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Fiscal Metering Systems Mismeasurement Management Experiences in Petronas

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1 INTRODUCTION

Mismeasurement management is about the detection and correction of systematic measurement errors in hydrocarbon quantities reported by a custody transfer flow metering system. A systematic (deterministic) error is due to an assignable cause, such as a transmitter failure, a disturbed meter pulse signal, a faulty parameter value or a measurement that fails its validation. This opposed to a non-deterministic error which is caused by natural variance.

The correction of a measurement error is not an obvious task and requires in-depth analysis of all available information to determine an accurate substitution for the faulty value. A poor correction could increase the error instead of rectifying it. A separate correction is required for every associated transaction, e g. a transmitter failing its quarterly validation may require the correction of dozens of daily reports.

Since 2014 Petronas has been automating the correction of measurement errors in a few its largest flow metering systems. This paper describes the error correction methodology [1] used in and field experiences with these systems.

2 MISMEASUREMENT DETECTION

Most metering control systems use the alarms that are generated by the flow computers to detect measurement problems but do not provide more sophisticated functionality to detect less obvious measurement errors. For this reason the Petronas flow metering systems use a number of additional detection methods.

2.1 Data validity checks

A simple yet highly effective check is to verify that a live measurement is continuously updated. An input value can be considered as ‘frozen’ and therefore invalid when its value does not change for a specific time period, e.g. 30 seconds.

Most flow computers apply limit and sometimes also rate of change checks on the field inputs such as temperature, pressure and density. The actual low and high limit values are usually set by operations and do not necessarily reflect measurement integrity. Therefore a second set of limit checks is applied that are not controlled by operations but by the metering engineers instead. Limits checks are also applied on the main gas components

2.2 Discrepancy checks

Redundant measurements provide the capability to automatically check for discrepancies. Examples of such redundant measurements are:

- Multiple dP transmitters measuring the same differential pressure.
- Dual station densitometers or gas chromatographs installed at the header.
- A density measured by a densitometer and inferred from a gas composition.
- A standard density determined in the laboratory and the corresponding value calculated by a flow computer.
- A pressure, temperature or density measurement on a prover compared to values of the lined up meter run
- A PRT element in a densitometer or flow meter and the primary temperature transmitter
- Process flow meters that are compared with the custody transfer meters
- Speed of sound measured by an ultrasonic flow meter and calculated from the fluid composition.
- A flow metering system with two or more flowing meter runs (parallel run data).

2.3 Logical checks

The correct operation of the measurement system is verified by applying a number of basic checks.

- A flow computer should not register flow while the meter run is closed unless maintenance is applied to the flow computer.

- An open meter run should indicate flow when parallel runs that are part of the same metering skid are registering flow.
- A flow meter shall not operate outside its calibrated range for a longer period of time. Most flow meters are calibrated in specific part of the full flow range, typically between 20% and 95%. Operating the meter outside this range may cause a systematic error.
- For a differential pressure (dP) type of flow meter with multiple dP transmitters operating in different dP ranges, the flow computer must use the correct dP transmitter for its flow calculations
- The real-time clock used by the flow computers should not deviate significantly from an external reference clock. This is especially of interest to continuous production systems in which quantities are reported on a periodic, typically hourly or daily, basis.

3 SUBSTITUTION VALUES

A different type of substitution value is required for a mismeasurement caused by a measurement failure than for a mismeasurement caused by a measurement offset (shift or drift)..

When a validation of an instrument fails, it is typically recalibrated and then validated again. The offset between the as-found and as-left validation is an indication for the adjustment of the instrument and the substitution value used for the error corrections will be the original measurement compensated for the adjustment.

When the original measurement value is faulty, then the substitution value has to be determined in another way. As explained further down this paper an accurate substitution value requires some sort of redundant measurement information.

- Redundant sensor
  Obviously the most accurate substitution value is provided by a redundant instrument, for example a dual gas chromatograph or a dual temperature transmitter.

- Secondary measurement
  Any other direct or inferred measurement of the same property, for example a pressure measurement on a gas compressor, a flow meter used for process control, a density calculated from compositional data or a transmitter installed at the header or the prover.

- Parallel meter run data
  For a flow metering system with two or more parallel meter runs the substitution value can be derived from the measurement data of the other meter run(s) that was /were flowing at the time of the failure.

When no redundant information is available for the error correction, there is no other option than to use data from before and after the failure. Several averaging methods are used in this case such as:

- Period Average
  The average value of a particular period (e.g. 7 days) before and after the mismeasurement

- Moving Average
  The moving average over a configurable period (e.g. 1 hour) just before the issue occurred.

- Linear interpolation
  The average of the instantaneous values just before and after the failure

- Last good value
  The instantaneous value just before the issue occurred is used as the corrected value.

