Permanent Downhole Temperature Sensing – A Success Even for Low Cost Wells

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Dino Simonits, André Franzen

e-mail: Dino.Simonits@lios-tech.com
LIOS Technology GmbH
Schanzenstrasse 6-20
51063 Cologne, Germany

e-mail: Andre.Franzen@shell.com
Shell International E&P B.V.
Kesslerpark 1
2288 GS Rijswijk (ZH), The Netherlands

Abstract

The oil and gas production industry faces continuously the challenge to optimize the production and reduce operation cost further. Following these motivations also new technologies and operating practices were adopted and/or developed. For a decade permanent optical in-well monitoring systems are gaining more-and-more acceptance in up-stream oil and gas production operation. However, so far mostly high-end and therefore usually complex – mainly deep-water wells – were the focus for these so called intelligent completions. High investments for the surface equipment, installation complexity, and the lack of standard tools for efficient data gathering and analysis were the main reasons for the general hesitation towards this technology; a major breakthrough is still awaited.

In a co-operation between Shell International Exploration and Production (SIEP) and LIOS Technology GmbH (LIOS) the feasibility and economical added value of permanent downhole temperature sensing have been successfully demonstrated in a number of recently deployed on- and offshore projects in Brunei. This paper presents the generic design and implementation of an exemplary case study for permanent DTS downhole sensing of low-cost land and offshore-wells. The entire scope of equipment and architecture from the well site to the office is taken into account with a view on fit-for-purpose, commercially sustainable, and cost-effective technical solutions for the end-user, the asset owner.

Introduction

Right from the beginning of the oil industry people wanted to know more about the reservoirs they were exploiting. Thus having a more sound understanding about their reservoir behaviour and obtaining knowledge how to optimize the recovery of the hydrocarbons. As it was - and still is - impossible to look directly into a reservoir other ways to obtain information about the reservoir needed to be investigated. Direct surface measurements are helpful and still required today but downhole sensing became quickly an important topic for reservoir monitoring. The first sensors were for pressure measurements, then temperature, until nowadays micro-sensing images a whole ground section in 3D. Due to temperature observations along the borehole, a relatively easy measurement, a lot of information can be derived such as water- or gas-break-through. When e.g. observing water injectors in the warm-back-phase one can find the producing zones, hence this kind of information has a major impact. The advances in fibre optics, packaging and the experience gained over the last 5 to 10 years enabled the industry to deliver low-cost Distributed Temperature Sensing systems. An additional factor was the further development of industry standards and electronics enabling to build an architecture that allows data flow from the well to the Production Technologist's desk.

Fibre optics early days in E&P

All sensors deployed in E&P[1] needed to be developed and adjusted for this specific application field and thus got ruggedised over time, whether it was/is hydraulic, electrical, or optical equipment. As such, all novel technology has to prove itself and at the early stage there is always a steep learning curve associated with it. Unfortunately, fibre optics when it was introduced into E&P had not the maturity level of what the oil field expected in general, especially when compared with field equipment for e.g. beam-pumps, ESP[2], inflow-control devices etc., and thus could not compete with alternative technologies. As a consequence, only for specific application, i.e. deep-sea wells, the relative high costs for fibre optic developments could be justified[3].

To give a better understanding where the optics market was and is heading find a market comparison between telecommunications and sensing[4], see Figure 1. As can be seen from this chart the time from laboratory-demonstrators to deployment was relatively short for telecommunications industry while the oil industry only picked up slowly on this new development showing its conservative attitude.

