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3-way PLS regression and dual energy gamma densitometry for prediction of total volume fractions and enhanced flow regime identification in multiphase flow

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Abstract

Dual energy gamma densitometry and 3-way partial least squares regression were applied to quantify the total volume fractions and improve flow regime identification in multiphase flow. Multiphase flow experiments were carried out with formation water, crude oil and gas from different North Sea gas fields in Statoil's High Pressure Multiphase Flow Loop in Porsgrunn, Norway. Four different flow regimes were investigated (stratified wavy, slug, dispersed and annular). A traversable dual energy gamma densitometer was used to measure the fluid densities in the pipe. Partial least squares regression was previously applied to identify multiphase flow regimes and quantify volume fractions of gas, oil and water. That study showed promising results for flow regime identification but the predictions of the total volume fractions were not acceptable. In this study a new method combining gamma densitometry and 3-way partial least squares regression was applied in order to improve the quantitative estimation of the total volume fractions gained the previous study. The proposed 3-way regression approach allows prediction of the total volume fractions directly using one model instead of multiple models which was reported earlier. The improved quantification of the volume fractions of gas, oil and water was used to improve the flow regime identification plots and increase the interpretability. The new 3-way prediction results for the volume fractions were significantly better than what was found earlier based on individual PLS models. The root mean square error of prediction for gas, oil and water from the 3-way PLS models were 4.1 %, 4.3 % and 4.6% respectively. All models reported were validated based on independent data (test set validation).

Keywords: 3-way PLS, Gamma densitometry, Multiphase flow, Volume fraction, Flow regime

1. Introduction

Reliable monitoring of multiphase fluids produced from oil wells is important for efficient oil exploitation and production [1,2]. Measuring directly on the production line will require flow meters which can handle multiphase flow. The advantage of real time multiphase flow characterization is that information about composition can be used directly to optimize operation of successive processing units more efficiently.

The flow regime or flow pattern in a pipeline is a qualitative description of the phase distribution in the pipe. Real time information about flow regime is important e.g. for identification of slug flow [3]. Slug control is getting more important, the oil industry's focus on detection of slug flow has increased due to the larger number of marginal oil wells.

Currently there are many commercially available multiphase flow meters which are based on different measurement principles [4-9]. All the commercially available multiphase flow meters have limitations. One of the common limitations is that they are flow regime dependent and can only work on one flow regime. Others are intrusive, disturb the flow pattern and create an unwanted pressure drop in the system [7]. Non-invasive measurement techniques such as gamma densitometry will obviously not disturb the flow pattern or create a pressure drop.

Statoil ASA (Porsgrunn, Norway) has designed and commissioned an industrial scale multiphase flow rig capable of producing realistic temperature and pressure conditions. A detailed description of the test facility has previously been reported in [10]. Multiple research studies have been carried out based on this flow test facility. Frøystein et al. [11] applied dual energy gamma tomography in this test facility to determine the local phase distribution in three phase mixtures. Hoffman and Johnson [12] carried out experiments using a traversable dual energy gamma densitometer for flow regime identification with process conditions which were considered realistic field conditions. They concluded that it was possible to identify the flow regime. Midtveit at al [13] used a capacitance transducer in combination with multivariate calibration for multiphase flow metering. They concluded that multivariate calibration may be used in advanced instrumentation for multiphase flow. In Arvoh et al. [14] multivariate analysis and modelling techniques were applied to the data obtained by Hoffmann and Johnson [12]. A high number (100+) of individual PLS-R prediction models were used simultaneously to predict the volume fractions in 37 equally spaced vertical positions along the cross section of the pipeline. The prediction results were combined and plotted for identification of flow regimes. It was concluded that it was feasible to identify the flow regime in all the experiments. The predicted compositions in all the 37 vertical positions were combined into estimated values for the total volume fractions of oil, gas and water in the pipe. Due to accumulation of systematic errors resulting from combining a large number of local predictions, as an attempt to estimate the total volume fractions in the pipe were not acceptable. Based on results from principal component analysis of the gamma data, it was concluded that the calibration and test data were not comparable, requiring development of a linear average scaling technique to compensate for these differences.

In another article Arvoh et al. [15] Principal component analysis and Partial least squares regression were applied to the data from experiments with inclined pipelines. It was concluded that the chemometric approach increased the interpretability by introducing the flow regime identification plots.

The present study is based on the same experiments as in the research articles above using Statoil's High Pressure Multiphase Flow Loop, however in this study the dual energy gamma densitometer is combined with 3-way regression modelling instead of traditional PLS-R. 3-way

Partial Least Squares Regression (NPLS-R) [16] was used to calibrate and predict the total volume fractions directly with the purpose of increasing the accuracy compared with the ordinary 2-way PLS approach. The advantage of using 3-way PLS regression is that the total volume fractions (holdup) can be predicted directly using one model for each phase and thus avoid accumulation of systematic errors from using multiple PLS-R models. Another advantage is that the linear average scaling technique developed in [14] can be avoided. A disadvantage of the 3-way PLS approach is that it is not possible to use it for flow regime identification directly since this requires predictions in all the vertical positions. Although 3-way PLS cannot be used for flow regime identification directly, the improved predictions of the volume fractions are here used to increase the interpretability of the flow regime identification plots previously reported.

2. Materials and methods

A detailed description of the test facility and experiments can be found in literature [10,11, 12]. However a brief overview of the most important properties is presented here.

2.1 The multiphase flow test rig

The High Pressure Multiphase Flow Loop used in this work is located at Statoil Research Centre in Porsgrunn, Norway. The Multiphase Flow Loop is a recirculation experimental test facility which can be operated with realistic process conditions for oil and gas production. A schematic drawing of the U-shaped flow loop is shown in Figure 1. The test loop pipeline which is made of Duplex steel is 200 m long and has a 3" diameter. The flow rates of oil, water and gas are controlled separately. Desired amounts of each phase are introduced in the mixing point. After the mixing point the fluids flow into the 3" test section. To ensure that the multiphase flow is fully developed before the measurements are taken, the measurement zone is strategically positioned at the end of a 100 m long horizontal pipe. In order to recirculate the fluids and span different compositions and flow patterns the multiphase mixture is separated into individual fractions in the multiphase separator before a new test starts.
A heat exchanger is used to control the temperature of the fluids. The most important parameters of the multiphase flow test facility can be found in Table 1.

