Fiber-optic Sensing is the Technology of Choice for Permanent Reservoir Monitoring Applications
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Abstract
Fiber-optic sensing technology is the right technology for Permanent Reservoir Monitoring (PRM) applications due to significant advantages in reliability, system design and installation flexibility, and enhanced compatibility with future field development trends.

It is well known that fiber-optic technology is inherently a more reliable technology choice for underwater applications. This has been proven by long-term use within military applications and the telecommunications industry. The application of fiber-optic technology for PRM offers the proven reliability benefits long recognized by the telecommunications industry to the oil and gas industry. The use of fiber-optic sensing technology removes the electronics and electrical power requirements from the seabed and replaces it with completely electrically passive components, which can be interrogated from a platform, FPSO or from shore, using only optical signals. This eliminates the potential for electrical leakage and decreases the potential for mechanical water leak-induced failures in the underwater equipment. The improved reliability drives down the through-life operations and maintenance costs for PRM applications.

It is less well known that the inherent flexibility available with fiber-optic PRM systems generates significant additional value beyond the reliability advantage. Fiber-optic systems enable more flexible system design and layout solutions compared to electrical based alternatives. Greater design and layout flexibility translates into significant advantages during system installation, which can reduce the cost and risk of PRM projects. Advanced optical architectures and proprietary system design techniques generate an expanded range of layout and connection options, which can be used to optimize the system supply and installation solutions during an integrated PRM project planning process.

The authors conclude that PRM systems based on fiber-optic technology offer a better platform for the future due to a number of key advantages. Fiber-optic systems offer greater potential for cost-effective expansion, technology upgrade and cost reduction moving forward. The very low propagation loss intrinsic to fiber-optic technology makes it ideally suited to address a number of developing trends in offshore field development.

In this paper, the authors present examples of clear advantages in reliability, flexibility, expandability and suitability to address future trends for operators to consider when selecting a PRM system for 4D seismic monitoring. Based on these examples and evidence, the authors conclude that fiber-optic sensing is the technology of choice for PRM.
Introduction
Since the first offshore field-scale experiment in 1995, the use of Permanent Reservoir Monitoring (PRM) as a tool for 4D (time-lapse) seismic has been explored, debated and, eventually, put into practice within our industry. For almost the same length of time, the question as to which technology is best applied to ensure successful PRM has also been debated. The earliest PRM installations utilized, out of necessity, retrievable OBC systems based on existing electrical sensing technology. Today, a number of sensing systems based on fiber-optic technology exist, which have been developed specifically for offshore PRM applications. In this paper, the authors will present several of the key reasons why fiber-optic sensing is the technology of choice for offshore PRM applications.

Permanent Reservoir Monitoring Application
Permanent Reservoir Monitoring is one method operators may use to acquire 4D, time-lapse seismic data over producing fields. In the offshore environment, Permanent Reservoir Monitoring involves the permanent placement of an array of seabed seismic sensors for the purpose of detecting and recording the dynamic properties of the subsurface to enable informed decisions to be taken during the production of the reservoir. The ultimate goal is to improve reservoir management and increase the recovery factor for producing fields.

A typical PRM system installed today may contain 3-6,000 sensor stations and be expected to operate reliably for durations of 25 years or more. While the very first attempts were made in the mid 1990’s, PRM is still viewed as an emerging technology and application in some circles. More recent case studies, most notably from Valhall, have confirmed the value of PRM and a drive to increase recovery factors is now accelerating the implementation of PRM systems worldwide (Meld, 2011).

The key factors that drive the PRM system technology selection are risk, both during installation and throughout the operation, together with initial and through-life cost. As with most offshore projects, highly reliable equipment and thorough project planning are two of the key ingredients for project success.

Why Fiber-optic Sensing is the Technology of Choice
Fiber-optic Sensing is the Technology of Choice Today as a Result of Improved Reliability and Increased Flexibility Over Earlier Alternatives

The Fundamental Reliability of Fiber-optic Sensing
The potential of fully fiber-optic sensing PRM systems to offer intrinsically high reliability has been recognized for some time. This arises from the complete removal of electronics and electrical power from the underwater arrays, and the use of electrically passive optical and mechanical components in their place. This has three main reliability benefits:

- Elimination of well-known “burn-out” and random failures associated with electronic components
- Reduced susceptibility to failures occurring as result of small or large scale water ingress into cables or pressure seals (water ingress will not lead to immediate optical component failure, while it normally does so with electrical components)
- Reduced susceptibility to failures caused by power surges, static or other unintended electrical effects.

These benefits have already been recognized and demonstrated in military systems, where in excess of 11 years of continuous operation of seabed optical sensor systems has been achieved. However to fully realize the potential of these benefits in PRM systems, a focus on long-term reliability needs to be a fundamental component of the system design and qualification efforts. The benefits can be maximized through a four-pronged approach encompassing:

- Optimization of system architecture
- Optimization of system mechanical design
- Careful material and component selection
- Rigorous qualification testing.