4 RECALCULATIONS

The Petronas flow metering systems are able to automatically quantify a measurement error allowing the user to quickly assess the impact of a mismeasurement issue.

4.1 Recalculation methodology

The recalculation methodology is in accordance with API MPMS 21.1 [2], which sets the requirements for online and offline computations to determine accurate flow quantities.

The standard specifies two different methods to compute the flow rate from the sampled input data.

1. A Full Flow Rate Calculation is performed (at least) once per second based on the sampled input data. This is the method used by all the current flow computers.

2. If the full flow rate calculation can’t be performed every second, then the method called Factored Flow Rate Calculation can be used instead. This method involves 1 second sampling of the inputs and a less frequent (typically once every 5 minutes) flow calculation based on averaged input data. Although less accurate than the first method, this method provides custody transfer grade of accuracy as well.

For recalculations it is not practical to perform a full flow calculation, because this would require the storage and processing of data with 1 second resolution. Therefore the 'Factored Flow rate Calculation' method is used to average and archive data that can later be used for the error corrections.

For the Factored Flow Rate Calculation Method the flow equation is factored in two parts. One part contains the live inputs that may change considerably with time, while the other part contains the live inputs that remain relatively constant with respect to time.

$$Q_i = IMVxDV_i$$

Where:

Qi	flow rate based on data taken at sample i
IMV	Integral Multiplier Value, representing the static variables
DVi	Dynamic Variables, representing the live inputs, taken at sample i

For the Factored Flow Rate Calculation the flow quantity is calculated over a number of samples.

$$Q = IMV \sum_{i=1}^{i=n} DV_i \, \Delta t_i$$

Where:

Q	flow quantity over n sample
Δti	sampling interval

The term $\sum_{i=1}^{i=n} DV_i \, \Delta t_i$ is called the Integral Value (IV), such that:

$$Q = IMVxIV$$

IMV is calculated at the end of each integration period using the flow dependent linear averages of the dynamic variables at the end of the period,

4.2 Quantity Calculation Period (QCP)

The integration period used for the determination of the IV is called the Quantity Calculation Period (QCP).

$$QCP = \sum_{i=1}^{i=n} \Delta t_i$$

The standard states that the QCP should not exceed 5 minutes. Longer periods may be used if it can be demonstrated that the additional uncertainty is no more than 0.05%. However, because the methodology is used for a large number of installations with very different flow regimes and process conditions, it is unknown if the actual additional accuracy will exceed the 0.05% limit. Therefore the methodology uses Quantity Calculation Periods of 5 minutes each.

A QCP includes all data that is required to report and recalculate the hydrocarbon quantity in terms of volume, mass and, in case of natural gas, energy. 2 records need to be stored for each QCP, namely a record with the original data and a record with the corrected data.

The following example illustrates the difference between an original and a corrected QCP.

BEGIN	END	PRES	TEMP	IV	Q
18:20:00	18:25:00	23.56412	36.59324	0.5478921	12.659321

BEGIN	END	PRES	TEMP	IV	Q
18:20:00	18:25:00	23.56412	**38**	0.5478921	**12.895012**

The original record contains the unedited values that are calculated from the inputs received from the flow computer. Original QCR records can’t be modified.

The corrected QCP record has the same format as the original record and contains the edited values and recalculated values. The 2 records will be equal as long as no corrections have taken place.

4.3 Integral Value for differential meters

The standard makes a distinction between differential and linear flow meters. Differential flow meters like an orifice and a venturi flow meter, measure the differential pressure drop over the primary flow element. Because the relation between the differential pressure and the flow is non-linear the averaging and recalculation methodology is different from linear flow meters (e.g. turbine and ultrasonic flow meters).

For differential flow meters the dynamic variables are differential pressure, static pressure and temperature. These variables need therefore be sampled at least once per second and a corresponding flow dependent linear average needs to be determined for each QCP.

API MPMS 21.1 states that at a minimum the Integral Value for differential flow meters will include the differential pressure and the static pressure, assuming that these two variables may show a relative large fluctuation in comparison to other inputs including temperature.

Therefore the following integral value applies in case of a differential pressure meter:

$$IV = \sum_{i=1}^{i=n} \left(\sqrt{h_{w,i} P_{f,i}} \Delta t_i \right)$$

Where:

$h_{w,i}$	differential pressure at sample i
$P_{f,i}$	absolute static pressure at sample i
Δt_i	sampling interval

4.4 Integral Value for linear meters

For linear flow meters the volume (or mass) rate at actual conditions, as indicated by the flow meter, needs to be included in the Integral Value. Static pressure and temperature are the dynamic variables that require sampling and averaging.

API MPMS 21.1 states that the Integral Value needs to include meter linearity data if applied. Linear meters provide either pulses or a flow rate. In the first case linearity may be through either a K-factor curve or a meter factor curve, while for the latter case a meter factor curve may be applied.