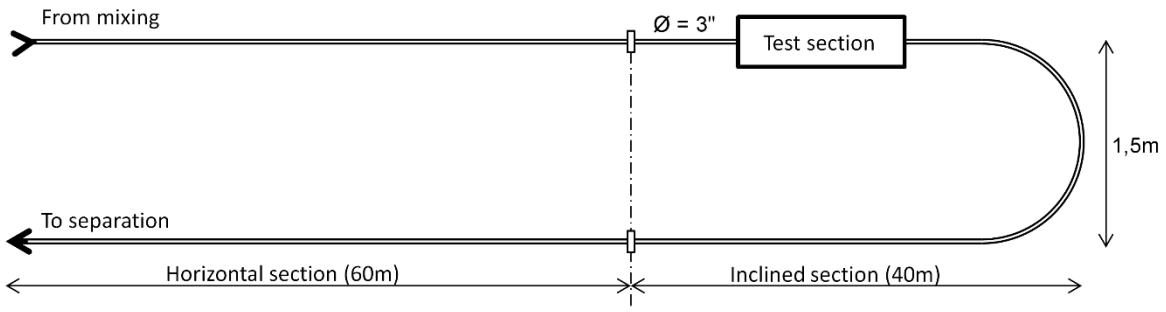

Figure 1. The schematic of the test section in the multiphase flow loop used in all the experiments reported in this article.

Table 1. The experimental multiphase flow loop characteristics [12].

Number of phases	3 (oil/water/gas)	**Flow loop length**	200 m
Water capacity	40 m^3/h	**Tilt**	-6° to +10°
Gas capacity	205 m^3/h	**Pipe material**	Duplex steel
Oil capacity	40 m^3/h	**Water phase**	Formation water
Maximum pressure	110 bar	**Oil phase**	Crude oil
Temperature range	4 °C to 140 °C	**Max. oil viscosity**	200cP
Inner pipe diameter	77.9 mm (3 inch)	**Gas phase**	Hydrocarbon

Since the purpose of the test rig is to investigate multiphase flow, a number of scientific instruments are installed in the test sections. Some of these are off-the-shelf instruments, while others are custom made. To measure the pressure drop over a test section the MPFL is equipped with a variety of pressure transducers of various types and measurement lengths. The pressure drop data used in this study were acquired using a Rosemount 3051 pressure transducer where the pressure tapings are top mounted and gas filled. The impulse lines cover a measurement length of 28 m. Pressure drop data is recorded continuously with a measurement rate of 1 Hz.

2.2 Dual energy gamma densitometry

Dual-energy gamma densitometry is a powerful technique for monitoring multi-phase flow in pipelines [11-12,14-15,17-18]. By application of a multi beam instrument or a traversable single beam instrument information about the phase distribution can be obtained. Once the phase distribution is determined, it becomes possible in principle to determine the volume fraction of each phase. In practice, however, extraction of the phase fractions from the densitometer data is complicated because of the wide variety of phase configurations which can arise in addition to difficulties in modelling multi-phase flows.

A gamma-ray source has discrete energies. These energies are often in the range where Compton scattering is the dominating interaction mechanism. The attenuation caused by Compton scattering is proportional to the density of the material and therefore the measurements can be used to determine the density of a fluid in a pipeline. The traversable dual energy gamma densitometer instrument used in this work consisted of a 30 mCi Ba^{133} source and a CdZnTe detector. A short test section of the 3" pipeline where the dual energy gamma instrument is located is made of reinforced carbon fibre with a wall thickness of 10mm. Figure 2 shows the principle of the traversable dual energy gamma densitometer used in this study.

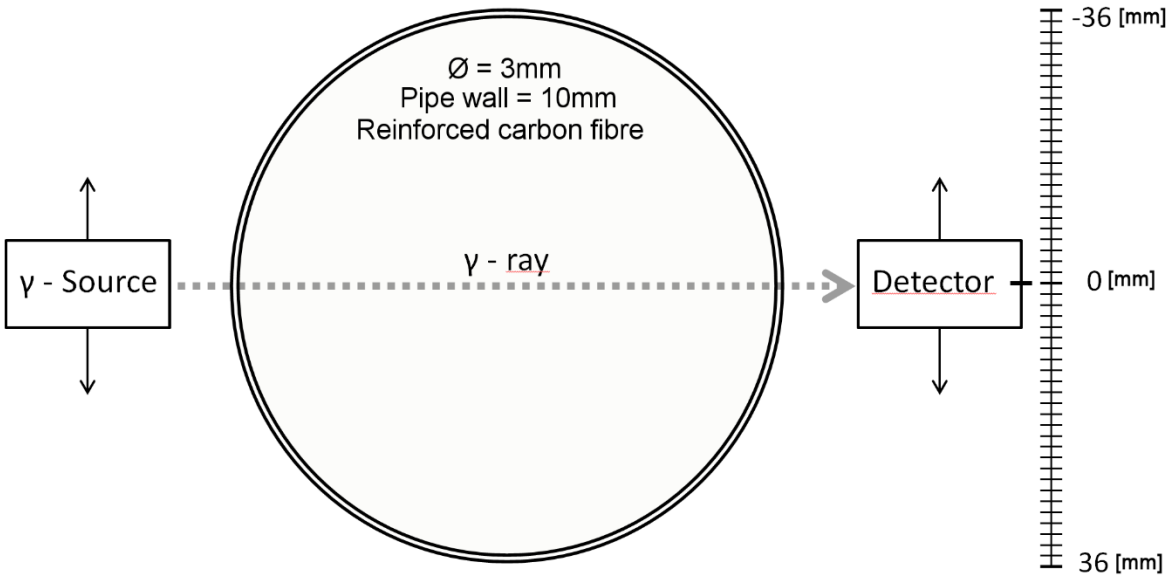

*Figure 2. Traversable dual energy gamma densitometer used to scan a pipeline. The γ-source (*30 mCi Ba^{133}*) and detector (*CdZnTe*) move simultaneously and measure in each of the discrete vertical pipe positions -36mm to 36mm indicated in the figure. The total volume fractions of gas, oil and water can then be estimated based on a 3-way partial least squares regression model.*

