SPE-205405-MS

A Real-Time Fiber Optical System for Wellbore Monitoring: A Johan Sverdrup Case Study

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This paper was prepared for presentation at the SPE Offshore Europe Conference & Exhibition held virtually on 7 - 10 September 2021.

Abstract

Fiber Optic (FO) sensing capabilities for downhole monitoring include, among other techniques, Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS). The appeal of DTS and DAS data is based on its high temporal and spatial sampling, allowing for very fine localization of processes in a wellbore. Furthermore, the broad frequency spectrum that especially DAS data is acquired with, enables observations, ranging from more continuous effects like oil flow, to more distinct effects like opening and closing of valves.

Due to the high data volume of hundreds of Gb per well per hour, DAS data has traditionally been acquired acquisition-based, where data is recorded for a limited amount of time and processed at a later point in time. This limits the decision-making capability based on this data as reacting to events is only possible long after the event occurred. Equinor has addressed these decision-making shortcomings by building a real-time streaming solution for transferring, processing, and interpretation of its FO data at the Johan Sverdrup field in the North Sea.

The streaming solution for FO data consists of offshore interrogators streaming raw DAS and DTS data via a dedicated bandwidth to an onshore processing cluster. There, DAS data is transformed into FO feature data, e.g., Frequency Band Energies, which are heavily decimated versions of the raw data; allowing insight extraction, while significantly reducing data volumes. DTS and DAS FO feature data are then streamed to a custom-made, cloud-based visualization and integration platform. This cloud-based platform allows efficient inspection of large data sets, control and evaluation of applications based on these data, and sharing of FO data within the Johan Sverdrup asset.

During the last year, this FO data streaming pipeline has processed several tens of PB of FO data, monitoring a range of well operations and processes. Qualitatively, the benefits and potential of the real-time data acquisitions have been illustrated by providing a greater understanding of current well conditions and processes. Alongside the FO data pipeline, multiple prototype applications have been developed for automated monitoring of Gas Lift Valves, Safety Valve operations, Gas Lift rate estimation, and monitoring production start-up, all providing insights in real-time. For certain use cases, such as monitoring production start-up, the FO data provides a previously non-existent monitoring solution.

In this paper, we will discuss in detail the FO data pipeline architecture from-platform-to-cloud, illustrate several data examples, and discuss the way-forward for "real-time" FO data analytics.

Introduction

Fiber Optics (FO) based sensing has been used in the oil and gas industry for over 20 years with the first downhole installation in 1993 which was a simple point pressure and temperature sensor in a land well in the Netherlands (Johannessen et al., 2012). Since then, it is has become an invaluable option for permanent in-well monitoring systems in offshore wells, and an increasing number of onshore wells (Canon and Aminzadeh, 2013).

Today, commercial FO sensing capabilities for downhole applications include (modified after Johannessen, 2012):

- Pressure and Temperature
- Distributed Temperature Sensing (DTS)
- Flow and Fraction Meters
- Seismic Accelerometers
- Distributed Acoustic Sensing (DAS)
- Distributed Strain Sensing (DSS)

Equinor focused on obtaining the ability to measure acoustic and temperature signals along its wellbores in the Johan Sverdrup field in the North Sea with the aim to optimize operation of its wellbores.

Distributed Temperature Sensing (DTS) is a passive fiber optic sensor technology that can measure temperature changes along the length of the fiber (Smolen and van der Spek, 2003, Hemink and van der Horst, 2018). A laser pulse is sent down the fiber and the back-scattered light is used to estimate the temperature. The Raman band of the back-scattered light is used for making DTS measurements. Frequency shifts associated with the Raman band are called the stokes and anti-stokes components of the backscatter. Since the fiber itself is sensitive to temperature, the amount of frequency shifts in the anti-stokes band can be correlated to temperature (Cannon and Aminzadeh, 2013).

Distributed Acoustic Sensing (DAS) is another passive fiber optic sensor technology that can detect acoustic waves anywhere along the length of the fiber with a very high spatial resolution and broad frequency response (Cannon and Aminzadeh, 2013). DAS systems are often dependent on detection of phase differences on the back scattered signal in the Rayleigh spectrum of the laser light (Hartog, 2017). The change of the phase between two different elements along the fiber for two laser pulses is proportional to the change in length along the fiber between these elements (Masoudi et al., 2013). This can be exploited to measure the strain along the fiber optic cable.

The appeal of both DTS and DAS data is based on its high temporal and spatial sampling, allowing fine localization of processes in a wellbore. For the Johan Sverdrup field, the typical DAS measurement setup is a spatial sampling at 1 m and temporal sampling at 10000 Hz. In contrast to that DTS is spatially sampled at 0.25 m and temporal at 0.0166 Hz. Furthermore, the broad frequency spectrum that DAS data is acquired with, enables observations ranging from more continuous effects, e.g., oil flow, to more distinct effects like opening and closing of valves (Canon and Aminzadeh, 2013).

The biggest hurdle for enabling distributed sensing technology to deliver on its full potential is to incorporate the data in an effective data stream from platform-to-cloud. While data volumes for DTS are relatively small, a typical DAS recording often produces hundreds of Gigabytes per well per hour. Due to this, DAS and DTS have traditionally been acquired acquisition-based, meaning that data was recorded and stored on an offline storage medium that was then transported to a processing center which produced results in a matter of days or weeks. This restricted potential decision-making efforts to long after the event occurred (Schuberth, 2020). Equinor wanted to significantly improve this situation for the Johan Sverdrup field especially for data acquisitions related to monitoring of in-flow in productions wells and oversight of valve operations. Therefore, a project focusing on building a real-time streaming solution for transferring, processing, and interpretation of FO data was initiated.