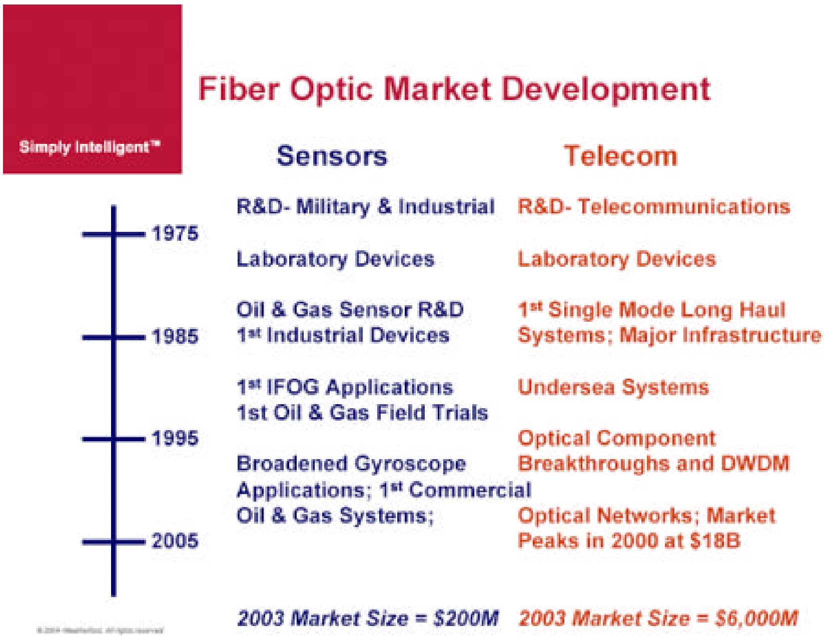

Figure 1: Fibre Optic Market Development, comparison Sensors versus Telecom[4]

Experiences – from first touches to latest developments

Despite numerous reported early success stories of successful downhole monitoring deployments with fibre optic sensors – either point type gauges (pressure) or distributed sensors (DTS) – its broad breakthrough in upstream oil and gas exploration is still awaited. In a world of rugged drilling equipment and harsh offshore environment the fibre was still looked at with scepticism. This resulted in hesitation that was constantly fuelled by typical "teething troubles" during the first commercial deployments; the release of premature surface equipment with unsatisfactory performance in terms of reliability, measurement stability and service life.

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[1] E&P: Exploration and Production
[2] ESP: Electrical Submersible Pump
[3] Internet Reference: http://www.oilonline.com/news/features/oe/20001201.Wytch_Fa.34.asp
[4] Reference: Weatherford International, Optical Sensors in the Oil and Gas Industry, Paul E. Sanders, 2004

This was a similar reaction to the time when linear heat detection using fibre optics in fire detection was introduced, almost a decade ago. At that time the market was dominated by traditional electronic point-type heat detectors which were usually mounted along a road tunnel with a distance of 10 m between them and wired peer-to-peer. Today, in fire protection, mainly distributed fibre optic temperature sensors are utilized and LIOS Technology[5] has established a new standard in this environment acting as a pioneering force.
The key success factors in this case are the strong focus on a technology which allows to utilize standard components approved by the telecommunications industry and an qualified industrial manufacturing process for the measurement equipment. This resulted in robust and reliable products compliant with industrial demands.
Based on an initiated development work in 1995[6], LIOS Technology provides DTS systems based on the Optical Frequency Domain Reflectometry (ODFR[7]). The used light source is a modern and durable semiconductor laser diode instead of a rather complex solid-state laser which typically powers Raman OTDR[8] systems.
The semiconductor laser diodes used have been critically type tested according to the Telcordia[9] GR-468 standard and are fulfilling telecommunication standards with a medium lifetime of > 25 years. Not only the laser diode has been tested but also the entire system has been comprehensively tested by various independent international bodies (e.g. the Germany VdS, the association of German asset insurers) in which EMI[10] tests as well as endurance tests at accelerated aging environments were conducted.
DTS units from LIOS have been extremely successfully deployed in critical applications like fire detection in road- and rail-tunnels as well as special hazard buildings, power cable and transmission line monitoring and for industrial induction furnace surveillance. And now, even found successful deployments in oil & gas exploration.
All the systems have been deployed in worldwide projects summing up to more than 1000 permanent installations since 1997. This extensive track record – with projects in various applications areas – has led to constant performance improvement in hard- and software plus the capability of deploying sensing equipment. The resulting practical experience and obtained feed-back has led to a professional industrial manufacturing process with an extensive test plan for each and every DTS product leaving the company's premises.

