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# Continuous 4D Monitoring is Now Reality

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## Abstract

With the implementation of smart fields where sensors play a major role for measurement and control of the production process, continuous monitoring becomes increasingly important. In wells it is common practice to constantly monitor parameters like flow, pressure, and temperature. For imaging techniques like (active) seismics so far monitoring has only been applied in a time lapse manner with a repetition interval generally in the order of a year, not in a continuous way. The Vallhall field probably comes closest to continuous monitoring with permanently installed ocean bottom cables (OBC) and repeated surveys in the order of months.

The main challenge with permanent seismic monitoring is not so much the technical feasibility, but more the data transfer and processing of the vast amounts of acquired data. TNO together with the TU-Delft, KNMI and ASTRON have started to implement a seismic monitoring network in the Netherlands using an ultra-fast digital optical fibre network linked to one of the most powerful computers in the world, the IBM BlueGene/L system. Data can be sent to this computer at speeds up to 20 Tera-bits/second. Currently passive seismic data is constantly acquired at Exloo, the first out of 50 test fields to be installed in the next year.

Besides seismics, the network and the ICT infrastructure make it possible to combine all sorts of observations from the natural environment, infrastructure and processes anywhere and any time. This paper will give an overview of the first results of the incoming data and a description of the ICT infrastructure and network. Furthermore a view will be given on future applications.

## Introduction

Recently astronomers, agriculturists, and earth scientists have joined forces in setting up the LOFAR network, a broad band monitoring ICT infrastructure in the Northeastern part of the Netherlands (figure 1, Van den Hoven et. al.[6]).

**Figure 1 (left): Artists impression of the LOFAR Network (source ASTRON).**

This project started as an innovative effort to force a breakthrough in sensitivity for astronomical observations at radio frequencies below 250 MHz. It was soon realized though that LOFAR could be turned into a more generic Wide Area Sensor Network. Sensors for geophysical research and studies in precision agriculture have been incorporated in LOFAR already. Several more applications are being considered, based on the increasing interest in sensor networks that “bring the environment on-line.”

Geophysical interest in the LOFAR project predominantly concerns seismic monitoring. In this respect three distinct monitoring approaches are recognized:

- monitoring seismic events related to small earthquakes;

- monitoring background noise and synthesis of subsurface models using seismic interferometry;
- monitoring subsurface properties by performing active time-lapse experiments.

Small earthquakes (< 3.5 on Richter scale) that occur in this area are expected to stem from gas extraction from nearby reservoirs (Figure 2). Analysis of these events helps to identify source positions and focal mechanisms and will yield an insight in the corresponding reservoir processes.

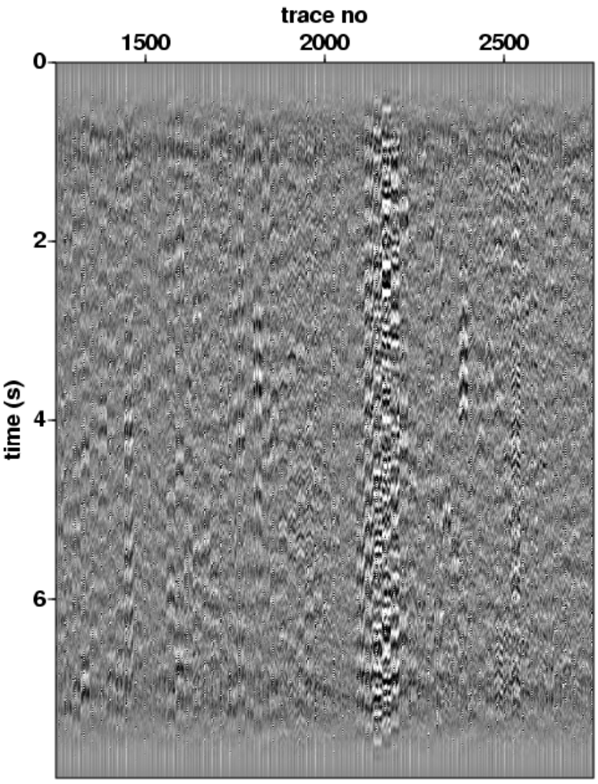



**Figure 2. Earthquake (Magnitude 2.3) as detected by passive seismic dataflow at Exloo**

Recording the 'diffuse' background noise wavefield and subsequent correlation of the response measured at different locations results in the Green's function of the medium (Wapenaar[7]). Repetition of this process at regular time intervals may reveal changes in the Green's function as related to changes in the sub-surface.