Fiber Optic Streaming Solution

Johan Sverdrup's streaming solution for DAS and DTS data consists of three main parts (see Figure 1). In the first step, the vendor provided fiber optic interrogators offshore are streaming raw DAS and DTS data via a dedicated cable to shore. Secondly, a High Performance Computing (HPC) processing cluster called *fibra* transforms the data into FO feature data, a transformed and heavily decimated version of the raw FO data that still maintains certain aspects of the information content. Thirdly, FO feature data are streamed to a custom-made, cloud-based visualization, integration and application platform called *fo.tone* which ingests the FO feature data and makes it available for user and/or application interaction.

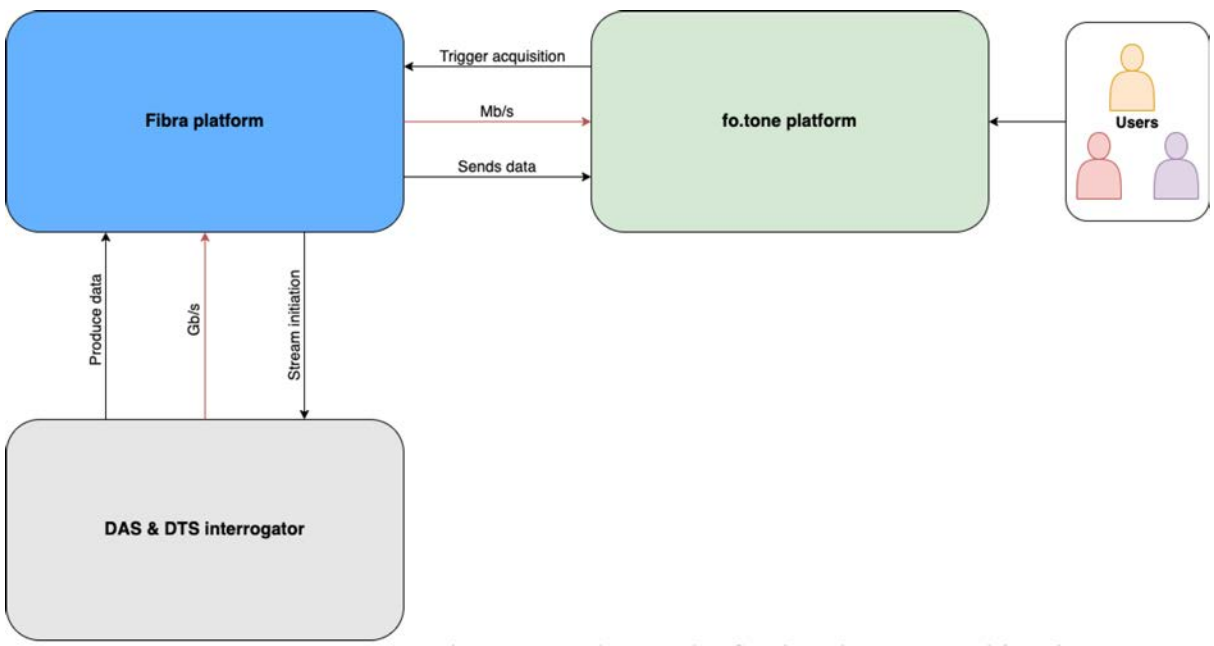

Figure 1—Schematic illustration of the Fiber Optic Data pipeline on Johan Sverdrup, data is streamed from the interrogators offshore to the fibra platform for processing & decimation and the streamed further to the fo.tone platform for user interaction in real-time.

The approach taken by the project is, to our knowledge, a first of its kind - streaming the raw FO data from the vendor into a custom designed platform that allows for maximum flexibility and interaction when processing the data.

To deliver on the project goals, which at the start of the project had large risks associated with it, the system needed to fulfil several criteria that would allow future maintainability:

- Flexibility: the Johan Sverdrup asset needed to retain full flexibility to develop, integrate, and deploy its own algorithms without involving vendors.
- Reliability: the system needed to be able to run for long periods of time without requiring any interference.
- Independence: all vendor-facing interfaces needed to be standardized via a single Application Programming Interface (API) across vendors

- Scalability: The entire solution needed to be deployable on- and offshore with standardized hardware solutions.

Offshore Interrogators

The Johan Sverdrup asset made the decision to purchase Fiber Optic interrogators from different vendors and install them offshore on the field center.

For the DTS interrogators, a basic solution was sufficient. One interrogator has multiple channels that are interrogated regularly by looping over them. With a measurement time of about 60 s and several other wells connected, the data update frequency is *number of wells * 60 s*. This means that every minute the DTS instrument will produce a data package for a different well, that can be parsed and sent to the *fo.tone* database.

For the DAS interrogators, it was contractually agreed that upon delivery of these, the vendors should adhere to Equinor's FO data streaming standard[1] that is based on the Apache Kafka streaming platform (Shree et. al, 2017) and the Apache Avro data format[2]. Additionally, the interrogators should be steerable via an API so that streams and parameters could be changed programmatically which enabled remote operations without the need to send personnel offshore.

As there are less interrogators available on Johan Sverdrup than there are wellbores with FO cables installed, an ad-hoc and scheduled switching methodology for the interrogation to all wells needed to be created. This was achieved by introducing FO switches that enabled one interrogator to acquire data on multiple fibers. One DAS interrogator on the Johan Sverdrup platform can be used to acquire data on up to eight fibers, similarly for the DTS interrogators setup. In contrast to the cycling DTS acquisition schedule, the DAS interrogators typically acquire data on one fiber for a longer period of time (> several hours) and then switch over to the next fiber.