The distance between the source and detector is 105 mm. The detector unit has a 5 × 10 mm aperture lead collimator Hence, the nominal lateral width of the beam (at the collimator aperture) is 5 mm. When each multiphase flow experiment was considered to have reached stable conditions the dual energy gamma densitometer was traversed vertically and measurements were taken in a series of discrete vertical positions as can be seen in Figure 2. 37 different positions were defined equally distributed along the cross section of the pipe with an interval of 2 mm. Position 0mm is at the centre of the pipe and positions -36mm and 36mm are the top and bottom positions respectively. Measurement time in each position was 20 sec. When the source and detector assembly is traversed from one vertical position to another there will be a short period of signal loss, this is the disadvantage of a traversing instrument. The detector of the dual energy gamma densitometer recorded the energy spectrum with a sampling rate of 7 Hz which implies that approximately 140 spectra were recorded in each of the vertical positions. The spectrum in one position measured from time t_0 to time t_n is the sum of all the spectra from time t_0 to t_n. The intensity I at position x for a pipe filled with a single medium (single phase) is defined as:

$$I_m(x) = I_0 e^{-\mu d(x)} \qquad (1)$$

where μ is the attenuation coefficient of the medium and d(x) is the distance between the inner pipe walls at the vertical position x. To obtain the intensity of a spectrum n the $(n\text{-}1)^{th}$ spectrum was subtracted from the n^{th} spectrum and divided by the time difference between spectrum n and (n-1). The spectrum range was 0 - 500 keV. Since the intensity is calculated using an exponential function all the spectra were transformed using the natural logarithm for the purpose of linearizing the data prior to multivariate analysis and calibration. Figure 3 shows a typical spectrum of gas in position 0mm of the pipeline before and after the logarithmic transformation. The most dominant peaks shown in figure 3 correspond to 31 and 81 keV.

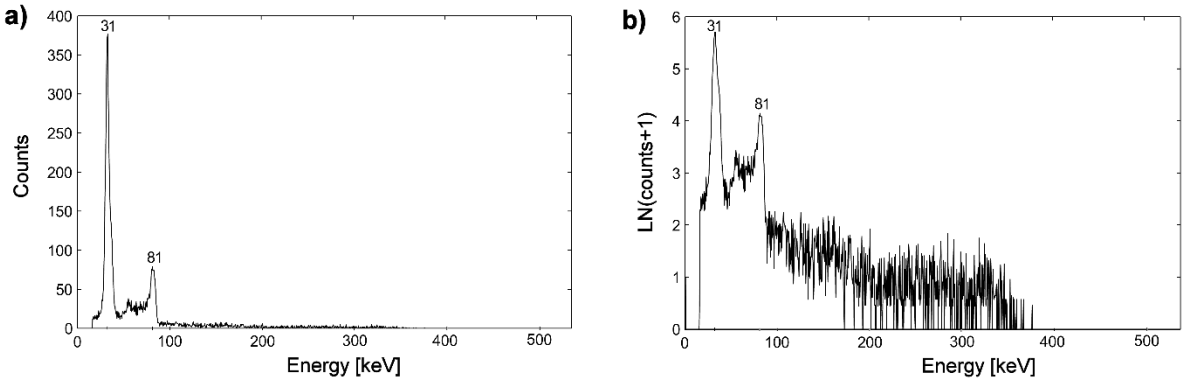

Figure 3. a) Dual energy gamma spectrum of gas measured in the centre (position 0mm) of the pipeline showing the two energy peaks 31 keV and 81 keV.b) the same gamma spectrum as in a) but here transformed using the natural logarithm as a linearization step prior to partial least squares regression modelling.

From interpretation of the multivariate models which is described in chapter 3 it was found that the energies 1-14 keV and 91-500 keV did not contain any information and most of these energies levels were zero. Therefore the data sets used in the multivariate analysis and modelling were all based on the energy range 15-90 keV.

2.3 Multiphase flow

Multiphase flow metering including estimation of volume fractions and flow regime identification has been an area of concern in most oil and gas drilling and refining sector. Since e.g. the fluids involved have different properties many different flow regimes (flow patterns) can occur in a multiphase flow pipeline.
For a more detailed explanation of multiphase flow, flow regimes and flow transitions, interested readers are referred to Mokhatab et al. [19].

2.3.1 Volume fractions

Information about the volume fractions in multiphase flow is important for flow rate allocation and efficient operation, which in term can lead to increased recovery. The volume fractions signify how much of the pipeline is occupied by gas, oil and water. In this study we only investigate horizontal pipelines and the volume fractions of gas, oil and water are reported in % of the pipe cross-section.

2.3.2 Multiphase flow regimes

The flow regime or flow pattern in the pipeline is a phenomenological description of the flow behaviour in the pipe. Real time information about flow regime is important e.g. for identification of slug flow. The parameters governing the differences in flow regime are operating conditions, fluid properties, flow rates, orientation of the pipe line (angle of inclination) and inner pipe diameter. The flow regimes investigated in this study includes; Stratified wavy flow, slug flow, dispersed and annular flow.

2.4 Experimental design

Both the single phase and three phase experiments were performed at realistic field conditions (p = 100 bar and T = 80 °C). The inlet conditions were constant in all experiments. After running single-phase calibration tests a series of two-phase and three phase experiments was conducted. However, only the three phase experiments are reported in this article. A series of 56 three-

phase experiments were conducted where seven superficial gas velocities (0.5 m/s . . . 5 m/s) were combined with eight superficial liquid velocities (0.42 m/s . . . 2 m/s). The first half of this series was oil-dominated with an oil/water ratio of 2, while the second half was water dominated with an oil/water ratio of 0.4. The flow regime map for the three phase experiments is not included here but can be found in Arvoh et al. [14].

When the fluid flow rates and flow conditions were decided upon in the present experiment, these parameters were kept constant during the measurements with the dual energy gamma densitometer. All measurements were taken in a horizontal section of the loop.
Maintaining the same flow pattern while taking measurements was very important because the traversable gamma instrument used several minutes to scan the entire cross section of the pipe and the measurements taken at the top must be comparable to those of the bottom since those spectra are used to estimate the same flow pattern. The gamma instrument measures each vertical position with a sampling rate of 7 Hz so detecting fast changing flow patterns such as slug flow locally in one position is not a problem. Only the transition from one vertical position to another will result in loss of data. Therefore, it is important that the measurements in subsequent positions are taken from the same flow regime since data from all the positions are used to identify the same flow regime.

Firstly single-phase experiments were conducted in order to obtain calibration data for all the vertical positions in the pipe After recording the calibration data, the key three-phase experiments were conducted according to a large set of test matrix in order to span all flow regimes and compositions.