Generic Set-up for low-cost DTS deployment

To give an overview of nowadays DTS implementations in E&P a generic set-up is presented here. In the generic layout the sensing is executed downhole with a fibre optic cable – see Figure 2 – while the actual interrogation is carried out on the surface where also the data is collected, see Figure 3. From here the raw data is transferred by some means, e.g. WiFi, twisted-pair, etc. to a central location where the measured information is stored in a database. The Production Technologists (PTs)/ Reservoir Engineers (REs) can retrieve the required information from the database using appropriate software, i.e. visualization software that presents the information graphically or an analytical tool that helps evaluating the data.
This set-up is fundamentally different compared to the time when fibre optics was introduced into E&P. The possibility to have online data – as with this set-up no one needs to go to the well site to collect data – is a major change. Additionally, the optical equipment was adjusted to the E&P environment, so it has now a small footprint and is ruggedised enough for field

[5] LIOS Technology GmbH, http://www.lios-tech.com/
[6] R&D project at Felten & Guilleaume Kabelwerke GmbH, Germany, see Final Report of Microsystems Framework Program NOVOS 1994-1997, Edition: Innovation in Microsystems, Volume 58, VDI/VDE-IT, March 1998
[7] OFDR: Optical Frequency Domain Reflectometry
[8] OTDR: Optical Time Domain Reflectometry
[9] Telcordia: Industry Requirements And Standards, http://telecom-info.telcordia.com/
[10] EMI: Electro magnetic interference

deployments. Most changes are not due to the advances in fibre optics but the progress in communications, especially with Ethernet, TCP/IP, and WiFi being well established. Another helping factor is the standardization of interfaces. This is not only referring to the hardware interfaces but to software as well. A new interface standard for DTS measurement devices in the E&P called *POSC WITSML*[11] was introduced and integrated for the first time, thus allowing raw data to be inserted into a Shell developed and owned database.
To recap, the main focus remains with the fibre optic sensor and interrogation unit as these are the elements that differ most from other previous electrical deployments – in price and technology.
First of all, the fibre needs to be deployed along the casing of the well which means that it needs to be packaged accordingly. A control-line with a plastic encapsulation has shown to be able to give sufficient protection against wear and tear – see Figure 2.