The major difference between DTS and DAS acquisition arises from the data volumes DAS is producing. With the typical acquisition setup on Johan Sverdrup a single DAS acquisition produces several hundreds of GBs per hour, while DTS acquisition only produce several MBs for the same time range.

DTS systems package data and meta data together into one file that is then self-contained. In contrast to that, the DAS streaming system needed to split the data transfer into two steps in order to enable near real-time/live data transfer:

- First, *fibra* and the DAS interrogator send the meta data associated with the requested / beginning DAS data acquisition, the so-called handshake.
- Second, the DAS interrogator then streams the data and the associated recording timestamps as numerous small packages.

The handshake is the initiation step between the *fibra* HPC cluster and the vendor system. A *PRODML DASAcqusitionProfile* object[3] serves as the carrier of all meta data information that *fibra* sends to the vendor system offshore requesting a data acquisition. The vendor system then checks if the combination of interrogator and optical fiber is available, parses the configurations of the laser, and prepares the operation. The feedback on acquisition preparation is sent back to *fibra* again as a *PRODML DASAcquisitionProfile* object. Thus, the meta data makes a roundtrip between *fibra* and the interrogators enabling checking of the acquisition settings. After a successful meta data exchange, *fibra* delivers a set of endpoints to the interrogators where the data packages will be streamed to.

Processing Platform, *fibra*

Fibra is the Johan Sverdrup FO data pipeline HPC cluster, receiving the streamed raw DAS & DTS packages via a dedicated cable/bandwidth from the interrogators offshore. The broad bandwidth to shore enabled placing the HPC cluster onshore. This makes the cluster easily accessible to personnel working with it, which proved to be beneficial especially during initial development phases. In the meantime, the *fibra* solution is matured and the whole system is available as *infrastructure as code,* making it also possible to deploy this solution close to the interrogators, e.g., offshore in regions with bandwidth restrictions.

Fibra's two main tasks are decimation and transformation of the in-coming FO data into FO feature data and then sending those on to FO cloud platform, all in near real-time.

Fibra is a Kubernetes cluster (e.g., Medel et.al., 2016) that is specifically designed to handle variable compute loads. It allows for dynamic deployment of Docker Containers / Virtual Environments (Merkel, D., 2014) so that tasks (streaming, processing, storing, etc.) can be executed fully flexible and on demand. The streaming is enabled via the Apache Kafka platform, which allows very close cooperation with the underlying hardware system, thus making optimal use of the available compute resources.

The *fibra* cluster is essentially divided in three parts:

1. The ingress part of the cluster which handles all in-coming data and distributes the load according to the specified processing needs
2. The processing part of the cluster which turns the raw FO data into FO feature data, allowing it to send the FO feature data to the cloud-based FO visualization & integration platform
3. The cold part of the cluster which stores raw FO data for up to five days at full load until it is overwritten again. This allows more detailed inspection of the raw FO data for a limited amount of time.

The processing of the cluster is implemented dynamical, e.g., *fo.tone* users can specify which FO features should be calculated and also specify the corresponding parameters of these computations. For example, the start- and end-frequencies of the so-call Frequency Band Energies (FBE) features, i.e., the energy within a certain part of the FO data spectrum, can be specified per acquisition. All algorithms running on *fibra* are implemented independent of any vendor specifications, thus, new processing algorithms can be implemented in a general manner, and less work needs to be spent on custom adaption.

Considering the several hundreds of GBs that one well on Johan Sverdrup is generating per hour in DAS data, decimation of is key to being able to send this to a cloud setting enabling numerous users to see the data at the same time independent of their location. This decimation is called FO feature computation. To give an example of the decimation rate that the *fibra* platform can achieve, one can look at Figure 2. Here, the decimation of FO raw data into FO feature data is illustrated via an FBE calculation. Per element along the fiber, *fibra* aggregates packages until 8192 samples are contained in a buffer. A Fast Fourier Transform (FFT) is applied, the real part of the complex result extracted, and then the energy within a frequency range computed. The operation results in a data decimation of 8192 samples to 1 per loci. For the chosen setup on Johan Sverdrup, this means that the DAS data volume is reduced from hundreds of GBs per well per hour to hundreds of MBs per well per hour. These or similar decimation operations depending on the interrogation settings and FO Feature processing algorithm enables real-time streaming to the cloud platform *fo.tone*.

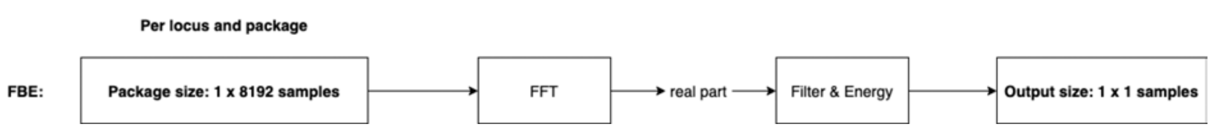

Figure 2—Schematic illustration of the decimation for a Frequency Band Energy (FBE) calculation. A data decimation of 8192 to 1 per locus along the fiber is achieved.

Upon request, *fibra* can also send raw FO data to *fo.tone* and thus enable raw data processing in the cloud. However, due to data amounts this is only used for certain use cases where a more detailed inspection of the underlying data is necessary or for general archiving purposes of crucial data sets.