2.5 Multivariate regression

The results obtained in this study are based on both Partial Least Squares Regression (PLS-R) from the earlier study and 3-way PLS-R for the prediction of the volume fractions. Theory and explanation of PLS-R and 3-way PLS can be found in literature [16, 20]. However, information on how the data was organized, basic interpretation of the plots and the 3-way PLS algorithm (see Appendix A) is included here.
3-way PLS-R is an empirical modelling approach requiring historical data spanning conditions expected to occur in the future. The data used for calibration of the 3-way PLS-R model is called X and y, where in this case X contains the gamma energy spectra and y is a vector containing the reference volume fractions of either gas, oil or water. Three separate models are required for prediction of the volume fractions of gas, oil and water. Calibration of a 3-way PLS-R model involves finding directions in the data structures often called latent variables or components which describe the variation in both X and y simultaneously. The number of components required to describe the variation in X and y can be found by interpretation of the errors resulting from testing the model on new independent data and compare the average prediction error calculated as a root mean square error of prediction (RMSEP) [20, 21]. The figures of merit which are used to interpret the model are normally plots of scores, loading weights, explained validation variance and predictions vs. references. The score plots are often plotted as a scatter plot using two components (latent variables). The score plot shows how the measurements (gamma spectra from different multiphase flow experiments) relate to each other. The score plots are often used to detect outliers in data which must be deleted to reach a stable solution. The loading weights plots are used to evaluate the importance of the variables. In this case there are two different variable directions (vertical pipe positions and gamma energy levels). The loading weights are directly related to the importance of the variables and are used for basic variable selection. The explained validation variance plot shows the RMSEP for each component and is used to determine how many components to use in the 3-way PLS-R model.

The component corresponding to the lowest RMSEP value is optimal. The predicted vs. measured plot shows how the 3-way PLS-R model performs on new independent test data. The reference values and the predicted values are plotted in a scatter plot for interpretation together with some statistical parameters reporting the prediction performance of the model.

In Arvoh et al. [14] three PLS-R models were calibrated for gas, oil and water in each of the 37 vertical position of the pipe. Prediction of gas oil and water volume fractions in each vertical position was necessary for flow regime identification. The only way to ensure reliable reference **y**-data for calibration of the PLS-R models was to calibrate the models using single phase experimental data.

In this study the data was organized differently to allow calibration of 3-way PLS models. Figure 4 shows how the calibration data from the gamma instrument was organized.

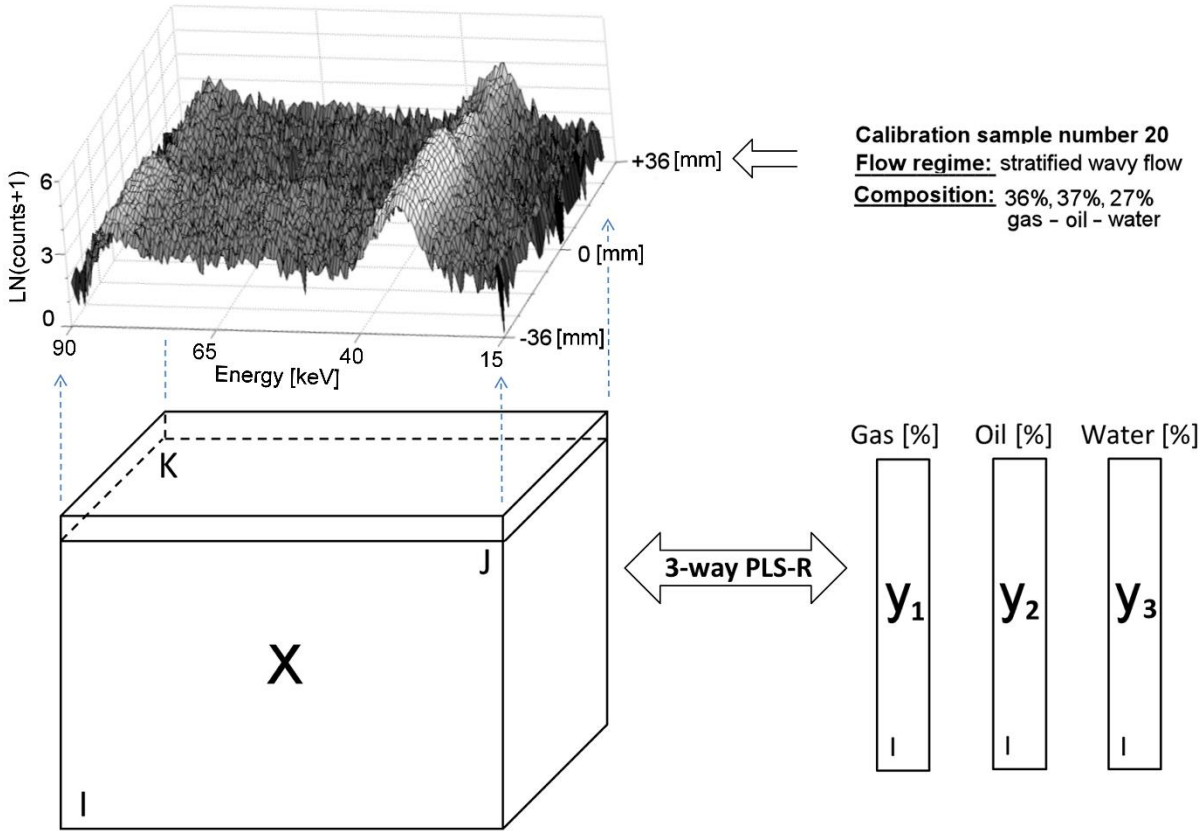

Figure 4. Organisation of gamma data for 3-way PLS calibration of the three separate models used to predict the total volume fractions of oil, gas and water. The so-called X data is a three way JxIxK cube where J is the gamma energy direction, I is the time direction, and K spans the vertical pipe positions from -36mm to 36mm with increment = 2mm. Calibration sample number 20 is shown above the X-data cube where the gamma measurements corresponding to total volume fractions of gas, oil and water = 36%, 37% and 27% respectively. The references needed for model calibration are shown as y1, y2 and y3 corresponding to the total volume fractions of gas, oil and water respectively. Three separate models are calibrated, one for each phase.