Combining the abovementioned passive monitoring techniques with active seismic tests at regular time intervals - sharing the installed sensor infrastructure - is expected to furthermore increase our understanding of reservoir properties and processes.

## ICT Infrastructure and Workflow

The Lofar infrastructure comprises a number of Lofar field sites connected to a central core by dedicated high speed Internet links. The Central core is directly connected to the Central Processing Centre that takes care of most of the data manipulation tasks and provides temporary storage. Permanent storage is implemented as a distributed – Grid type - database. Authenticated users have access to permanent storage, Central Processing Centre, Central Core as well as individual field sites. The Internet link is designed on the bandwidth requirements as specified by astronomers. In total the network can transport data to a total bandwidth of 20Tbit/second to the central LOFAR computer at the University of Groningen. The infrastructure available in the current (experimental) setup uses the wide area network provided by Surfnet to connect to the Central Processing Centre, and implements a dedicated (high-speed) connection to the first test site in Exloo. At this moment this site also serves as the Central Core. A remote server in Utrecht currently monitors and controls data collection at the Exloo test site.

In the current experimental setup this server makes necessary connections to and retrieves the data from the test site using a peer-to-peer setup. At the test site a data acquisition server is responsible for collecting data from the various sensors and a communication server for accepting remote connections and transporting data to Utrecht.

With the completion of additional sensor fields this simple setup will no longer be possible and operation of the Lofar network will be implemented according to the diagram in figure 3. When the Blue Gene/L super computer of LOFAR is operational in the Central processing Centre the data will be temporarily stored and processed in Groningen. Processing results are sent to Utrecht and stored in the system for Data and Information of the Netherlands' Subsurface (DINO) at TNO Built Environment and -- *Geological Geosciences Survey of the Netherlands.* Event data are subsequently transferred to and and archived by the seismological institute of the Netherlands (KNMI). Retrieval of archived data from DINO as well as KNMI is possible for parties interested in further scientific applications.

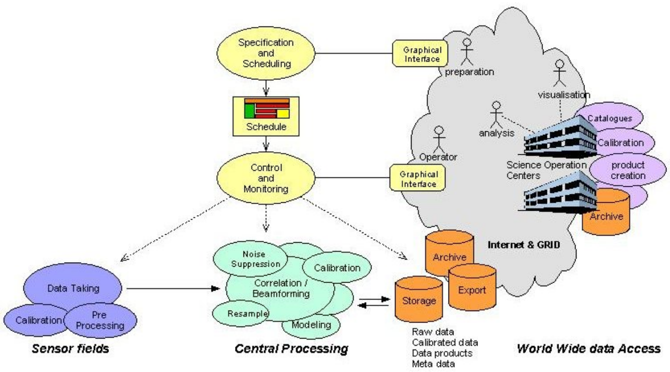



**Figure 3. Operational view on LOFAR. Shown is how the processing tasks at the bottom left of the figure are controlled through Specification, Scheduling, Control and Monitoring software (source ASTRON).**

The monitoring experiment can be divided in distinct activities. The first is to control and to adapt the settings on the sensors, individually for each sensor or simultaneously for a whole range of sensors. The second activity is to transport the collected data in a secure, efficient way and to keep track with the flow of data. Preventing congestion, every call for delivery is checked to ensure that there is enough space and capacity on the destination. To reduce the volume of the dataflow, the IBM Blue Gene/L is used in the third activity of reducing/compressing the data as much as possible. After storing the data in the DINO database it is important to be able to find and retrieve the data again, so generation of Metadata (the fourth activity) is necessary. The Gigabytes of data collected daily by the sensor network must be stored in a way that allows easy and flexible access and facilitates retrieval of data of specific time windows at selected receiver locations. To this end an extensive archive of metadata is kept.