Visualization and Integration Platform, *fo.tone*

fo.tone is a FO data integration, visualization, and application hosting platform, allowing inspection of large FO data sets, steering and evaluation of applications based on these data. It is implemented as a web-based application consisting of a back-end and front-end service. The back-end collects and processes the FO feature data and its respective meta data. The front-end provides insight and integration possibilities for fiber optic data combined with wellbore and process data. The whole platform is built on a cloud platform and makes heavy use of some of the latest technologies with regards to streaming and databases.

Figure 3 shows an architectural diagram of *fo.tone*. When data is streamed to *fo.tone*, it follows the principals set by the *fibra* / interrogator handshake, that meta data and data are sent separately for efficiency reasons. Meta data is sent to a messaging service (*Service Bus Queue* in Figure 3) which parses the meta data and stores it in a relational database. DTS data as well as DAS feature data is streamed to an event ingestion service (*Event Hub* in Figure 3) and then stored in an instance of unstructured databased (*MS Azure ADX* in Figure 3). This is a data analytics cloud platform and data exploration service, which handles large amounts of data efficiently. The architecture as illustrated in Figure 3 ensures that all data is retrievable and allows for efficient database queries by several users at the same time.

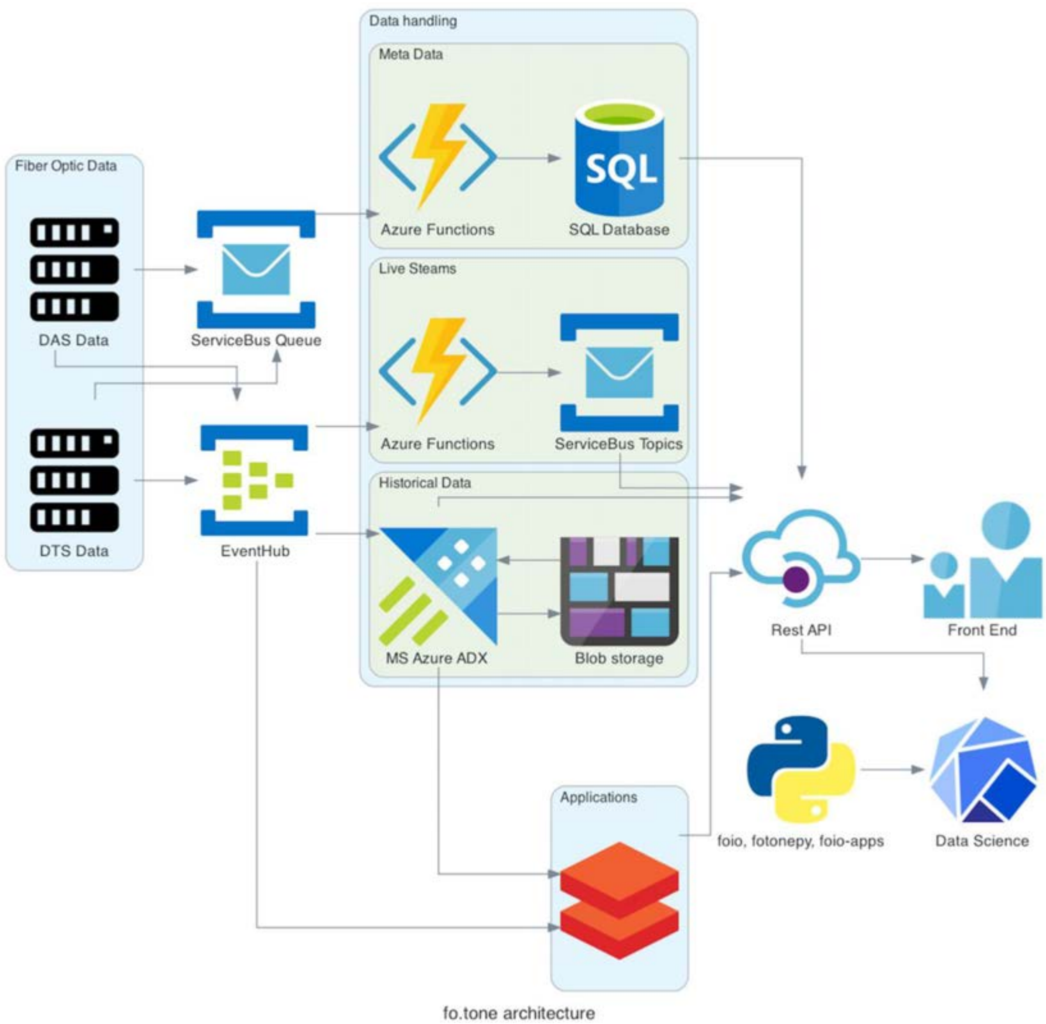

Figure 3—Architecture Diagram of the fo.tone platform. FO data is streamed into the platform and efficient handling of the data allows "live" user inspection of events happening in the connected wellbores.

In order to facilitate *live* DAS feature data viewing in *fo.tone*, the solution needed to keep the latency as small as possible in order to give a satisfying user experience. For the Johan Sverdrup, FO feature data is typically sampled every 0.8192 s after the decimation processes on *fibra*. To keep up with these sampling rates and being able to display them real-time in a web browser, a third data flow was enabled (see top data flow in Figure 3) that sends *live* FO feature data directly to a messaging service instance that only serves the front-end with a live feed as it is requested by the user.

All communication between front-end and back-end is handled via the *fo.tone* API, allowing clear specifications for what data to request and which to provide. The front-end is programmed highly modular to accommodate future changes. Furthermore, it is optimized for ease of use and performance so that the user experience is intuitive and fast.