Each sample consists of gamma spectra from all the vertical positions of the pipe as can be seen in the upper part of Figure 4 where calibration sample number 20 is shown. The references $\mathbf{y}_1$,

$\mathbf{y}_2$ and $\mathbf{y}_3$ contain the volume fraction of gas, oil and water respectively and were used to calibrate separate prediction models for each phase. The reference volume fractions are based on data from the experiments described in Hoffman et al. [12]. The 3-way data matrix X is defined by J, K and I where J is the number of energy levels (75), K is the number of vertical positions of the pipe (37) and I is the number of samples (150). 150 samples containing 10 complete scans from 15 experiments with different conditions were used for calibration of the 3-way PLS models for gas, oil and water.

3. Results and discussion

In the 3-way PLS approach, the models were used to predict the composition in the entire pipe and not in each vertical position. Since reference data for the composition in each vertical position were not needed, models could be calibrated directly using the total volume fraction references, thereby avoiding the problems related to single-phase calibration.

3.1 Prediction of volume fractions

Data from 15 multiphase experiments spanning different compositions and flow regimes were used to calibrate the 3-way PLS models for volume fractions of gas, oil and water. All the models were test set validated [21] based on independent data from 15 multiphase experiments spanning different compositions and flow regimes.

Figure 5 shows the validation results for the model used to predict the volume fraction of gas in the pipe (models for oil and water are not shown here). The score plot of component one and two (t_1-t_2) shows the 15 multiphase flow calibration experiments represented as clusters of circles, one cluster for each of the 15 experiments. The numbers in the score plot indicates the reference volume fraction [%] of gas. The volume fraction of gas increase consistently along a direction explained by PLS component 1 and 2 as a broken line in the score plot in Figure 5. The score plot shows that experiments with similar gas volume fractions are located close to each other if they are projected down to the direction indicated by the broken line.

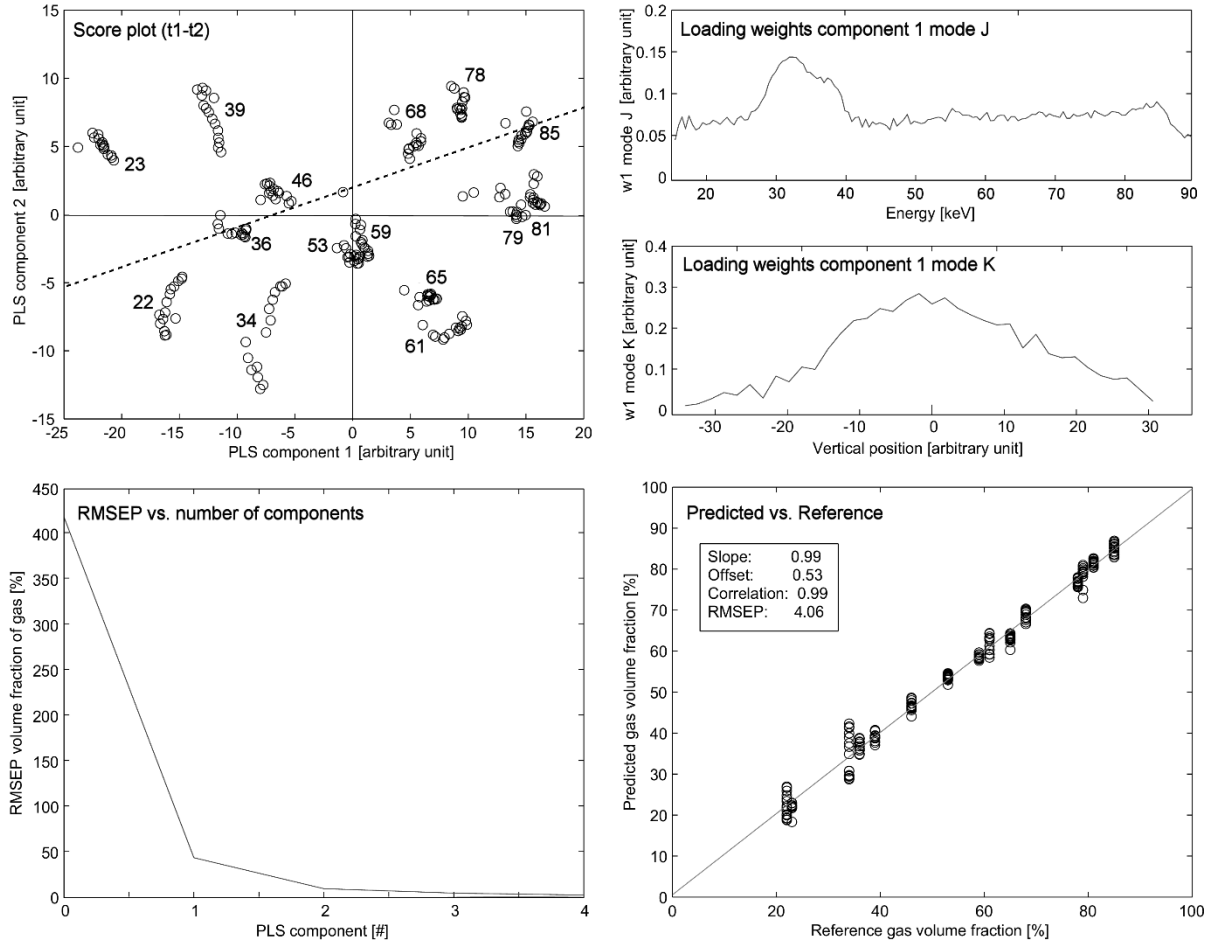

Figure 5. Validation results for 3-way prediction of volume fraction of gas. Upper left: Score plot t1-t2, the broken line indicates the variation direction of volume fraction of gas. The gas volume fraction is indicated by a number for each cluster. All 15 experiments follow the gas volume fraction direction so no outliers were detected in the score plot. Upper right: Loading weights (w1) for mode J (energy spectrum) and K (vertical pipe positions). The loading weights show the importance of the variables. e.g. the peak observed at energy level 31-33 keV is most important along mode J as this range has the highest loading weight, while the most important vertical position (highest loading weight values) along mode K are the ones in centre of the pipeline, and the extreme positions -36mm and 36mm are the least important positions for prediction of gas volume fraction. Lower left: RMSEP for components 1-4 showing the prediction error for models with components from 1 to 4. 2 components were selected in the model as the decrease from component 2 to 3 and 3 to 4 is not significant. Lower right: Predicted gas volume [%] vs. reference gas volume [%] showing that gas volume fraction can be predicted reliably with an average prediction error (RMSEP) of 4%.

