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Parallel calibration of multiphase flow meters vs separator

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1 Introduction

In recent years, the number of marginal oil fields put into production has increased. The typical scenario is that these small fields are tied back to an existing installation that acts as host. This way of arranging production of oil and gas in a production hub makes the development of marginal fields economically viable. One challenge with this type of arrangement is that as the owner structure gets more complex, the complexity in the allocation system also increases. It is essential for a viable long-term collaboration that the produced oil and gas revenue is accurately split according to owner fraction in a transparent and robust manner.

Tying the production from small surrounding fields, often called 3rd party fields, to a host installation usually requires modifications of the process at the host installation. To achieve accurate allocation measurements, the production from each license should ideally be processed and measured isolated from the other licenses. This would require enormous investments and is not realistic. Another approach is to have a dedicated inlet separator for each license. This method provides good accuracy of production volumes, but still requires relatively large investments in addition to space and weight reserves on the host installation.

The cheapest, smallest and lightest solution usually involves using Multiphase flow meters (MPFM) for allocation. The individual mass flow of the oil, gas and water phases of the production fluids from each separate field is measured by a dedicated MPFM, and allocation can be performed based on these measurements. Production from different fields can then be processed with minimum modifications of the hosts processing systems. The downside of using MPFMs for allocation is a reduction in measurement accuracy. MPFMs have been shown to drift with varying flow conditions [1]. To reduce the uncertainty in the MPFM measurements and ensure that the measurements are representative for the present conditions, periodic calibrations of the meters is necessary.

The Alvheim Floating Production Storage, and Offloading (FPSO) installation produces oil and gas from the Alvheim field and three 3rd party fields. Alvheim's allocation regime utilize, amongst other, topside MPFM measurements. The MPFM measurements are calibrated against single phase meters downstream from an inlet separator. The calibration method is well proven in terms of accuracy, but it leads to significant deferrals in production. This is due to required rerouting of the flow during calibration from one of the inlet separators to the other. The rerouting causes the load on the other separator to exceed its maximum capacity and production must be reduced during the calibration process.

In this paper we will present a novel method for calibrating MPFMs. The method is tailored to reduce production deferrals connected to Alvheim's existing calibration method. Our proposed scheme has been shown to reduce deferrals by more than 95%.

Emphasis in this paper will be put on the theoretical foundation of the method, results from tests of the new method performed by Alvheim asset and an evaluation of the uncertainty of this new method compared to the existing calibration method. We are presenting a solution that is still in development, so we will include the missing parts of the routine is described together with a rough roadmap for further improvements.

The work presented in this paper has been made possible through AkerBP's [2] digitalization initiative Eureka and Cognite's [3] data platform: Cognite Data Fusion (CDF). Within the CDF data storage repository, large amounts of historical data from different system is contextualized and stored. In parallel to the work performed in the Eureka project, the problem has also formed the basis for a master thesis that has been executed at the University of South-Eastern Norway [4]. The results presented herein is taken from both the master thesis and the work performed in the Eureka project.

2 Current MPFM calibration regime at Alvheim

The Alvheim field, situated in the central part of the North Sea, comprises the six discoveries 24/6-2 (Kameleon), 24/6-4 (Boa), 25/4-7 (Kneler), 25/4-10 S (Viper), 25/7-5 (Kobra) and 25/4-3 (Gekko). The water depth in the area is 120-130 meters. Alvheim was first discovered in 1998, the plan for development and operation (PDO) was approved in 2004 and production started in 2008. Alvheim is developed with subsea wells tied to an FPSO. The Vilje (2008), Volund (2009) and Bøyla (2015) fields, referred to as 3rd party fields, are tied-back to Alvheim [5].

Table 1 – ownership allocation of fields produced by the Alvheim FPSO

Owners	Field share [%]			
	Alvheim	Vilje	Volund	Bøyla
Aker BP ASA	65	46.904	65	65
ConocoPhillips	20			
Lundin	15		35	15
DNO North Sea AS		28.853		
Vår Energi AS				20
PGNiG Upstream Norway		24.243		

The owner structure of Alvheim is rather complex, see Tab.1. In total six Norwegian and international oil companies own a share of the hydrocarbons produced from 32 wells. Five owners in total have a stake in the produced hydrocarbons of the so-called 3rd party fields and the fraction of ownership is unique for each field.

There are in total six incoming flowlines to the Alvheim FPSO vessel, whereof three are producing from the Alvheim field and the other three are producing from different 3rd party field. The flowlines that have production solely from the Alvheim field are conveniently routed to a dedicated inlet separator (the Alvheim separator) where the production is measured. The 3rd party licenses' flowlines are routed to a shared 3rd party separator, as shown in Fig. 1. This means that the flow from each 3rd party field must be monitored to ensure that the owners get their share of the produced oil and gas. Hence, MPFMs are installed on the incoming 3rd party flowlines, see Fig. 1.

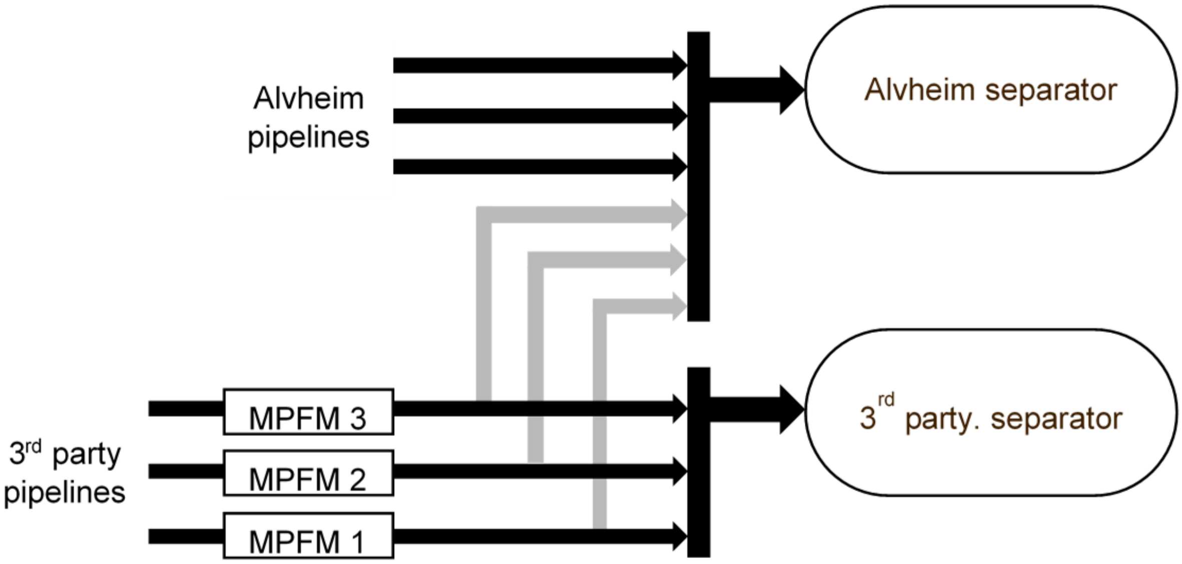

Fig. 1 – Simplified flowline and separator configuration on Alvheim FPSO.

According to the license agreement, the MPFMs shall be calibrated *with an interval and test time to be determined from operational experience* to maintain appropriate accuracy.

A calibration measurement entails that the three 3rd party lines are isolated in turn in the 3rd party separator to facilitate a direct comparison between the MPFM and the reference measurements at the oil, gas and water outlet of the separator. This means that during a calibration run, two 3rd party flowlines needs to be re-routed to the Alvheim separator.

In the existing calibration technique, three separate measurements performed in order to determine three calibration coefficients. The resulting system of linear equations is:

$$\begin{aligned} m_{MPFM1}k_1 &= m_{sep1} \\ m_{MPFM2}k_2 &= m_{sep2} \\ m_{MPFM3}k_3 &= m_{sep3}, \end{aligned} \tag{1}$$

where k_i are the calibration coefficients that are target for the measurement, m_{MPFMi} are accumulated masses of hydrocarbons measured by the MPFMs to be calibrated, and m_{sepi} are the reference measurements, where $i \epsilon \{1,2,3\}$, see Fig. 1. A separate set of calibration coefficients are deduced for the gas, oil and water. The accumulated masses in Eq. (1) is calculated by integrating the mass flows, $\dot{m}$, of the individual phases measured by the single phase meters and the MPFMs over the calibration interval $[t_0, t_1]$ as seen in Eq. (2):

$$\begin{aligned} m_{MPFMi} &= \int_{t_0}^{t_1} \dot{m}_{MPFMi}\, dt \\ m_{sepi} &= \int_{t_0}^{t_1} \dot{m}_{sepi}\, dt \end{aligned} \qquad (2)$$

Equation (1) gives a linear relationship between the accumulated mass in and out of the separator, when the mass rates are accumulated over a sufficient time interval. Liquid levels, pressure and temperature are monitored in the separator during the accumulation period to ensure that the assumption of mass balance in and out of the system is valid.