The Integral Value is calculated as follows by using the pulse count or actual volume accumulator provided by the flow computer.

$$IV = \sum_{i=1}^{i=n} \frac{MF_i}{Kfactor_i} Counts_i$$

$$IV = \sum_{i=1}^{i=n} MF_i Q_{f,i}$$

Where:

Counts$_i$	pulse increment for sample period i (from accumulator)
Q$_i$	flow increment at actual conditions for sample period i (from accumulator)
MF$_i$	meter factor at sample
Kfactor$_i$	K-factor at sample i

4.5 Recalculations for differential meters

The main ISO-5167 flow equation for orifice plates is:

$$Q_m = \frac{C}{\sqrt{1-\beta^4}} \epsilon \frac{\pi}{4} d^2 \sqrt{2\Delta p \rho_f}$$

Where:

Qm	mass flow rate
C	discharge coefficient
β	beta ratio at flowing temperature
ε	expansion factor
π	3.14159265
d	orifice diameter at flowing temperature
Δp	differential pressure
ρf	density at flowing pressure and temperature

Rewriting this formula using the PTZ relation between flowing and base density reveals the Integral Value in terms of differential pressure and static pressure.

$$Q_m = \frac{C}{\sqrt{1-\beta^4}} \epsilon \frac{\pi}{4} d^2 \sqrt{\frac{2\rho_b T_b Z_b}{P_b T_f Z_f}} \sqrt{\boldsymbol{\Delta p P_f}}$$

Where:

Pf	flowing static pressure absolute
Tf	flowing temperature
Zf	compressibility at flowing pressure and temperature
ρb	density at base pressure and temperature
Pb	base static pressure absolute
Tb	base temperature
Zb	compressibility at base pressure and temperature

Recalculations are based on QCP records. For each QCP the Integral Value $\sqrt{\Delta p P_f}$ has been calculated and stored together with the flow-dependent linear averages of the differential pressure, flowing static pressure and flowing temperature. Also the Flowing time (FT) is stored for each QCP record, which is the time within the QCP that the flow was above the No Flow Cut-off Limit. The remaining variables used in the flow equation are either stored as a constant value to the QCP record or recalculated from the flow-dependent linear averages of the dynamic variables and in case of the compressibility and density, the gas composition. Therefore each QCP record also holds the values for the individual gas components that were determined at the latest chromatograph cycle.

4.6 Recalculations for linear meters

The main flow equation for linear meters is:

$$Q_b = \left(\frac{P_f}{P_b}\right)\left(\frac{T_b}{T_f}\right)\left(\frac{Z_b}{Z_f}\right) IV$$

Where:

Qb	base volume flow rate
Pf	flowing static pressure absolute
Tf	flowing temperature
Zf	compressibility at flowing pressure and temperature
Pb	reference static pressure absolute
Tb	base temperature
Zb	compressibility at base pressure and temperature
IV	Integral Value

Each QCP record contains the Integral Value, the flow-dependent linear averages of flowing static pressure and flowing temperature, the Flowing time and the gas composition. The reference pressure and temperature are stored in the QCP record, while the compressibility values are calculated.

4.7 Quantity Transaction Record (QTR)

API MPMS Chapter 21 applies the term Quantity Transaction Record (QTR) for an hourly or daily report or a measurement ticket.

The standard requires that a whole number of QCPs fits in one QTR. The underlying reason is that the recalculation of a QTR is most accurate when the corresponding QCPs represent exactly the same period of time. For this purpose a QCP is ended at hourly rollovers as well as batch ends.

Two types of QTRs are stored. The original QTR contains the unedited custody transfer data as received from the flow computer and can't be changed by the user, while the corrected QTR contains the corrected data.

The hydrocarbon quantities of a corrected QTR are calculated as follows:

$$Corrected\ QTR = \frac{\sum Q\ from\ corrected\ QCP}{\sum Q\ from\ original\ QCP} \times Original\ QTR$$

5 BASIC MISMEASUREMENT EXAMPLE

Consider an example where a flow rate is calculated from two inputs x and y (flow rate = x * y) and suppose that input x fails for 22 minutes within a single hour and that during the failure the last good value remains in use for the flow rate calculation.

The result is that the reported hourly total differs by 18 percent from the actual value that would have been calculated when no failure would have occurred.