Figure 4 shows a screenshot of the *fo.tone* main FO feature inspection view. The central element is a heatmap, showing the FO feature data in depth (vertical axis) and time (horizontal axis). The data is contextualized with a wellbore completion diagram (right hand side) as well as single point sensor data (top trace plot). The user inspects data in a Google Maps like fashion, starting from a wide zoom covering long time ranges and then inspecting interesting features in more detail. Alternatively, data can also be accessed via specified time range or events marked by the users.

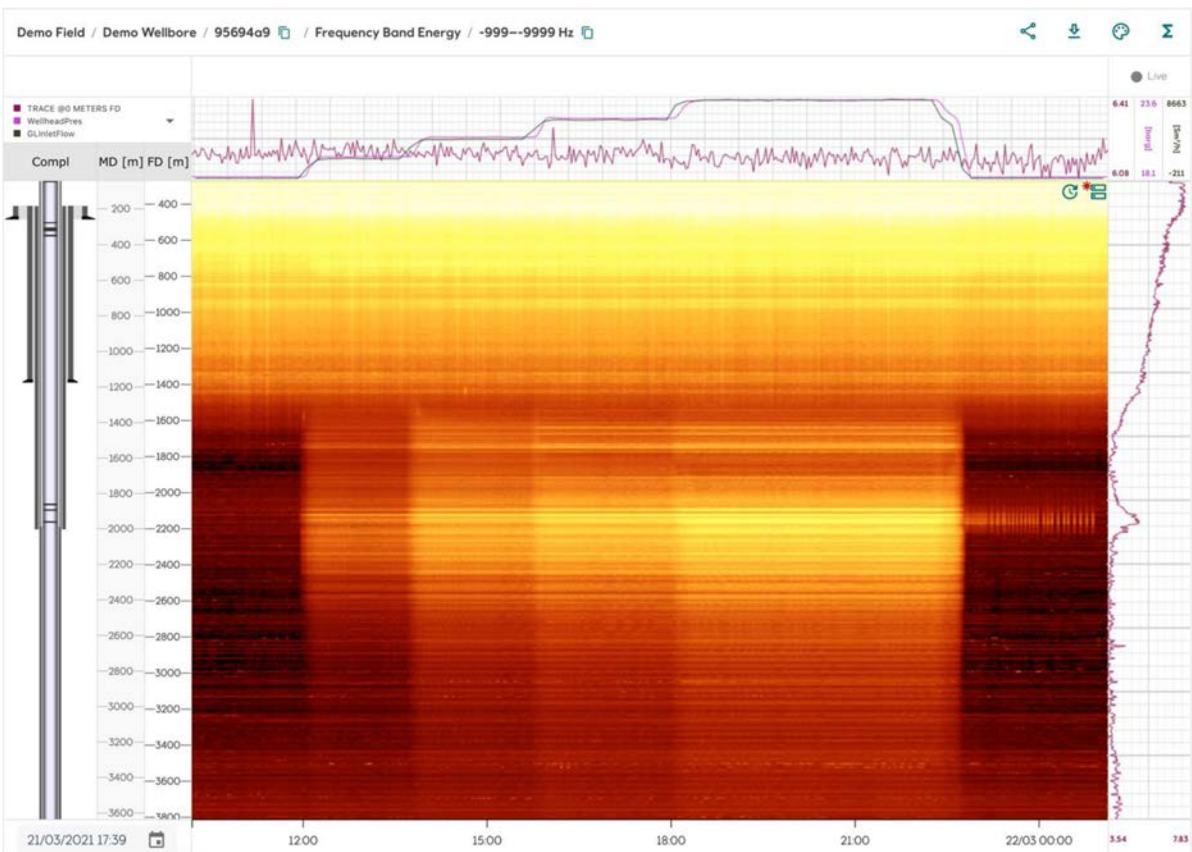

Figure 4—The fo.tone feature view displaying data in time and depth. The left hand side panel contextualizes the data with wellbore completion information, the top side panel shows point sensors from other data sources. Here an example of a gas lift valve operation on a FBE is shown.

The API can also be accessed in a more programmatic order, e.g., to prototype new applications based on the existing data, or to extract long periods of training data for machine learning purposes.

The latency of total FO data pipeline as described above currently amounts to less than two seconds from data being acquired offshore until it appears on screen in front of the users.

Data Examples

During last year, the FO data pipeline on Johan Sverdrup has recorded about 14 TB of FO feature data and stored several hundred of TBs of raw DAS data. Contained in this data are numerous interesting examples that illustrate the potential of this data for providing insight on wellbores processes. In the following section, two data examples illustrating the value of real-time monitoring will be discussed in more detail.

Wellbore Unloading

Wellbore unloading is a process in which brine in the wellbore annulus is displaced by gas. The brine is displaced from the annulus through the gas lift valve, and then rises back up and out of the well. This needs to be done prior to starting gas lift, and the speed of the operation is governed by the upper limit for the liquid rate through the gas lift valve[4]. Traditionally, this liquid rate would be estimated from pressure measured topside and downhole[5], and due to the compressibility of gas this estimate would be uncertain. This uncertainty enforces larger safety margins and slower operations, i.e., potentially delaying production start-up.

Figure 5 shows unloading of a well monitored with DTS in real-time using the *fo.tone* application. The figure shows temperature gradients (°C/min), essentially a running differential of the individual DTS traces. As the gas displaces the brine, the contrast in temperature and heat capacity results in a clear separation forming at the interface between the two fluids. Since this could be monitored in real-time, the velocity of this interface can be tracked using the *fo.tone* application. With the known velocity and the known annulus volume, the operators have a direct measurement of liquid rate through the gas lift valve, allowing smaller safety margins resulting in faster operations.

