to monitor the difference between the 4P & 1P in a 4+1. Manufacturer's guidance should be sought regarding suitable limits for the design in use. Papers are available discussing use of the 4+1 in disturbed profiles. [25] shows 12" 4+1 test data with a blocked flow conditioner which created a ~-0.15% error on the 4P with the 1P showing ~3.5% difference. For a smaller blockage the change in performance of the 4P was not detectable but a change in the 1P of ~-0.6% remained. Further tests of a 12" 4+1 design were performed with contaminated pipework which resulted in errors -0.12% or less on the 4P with a change in 1P of ~0.6% or less. To best utilise extra diagnostic paths the above suggests that careful trending is critical, and that trending should be capable of identifying small changes, such as 0.5% or less, in the difference between the 4P and 1P. The above, and the example at the end of 5.3.3, also demonstrate that the size of the difference does not necessarily indicate the magnitude of the error.

Process changes can lead to the appearance of wet gas in what is assumed a dry gas system. Wet gas has various effects on the diagnostics which include an increase in reported turbulence and gain, and a decrease in signal to noise ratio and VOS [49]. Rather than wait for the USM to indicate wet gas is present, it is good practice to periodically check the hydrocarbon dewpoint of the gas is sufficiently below the meter station operating conditions. Wet gas will show itself elsewhere with potential problems in the gas chromatograph and pressure let-down system. The effects on the measurement are discussed in [49] and [50].

5.3.5. Measurement Integrity Checks

As is well known, the USM provides a measurement of VOS which can be calculated independently on gas systems using other elements of the metering system which to some extent validates the USM, GC, pressure and temperature transmitters. The tolerance often used in this check is 0.21% [39]. The importance of these instruments increases further if calculated density is being used instead of measurement by densitometer. This should not replace the need for further verification checks of those individual instruments and users should consider the sensitivity of this test for their composition and operating conditions when using it to establish whether instrumentation is within specification.

Table 3 was constructed using AGA 10 with a composition from an offshore gas field with high methane and ethane but low C6 and CO2/N2. For each base case, slight changes were made to line temperature and pressure according to typical tolerances used in measurement systems (0.5 degC for temperature and 0.25% of span for pressure with span being 100 bar for the low-pressure cases and 200 bar for the high pressure cases). The % change in VOS and line density from the base case values have been recorded. By comparing the different cases, the sensitivity of calculated VOS to pressure or temperature measurement issues can be established. The comparison between VOS and line density allows the user to gauge changes in the VOS discrepancy and what they may equate to in line density errors, which translate into flow measurement errors in calculated density systems.

As reported in [39], at the lower pressure base case, VOS is sensitive to errors in temperature and not very sensitive to errors in pressure. At higher temperatures in the low-pressure case the sensitivity to pressure reduces further as does the sensitivity to temperature. In the higher pressure case, the sensitivity to pressure increases but sensitivity to temperature reduces further.

At high temperatures and high pressures, the check is becoming less effective at identifying temperature errors.

Table 3 – Sensitivity of AGA 10 VOS and AGA 8 line density to errors in pressure and temperature at different conditions

Base Case	Base Case Change	% Change VOS	% Change Line Density
60 barA, 10 degC	10.5 degC	0.16	-0.37
	60.25 barA	-0.02	0.53
60 barA, 35 degC	35.5 degC	0.12	-0.28
	60.25 barA	-0.01	0.48
60 barA, 60 degC	60.5 degC	0.10	-0.22
	60.25 barA	-0.01	0.46
140 barA, 10 degC	10.5 degC	-0.09	-0.51
	140.5 barA	0.22	0.36
140 barA, 35 degC	35.5 degC	0.04	-0.40
	140.5 barA	0.13	0.39
140 barA, 60 degC	60.5 degC	0.07	-0.31
	140.5 barA	0.08	0.38

Table 3 highlights the importance of extra checks on pressure and potentially temperature depending on the operating conditions. Duplication of pressure transmitters and temperature transmitters/RTDs is recommended with discrepancy monitoring between the two. Table 3 also highlights the value of using line densitometers to cross check the pressure and temperature measurements. The same errors cause much larger changes in calculated line density which could be cross checked against a densitometer (assuming the densitometer installation is not impacted by ambient conditions). If there is a desire to move to calculated density to reduce maintenance and calibrations costs for densitometers, then as the densitometer is being used for comparison purposes only it doesn’t need regular calibration and a less frequent vacuum check alone may suffice.

As mentioned, the VOS comparison also cross checks the GC although again some attention should be given to the relative sensitivities. Table 4 has been constructed using the same composition as Table 3 but instead C6 has been reduced from 0.1 mol% to 0.05% with the difference being added onto C1. This simulates loss of C6, perhaps through phase change in the PLS with loss of heat tracing or perhaps an integration problem within the GC. The % change in VOS, line density and RD against the base case are shown. Volumetric CV has also been included to give some appreciation of how the error may affect the fiscal measurement of energy after its impact on mass and standard volume. Except for high pressure and low temperature, the error should be visible in the VOS comparison, however it is most noticeable in line density which appears twice as sensitive. RD but is also more sensitive to this issue than VOS but less so than line density. This also shows the value of comparison against measured line density and highlights that RD analysers should also be given consideration. It is noted that continuous GC CBM methods are also available and can identify this type of issue if properly used and are supplemented with comparisons of spot samples with GC analysis reports from the time the sample was taken.

Table 4 – Sensitivity of AGA 10 VOS, AGA 8 line density & ISO 6976 RD & CV to loss of C6+ of 0.05 mol%

Base Case (0.1 mol% C6+)	% Change VOS	% Change Line Density	% Change RD	% Change Vol. CV
60 barA, 10 degC	0.18	-0.35	-0.23	-0.21
60 barA, 35 degC	0.18	-0.30		
60 barA, 60 degC	0.17	-0.28		
140 barA, 10 degC	0.04	-0.35		
140 barA, 35 degC	0.12	-0.34		
140 barA, 60 degC	0.15	-0.32		

Considering the results of tables 3 and 4, it becomes clear that very significant measurement errors can occur within the 0.21% limit. Virtually all the above tests result in VOS change which is within 0.21% with some errors potentially exceeding 0.5% of mass. The 0.21% limit is sensible and is based on the inherent uncertainties in the USM and EOS. However, the above does illustrate that monitoring for changes of less than 0.21% in the VOS discrepancy is of value if it is sufficiently stable.

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