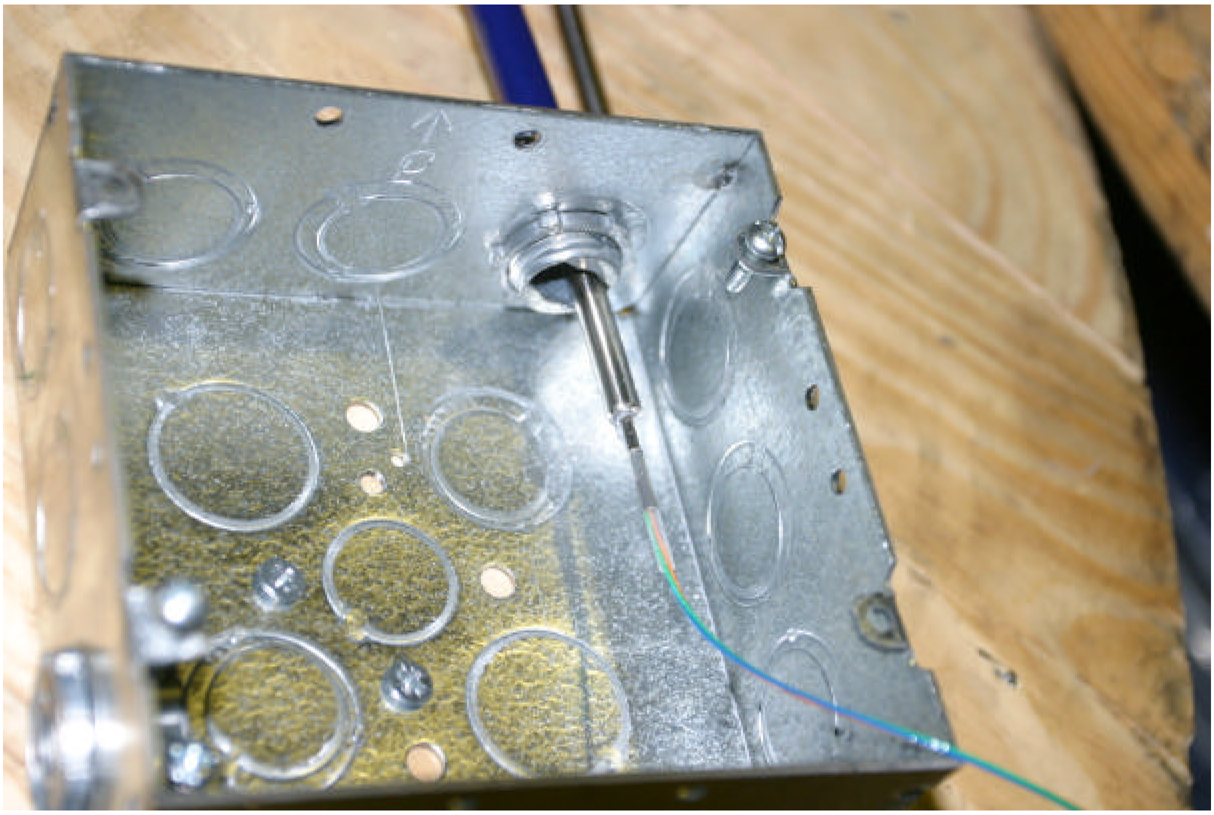

Figure 2: Downhole cable - fibre inside with a 1/4" control-line and 11x11mm encapsulation (blue)

Another aspect that changed over time is the footprint and power consumption of DTS readout units. From bulky cupboards they used occupy, they now fit into a 19" rack and even smaller sizes are predictable, see Figure 4. Some designs use e.g. 120cm high racks whereby more than half is used for UPS[12] and only 1/3 of the remaining space for the actual DTS evaluation unit.
Still, to have a truly successful low-cost DTS-deployment an architecture allowing measurement data to be streamed into a database is required. This is shown in the next section of this paper.

[11] POSC WITSML: Petrotechnical Open Standards Consortium, http://www.posc.org
Wellsite Information Transfer Standard Markup Language, http://www.witsml.org/
[12] UPS: Uninterruptible Power Supply

Figure 3: Field cabinet with DTS (PC & OTS40P) equipment

Figure 4: DTS equipment

Low-cost DTS pilot program for permanent downhole sensing in BSP

The field trial consisted of 3 main parts. Those are identified by its physical location – well site, transmission, and central office or headquarters.

On the onshore well site a fibre optic cable is installed downhole into the well with the help of a local crew (which obviously has a cost impact). At the end of it a mini-bend was mounted, a device establishing a light return path over sub-mm space and thus enabling 2 optical fibres to connect inside a ¼“ control line. This allows to have a double-ended system. The DTS evaluation unit at surface measures both ends of the fibre alternately. The results of the measurements are collected on-site and then prepared according to the POSC standard for transmission by a PC running the required software. A similar scenario can be found in an offshore installation; here an existing fibre optic cable is used and only the above-described surface equipment is installed including a UPS.

The transmission is based on TCP/IP and hence a wide variety of transmission media is available. All of those solutions are commercial readily deployable; in the land-trial WiFi was used to overcome a distance of approximately 1.5km from the well site to the Headquarter of Brunei Shell Petroleum (BSP) while the offshore set-up uses a combination of WiFi, microwave, and land line. Due to the end-to-end use of TCP/IP from the well site to the office domain, configuration and maintenance access is available. The operator can easily configure various DTS systems installed at remote well sites – onshore and offshore - from the office. For the DTS measurement data a different transfer procedure was established. In order not to congest the network a special remote-transfer agent was developed which transmits the generated POSC files at pre-defined intervals. State-of-the art industry standard TLS encryption and authentication protects against intrusion or data sniffing. At the central office the data is received, verified and then inserted into a Shell developed DPD[13]-database.