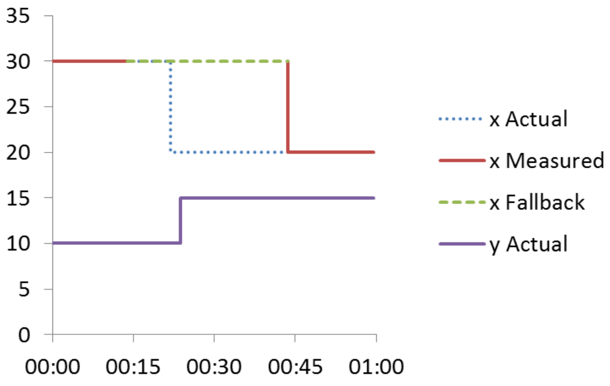


Figure 1: Basic recalculation example

To correct the hourly report a substitution value needs to be determined for the hourly average of input x. In the ideal situation the hourly average of the actual value would be available and used as the substitution value for the error correction. For the correction a first total is calculated from the original hourly averages of inputs x and y and a second total is calculated using the substitution value for input x instead. These two totals provide a correction factor that is applied to the original total to obtain the corrected total.

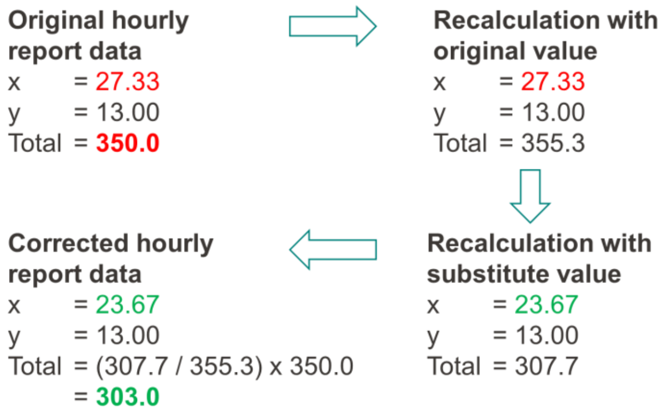


Figure 2: Recalculation methodology

In reality the actual hourly average will be unknown, so a different substitution value needs to be determined instead. If no additional information is available, then an often used substitution value is the average of the hourly values before and after the failure. A more accurate substitution value can be determined from a data trend of input x. A redundant measurement, e.g. by a second sensor, would provide the most accurate correction but only when the offset from the primary measurement is either small or compensated for as illustrated in the following figure.

Hourly data	Average of actual value	Hour before/after	Trend data	Redundant 'as-is'	Redundant compensated
x original	27.33	27.33	27.33	27.33	27.33
x subtitute	**23.67**	**25.00**	**24.83**	**24.67**	**23.77**
Original total	350.0	350.0	350.0	350.0	350.0
Calc. total (x original)	355.3	355.3	355.3	355.3	355.3
Calc. total (x substitute)	307.7	325.0	322.8	320.7	309.0
Corrected total	303.0	320.1	318.0	315.9	304.3
Error after correction	**2.2%**	**7.9%**	**7.2%**	**6.5%**	**2.6%**

Figure 3: Influence of substitution value on the correction accuracy

The accuracy of the correction not only depends on the substitution value but also of the resolution of the data used for the recalculation.

For instance, averaging and logging the inputs at a 5 minutes interval in accordance with the methodology described in this paper, would significantly improve the correction of the hourly total.

Error after correction	Average of actual value	Trend data	Redundant 'as-is'	Redundant compensated
Hourly data	2.2%	7.2%	6.5%	2.6%
5 minutely data	0.1%	6.6%	2.7%	0.4%

Figure 4: Influence of data resolution on correction accuracy

From the basic example it can be concluded that the accuracy of the error correction is determined by the accuracy of the substitution value and the resolution of the measurement data.

6 FIELD EXPERIENCES

The following cases describe actual mismeasurements that have occurred in a gas flow metering system with 4 parallel meter runs of which 3 meter runs are flowing and 1 run is closed. Each meter run has both a panel-mount flow computer and a field-mount flow computer, both with their own set of dP transmitters, pressure and temperature transmitters. Because this system has both redundant measuring instruments for each meter run and multiple flowing runs, it provides two type of substitution values, creating an ideal environment for field-testing the mismeasurement management functionality.

6.1 Practical case: Transmitter failure

In February 2014 the primary temperature transmitter of meter run 2 failed, causing the flow computer to fall back to a value of 19 degrees Celsius.

9 days after the failure occurred run 4 was opened and run 2 was closed. The following graph shows the primary temperature value recorded during the failure period for meter runs 1 and 3 and by the redundant value of run 2. The daily fluctuations are due to the ambient temperature and solar radiation.