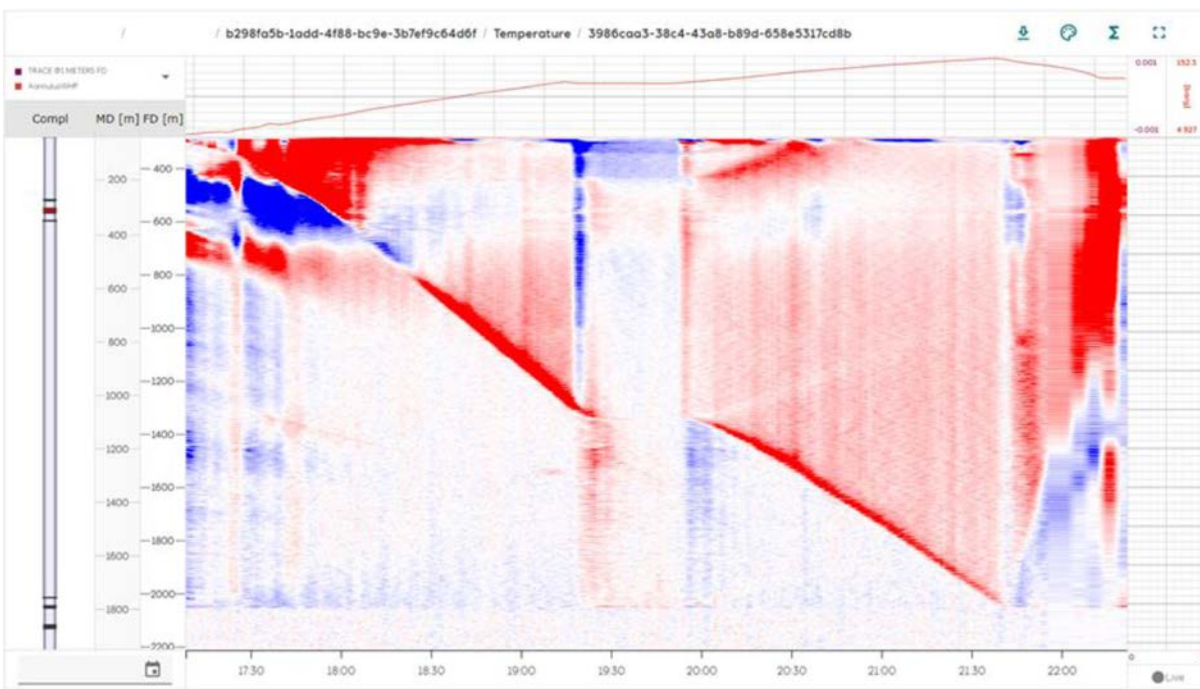

Figure 5—Unloading of well monitored in real-time with DTS using fo.tone. The figure shows temperature gradient with a scale of +-0.15 °C/min. The gas-liquid interface is seen as the base of the heating front moving down the well.

Gas Lift Slugging

Gas lift is used in oil wells to increase production rates by reducing the density of the producing fluid. This is done by pumping gas down the annulus of the well and introducing it into the production stream at depth effectively reducing the average density of the produced fluid. Gas lift can be prone to several issues that can impact the efficiency of the system or reduce the lifetime of the associated valves. Periodical opening and closing of the valve can cause wear and would also introduce gas periodically in the system resulting in slugging. If not mitigated, slugging can cause severe production loss (Haidan et. al., 2018).

Figure 6 shows an example of slugging detected by DAS in real-time using the *fo.tone* application. The plot shows an FBE which indicates periodic energy coming from the gas lift valve. This is a clear indication of slugging and having this data in real time allows the operators to detect and mitigate the issue. The potential impact is increased lifetime of the valve, and reduced energy consumption and higher production through improved lift performance.

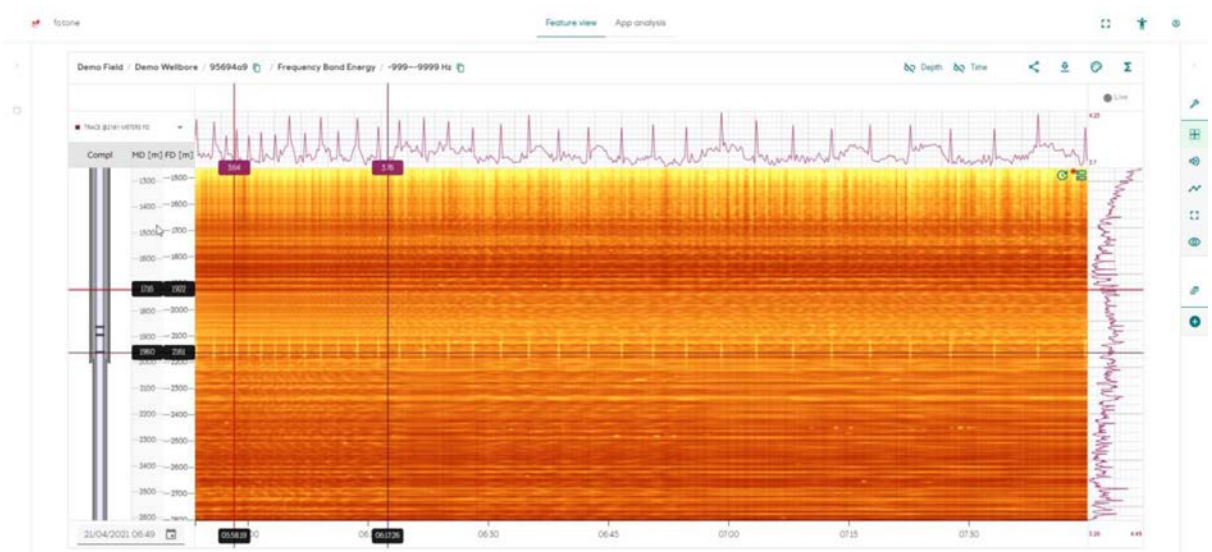

Figure 6—Anonymized DAS FBE data in fo.tone showing slugging indicated by periodic energy propagating from the gas lift valve.