See Figure 2 and Ref. [4] for a more detailed description of the current calibration method at Alvheim.

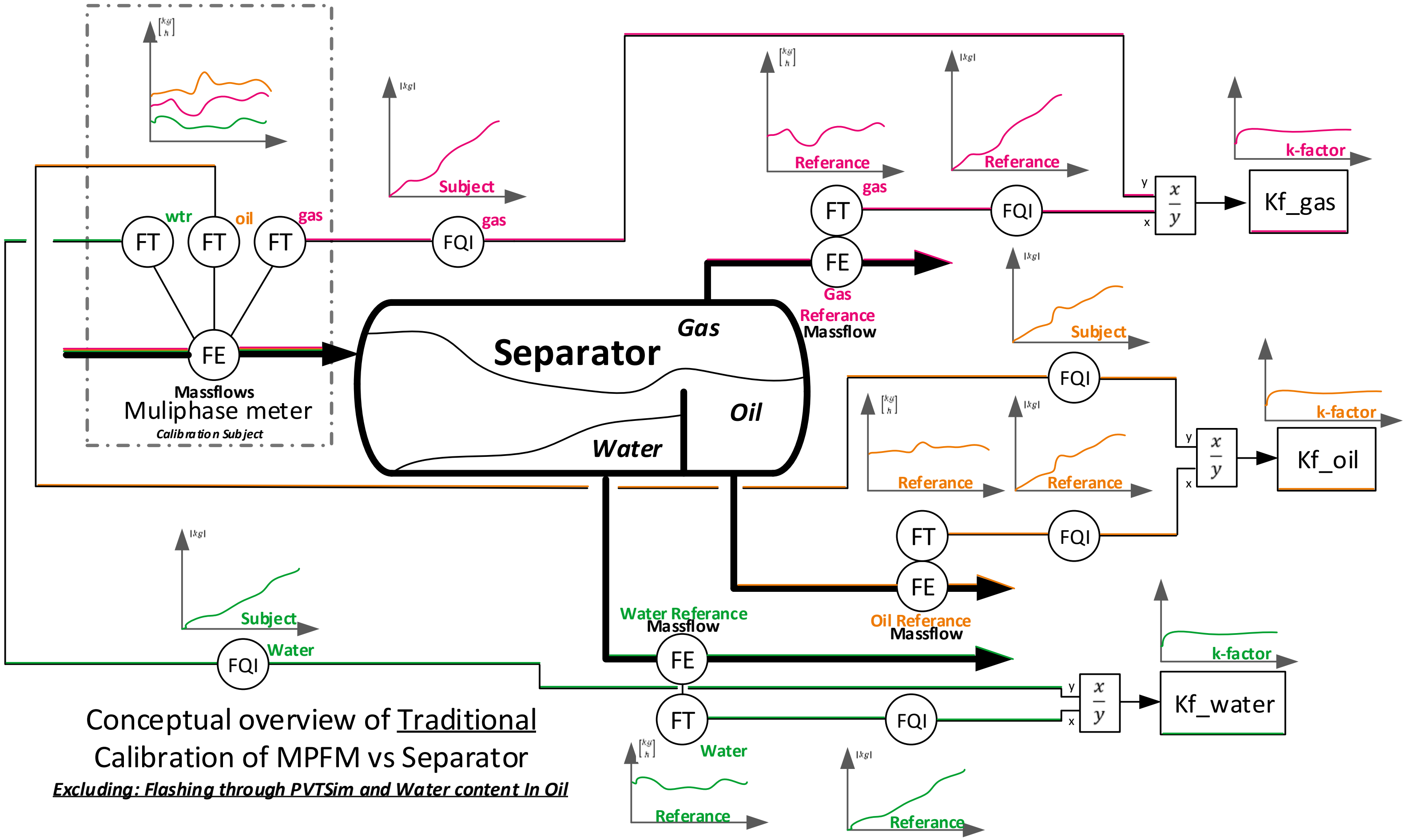

Fig. 2- Conceptual overview of the traditional calibration method in use at Alvheim [4]

Figure 3 shows the development in calibration factors resulting from different MPFM calibrations. For the selected sample intervals, MPFM 1, 2 and 3 has a standard deviation of 9.4%, 5.6% and 16.2% respectively. Change in calibration factors for the oil phase are normally less than 10%, but changes above 50% are observed in the most extreme situations. A 5% error in measured oil production would for 2018 oil production from one of the 3rd party fields amount to approximately 10^7 USD. It illustrates that the MPFMs are drifting and that relatively frequent calibration is warranted to ensure that production allocation is as correct as possible. At Alvheim FPSO the 3rd party flowline MPFMs are normally being calibrated every month.

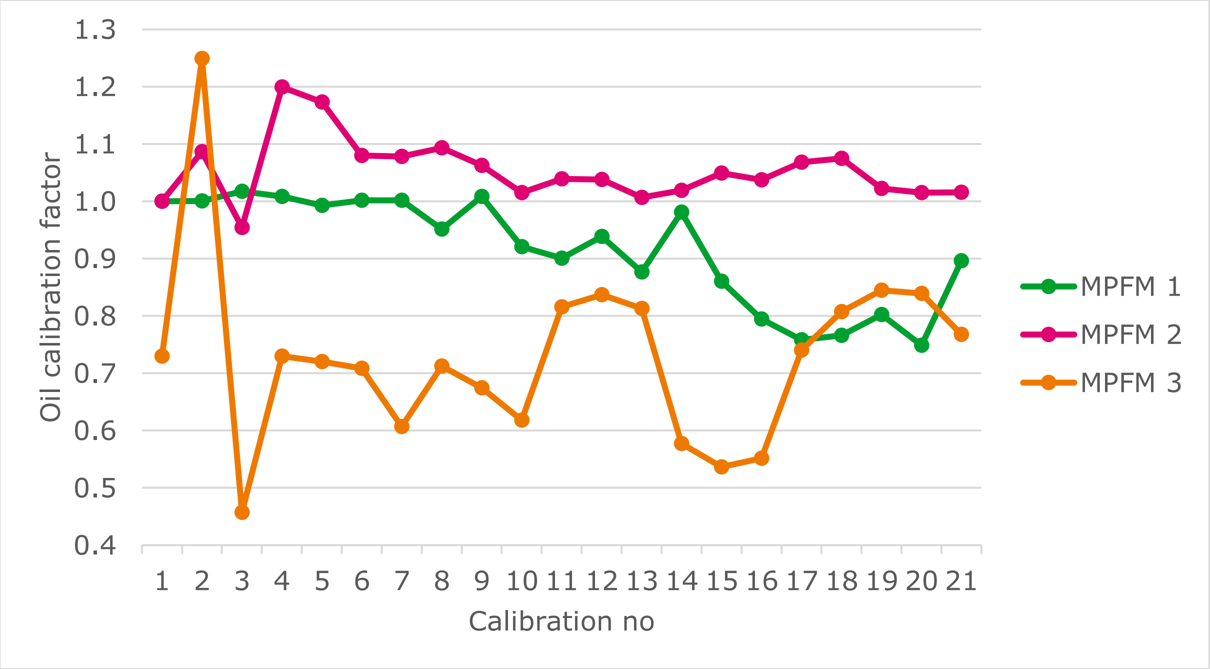

Fig. 3: Development of oil calibration factor for 3rd party flowline MPFMs on Alvheim.

Pro-rating is used for allocation of production on Alvheim. This paper focuses on the pro-rating principle between 3rd party flowlines. The pro-rating factors *A* for the different phases are calculated from accumulated mass measured by the topside MPFMs on 3rd party flowlines

$$A_{line1} = \frac{m_{line1}}{m_{line1} + m_{line2} + m_{line3}} \tag{3}$$

3 An alternative calibration method: parallel calibration

In the following, we will present an alternative to the present calibration method used at Alvheim today. The main motivation for identifying a new method is, as mentioned in Sec. 1, the limited capacity of the inlet separators at Alvheim. The necessary simultaneous routing of in total five flowlines to one separator during the present monthly calibrations leads to a total flow of fluids that exceeds the capacity of the Alvheim separator. Reduction in production during the calibration events is therefore necessary, resulting in deferred production. The overreaching goal of our new method is to reduce the need for rerouting and at the same time keep the uncertainties connected to the calibration as small as possible.

As our new method is a generalization of the present one, we refer the reader's attention to Equation (4). Here we have a set of three linear equations, containing three unknowns, i.e the calibration coefficients of interest. This is the simplest version of three equations and three unknowns, where the solution is straight forward

$$\begin{aligned} k_1 &= \frac{m_{sep1}}{m_{MPFM1}} \\ k_2 &= \frac{m_{sep2}}{m_{MPFM2}} \\ k_3 &= \frac{m_{sep3}}{m_{MPFM3}} \end{aligned} \qquad (4)$$

As long as we have three linear independent equations, in our case, three *unique* calibration measurements, the calibration coefficients can be determined. With unique we mean linear independent, i.e as long as we do not perform measurements on the same configuration of flowlines connected to the separator, with unchanged flow through the pipes, the system will be solvable. One could envisage routing the lines with MPFM1 and MPFM2 to the separator for a first calibration measurement, then MPFM3 and MPFM2, and for a last run MPFM1 and MPFM3. An ensemble of possible configurations exists. All with less need for rerouting. We have chosen to refer to our new calibration method as *parallel* calibration since it opens up for calibration measurements where several lines are connected to the separator.