[13] DPD: Distributed Production Data

This database was optimized to handle large data arrays, typically generated by DTS systems. It, too, has the capability of storing vast quantities of DTS wells, possibility up to several assets. In the office the Petroleum Technologists and Reservoir Engineers can query the database and get the measurements displayed on the desktops using a visualizer that was developed as an Excel Add-in. Figure 5 shows the generic deployed architecture as described above. The following chapters provide further details on the deployed products and practices.

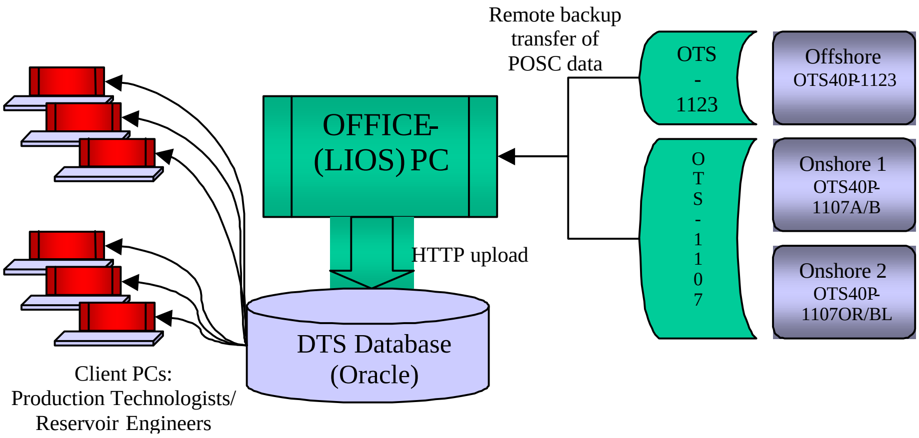

Figure 5:Generic DTS architecture deployed

The Pilot: Implementation of the DTS systems

The DTS surface equipment for the low-cost land wells comprises a LIOS OTS40P system with 4 fibre optical measurement channels. Each channel covers a range of up to 4 km of a single-ended multimode fibre. The product portfolio of LIOS consists of DTS systems with ranges of up to 10 km at a single end multimode fibre with up to 8 measurement channels. In this case the distributed temperature profile along the well bore is provided with a spatial resolution of 1 m. The setup can cover either 4 independent wells with single-ended fibre or up to two independent wells with looped fibres. The looped fibre or also referred to as double-ended setup was chosen in order to have additional means at hand for comprehensive data analysis.

Data and event processing is handled by the DTS system itself: The temperature and backscattering profiles are provided via its Ethernet interface through TCP/IP. Whereas the initial setup required a local PC to store data and generate the POSC WITSML compliant protocol data, the latest setup is designed without an additional PC on site. The newly-available Embedded Communication Module[14] for the DTS incorporates onboard storage of all measurement data for more than 72 h, the POSC WITSML protocol generating engine and the automated transfer procedure into the DPD-database. Direct benefits for the operators of this highly integrated setup are reduction of cost and power consumption of the well surface equipment and simplified configuration procedure as well as a smaller total footprint for the system.

Measuring Principle - OFDR Technology

The LIOS DTS evaluation unit deploys the method of Raman backscattering light detection in the frequency domain (OFDR). The OFDR system provides the distributed temperature profile along the fibre, therefore the Raman backscatter signal detected during the entire measurement time is recorded as a function of frequency in a complex fashion, and then subjected to Fourier transformation. The essential benefits of OFDR technology are the

[14] ECM: Embedded Communication Module

quasi-continuous wave-modes deployed by the laser and the narrow-band detection of the optical backscatter signal, whereby a significantly higher signal to noise ratio is achieved than with conventional pulse technology (OTDR). This technical benefit allows the use of affordable semiconductor laser diodes and electronic assemblies for signal averaging. This is offset by the technically difficult measurement of the Raman-scattered light and rather complex signal processing, due to the FFT[15] calculation with higher linearity requirements for the electronic components.

Data processing and data flow

This project focuses also on integrated solutions with direct benefits for the daily operation of the involved asset;. measurement data shall be at the direct disposal of the PTs & REs.
The following schematic, see Figure 6, demonstrates the generic data flow from DTS systems at the well site to the office domain. This is already described above and hence not repeated.