## Monitoring Workflow

The distinct monitoring approaches mentioned require specific workflows (figure 4).

Monitoring seismic events involves – at some point in the workflow – recognition of these events and isolation of the corresponding time windows, thus resulting in a considerable and required data reduction. As the frequency content of the event data is supposed to be limited this workflow also involves temporal resampling. The background noise workflow takes the complete data set as input and involves the application of cross-correlations as a means for data reduction and the synthesis of subsurface models. Recording time-lapse data is basically a triggered operation and records of specific length are selected and integrally stored. Although the three approaches are different by nature they all use the existing ICT infrastructure.

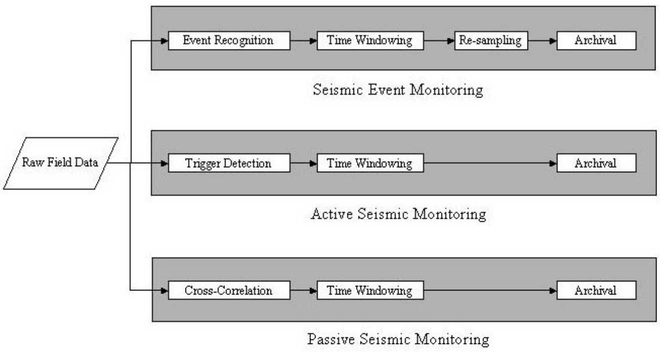



**Figure 4. Schematic workflow**

## Application

A good example of semi-permanent monitoring is carried out at the Valhall field offshore Norway (Barkved et al.[2]), where the license partners have decided to implement the Life of Field Seismic (LoFS) project. Over an area of 45 square km more than 120 km of permanent four component (4C) seismic cables have been installed at the sea bottom. The first survey using the permanent array was acquired in 2003. The Valhall field is a chalk field that compacts during production. This causes subsidence in the overburden, posing a serious difficulty in drilling the overburden and avoiding well bore failure.

The main objectives for the Valhall field in particular are to provide images of the seismic response on demand to support placement of new wells, to guide interventions in existing wells for improved production rates and to manage the water injection strategy.

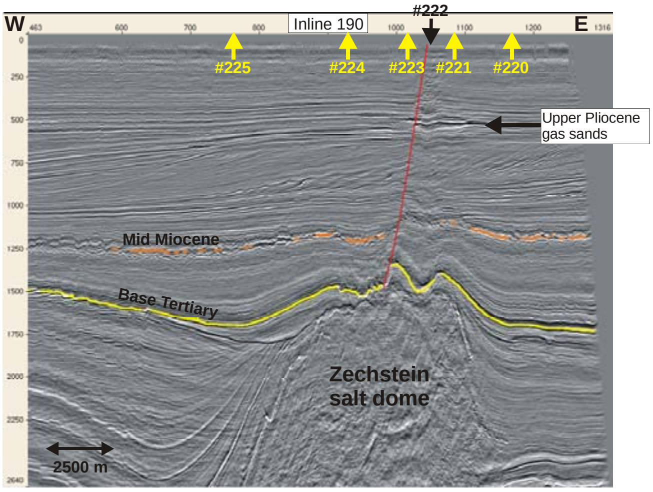
Currently repeated seismic surveys are being acquired with a frequency in the order of several months (Barkved et al.[2,3]). By using the same source for every survey extremely high repeatability can be achieved providing detailed information on the 4D effects. These 4D effects are detected as traveltime changes and seismic amplitude changes both in, above and below the reservoir.