At Alvheim the three 3rd party lines, Bøyla, Vilje and Volund, can be routed to the 3rd party separator. The relationship between accumulated flow through the MPFMs and the separator is then:

$$\int_{t_0}^{t_1} \dot{m}_{p,Bøyla}\, dt \cdot k_{p,Bøyla} + \int_{t_0}^{t_1} \dot{m}_{p,Vilje}\, dt \cdot k_{p,Vilje} + \int_{t_0}^{t_1} \dot{m}_{p,Volund}\, dt \cdot k_{p,Volund} = \int_{t_0}^{t_1} \dot{m}_{p,sep}\, dt\,, \qquad (5)$$

where $p \in \{\text{oil, gas, water}\}$, $\dot{m}_{p,i}$ and $k_{p,i}$ are the mass flow rates measured by the MPFM and calibration coefficients connected to line i, where $i \in \{Bøyla, Vilje, Volund\}$. Lastly, $\dot{m}_{p,sep}$ is the flow rate measured at the outlet of the 3rd party separator. When expressing Eq. (5) in terms of accumulated masses (see Eq. (2)), we get:

$$m_{p,Bøyla} \cdot k_{p,Bøyla} + m_{p,Vilje} \cdot k_{p,Vilje} + m_{p,Volund} \cdot k_{p,Volund} = m_{p,sep} \qquad (6)$$

We let Eq. (6) represent a calibration measurement. We need three separate calibration measurements, as follows:

$$\begin{aligned} m_{p,Bøyla,1} \cdot k_{p,Bøyla} + m_{p,Vilje,1} \cdot k_{p,Vilje} + m_{p,Volund,1} \cdot k_{p,Volund} &= m_{p,sep,1} \\ m_{p,Bøyla,2} \cdot k_{p,Bøyla} + m_{p,Vilje,2} \cdot k_{p,Vilje} + m_{p,Volund,2} \cdot k_{p,Volund} &= m_{p,sep,2} \\ m_{p,Bøyla,3} \cdot k_{p,Bøyla} + m_{p,Vilje,3} \cdot k_{p,Vilje} + m_{p,Volund,3} \cdot k_{p,Volund} &= m_{p,sep,3}, \end{aligned} \tag{7}$$

where each row represents one particular measurement.
At this point we introduce matrix notation for a more efficient representation of the system of linear equations:

$$\begin{bmatrix} m_{p,Bøyla,1} & m_{p,Vilje,1} & m_{p,Volund,1} \\ m_{p,Bøyla,2} & m_{p,Vilje,2} & m_{p,Volund,2} \\ m_{p,Bøyla,3} & m_{p,Vilje,3} & m_{p,Volund,3} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix} \tag{8}$$

or as

$$\boldsymbol{M}_p \boldsymbol{k}_p = \boldsymbol{m}_p, \tag{9}$$

where **M**$_p$ is the matrix representation of the accumulated masses from the MPFMs, **k**$_p$ is the vector of calibration factors and **m**$_p$ is the vector of accumulated masses from the separator measurements.

To ensure that Eq. (9) is solvable and that the solution is unique, the rows of the square matrix $\boldsymbol{M}_p$has to be linear independent. If so, the matrix is invertible and we obtain a unique set of calibration coefficients:

$$\boldsymbol{k}_p = \boldsymbol{M}^{-1}{}_p \boldsymbol{m}_p \tag{10}$$

We now have all the necessary requirements for a calibration measurement. In the next section we will list the most promising ones. In the following, we will list some of the possible calibration configurations that satisfies these requirements.

3.1 Possible calibration configurations

One obvious way to ensure that $\boldsymbol{M}_p$is invertible is to route a distinct combination of two flowlines to the 3rd party separator for each of the three necessary calibration runs. The system of equations becomes

$$\begin{bmatrix} m_{p,Bøyla} & m_{p,Vilje} & 0 \\ 0 & m_{p,Vilje} & m_{p,Volund} \\ m_{p,Bøyla} & 0 & m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}, \tag{11}$$

We will refer to this solution as the **2-2-2** solution. Here only one extra flowline would need to be rerouted to the Alvheim separator per calibration run and the need for reduction in the production during calibration is decreased significantly.

Another possible solution that would lead to even less need for deferments is a **3-2-2** solution, where the total number of rerouted lines during the whole calibration is two. There are three different versions of this solution:

$$\begin{bmatrix} m_{p,Bøyla} & m_{p,Vilje} & 0 \\ 0 & m_{p,Vilje} & m_{p,Volund} \\ m_{p,Bøyla} & m_{p,Vilje} & m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}, \tag{12}$$

or

$$\begin{bmatrix} m_{p,Bøyla} & m_{p,Vilje} & 0 \\ m_{p,Bøyla} & 0 & m_{p,Volund} \\ m_{p,Bøyla} & m_{p,Vilje} & m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}, \tag{13}$$

or

$$\begin{bmatrix} m_{p,Bøyla} & 0 & m_{p,Volund} \\ 0 & m_{p,Vilje} & m_{p,Volund} \\ m_{p,Bøyla} & m_{p,Vilje} & m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}, \tag{14}$$

Observing the **3-2-2** versions, we see that one of the three flowlines, Bøyla, Vilje or Volund is lined up towards the 3rd party separator for all the runs. In order to optimize the use of separator capacity, the line that produces most should be the one that is left in the 3rd party separator.

Other possibilities are the **1-1-2**, **1-1-3** and **1-2-3,** but none of these have particular merit.

Is it possible to avoid the rerouting altogether? Is a **3-3-3** solution possible? That would mean keeping all 3rd party and Alvheim lines in their respective separators during all three calibration runs. Certainly, it is possible as long as three rows in $\mathbf{M}_p$ are linearly independent. Let's say that one performs three calibration runs on three consecutive days. During normal operation, the average flowrates in the three lines are likely to be quite stable. This means that all rows in our matrix will be linearly dependent and in practice we have *one* equation and three unknowns. So infinitely many solutions. But if the three calibration runs were to be performed in connection with for example well integrity tests or other activities causing a change in the flowrate, this could be sufficient to form a solvable system. It would in such a case be important to track the stability of the solution by checking how well-conditioned the system is. Another concern could be the representativeness of such a calibration if the flows are deviating from those at normal operating conditions.

Lastly, we have the **1-1-1** solution of our system, which corresponds to the present calibration method used at Alvheim:

$$\begin{bmatrix} m_{p,Bøyla} & 0 & 0 \\ 0 & m_{p,Vilje} & 0 \\ 0 & 0 & m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}, \tag{15}$$

Solving the **1-1-1** system would lead to the well-known solution:

$$\begin{aligned} k_{p,Bøyla} &= \frac{m_{p,sep,1}}{m_{p,Bøyla}} \\ k_{p,Vilje} &= \frac{m_{p,sep,2}}{m_{p,Vilje}} \\ k_{p,Volund} &= \frac{m_{p,sep,3}}{m_{p,Volund}}, \end{aligned} \tag{16}$$

equivalent to Eq. (4). This shows clearly the parallel calibration method is simply a generalization of the existing calibration.

3.2 Parallel calibration for random number of MPFMs

Our method works equally well cases when more than three MPFMs are targets for calibration. Eq. (10) shows a general overview of a parallel calibration system with S number of multiphase streams. T number of calibration runs are needed to build an accumulated mass matrix **M**$_p$ as shown in Eq.(17).

$$\boldsymbol{M}_p \in \mathbb{R}^{T\times S} = \begin{bmatrix} m_{p,1,1} & m_{p,2,1} & \cdots & m_{p,S,1} \\ m_{p,1,2} & m_{p,2,2} & \cdots & m_{p,S,2} \\ \vdots & \vdots & \ddots & \vdots \\ m_{p,1,\mathrm{T}} & m_{p,2,\mathrm{T}} & \cdots & m_{p,S,\mathrm{T}} \end{bmatrix} \tag{17}$$

Each calibration run in the matrix **M**$_p$ is contains accumulated masses from the MPFMs being calibrated. The reference measurement populates the vector **m**$_p$ as shown in Eq (18)

$$\boldsymbol{m}_p \in \mathbb{R}^{T} = \begin{bmatrix} m_{p,ref,1} \\ m_{p,ref,2} \\ \vdots \\ m_{p,ref,T} \end{bmatrix}, \tag{18}$$

and the vector of the calibration coefficients $\mathbf{k}_\mathrm{p}$ is

$$\mathbf{k}_\mathrm{p} \in \mathbb{R}^{S} = \begin{bmatrix} k_{p,1} \\ k_{p,2} \\ \vdots \\ k_{p,S} \end{bmatrix}. \tag{19}$$

When T = S, i.e the number of equations equals the number of unknown, and the rows of $\boldsymbol{M}_p$ are linearly independent, the system is solvable and

$$\boldsymbol{k}_p = \boldsymbol{M}_p^{-1}\boldsymbol{m}_p \tag{20}$$

3.3 Measuring convergence of calibration factors

What most clearly distinguished the **2-2-2** and **3-2-2** from the traditional, or **1-1-1** method, is *at what point* in the calibration process the coefficients can be determined. As seen from Eq. (4), each calibration run in the **1-1-1** method determines a calibration coefficient for a particular line. This allows the metering technician to monitor the time-evolution of the *actual* calibration coefficients and determine to complete the calibration run when that coefficient is sufficiently stable, or in other words seems to have converged.