The loading weights (w_1) for variable direction J and K shows how each variable contribute to modelling of the gas volume fraction. A loading weight value significantly different from zero indicates that the corresponding variable is important for the model. Loading weights (w1) for mode J indicate that the most important variables are the ones in the range 31-33 keV while the range 81-85 keV contains the second most important energy levels. This is as expected since the gamma instrument used in these experiments has the two energy levels 31 and 81 keV. The loading weights (w_1) for mode K shows that the most important energy spectra for prediction of volume fraction of gas are those taken in the centre section of the pipe (the vertical positions around zero mm). The reason for this is probably that the gamma ray travels a relatively long distance in fluid in contrast to the distance in the wall of the pipe. In the extreme positions -

36mm on top and +36mm at the bottom, the signal to noise ratio is low for the opposite reason, i.e. because of the relatively long traveling distance in the pipe wall.
The average prediction error (RMSEP) is used both for determination of model complexity and to evaluate the prediction performance of a model. The RMSEP is calculated in original units which in this case is volume fraction [%]. RMSEP is defined as:

$$RMSEP = \sqrt{\frac{\sum_{i=1}^{I}(\mathbf{y}_{predicted} - \mathbf{y}_{reference})^2}{I}} \qquad (2)$$

where $\mathbf{y}_{\text{predicted}}$ is the prediction corresponding to $\mathbf{y}_{\text{reference}}$ and I is the number of samples in the validation data set.
A PLS model for gas volume fraction with two components is optimal as can be seen in in Figure 5 where the RMSEP is plotted for components one to four. The effect of adding a third and fourth component is superfluous since the decrease in RMSEP is not significant for the components 3 and 4. The final validation results based on the two component model is shown in the predicted vs. measured plot (Figure 5, lower right). RMSEP for the volume fraction of gas is 4.1%. The modelling results for oil and water (not shown here) resulted in RMSEP values of 4.3 % and 4.0% respectively, while in Arvoh et al [14] the corresponding RMSEP values for gas, oil and water were 6.5, 8.9 and 4.4% respectively..
The combined predictions of gas, oil and water were scaled to 100% total volume and plotted beside the corresponding reference values for all the 15 validation experiments as can be seen in Figure 6.

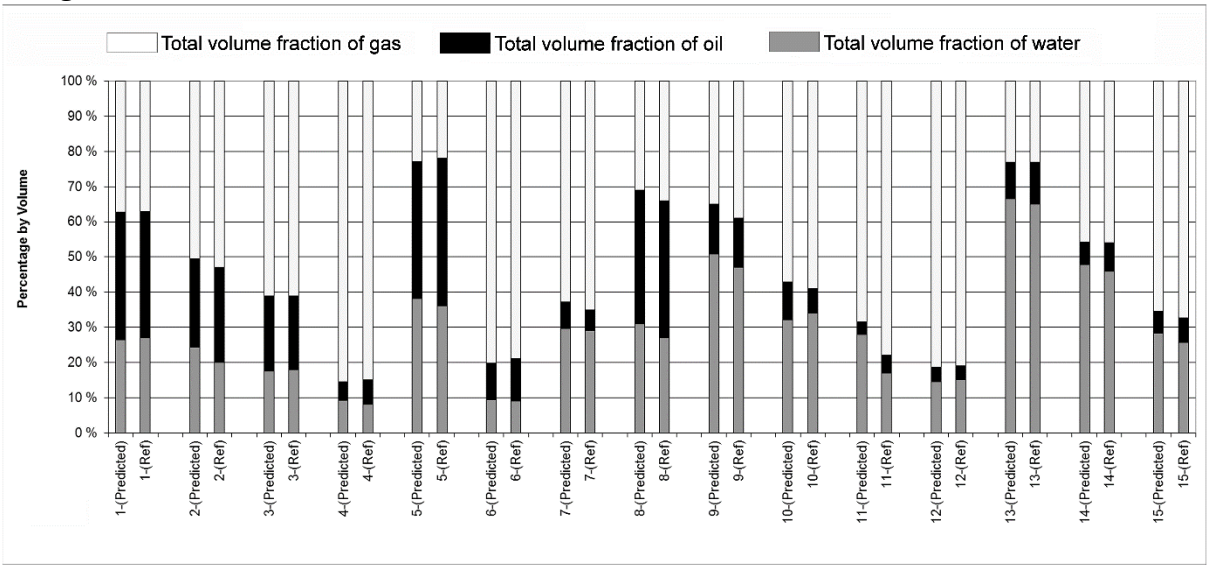

Figure 6. 3-way PLS predictions of volume fractions of gas, oil and water in 15 multiphase flow experiments spanning different compositions and flow regimes. The water fraction is shown in grey while the black and white are the oil and gas fractions respectively. The 15 pairs of stacked bar plots correspond to the 15 multiphase flow experiments. For each experiment (each pair) the left shows the predicted volume fractions of gas, oil and water stacked upon each other to a total of 100%, while the right one shows the corresponding reference volume fractions.

As can be observed from Figure 6 the combined prediction results shown as stacked bars agrees well with the references also plotted as stacked bars. The total volume fraction of gas, oil and water are shown in white, grey and black respectively.
The 3 way PLS-R models use the multi-way data structure along both the energy direction and vertical position direction simultaneously utilizing the multivariate information to estimate the total volume fractions. The modelling approach previously reported in Arvoh et al [14, 15] utilized only the energy direction, thus a much larger numer of models (111 models in total) had to be used to cover the vertical positions of the pipe. The total error from combining such

a high numer of predictions to estimate the total volume fractions were significantly higher than what was gained in this study.
The 3-way PLS-R model predict the total volume fractions of gas/oil/water seven times a second (corresponding to the 7Hz sampling rate of gamma spectra, and thus makes it possible to monitor changes in the volume fractions over time. The data slice used to predict the volume fractions of gas, oil and water from one sample is indicated in Figure 4.
The 3-way PLS-R approach can also be applied in combination with a multi beam instrument directly. The advantage of the multi beam appraoch would be accurate total volume fractions even when the total volume fractions are changing much faster than what was the case in the experiments used in this article. The prediction errors reported here are based on experiments with constant inlet conditions. Fast changes in volume fractions will lead to higher prediction errors than what is reported here.