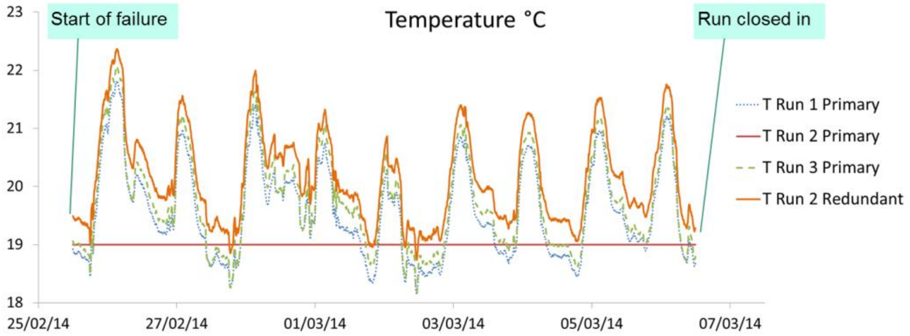


Figure 5 : Transmitter failure case – Substitution value

The most accurate substitution value is provided by a redundant instrument sensor installed in the same meter run. By using this redundant sensor value as the substitution value the daily mass total was corrected up to 0.3% as shown by the following picture.

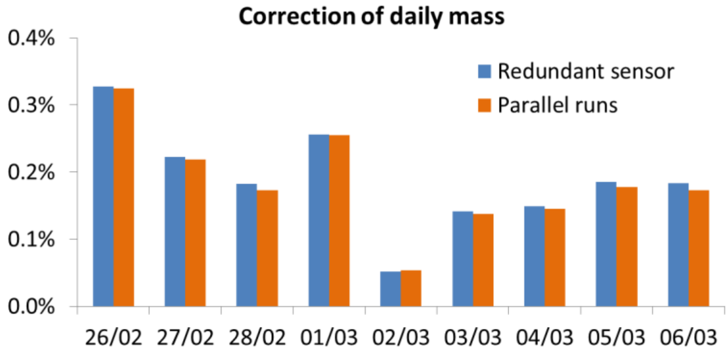


Figure 6 : Failed validation case – Error correction

Using the average of the temperature values of meter runs 1 and 3, being the two other flowing runs during the failure, as the substitution value results in similar correction values, indicating that parallel run data can provide equal accuracy as a redundant sensor.

Note that both substitution values have been compensated with a 3 month average offset prior to the failure.

6.1.1 Uncertainty of the correction

A question that arises when correcting a mismeasurement is how accurate the correction actually is. How can one be sure that a corrected total is closer to the true value than the original total?

One way to check this is by simulating a failure for a period with similar process conditions and without any known issue. The blue dotted line on the graph below shows the difference between the original flow computer totals and the totals that would have been calculated by the flow computer in case the temperature would have failed like in the previous case. This is the actual mismeasurement that needs to be corrected for. The other two lines show the difference between the original flow computer totals and the corrected totals. Ideally, when the correction would be 100% accurate, the differences would all be zero. In reality there will always be a remaining error after corrections because of the inaccuracies of the substitution values and the use of averaged data for the recalculations.

The simulation shows that for this case the totals after correction for the simulated failure are within 0.03% of the original totals without the failure, also when the correction is based on parallel run data.

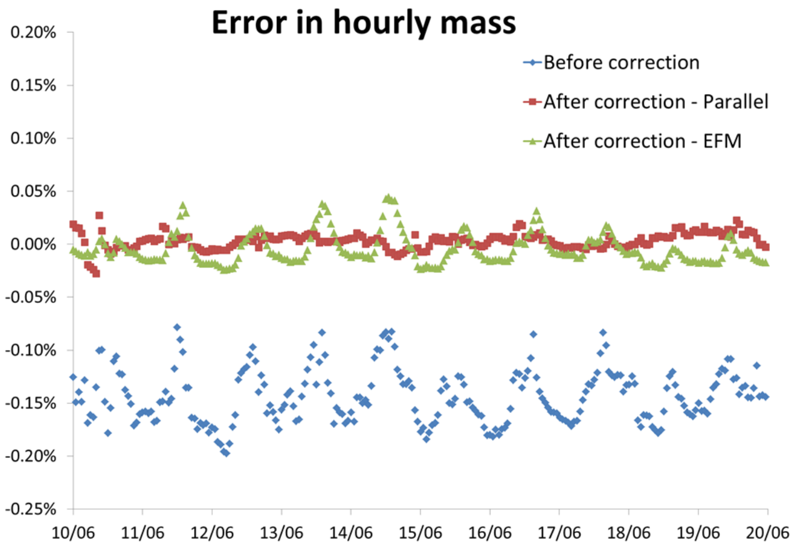


Figure 7 : Simulation to quantify the correction uncertainty

6.1.2 Using parallel run data under transient conditions

The previous test case was under steady conditions. How accurate is the correction based on parallel run data under transient conditions, e.g. when a different meter run is lined up?

As shown by the graph the correction based on parallel run data is inaccurate for temperature corrections under transient conditions. The graph is based on actual flow data from December 2016 for a period of 5 days in which 3 run switches occurred. The graph shows the difference between the hourly total calculated from the primary temperature value and the total calculated from the parallel runs.

As can be expected, it takes time for a meter run after a line-up to reach equilibrium between the fluid and the ambient temperature and that during this time the corrections will be less accurate. For pressure this is not the case though, because pressure settles almost instantly.