In a parallel calibration, *all measurements need to be completed* before we have all necessary information to solve the system. This means that the calibration coefficients themselves cannot be used as a metric for convergence. We propose to use the ratio of the MPFM measurements and the separator measurements instead. To give a specific example, let's look at the **2-2-2** method. In the first calibration measurement (first row) one would monitor the "quasi"-calibration coefficients:

$$k_{quasi\_Bøyla} = \frac{m_{p,Bøyla}}{m_{p,sep,1}} \tag{21}$$

$$k_{quasi\_Vilje} = \frac{m_{p,Vilje}}{m_{p,sep,1}} \tag{22}$$

Convergence of these parameters for all three calibration runs will indicates that the real calibration coefficients will converge to a stable solution when the system is finally solved. Surveillance of process parameters during calibration is of course very important to ensure sufficient quality of the parallel calibration.

4 Results from parallel calibration

Two different approaches have been used to test the parallel calibration method on data from Alvheim. First, we will present the results from time series using time-shifted time series from traditional calibration. Thereafter, data from actual parallel calibration runs has been used, where the Alvheim FPSO has configured fluid streams to generate required data for the parallel calibration method.

The results given in this paper are generated without density adjustment and with a simplified flashing calculation. Key aspects of the algorithm are covered in Appendix A and [4].

4.1 Synthetic parallel calibration

Three synthetic reference measurements have been generated by adding reference measurements from combinations of two and two traditional calibrations. These reference measurements populate the reference matrix $\mathbf{m}_p$. For each synthetic reference measurement, the corresponding measurements from the MPFMs are inserted in the accumulated mass matrix, $\mathbf{M}_p$. The solution of the synthetic parallel calibration dataset is shown in Figure 4. and compared to the solution where the calibration factor is found using the traditional calculation method. The results show that the solution from parallel and traditional calibration method matches. This is as expected since the calibration factor is calculated from the exact same time series.

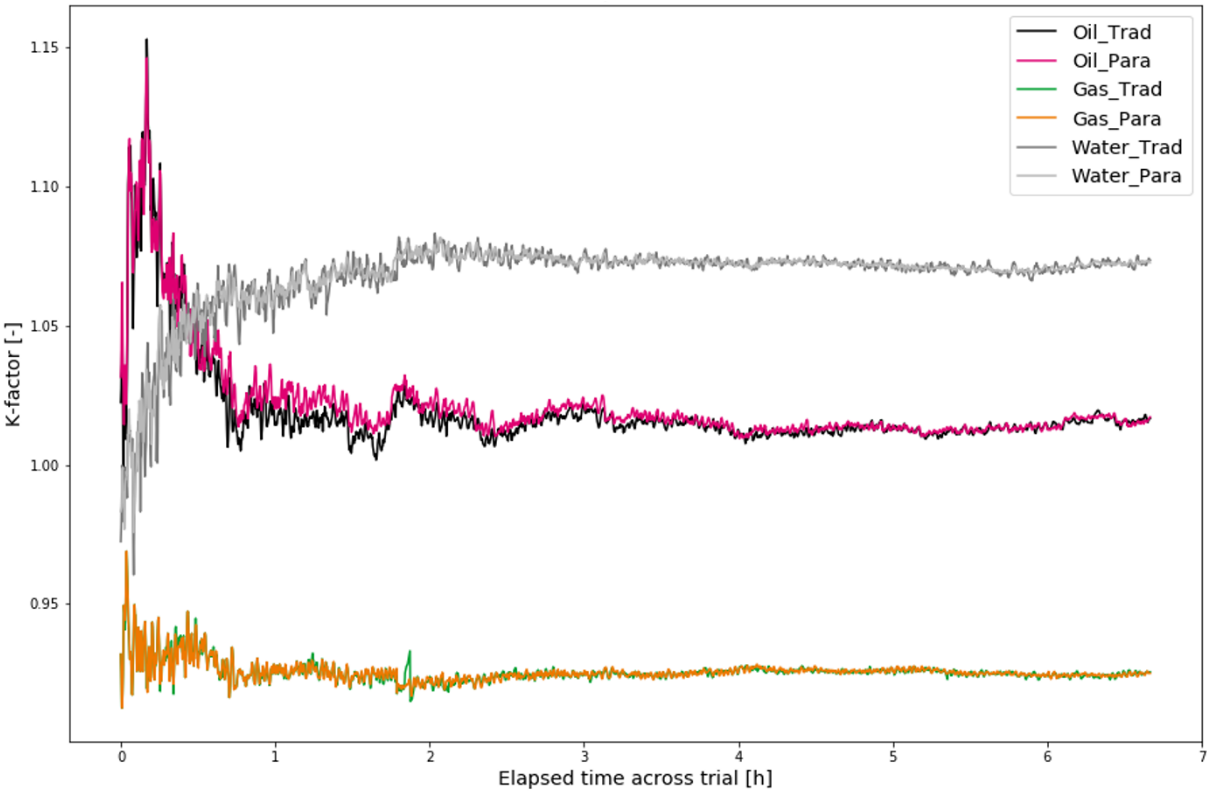

Fig. 4 calibration factor development of traditional vs synthetic parallel calibration of an MFPM on Alvheim [4]

4.2 Results from field test of parallel calibration method

In early and late April 2019, measurements were done where streams were rerouted to give real data for parallel calibration. This was done immediately after traditional calibration enabling comparison of the methods. Figure 5 shows the resulting calibration factor for one of the MPFMs determined from different test run configurations. As the data is based on different time series, the resulting calibration factors are not expected to be equal as instabilities in the process and MPFMs can give different results for the different trials. Included in the results are also the calibration factor given by the metering system and includes composition and density adjustment of the measurement.

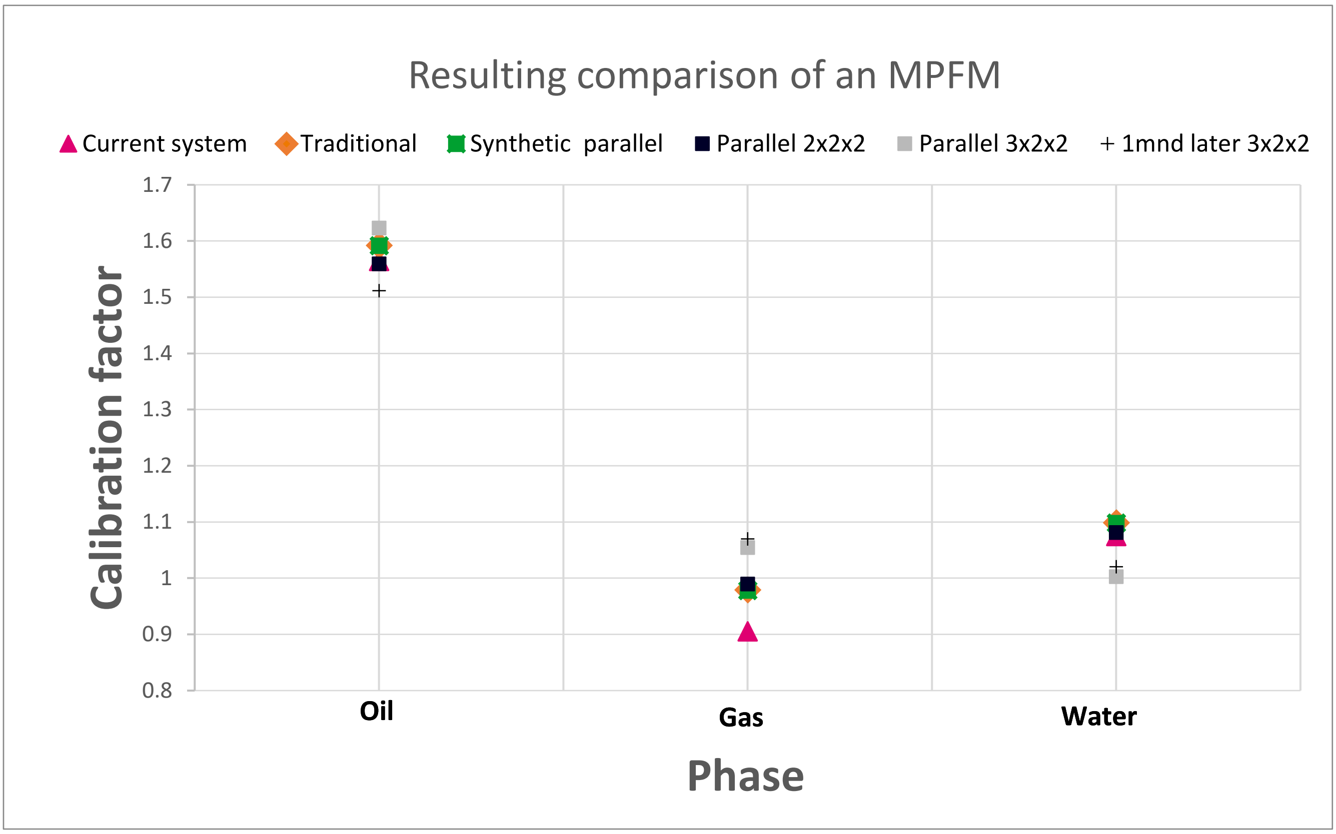

Fig. 5 – Result comparison of one of the MPFMs at Alvheim FPSO during March/April calibrations [4]