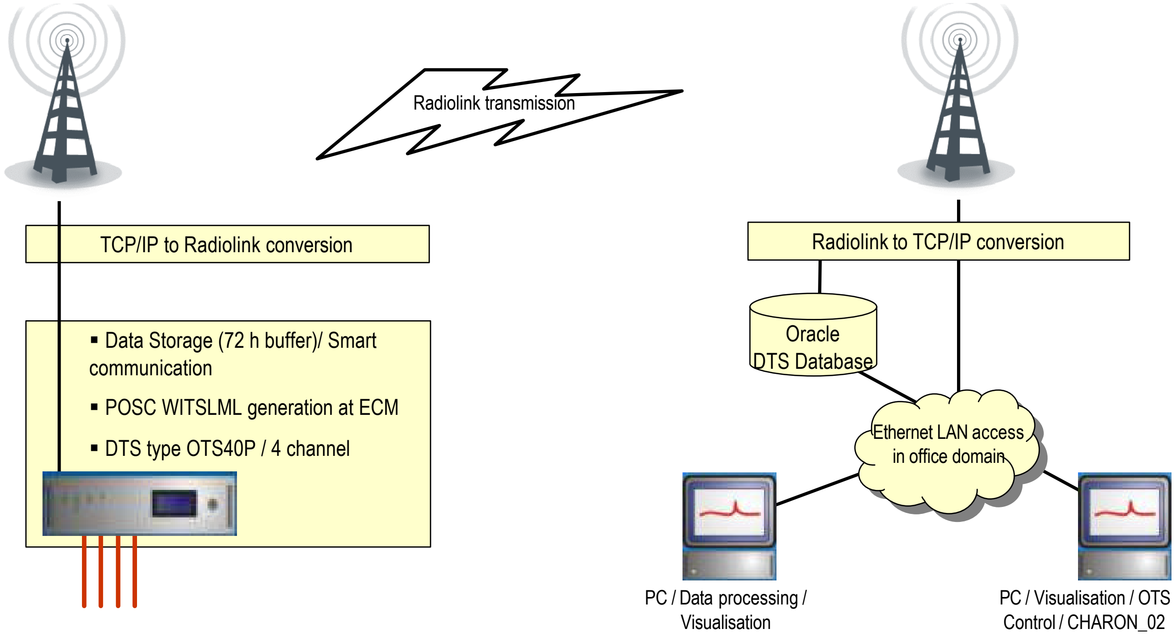

Figure 6: Data processing and data flow form the process control domain to the office domain

POSC WITSML data generation

The DTS system transmits its measured data using POSC files according to the latest POSC/WITSML version 1.3.1 specifications.[16] The petro-technical protocol standard POSC WITSML ensures compatible data streams of distributed temperature profiles, backscattering profiles and event data. It is a logical protocol structure based on XML coded text files and data streams; the measurement data is compressed to optimize the data flow. The POSC files are generated and stored on the Embedded Communication Module (ECM) of the LIOS DTS system.

Data transfer to the office domain / Remote backup

In order to automatically transmit all measurement data from the DTS to the office domain, a LIOS product called Remote Backup is utilized. It can either be run on a PC where the measurement data is gathered on site, or executed as a plug-in module on the DTS system

[15] FFT: Fast Fourier Transformation
[16] Internet Reference: http://www.witsml.org/Docs/Documents.html#v131schema

itself. The LIOS Remote Backup is an application that copies exported measurement data from a remote installation over an encrypted network connection to a central location. It consists of one computer running the LIOS Remote Backup Client (typically in the office domain) and an arbitrary number of machines – either PCs or Embedded Communication Modules – each running the LIOS Remote Backup Server. The client will automatically detect and connect each remote server over an authenticated and encrypted channel and receive remote measurement data files. Measurement data will be checked on server and client side to ensure that data is transferred only once and data only transferred partially, e.g. due to network problems, will be automatically continued during a later session, this will optimise the utilisation of the network's bandwidth. The complete backup process uses secure state of the art authentication and encryption according to the TLS[17] version 1 Internet standard and is thus protected against all known kinds of attacks.