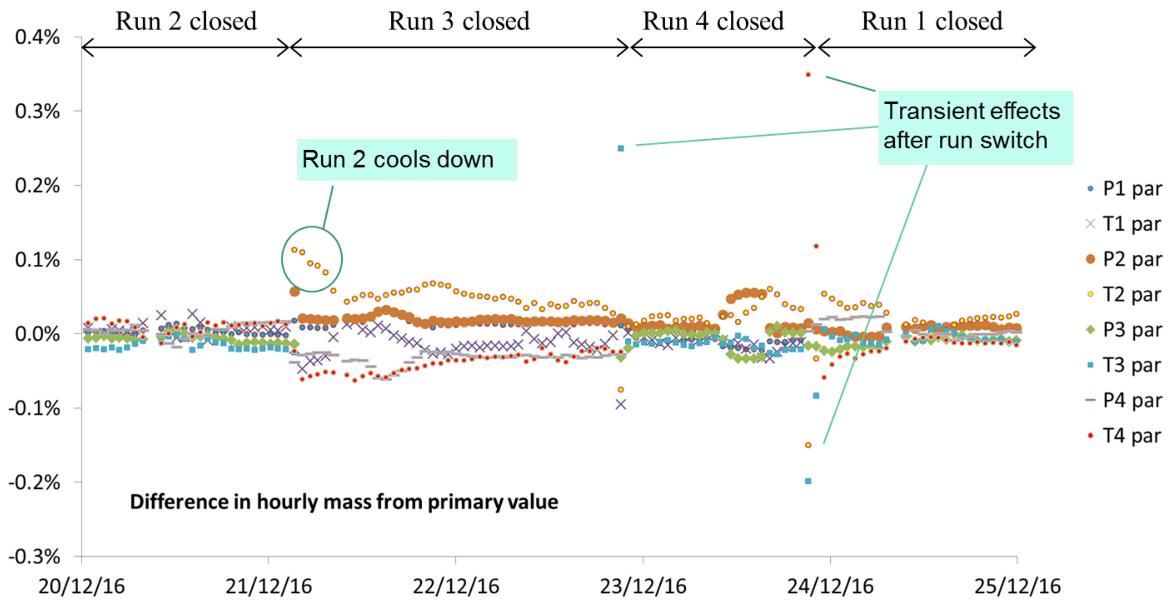


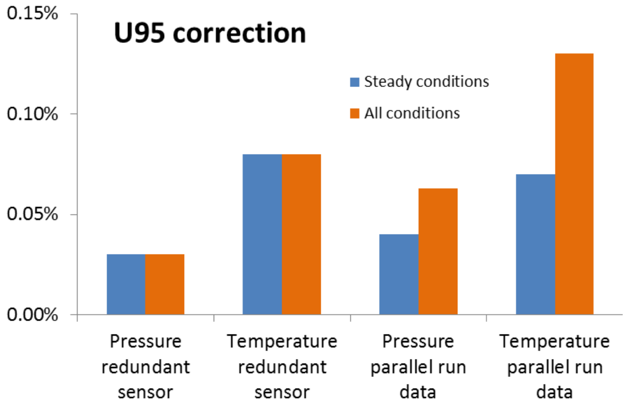
Figure 8 : Transient conditions

6.1.3 Correction uncertainty

The overall measurement is assumed to be within the contractual limit when all measurements are operating within their tolerances and no failure has occurred. The uncertainty of the corrected total is usually unknown though. A poor correction may even increase the error.

An automated system has the additional benefit that the difference between the original and the corrected totals can be determined in real-time, e.g. on an hourly basis. By trending this difference over time for periods without a mismeasurement the correction uncertainty can be quantified.

By knowing this uncertainty, it can be assured that corrections are only applied when the corrected total is more accurate than the original total. Furthermore, it can be proved to the customer; what the overall measurement uncertainty is even in case of a failure.



Original hourly data
x = 27.33
y = 13.00
Total = 350.0

Corrected hourly data
x = 23.67
y = 13.00
Total = 303.0

U95 correction 0.08%

Figure 9 : Correction uncertainty

6.2 Practical case: Failed validation

This case is about a primary dP sensor that has been recalibrated after is has failed its periodic validation. The normal practice is to correct the daily totals for the adjustment for half the period between the previous, and this validation.

The adjustment is usually determined from the difference between the as-found and as-left validation results and applied to the original measurement value to obtain the substitution value for the correction.

For this case this was not an obvious task because there is no clear relation between the as-found and as-left validation results as shown in the following graph. Would the validation results have been used instead then the average adjustment would have been around 0.4 mbar. However, the redundant sensor data showed a clear shift of around 0.7 mbar before and after the calibration. This adjustment value was considered to be more accurate than the value determined from the validation results and used for the corrections. The redundant sensor data also showed that the shift in measurement applied for all days with actual flow since the previous validation.