5 Uncertainty analysis of parallel calibration

It is beyond the scope of this paper to attempt a complete uncertainty analysis of the calibration process (and probably impossible). MPFMs are known to have a rather complex dependency of flow conditions, making it very difficult to estimate an uncertainty associated with its measured values. Our approach to the uncertainty analysis is to estimate the uncertainty of the parallel calibration method *relative* to the traditional one. That is, we will investigate if parallel calibration introduces new sources of uncertainty that influences the accuracy of the calculated calibration coefficients. As our calibration method has become more complex, the correct treatment of the propagation of errors is important. As we argued in Sec. 3.2, the parallel calibration method can in theory be used for calibrating any number of MPFMs, N, in parallel. Tracking how measurement errors are propagating through the matrix inversion of an (N x N)-matrix and vector multiplication can be done analytically, but as N becomes large Monte Carlo (MC) simulations would simplify the task. In our error analysis, we find both analytical expression for the error and perform MC simulations.

We will in the following focus our analysis of the uncertainties connected by parallel calibration by discussing two questions:

1. Will one drifting/unstable MPFM lead to less accuracy in the measured calibration coefficients of the two other MPFMs?
2. Will a difference in flowrate through the MPFMs calibrated in parallel lead to increased uncertainty in the calibration factor of the low producing lines?

After presenting a theoretical analysis of the relative errors between the traditional calibration and parallel calibration, we will take a look at historical data from Alvheim and see how they relate to our analysis.

5.1 Systematic uncertainty

The first question will be answered by investigating how systematic uncertainty in the measurements propagates through the calculations. Systematic uncertainty is here defined as an uncertainty that is not statistical. A MPFM that reports a systematical shifted measurement is assumed to stay shifted during the three calibration runs. We make no assumptions about what causes the systematic errors.

Let us go through an example assume that a MPFM measuring the flow rate from the Volund is particularly unstable and for the time interval of the calibration it systematically reports a very low flow rate. Will this shift in measurement affect the calibration coefficients of Vilje and Bøyla?

Constructing this scenario, we assume a set of "true", unshifted calibration coefficients, $\mathbf{k}_{\mathrm{p}}^{*}$. These are used to construct the corresponding reference measurements, $\mathbf{m}_{sep}$. The systematically shifted measurement from Volund is given by, $m_{p,Volund} - \Delta m_{p,Volund}$

We start by looking at the traditional **1-1-1** case:

$$\begin{bmatrix} m_{p,Bøyla} & 0 & 0 \\ 0 & m_{p,Vilje} & 0 \\ 0 & 0 & m_{p,Volund} - \Delta m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}. \tag{23}$$

We now express the $\mathbf{m}_{sep}$vector in terms of $\mathbf{k}^{*}$ and the total mass measured by the MPFMs during one calibration run (one row in the matrix):

$$\begin{bmatrix} m_{p,Bøyla} & 0 & 0 \\ 0 & m_{p,Vilje} & 0 \\ 0 & 0 & m_{p,Volund} - \Delta m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} k_{Bøyla}^{*} m_{p,Bøyla} \\ k_{Vilje}^{*} \ m_{p,Vilje} \\ k_{Volund}^{*} m_{p,Volund} \end{bmatrix} \tag{24}$$

Solving this system gives the calibration coefficients:

$$\begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} k_{Bøyla}^{*} \\ k_{Vilje}^{*} \\ \dfrac{m_{p,Volund}}{m_{p,Volund} - \Delta m_{p,Volund}} k_{Volund}^{*} \end{bmatrix} \tag{25}$$

We see as expected that a shift in the Volund MPFM measurements only gives an error in the calibration coefficient of Volund. This is rather intuitive, since the calibration of the meters are done separately.

Now, let's look at the corresponding **2-2-2** case:

$$\begin{bmatrix} m_{p,Bøyla} & m_{p,Vilje} & 0 \\ 0 & m_{p,Vilje} & m_{p,Volund} - \Delta m_{p,Volund} \\ m_{p,Bøyla} & 0 & m_{p,Volund} - \Delta m_{p,Volund} \end{bmatrix} \begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} m_{p,sep,1} \\ m_{p,sep,2} \\ m_{p,sep,3} \end{bmatrix}. \tag{26}$$

Or, in terms of "real", unshifted coefficients, $\mathbf{k}^*$:

$$\begin{bmatrix} m_{p,Bø} & m_{p,Vi} & 0 \\ 0 & m_{p,Vi} & m_{p,Vo} - \Delta m_{p,Vo} \\ m_{p,Bø} & 0 & m_{p,Vo} - \Delta m_{p,Vo} \end{bmatrix} \begin{bmatrix} k_{p,Bø} \\ k_{p,Vi} \\ k_{p,Vo} \end{bmatrix} = \begin{bmatrix} k_{Bø}^* m_{p,Bø} + k_{Vi}^* \; m_{p,Vi} \\ k_{Vi}^* \; m_{p,Vi} + \; k_{Vo}^* m_{p,Vo} \\ k_{Bø}^* m_{p,Bø} + k_{Vo}^* m_{p,Vo} \end{bmatrix}, \tag{27}$$

where {Bø, Vi, Vo} = {Bøyla, Vilje, Volund}. Solving this system analytically, gives exactly the same solution as for the **1-1-1**:

$$\begin{bmatrix} k_{p,Bøyla} \\ k_{p,Vilje} \\ k_{p,Volund} \end{bmatrix} = \begin{bmatrix} k_{Bøyla}^* \\ k_{Vilje}^* \\ \dfrac{m_{p,Volund}}{m_{p,Volund} - \Delta m_{p,Volund}} k_{Volund}^* \end{bmatrix} \tag{28}$$

We have performed this exercise for the **3-2-2** calibration version as well. The result is the same. We have also tested cases where several flowlines have systematic uncertainties. The results are the same: systematic uncertainties in the measurements are the same for the traditional calibration as for the new methods.

So, our answer to the first question 1) is that no, one drifting/unstable MPFM does not lead to less accuracy in the measured calibration coefficients of the two other MPFMs. In this sense, the parallel calibration method does not introduce additional systematic uncertainties compared to the traditional method.

5.2 Statistical uncertainty

In the following, the statistical uncertainty is defined as a general, gaussian distributed measurement error, distributed as:

$$P(x) = \frac{1}{\sqrt{2\pi\sigma}} \mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{29}$$

where σ is the standard deviation and μ are expectation value. In the following analysis, we have modified the standard calibration equation:

$$\boldsymbol{M}_p\boldsymbol{k}_p = \boldsymbol{m}_p \tag{30}$$

Now, we populate $\boldsymbol{M}_p$and $\boldsymbol{m}_p$with gaussian distributions instead of specific numbers. We assume that in general $\sigma \propto \mu$, i.e that the measurement uncertainty is proportional to the size of the mass flow. As an example, $\sigma = a\mu$, where a is set to 0.03 for the MPFMs. This number is randomly chosen, but since our focus is on the relative uncertainties between the traditional and parallel calibration the absolute value of *a* is not important. The distributions in $\boldsymbol{m}_p$, that is, the distributions of the measurements from the single phase meters have been assigned a flow, Q_s, dependent *a* parameter, $\mathrm{a}(\mathrm{Q}_s)$. This only is done to catch the behavior of the single phase meters when the flow, Q_s, out of the separator get very low, as can be the case at Alvheim when a **1-1-1** calibration is being performed. In the Monte Carlo simulations, we produce versions of $\boldsymbol{M}_p$and $\boldsymbol{m}_p$ by sampling from the distributions and produce a $\boldsymbol{k}_p$ by solving the system using a linear solver.