The severe subsidence at Valhall causes substantial microseismic activity (Caley et al.,[4]). In 1997 a microseismic survey has been carried out using borehole seismometers. Reliable event locations were obtained for over 300 events placing most of the seismicity just above the Chalk reservoir in a sequence of Claystone and Limestone. These events resulted from slip on small faults. Instead of the borehole seismometers the permanent surface array could also be invoked for passive recordings.

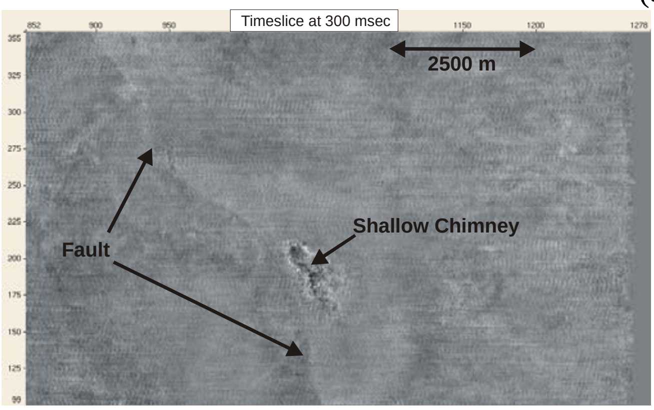
The latter is exactly what is currently tested in the LOFAR project. Over the test site in Exloo geophones are "listening" to the subsurface continuously. In this particular case the aim is to detect small earthquakes in the overburden induced by gas production and/or gas storage.

In case of the production of heavy oils a fixed array of receivers can be extremely useful. Heavy oil reservoirs are shallow. To produce the oil conventionally cyclic steam injection is applied. The large pressure and temperature variations cause major uplift and subsidence of the reservoir and of the overburden. Continuous passive seismic monitoring with the surface array of geophones combined with 4D seismics on demand can be extremely helpful to control the process and to minimize the steam injection. Interpretation of the seismic signals under these conitions require comprehensive coupled modeling tools (fluid flow, thermal and geo-mechanical aspects) capable of describing the system in terms of stresses (pressures) and saturations

Besides for oil and gas a major application is for storage of Carbon Dioxide ($CO_2$). Large-scale implementation of $CO_2$ storage is essentially hampered by safety issues. In contrast to gas storage, $CO_2$ storage is meant to last virtually forever.




(a)




(b)

**Figure 5. Example of a shallow gas chimney offshore the Netherlands (a). The outline of the gas chimney is well defined on a timeslice at 300 msec depth (b).**

This puts more severe demands on the monitoring program. Repeated seismics at Sleipner, the first industrial scale underground $CO_2$ storage project in the world, have proven to be very successful in showing the spreading of $CO_2$ in the reservoir (Arts et al.[1]). It is strongly believed that major leakages would have been detected on the time lapse seismic data.

This assumption is also based on the detection of gas chimneys above a number of gas fields in the North Sea on conventional 3D seismics (Schroot et al.[5]). Figure 5 shows an example of such a gas chimney.

In summary the main advantages of using a fixed array of geophones are:

Improved repeatability of the time-lapse seismic data since the acquisition geometry of the receivers is repeated exactly.

Flexibility of acquiring new time-lapse seismic data, only a source is required. Moreover, only part of a survey can easily be repeated, where changes are expected.

The permanent array can be used for continuous passive seismic monitoring.

The ICT network used to continuously transmit the monitoring data is not restricted to seismic data alone. For example time lapse micro-gravity measurements are conducted both for oil and gas production and for monitoring $CO_2$ storage. A permanent set-up with continous acquisition can have great benefits. The required corrections, necessary for the calibration of the gravity measurements caused by external factors like tide or groundwater fluctuations, can better be estimated with a continuous set of measurements.

## Discussion

Use of ICT networks, such as LOFAR allow for continuous passive monitoring and for 3D seismic on demand. Constant monitoring of oil/gas fields, in combination with suitable modeling tools makes constant optimalisation of the production process possible. The high speed network and complete ICT structure, which is currently in place in the Northern part of the Netherlands covers an area with gas fields providing opportunities for bringing smartness to the production process.

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