Database interfacing/HTTP upload

Shell uses an Oracle database to store the collected DTS data. Oracle contains a server which can receive data through the industry standard HTTP protocol[18] and is also capable of interpreting XML files as well as inserting the data contained therein into a database. For security reasons, no direct connection between the systems creating the POSC files (DTS or PC) and the database server exists. Therefore, an additional application was developed by LIOS to transfer the POSC files collected by the Remote Backup client in the office domain to the Oracle database using the HTTP "PUT" mechanism. The application supports both HTTP authentication and TLS[17] encryption to allow its use in security-sensitive environments.

The application reads back the HTTP status code from the Oracle database server after the transfer of each POSC file and is able to either erase or archive the POSC files based upon the status reported by the server allowing a verification of the data. The HTTP PUT tool is designed to run unattended to make minimum user interaction necessary.

Embedded P/T gauge data

A variation to the above described scenario is the Charon_02 visualization software which is preliminary designed to store and visualize LIOS OTS controller distributed temperature data. Its XMLIOS feature extends its functionality to third party sensors and data sources. The XMLIOS feature enables the acquisition of point type data. The received data will be stored in the Charon_02 database and can be visualized, printed and exported. The data acquisition is based on a three-layer model:

- An external sensor produces data and publishes it by a standard industrial protocol e.g. MODBUS TCP.
- The LIOS XML Data Server polls the data from the MODBUS TCP connection and translates the data to a XML structure. The LIOS XML Data Server notifies Charon_02 of the new available data by sending an UDP message.
- Charon_02 reads the XML Data by using a HTTP protocol request and stores the measurement data in a database for further processing and evaluation.

Each mentioned layer may be located on a different host. Further details are shown in the following Figure 7.

[17] TLS Reference: http://www.ietf.org/html.charters/tls-charter.html
[18] RFC 2616, http://www.ietf.org/rfc/rfc2616.txt

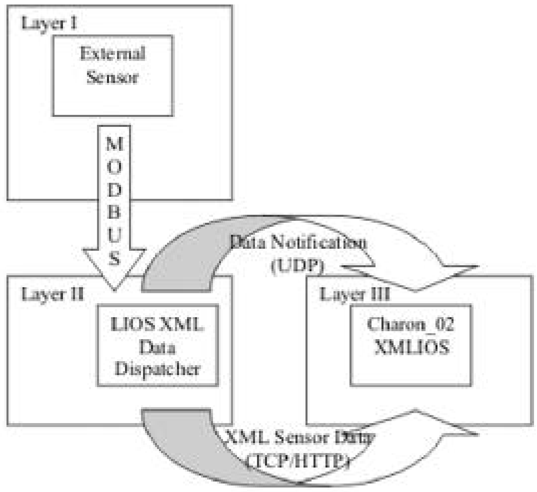

Figure 7: Three layer model for the integration of external point type data into the CHARON_02 database

Data Visualization

An efficient visualization is essential for the evaluation of the measured data. The amount of data produced by a DTS is enormous: At a given sensor fibre length of 10 km it may result up to 65536 data points every 30s. This scenario could produce more than 7 million data points per hour. Additionally, long time monitoring will increase the data volume significantly. This overall-scenario is quite challenging for data transmission, data management and data visualization. The LIOS DTS system of which Charon_02 is a part provides all these features. However, for a large scale deployment the DPD-database based on Oracle is the preferred solution.

Charon_02 provides the display of temperature measurement data and backscattering data Stokes and Anti Stokes channel as a function of distance. Zooming, panning, printing and exporting to ASCII text files are implemented as well. A software interface for direct data exchange (DDE) is available to publish the data to third party software (e.g. Math Lab, MS Excel).

The dynamic behaviour of the temperature profile along the well bore can be revealed by replaying the traces sequentially. Measurement traces will be displayed like a time lapse movie forward and backward at a user defined speed.

Temperature trends may be identified and inspected by displaying temperature data in the time domain. Navigation in terms of time and position is very easily achieved by double clicking a position or a timestamp.