3.2 Multi phase flow regime identification

3-way PLS predictions cannot be used for flow regime identification directly since these models predict the volume fraction in the entire pipe only and provides no information about the spatial phase distribution in the pipe. Flow regime identification can be accomplished however, using the PLS models reported in Arvoh et al. [14] in combination with the present 3-way PLS models. In Arvoh et al [14] it was reported that the total volume fraction of oil was consistently over-predicted. Since the volume fractions of oil, gas and water were scaled to 100%, the over-predicted oil fraction also affected the volume fractions of the other two phases. In this study the results reported in Arvoh et al are corrected based on the much more accurate total volume fraction predicted by the 3-way PLS-R models developed here. Since the total volume fraction of oil was calculated as the sum of the oil predictions in all the 37 position in the study by Arvoh et al, all these predictions were corrected (scaled down) using the more correct sum predicted by the 3-way models. The volume fractions of gas, oil and water in each position were scaled so that the total volume fractions (the sum over all vertical positions) were equal to the total volume fractions predicted by the 3-way PLS-R models. The volume fractions after correction represent a much more correct distribution of phases in each vertical position, thus makes the flow regime identification plots more correct and somewhat easier to interpret.
Figure 7 compares results from Arvoh et al. [14] with the same plots corrected using the predictions from the 3-way PLS models where the degree to which a slight improvement in multi-phase flow regime characterization is graphically prominent.

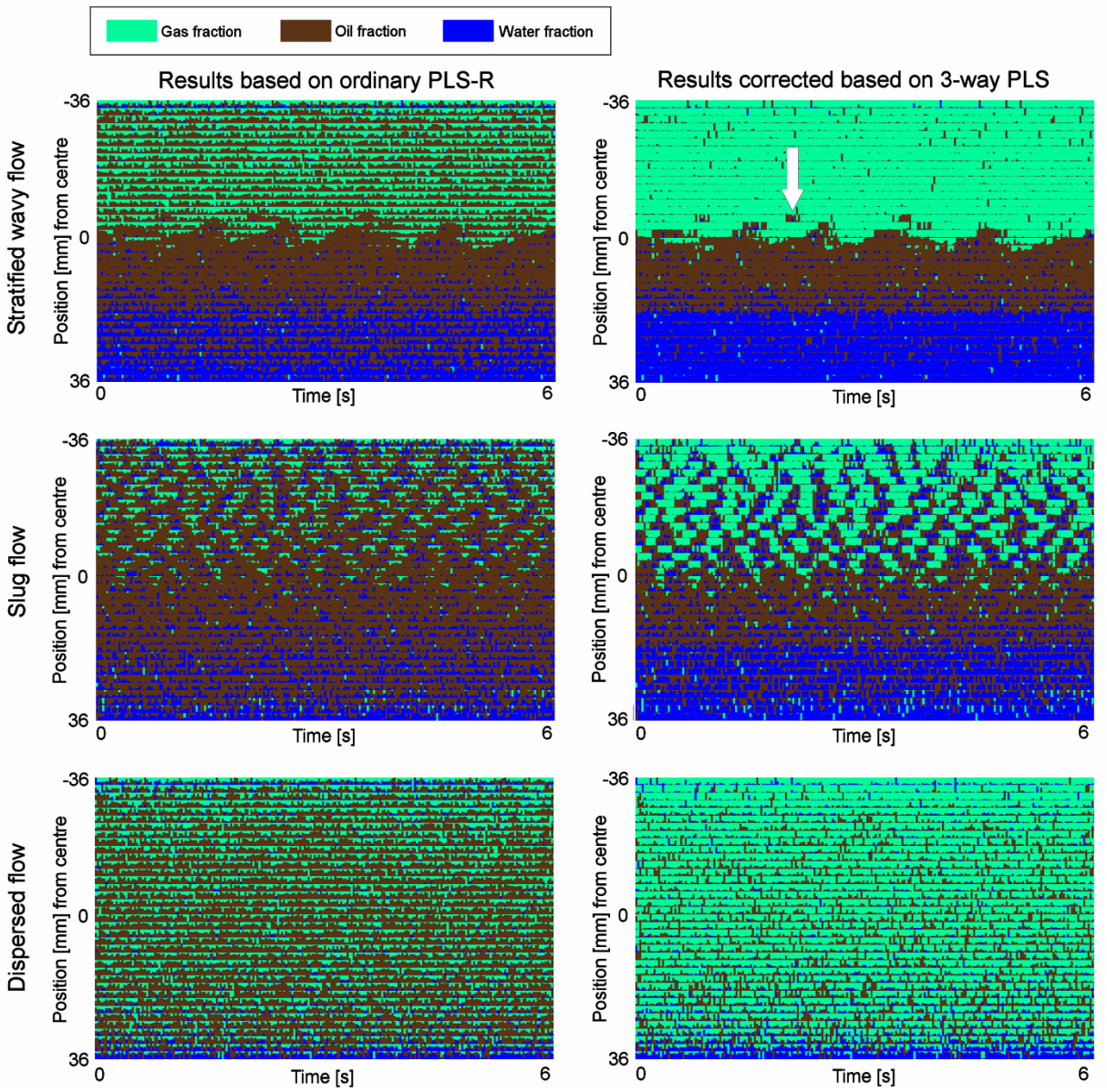

Figure 7. The left column of plots shows the flow regime identification results reported in Arvoh et al. [14], while the plots in the right column which is based on the same experimental data show the corrected results based on 3-way PLS predictions of the total volume fractions developed in this study. The rows show results from experiments with different flow regimes. Row 1: stratified wavy flow, row 2: slug flow and row 3: dispersed flow. The total time shown in each of the six plots is six seconds. Vertical position -36mm is the top of the pipe, while 0mm and 36mm is the centre and bottom respectively. The green colour represents the gas fraction while the dark red and blue colour represents the oil and water fractions respectively. The waves can be observed for the stratified wavy flow, although the vertical positions were not measured at the same time since a traversable gamma instrument was used. The arrow shows a wave top which is shifted in time relative to the position below. In the slug flow the slugs can be observed in the upper half (positions 0 to -36)) of the pipeline. The results for the dispersed flow show an even distribution of gas and oil and some water at the bottom and top of the pipeline. The volume fraction of water was 7% in this experiment. The water which can be seen in the upper positions (-36mm and -34mm) is an error caused by the relatively low signal to noise ratio in these positions. The arrow indicates the top of a wave which is not aligned with the rest of the wave in the position below due to the traversing instrument measuring the positions sequentially and not simultaneously.