The resulting $\boldsymbol{k}_p$distributions from the **1-1-1**, the **2-2-2** and the **3-2-2** versions are compared. The simulations take measurement time and the relative flowrate through a meter as input. The relative flowrate parameters are used to quantify the way uncertainty in lines with small production is affected by being measured together with lines with higher production. Figure 6 shows an example of results from simulations of the distributions of the calibration factors for the MPFM connected to the Vilje flowline. As the standard deviations indicates, doubling the measurement time will produce a resolution as good as for the 1-1-1 calibration.

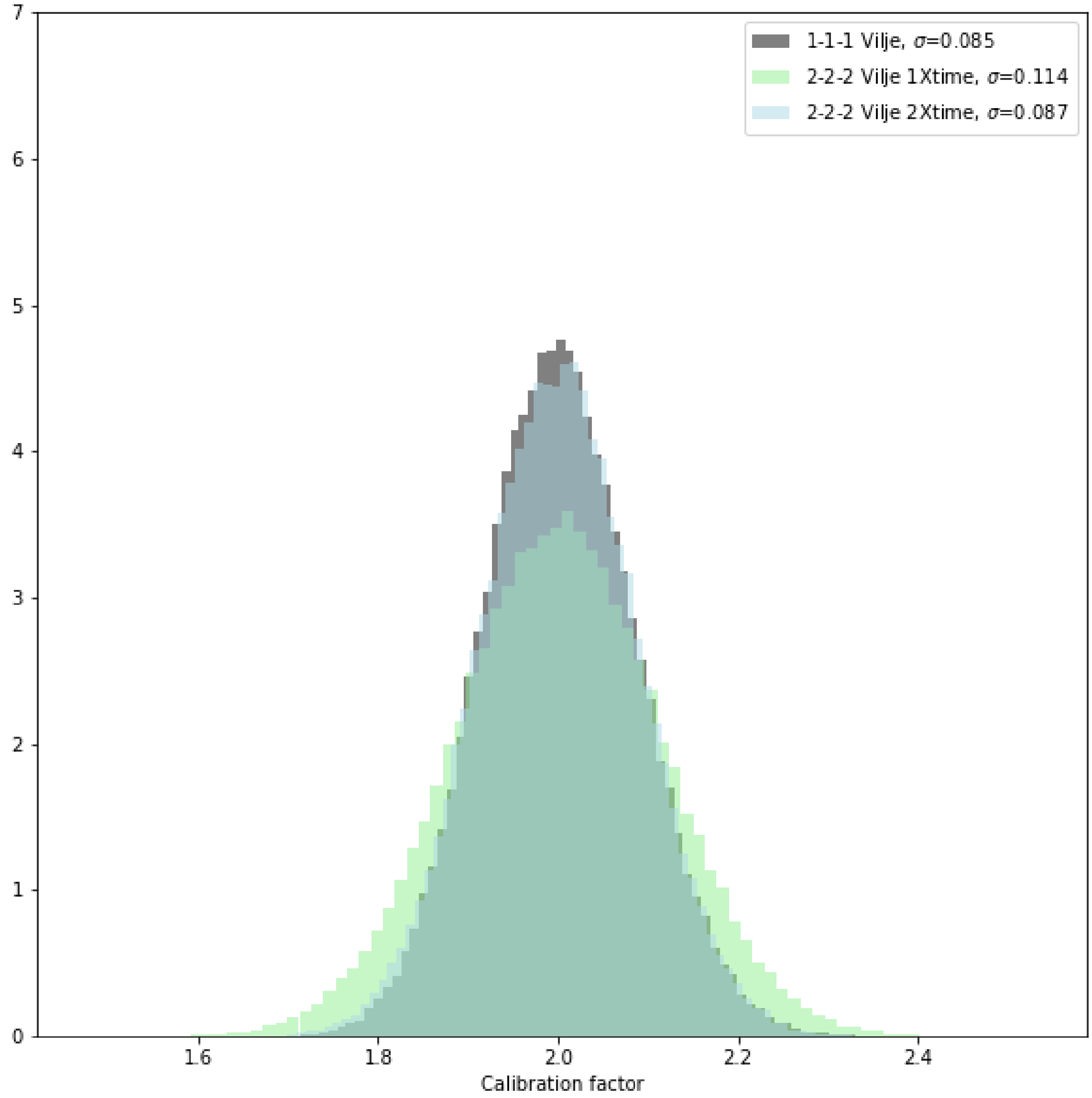

Fig. 6 – Simulated calibration factor distributions for Vilje for the 1-1-1 and 2-2-2 version and varying time intervals.

After looking into variations of measurement time or ratios of flow rates we conclude that the answer to question 2) is: yes, *if we assume that the individual measurement error from each meter is dependent on flowrate*, the parallel calibration method leads to an increased uncertainty in the calibration factor of the low producing lines. But this effect could be remedied by prolonging the calibration time periods over which the meters are calibrated.

5.3 Historical data from Alvheim calibrations

Until this point in we have looked at *theoretical* error distributions of the MPFM and single phase meters. We will now try to use historical data from calibration runs at Alvheim to investigate if the relative difference in uncertainty between a traditional **1-1-1** calibration and the parallel versions **2-2-2** and **3-2-2**. The analysis is based on time series from four historical **1-1-1** calibrations. As described in Sec. 4.1, we produce synthetic time series to test compare the time evolution of the calibration coefficients from the **1-1-1** calibrations with **2-2-2** and **3-2-2**. To get a sense of the statistical fluctuation in the calibrations, we find the standard deviation, σ, of the calibration coefficients for the last two hours of calibration. We chose to interpret this distribution as the statistical distribution the calibration coefficients. At present we have done this analysis for the last six months of calibrations. The preliminary results indicate that the statistical fluctuations of the measurements are so small that there the difference between a **1-1-1** and a **2-2-2** and **3-2-2** calibration is practically negligible.

6 Implementation of the parallel calibration method

When it comes to the implementation and execution of the calibration algorithm, having access to and control over data quality from different Supervisory Control and Data Acquisition (SCADA) systems is important. Possible implementations can be on the metering SCADA level or through a data platform such as the Cognite Data Fusion platform. Implementation on the SCADA level will require additional information from the main vessel Safety and Automation system (SAS). The data from the SAS system is used to identify calibration time windows based on valve positions and to document stability during the calibration window.

Through the Cognite Data Fusion platform, which is used today, and the results of this paper is based on, all necessary data is available. However, the integrity/data quality is reduced as the timeseries values used are historical values with varying timesteps. This is caused by data compression taking place in the systems feeding the CDF. To ensure high fidelity, uncompressed data from each flow computer should be available via CDF. The data should be immutable between the flow computer and the algorithms execution. The implementation of the method could then be done on any machine with access to CDF.

7 Density, composition and phase equilibrium

This section discusses the processing of the measured data that is done in the parallel and traditional calibration algorithms. It is included as information of remaining work to increase the accuracy of the parallel calibration method.

The traditional calibration method performs some processing of the flow measurements using a thermodynamic software package. Pre-defined well fluids for each MPFM are used as basis for this processing. For Alvheim FPSO, the processing can be divided in the following main steps:

- Adjust composition data to match oil measured density.
- Adjust composition to match measured GOR.
- Flash fluid in MPFM and separator to common conditions for calculation of calibration factors.

For single MPFM calibration, this processing is relatively straight forward. When more than one flowline is introduced, the complexity increases. As an example, the density of the oil will now be a mix of the density from multiple incoming flowlines. Further, the temperature and pressure in each MPFM and the separator will be different.

Future work will investigate resolving these challenges. Regarding allocation of densities to the respective flowline, it is envisaged that this can be done by solving a system of linear equations similar to how the calibration factors are calculated.

In Alvheim's case, preliminary results have shown that the measured oil density is similar to densities from the PVT simulation software and also from the lookup-tables in the MPFM process computers. The difference is about 1%. Further, it appears that the compositional adjustment done to match the measured GOR does not impact the composition of the oil and gas phase. Pressure in the MPFMs and separator is also similar making the effect of flashing moderate. Temperatures can vary from flowline to flowline. Preliminary tests of the amount of flashing of oil shows that it is in the range 0.5 – 2%. These factors will have some impact on the resulting calibration factors.

The results shown in this paper is based on a fixed flashing of 2.0 wt% of the oil mass to the gas phase. It has been calculated based on approximate conditions at the MPFMs and in the 3rd party separator. The amount of flashing has been estimated using UniSim design process simulation software.

8 Other possible applications

Through the Third Party Access (TPA) agreement, the Norwegian government encourages to utilize existing infrastructure on the NCS to develop new licenses. The parallel calibration method supports this initiative by enabling reduced investments while maintaining the health and accuracy of multiphase flow meters used for allocation purposes. Alternatively, it can be used in combination with traditional calibration as a verification method to increase or decrease the time between traditional calibrations, thereby increasing allocation accuracy and/or reducing production deferrals, similar to the Alvheim FPSO case.

The parallel calibration methodology is not limited to use with MPFMs, it can also be applied for calibration of single-phase meters.