Applications

In addition to being able to see FO data in real-time, it is desirable to have automated procedures analyzing the constant streams of data into *fo.tone*. In order to facilitate this, *fo.tone* also hosts an application deployment platform. This ensures that applications that are developed for current and/or future use cases can be taken into production without the need for long periods of adaptions to the platform infrastructure. Examples of such applications are monitoring of downhole equipment or estimation of flow rates from FO data.

In this context, an application consists of data ingestion, a set of one or more processing steps (e.g., filtering and classification), and storage and visualization of results. Results are presented in near real-time through the *fo.tone* web interface, and made accessible via an API for integration with other systems. We give two examples of applications in the following section.

Gas Lift Valve monitoring

The aim of the Johan Sverdrup asset is to double the lifetime of its gas lift valves via FO data, i.e., optimize the usage of these valves. To deliver on this goal, we built an application to classify the state of the valves during operation. We chose the states to be identified as "closed", "open" or "anomaly" ("chatter"), with particular interest on the latter to avoid unnecessary wear on the valves. To develop a classification model, we acquired a training set with DAS data from the full operating range of the valves and used FBEs as input to the classification. With the assumption that any anomalous valve behavior could be picked up by acoustics, we created a model that described the normal state of the valves and used anomaly detection techniques to flag potential chatter. Figure 7 shows an example of the processing flow for gas lift valve monitoring. Several FBEs for a limited range of loci are input to the flow. The FBEs are filtered and fed to a classifier to predict the state of the valve. In the figure, anomalies are marked with red arrows on the input and output, demonstrating successful classification in this example. In operation, the classifier gives a prediction approximately every second, allowing rapid mitigations if anomalies are detected.

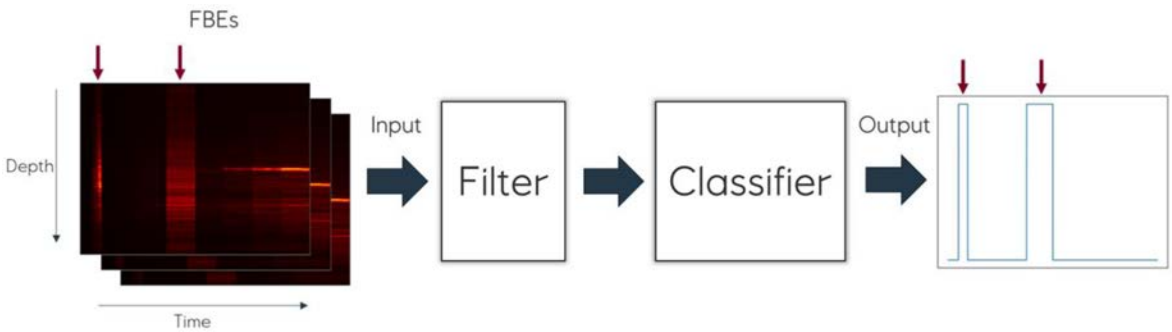

Figure 7—Example of processing flow for the gas lift valve monitoring application. Anomalies are marked with red arrows on the input and output.

Inflow Profiling

Information pertaining to a well's inflow profile and the individual flow contributions from the different inflow points (Inflow Control Devices (ICDs) in this case), is valuable from a completion performance, production optimization and reservoir management perspective. Inflow profiles derived from continuous, distributed DAS measurements are unique in that they facilitate continuous monitoring along the entire well trajectory, thus providing early diagnostic information which can be acted upon quickly. This contrasts with the more traditional method of acquiring such information via a production logging (PLT) intervention, which only provides snapshots of the producing conditions at a particular point in time. Figure 8 shows an example of the acoustic signal generated by the ICDs for a Johan Sverdrup completion. The aim of the Johan Sverdrup asset is to significantly reduce the amounts of PLTs with the help of its FO technology. Furthermore, real-time inflow profiling allows for real-time optimization of production in response to identified changes.