The gamma measurements which are used for prediction of composition in each vertical position are recorded at different times. The time difference between the vertical positions results in predictions which does not correspond (in time) to the other positions, and horizontal shifts can be observed. The time shifts can clearly be observed in the stratified wavy flow shown in row 1 in Figure 7 in which wave tops are shifted in time with respect to positions below because the traversable gamma instrument measure the vertical positions of the pipe sequentially. The arrow shown in figure 7 indicates the top of a wave which is shifted in time (horizontally) with respect to predictions in the position below. Since the experimental conditions are kept constant while the sequential gamma recordings are taken, all the vertical predictions are based on the same flow regime and perfect alignment of the predictions in all the vertical positions is not always possible. Alignment of prediction results from the different vertical positions is not necessary for predicting the total volume fractions based on 3-way PLS-R since the data is organized differently and no information about the spatial distribution of oil, gas and water is provided. Alignment is an issue only in the flow regime identification plots resulting from ordinary PLS-R predictions.

The flow regime identification plots which were corrected based on the 3-way PLS results which enhanced the interpretation although it was still possible to accurately identify the flow regimes shown in figure 7 based on the ordinary PLS approach alone. The plot of stratified wavy flow in Figure 7 contain too much oil in all vertical positions in the left column while in the corrected plots shown in the right column the amount of oil is significantly decreased, and more in accordance with the reference density measurements available for those experiments [12]. The corrected flow regime identification plots for slug and dispersed flow are also improved and slightly easier to interpret due to lower prediction errors in the local phase distributions in each vertical position.

Conclusion

Dual energy gamma densitometry and 3-way PLS regression were applied to predict the total volume fractions of gas, oil and water in 15 multiphase flow experiments spanning typical and realistic flow regimes and volume fractions for: stratified wavy, slug and dispersed flow. The RMSEP for prediction of volume fractions of gas, oil and water were 4.1 %, 4.3 % and 4.0% respectively. The 3-way PLS approach predicted the total volume fractions more accurately than what have been reported earlier [14, 15]. The results from 3-way PLS cannot be used to identify flow regime directly since the predictions report the total volume fractions in the pipe and no information about the spatial phase distribution is provided. Flow regime identification was managed using flow regime identification results based on ordinary PLS-R which were corrected based on the more accurately predicted volume fractions from the 3-way PLS models making regime identification more comprehensive and easier to interpret. Flow regime identification plots showing stratified wavy, slug and dispersed flow were used as an example. All the corrected plots were slightly easier to interpret than the plots without correction because the prediction errors were significantly decreased.

Ordinary PLS-R can be used to identify flow regimes in multiphase flow but the predictions of volume fractions are not acceptable. 3-way PLS can be used to predict the volume fractions more accurately, and a combination of PLS-R and 3-way PLS can be used for prediction of volume fractions, and enhanced flow regime identification in multiphase flow.

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Appendix A: 3-way Partial Least Squares Regression

In 3-way PLS individual models of **X** and **Y** are defined as:

$\mathbf{X} = \mathbf{T}\,\mathbf{P}' + \mathbf{E}$

$\mathbf{Y} = \mathbf{T}\,\mathbf{Q}' + \mathbf{F}$

Where **T** contains the score vectors and **P** and **Q** contain the loading vectors for **X** and **Y** respectively. E and F are the residuals corresponding to X and Y respectively. The aim is to determine loadings for the **X** and **Y** models so that the scores T and U have maximum covariance. Hence, PLS regression tries to model **X** and **Y** using the common components in **T**. The so-called tri-PLS1 algorithm for one response variable **y** can be found below.

A matrix of independent data **X** (*I x J x K*) and a vector of dependent reference data **y** (*I* x 1) are required for calibration of the tri-PLS1 model. The algorithm below was used to calibrate all the 3-way PLS models reported in chapter 3.

Prior to calibration, both the independent data **X** and the single response reference **y** are centred along the first mode (the sample mode).

Tri-PLS1 algorithm

Let $f = 1$

1. Calculate $\mathbf{Z}_f$ where the elements are found from $z_{jk} = \sum_{i=1}^{I} y_i x_{ijk}$
2. Determine $\mathbf{w}_f^J$ and $\mathbf{w}_f^K$ as the first left and right singular vectors of $\mathbf{Z}_f$ respectively
3. Calcualte $\mathbf{t}_f$ from $\mathbf{t} = \frac{\mathbf{Xw}}{\mathbf{w}'\mathbf{w}} = \mathbf{Xw}$ where $\mathbf{w} = \mathbf{w}^K \oplus \mathbf{w}^J$
4. $\mathbf{b}_f = (\mathbf{TT})^{-1}\,\mathbf{T}'\mathbf{y}$ where $\mathbf{T} = [\mathbf{t}_1, \mathbf{t}_2, \ldots, \mathbf{t}_f]$
5. Each sample $\mathbf{X}_i$ is replaced with the residual $\mathbf{X}_i - \mathrm{t}_{if}\mathbf{w}_f^J\left(\mathbf{w}_f^K\right)'$ and $\mathbf{y} = \mathbf{y} - \mathbf{Tb}_f$

The steps 1-6 above are repeated until *f*=*A* where *A* is the optimal number of components in the model.

A is determined from interpreting the residual variance plot showing the variance of the residual for each component.

X *(I x J x K)* = A multidimensional matrix of independent measurement data where J is the first mode (samples) and J the second mode (variable mode *J*) and *K* is the third mode (variable mode *K*).

Y *(I x 1)* = Dependent reference data where I is the number of samples.

f = component number

$\mathbf{Z}_f$ = A matrix defined as the inner product of **X** and **y** for calculation of component *f*

$\mathbf{w}_f^J$ = Loading weights along mode *J*, for component *f*

$\mathbf{w}_f^K$ = Loading weights along mode *K*, for component *f*

$\mathbf{t}_f$ = Score values for component *f*

T = Score matrix, $\mathbf{T} = [\mathbf{t}_1, \mathbf{t}_2, \ldots, \mathbf{t}_f]$

$\mathbf{b}_f$ = regression coefficients based on *f* components

A = the optimal number of components in the model