8.1 Process configurations concepts enabling parallel calibration

Key to the parallel calibration method is to have changes in flow rates between the trials to enable solution of the system of equations. The easiest way to generate this change is by closing upstream valves for one of the flowlines. Having two parallel separators where flowlines are continuously rerouted between the separators is one possible configuration to enable this for incoming flowlines. Another option is to use a compact/inline separator in parallel to the inlet separator, where one flowline at a time is re-routed to this compact separator. Both methods will give changes in flow rate that enables a semi-continuous calibration or verification of the flow meters.

If the production cannot be routed elsewhere it will normally have to be choked back to generate the required change in flowrate for the parallel calibration technique. This is of course undesirable. Another option to achieve change in flow rate could be to increase the flow, e.g. through recirculation of fluids. As an example, oil and gas could be recycled from downstream stages of the process plant to upstream of the MPFMs. This does however imply that the flow meter is calibrated at a different rate and with a potentially different fluid than what is normally flowing. It also requires installation of facilities for routing and measuring of a stream upstream of the MPFM.

9 Notation

Bolded letters are matrices or vectors, the masses and calibration factors always have subscripts to associate the values to the correct stream and phase.

$\dot{m}$	mass flow
m	Accumulated mass in stream
$\mathbf{M}$	Matrix of accumulated masses $\in \mathbb{R}^{TxS}$
$\mathbf{m}$	vector of accumulated-reference masses $\in \mathbb{R}^{T}$
k	calibration factor [-]
$\mathbf{k}$	calibration factor vector $\in \mathbb{R}^{S}$
t	time / timestamp / time-segment
$\mathbb{R}$	Denotes the matrix or vector only consist of real values.

Subscripts

p	phase [Oil, Gas, Water]
s	Stream number / index
S	number of streams
T	Trial number / index
	Number of trials
n	Index / index counter
ref	Reference measurement
sub	Calibration-Subject measurement

Superscripts

-1	Matrix inverse

10 Conclusion

The work in this paper demonstrates how calibration factors for flowmeters can be determined while still having multiple streams routed towards the reference flow meter. To be able to determine the calibration factor, a set of trials equal to the number of flow meters being calibrated must be undertaken. Each flow meter being calibrated must be routed towards the reference flow meter during one of the trials at least. All meters being calibrated can be routed to the reference meter in all trials given that there is enough difference in flow rate between each trial. For the MPFMs on Alvheim, variation in flow rate is achieved by re-routing one of the streams at a time away from normal third-party separator.

Where the method is used for calibration of multiphase meters, adjustment for difference in process conditions between the MPFMs and the reference meter should be done to increase the accuracy of the calibration. Further, adjustment of composition and component to match measured GOR and densities could be done. This has not yet been investigated in detail but will be the focus in future work. However, without any such adjustment, calibration factors that is close to single flow meter calibration is achieved. The error introduced when allocation is performed will be further reduced as the tests performed shows that the calibration factors for the different meters are shifted in the same direction relative to the single MPFM calibration method.

The uncertainty analysis shows that systematic uncertainty in one of the flow meters being calibrated does not propagate to the other meters in the system. An analysis of the statistical uncertainty demonstrates that this will increase compared to calibration of one flow meter at a time. This can be compensated by increasing the duration of the trials. Analysis of synthetic historical data shows that the statistical uncertainties connected to the calibration measurements are so small, that their difference in statistical uncertainties between a **1-1-1** and a **2-2-2** or **3-2-2** is negligible. It is important to note that this conclusion is drawn based on synthetic data, and that more actual tests from Alvheim will be important.

The concept of parallel calibration can open for simplified design solutions for tie-in of 3rd party fields and/or an opportunity to reduce deferrals associated with calibration of multiphase meters. The latter is the case at the Alvheim FPSO. It is also envisaged that the method can have other similar applications that can both reduce investments requirements, increase metering accuracy and/or reduce production deferrals.

11 Acknowledgments

We want to thank the offshore operations and onshore metering engineers on Alvheim, whom has assisted us with field test runs giving us data to test the parallel calibration method and supporting us with knowledge and information about the Alvheim metering system and allocation algorithms, as well as challenging us on the subject of accuracy and uncertainty of the method.

12 References

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Appendix A – Algorithm

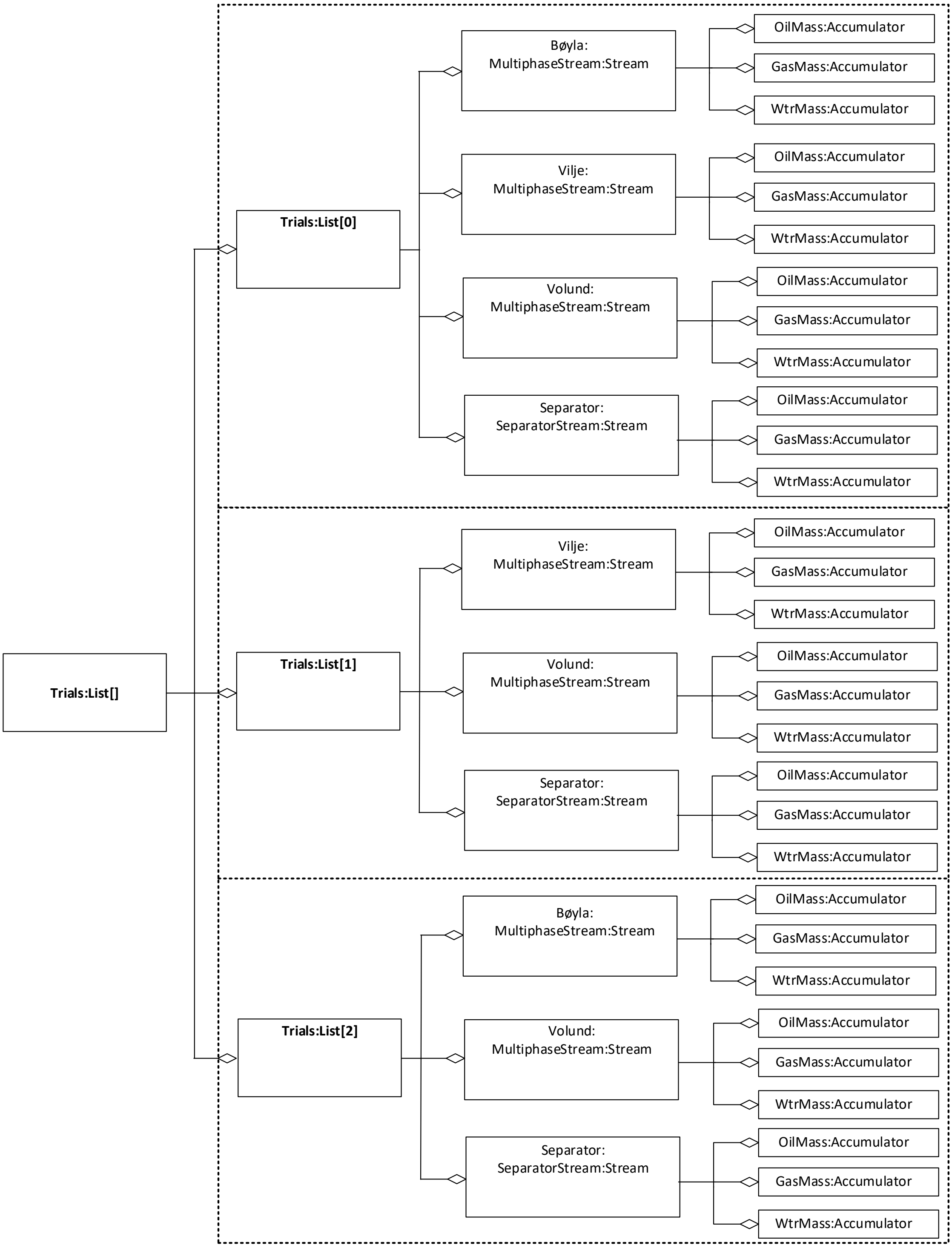
The calibration figures are solved in a post calculation, since the all the trial windows is needed to perform the calculation. The algorithm is written in the program language python, and the stored datapoints are received from historical datapoints from the Cognite Data Fusion repository (CDF), which collects data from Aker BP's OsiSoft PI system, that in turn collects data from both the control system and the measurement system through OPC DA servers on each respective system onboard the Alvheim FPSO. This data infrastructure entails a risk of the real-time datapoints stored historically may not be of the same quality as the data inside the real-time embedded devices / flow computers running on the SCADA level.

In the creation of the trials, initially the datapoints are all collected form the CDF through the Cognite-SDK for the specific stream. Then a flashing of the multiphase stream is executed, or if it is the reference stream the water in oil is removed from the oil stream and added to the water stream. More details of how this is executed is shown in [2] as referenced in the technical paper.