Customized visualization options for E&P show temperature against true vertical depth (TVD) and horizontal displacement (HZD). This implies that data can be loaded containing TVD/HZD vs. along hole depth data, to reconstruct the well trajectory and plot temperature against TVD/HZD, see Figure 8

Loading or specifying a geothermal gradient through copy-paste from MS Excel determines the gradient in the TVD/HZD view as well. Important points along the well bore (e.g. the position of P/T gauges) can be marked through the user interface in Charon_02 at specific depths and displayed at all temperature windows using selected symbols and a short text.

Charon_02 can be operated in the operator's native language. Charon_02 currently comes with the language sets English, German, French, Italian, Portuguese, Danish, Simplified

Chinese, Traditional Chinese and Korean. A software tool can be used to customize the Charon_02 application and to fit the software to the operators' demands.

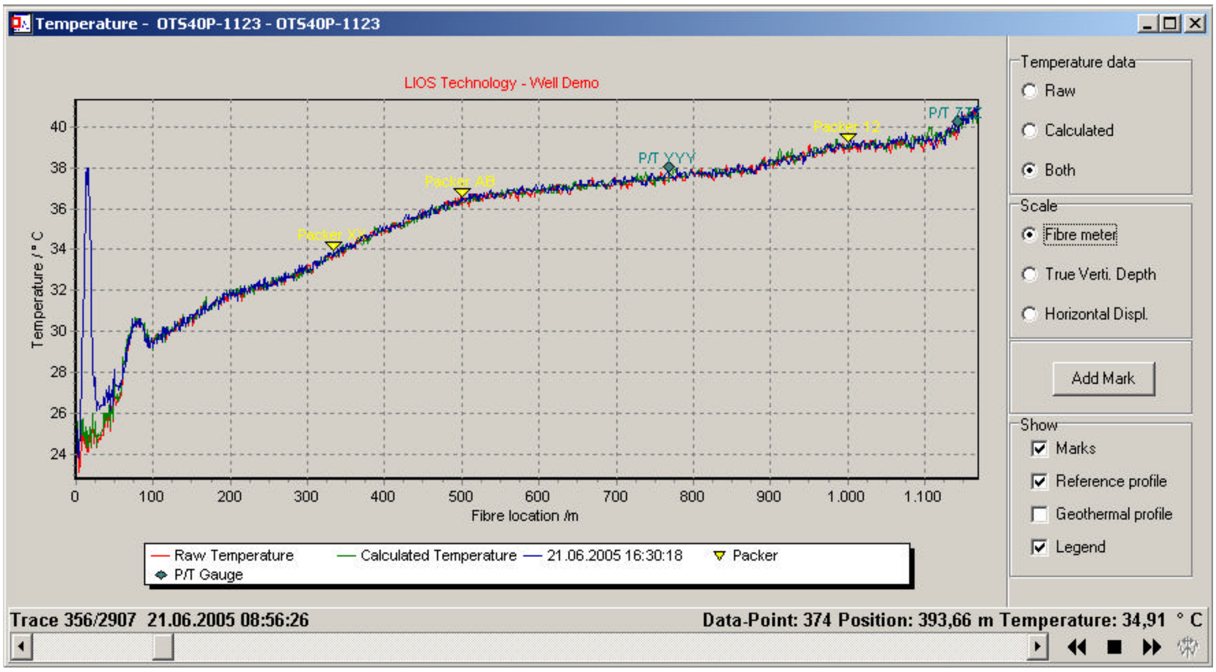

Figure 8: Charon_02 DTS temperature visualization of land well deployment

Conclusions

We presented several successful low-cost DTS installations in BSP in this paper, on- and offshore. This shows that once certain maturity and robustness in a technology has evolved and an agreement on standards has been implemented low-cost equipment can be designed, manufactured, and deployed even for low-cost wells. The applied design and working practices enable permanent in-well sensing for a large-scale role out. Additionally, a DPD-database has been developed and successfully deployed. The PTs and REs in BSP have now full access to the low-cost DTS installed wells around the clock, every day of the year.

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