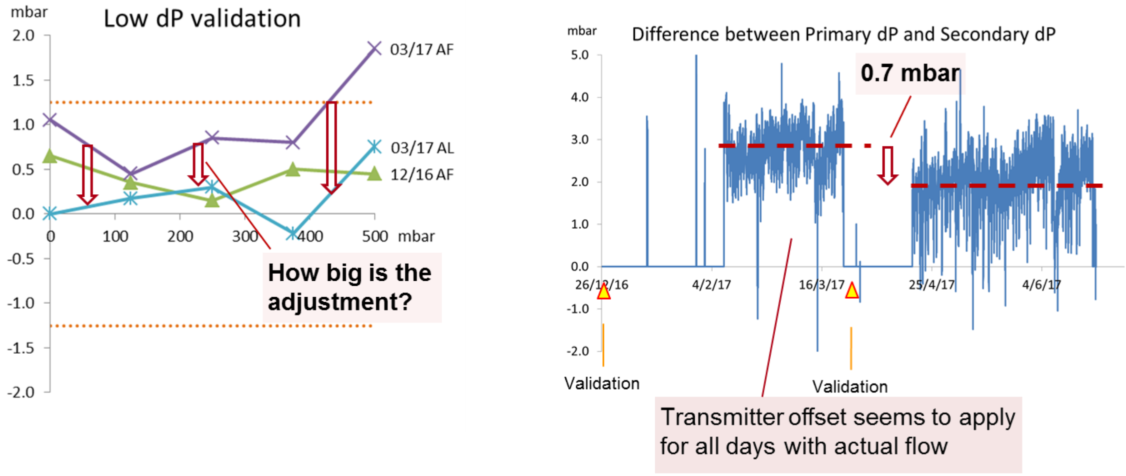


Figure 10 : Failed validation case – Substitution value

The adjustment based on redundant sensor data resulted in the corrections shown by the following graph. This shows that an automated system helps the user to make the best possible correction based on all available information.

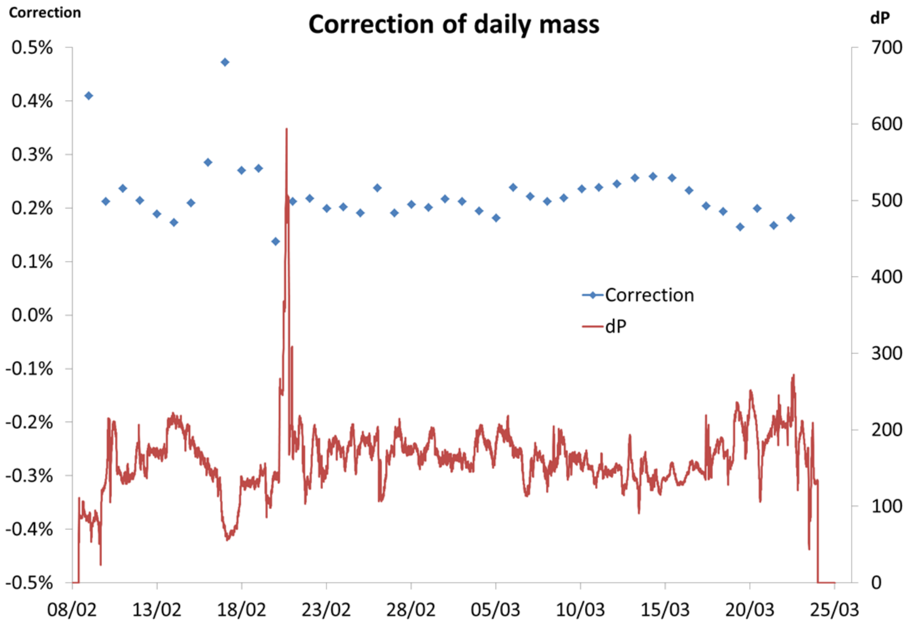


Figure 11 : Failed validation case – Error correction

6.3 Practical case: Shift in measurement

This case is about a primary temperature with a shift in measurement that was not detected by the flow computer, but that became apparent when comparing the primary value with both the substitution values.

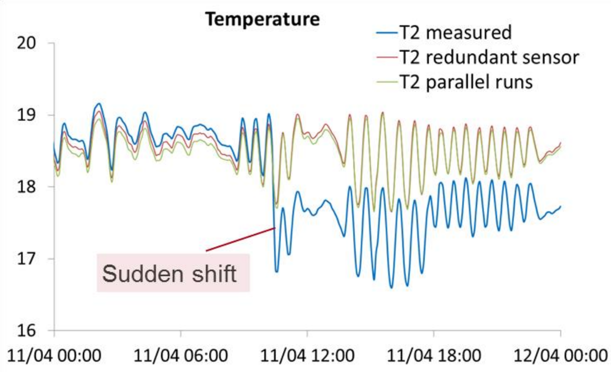


Figure 12 : Measurement shift case – Substitution value

Again there is good agreement between the corrections based on redundant sensor data on one hand and corrections based on parallel run data on the other hand.