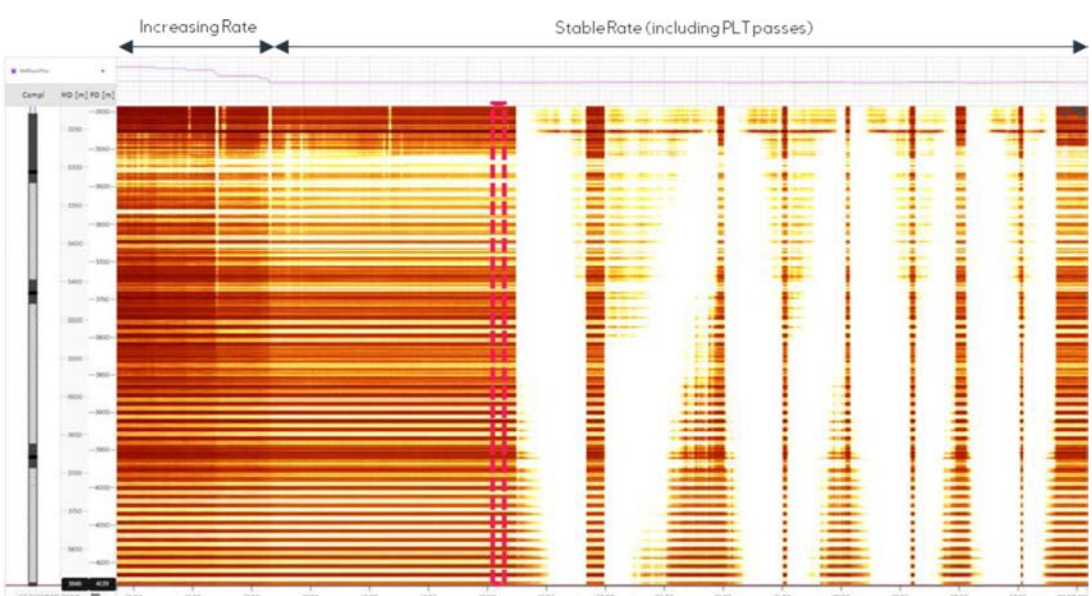

Figure 8—fo.tone panel showing DAS data (from reservoir section) during PLT operations. Highlighted time period (dashed pink box) shows the period where the inflow profile shown in Figure 9 below was computed and which was subsequently compared to the PLT results.

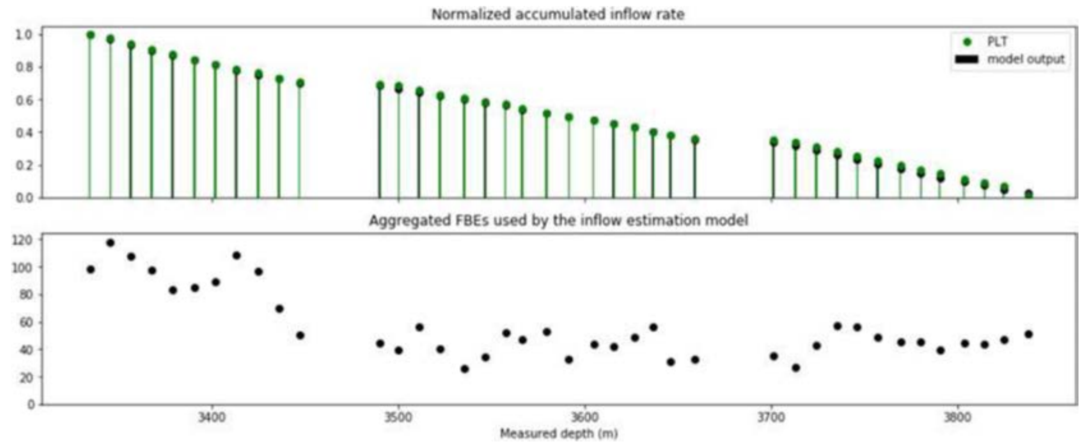

Figure 9—Aggregated, background corrected DAS signal from selected (weighted) FBE's i.e. input to 'noise to flow' model (bottom panel), Normalized cumulative inflow profile output from 'noise to flow' model with comparison to PLT results (top panel).

Converting the acoustic response, measured by the DAS fiber in the reservoir, into a production profile was facilitated by analyzing the frequency content of the DAS signal, to ascertain the frequency ranges (FBE's) in which the acoustic energy is dominated by the contribution from a specific flow noise source. In this case, the sources are predominantly related to flow across the ICDs, flow in the annulus (screen) and flow axially along the well. The noise generated by flow across ICDs was found to be the most robust source of inflow information and the first version of the inflow profiling application is based on this. However, work is ongoing regarding use of the other noise source components, for increased robustness of the method and for use in other completion types. With knowledge of those FBEs that best isolate the characteristic ICD inflow noise response, the signal from the chosen frequency bands are then appropriately weighted and aggregated over a window of optimized length (encompassing the ICD location), background noise is subtracted before the processed signal is finally converted to a flow rate contribution per ICD. This conversion is done by a 'noise to flow' model which was developed and then verified using production logging data acquired in the well. Currently the model is applicable for the single-phase producing conditions found on Johan Sverdrup, investigation into possibilities under multiphase flow conditions is planned. The application workflow then provides quantitative inflow by zone and a cumulative inflow profile, approximately every second in close to real time, which can then be displayed in *fo.tone* for visualization by the user. Figure 9 shows the result of this inflow profiling application for a Johan Sverdrup example. The match with the reference PLT is very consistent.

Summary and Conclusions

We presented a newly developed FO data pipeline for the Johan Sverdrup field which allows for FO data streaming from offshore to the user interface in less than two seconds. The platform-to-cloud data transfer is enabled by modern streaming technologies, the possibility of dynamically reacting to varying computational demands, and a modern web-based platform for data inspection and integration. The system is highly flexible, reliable, and scalable to other settings/assets.

In order to analyze the large amounts of data, which accumulate to hundreds of GBs per well per hour for raw FO data and hundreds of MBs per well per hour of FO Feature data, automation attempts are paramount. This need drives the development of applications that allow new ways of monitoring wellbore processes based on FO data in a continuous manner. Additionally, the underlying data platform and the applications then also enable reacting to events in real-time. The anticipated implications for wellbore operations and production range from predictive maintenance of valves, e.g., doubling the life time of gas lift valves, to continuous production optimization due to real-time in-flow information, thus removing the need for PLTs.

Acknowledgements

The authors would like to thank the Johan Sverdrup license Operator Equinor and Partners Lundin Energy Norway AS, Petoro, Aker BP ASA and Total E&P Norge AS for permission to publish the work. The authors would like to thank all Equinor colleagues who contributed to the development of this system, in particular the *fibra* & *fo.tone* IT development teams.

"The views and opinions expressed in this paper are those of the Johan Sverdrup field operator and are not necessarily shared by the license partners".

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