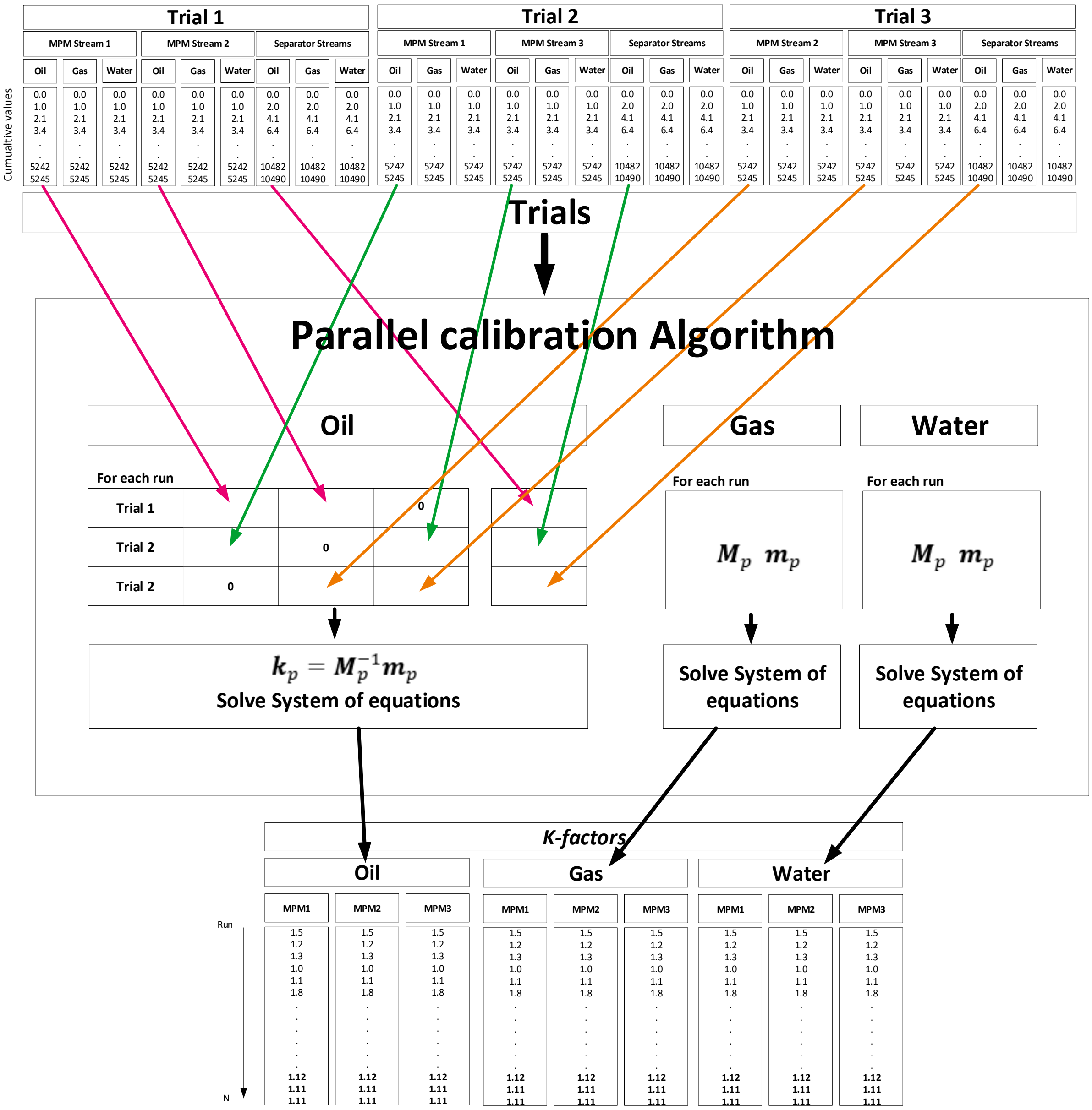
But each stream is collected in a trial collection, and each trial is collection of trials called trials, which simplifies the calculations done where the data is structured in a manner to combined data from each trial. The essential parts of the data structure explained and shown in Figure 1 and is the data input into the calibration algorithm, but since each stream is an object it contains also datapoints of intensive variables such as pressure, temperature and soon densities and phase flow fractions.

In the algorithm the first thing done, and the most computationally expensive of the entire calibration is where each phase in every trial is time synchronies, where the closes datapoints in time is indexed toward each other in order to ensure that each phase in each trial is using data, which has accumulated over the same time-period. This is due to the spurious spreading of the time between each datapoint is different for each stream and phase.

The next step is to create a frame of the $\mathbf{M}_p$ matrix, and is done by setting up a matrix frame, containing information about which stream to be set into what cell in $\mathbf{M}_p$. And when the $\mathbf{M}_p$ matrix form is found, the system of equations can solve as shown in Figure 2 for a 2x2x2 calibration.



A Fig. 1 – Data structure / object diagram of trial data containing the data used to perform the calibration of a 3x2x2 calibration of Third party Alvheim streams



A Fig. 2 – Overview of the solving of the parallel calibration algorithm of 3 streams and 2x2x2 trial combination, where all phase streams in trials are time synchronized

The formation of the accumulated mass matrix $\mathbf{M}_p$ can also be solved with another cell configuration, there is S! (factorial) number of trial combinations which can solve the system of equations, and each can provide a collection of apparent k-factor developments. And analysis of theses development is used to establish the resulting k-factor. When a development of k-factors has stabilized a subset of theses stabilized data can then be used as a statistical basis for calculation of a final k-factor, with pseudo-statistical stability values form the subset.

Parallel calibration evaluation

For a quick overview of the data used by the algorithm the plots are set into a grid, with the same dimensions as an augmented matrix of $\mathbf{M}_p$ and $\mathbf{m}_p$. The form of plotting gives an in-depth overview of the systems in question. Figure 3 shows an example of this which is of the intensive variables of the system, which are of interest, such as the liquid levels in the separator, water cut, pressure and temperature. By looking at the separator stream on the first column this shows changing liquid oil levels and water cut out of the separator, which give good indication of the process states during the time window of the trial.

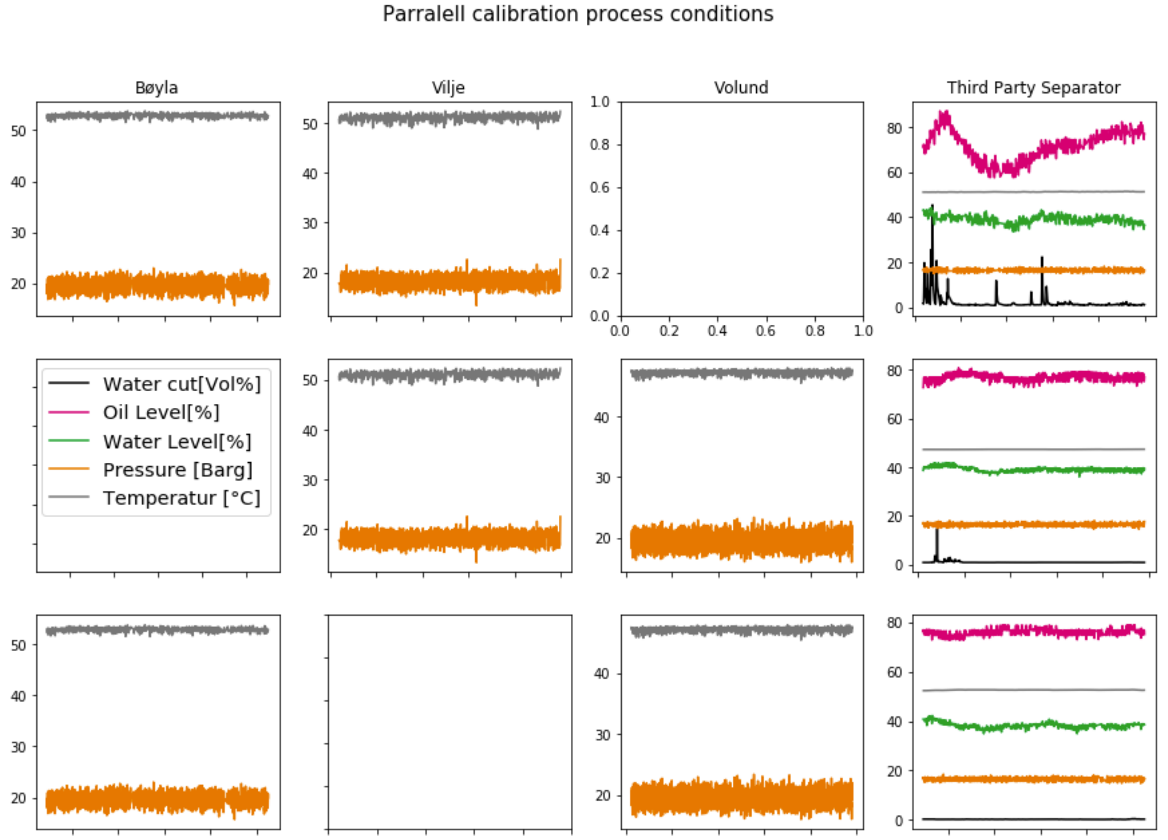


Fig. 3– Augmented matrix plot of Process conditions during trials, where the x axis is successive raw datapoint during the trial, and therefore no numbers [2]