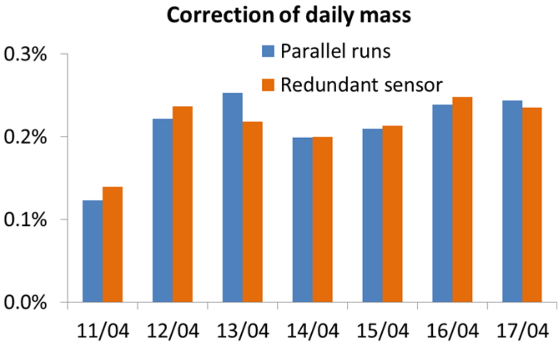


Figure 13 : Measurement shift case – Error correction

6.4 Potential of using parallel run data for quantitative corrections

Using parallel run data for the substitution of qualitative measurements like pressure and temperature has proven to work at least for metering systems with relative stable conditions of flow, pressure, temperature and fluid composition. The following figure shows the daily average difference between the measured dP and its substitution value based on parallel run data. The chart covers a period of about 30 days with no flow control, allowing the fluid to freely flow through the different meter runs.

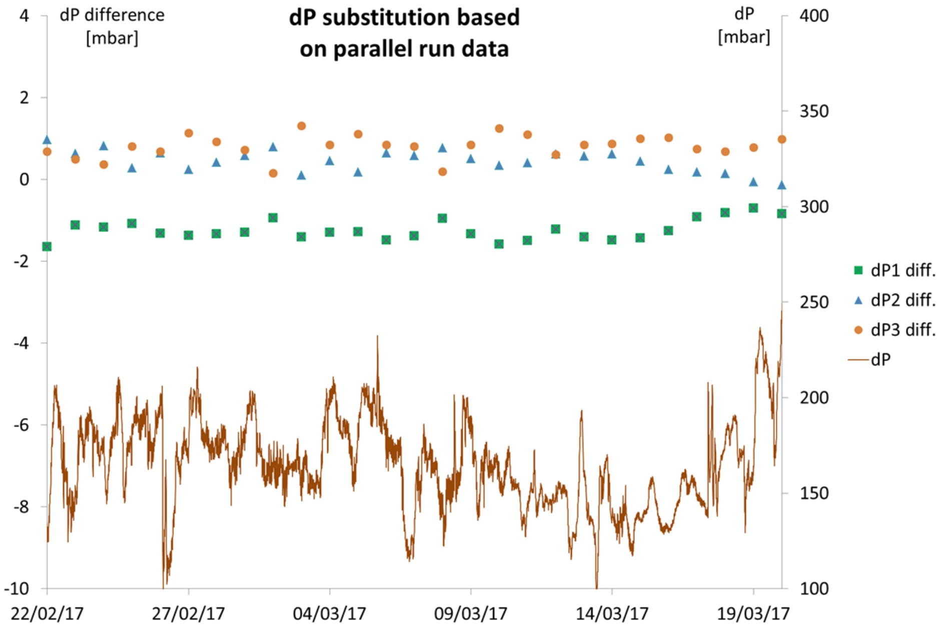


Figure 14 : Potential of parallel run data for quantitative corrections

The chart reveals the potential to use parallel run data to obtain reasonable accurate substitution values for quantitative measurements as well, at least under stable and equal flow conditions. However further analysis and field testing is required to either affirm or reject this hypothesis.

7 CONCLUSION

For a fair trade of hydrocarbon products it is essential that measurements errors are detected and corrected for. The accurate correction of a measurement error is not an obvious task to do and requires both an accurate substitution of the faulty input value and an accurate recalculation of the reported quantity.

Accurate substitution requires a value that more or less resembles the actual value during the failure, ideally from a secondary sensor installed in the same meter run. If that is not available then data from parallel meter runs would be the second best option especially at steady flowing conditions.

The accurate recalculation requires data with a higher resolution than the quantity being corrected. For instance for hourly totals data with a 5 minute interval is required to enable accurate corrections, especially for a compressible fluid like a (liquefied) natural gas.

An automated system with consolidated data allows the operator to conveniently and promptly deal with measurement errors and to generate accurate data for billing purposes even in case of a measurement failure..

8 REFERENCES

(1) Determining a quantity of transported fluid - US 20130124113 A1 - Han van Dal

(2) API MPMS Chapter 21—Flow Measurement Using Electronic Metering Systems, Section 1 – Electronic Gas Measurement