The success of this approach can be validated by a thorough qualitative reliability assessment that informs the overall system design and qualification. The four key aspects are discussed below in more detail:

Optimization of System Architecture. One of the key elements of any system design is the system architecture i.e. how the outputs from many thousands of sensors are combined together and transmitted to the surface. Architecture design should address the reliability issue by (a) minimizing the potential for failure, and (b) minimizing the impact of failure. Reducing the potential failures is achieved by making architecture choices which minimize the number of components and/or allow the use of components with proven high reliability. For instance, to minimize the number of components, it is possible to develop architectures which require the use of a single optical fiber coil for each sensor, together with a single optical reflector. It is
also possible to develop architecture with very high multiplexing capacity. This means that connectivity can be achieved using highly reliable, commercially proven 4- or 8-way optical connectors (Nash, 2008). The impact of failure can be minimized by using parallel (tree) architecture. Figure 1 shows the difference between parallel and serial architectures. In the alternative serial architecture, the fiber sensors are spaced along a single fiber line. The failure of any single sensor or any sensor connecting fiber can lead to the failure of all other sensors after that point. In a tree architecture, the sensors sit on parallel branches with no more than four sensors (one multi-component or 4C sensing unit) on each branch. The failure of any single sensor or the connecting branch fiber will therefore never cause the failure of more than one 4C sensing unit. Note, also, that at the trunk of the tree (i.e. at the far left of the diagram) only a small number of fibers are needed; it is at this point that connectors are normally used and so the number of connections can be minimized as described above.

**Figure 1: Parallel (Tree) and Serial Architectures**

Optimization of Mechanical Design. In addition to the fundamental reliability of the optical system approach, there are aspects of the mechanical design that also drive the reliability. These are in two main areas: active sensor components and pressure seals. Active components in an optical system include mechanical springs within accelerometers and the fiber sensor coil itself. It is important that these components are chosen carefully, and the housings designed to minimize stresses on these components. Fundamental design choices, such as the use of internal pressure housings or pressure balancing designs will influence the complexity, cost and reliability of the final product. The isolation of accelerometers within a pressure housing produces a simple, robust design, which considerably reduces the stresses to which these components are exposed (especially in deep water). Use of pressure housings does however require very careful attention to pressure sealing. Reliability can be increased by using multiple pressure barriers. As an example, a sealed pressure housing as a primary barrier can be encased in a polyurethane overmould to add a secondary barrier in the design. Another factor that requires careful attention during mechanical design optimization is corrosion, which can have a significant effect on long-term reliability. The impact of corrosion can be minimized in the design by making use of materials chosen to have carefully matched galvanic properties and ensuring no metalwork is directly exposed to seawater.

Careful Material and Component Selection. The best technology and mechanical designs can still fail if they are implemented using inappropriate materials and components. Careful selection of both should include reliability and lifetime requirements, and purchasing from reputable manufacturers with an established track record able to provide evidence of full product qualification and assurance testing. In particular, many components will have been qualified to recognized industry standards. For instance, optical components, if commercially available, should have been qualified to the appropriate Telcordia standard. In general, it is good practice to use as many commercially available components as possible, especially where an established reliability record exists. Providing these procedures are followed, the potential component reliability benefits of optical systems compared to electrical should be realized.

Rigorous Qualification Testing. New components within the system (such as the sensors) are unlikely to have a long track record due to their innovative nature. In addition, when the components are assembled into sub-systems, and then the complete system, additional possible failure modes exist. The reliability of these new components, and of the complete system, can only be established by a process of qualification testing of both the design and the manufacturing processes, which involves both factory and field testing. The factory testing will normally involve exposing the key sub-systems to stresses, which
significantly exceed their normal operating conditions. For instance, qualification of a sensor station typically involves pressure testing to the equivalent of 3,000 m water depth, temperature cycling over a range of -5 deg C to +50 deg C, and in excess of 2 million cycles of seismic shock (expected to be greater than the total numbers of seismic shock seen during a typical PRM lifetime). Cable qualification testing involves bending, twisting and stretching the cable to limits beyond those expected to be encountered during system installation. At the end of each qualification test, the sub-system or system is retested to ensure there has been no change in performance. Examples of qualification testing are shown in Figure 2 below.

The final stage of qualification involves testing in the field. This should include installation of a system using realistic installation equipment and water depths. As part of a field qualification process, cable and associated sensor units (48 sensor channels) were installed in 270 m of water in the North Sea. Importantly, due to the nature of the PRM application, field testing is not just a one-off event. Periodical re-testing has been carried out which shows that 100% of sensors are still operational after 3.5 years, with ongoing testing scheduled to further establish its longevity.

Figure 2: Example of Rigorous Qualification Activity

Reliability Validation
Quantitative availability, reliability and maintainability (ARM) assessment is a powerful tool, which can be used to assist with system design, and to give predictions of likely failure rates for specific system configurations. The ARM assessment process was originally developed for military applications, and is covered by industry standards such as DNV-RP-230. The ARM process involves first establishing the failure modes of a system, then assigning failure probabilities to all the system components, using a combination of manufacturer’s actual failure data (preferred) or generic component failures rates from established industry databases. A statistical analysis of the whole system failure rate is then carried out, taking into account the system architecture including elements of redundancy, etc. This analysis, which is based on a Monte Carlo simulation, gives a probability of failure as a function of time for the whole system. Typically, this may be expressed as a percentage of sensor units still operational after a certain number of years.

Figure 3 shows a failure rate prediction from an independent ARM study performed on a optical PRM system, predicting that 99.2% of sensor units will be operational after 5 years, and 97.8% after 20 years.
System reliability is one key aspect of a system which establishes its suitability for 30 years’ operation. Another key aspect is stability – the sensors need to not only survive, but also give stable and repeatable performance (including sensitivity) throughout the operating period. Highly stable, repeatable sensors are essential to allow detection of the small changes in reservoir properties seen during PRM.

**Stability Validation**

Since the fiber-optic sensor technology is relatively new to the seismic business for Permanent Reservoir Monitoring applications, the sensor stability and sensitivity are not yet tested in-situ on an operating field over a period of several years. However, an alternative method that can be employed is the use of an accelerated lifetime testing procedure. This involves exposing the fiber-optic sensor to extended periods at a temperature significantly higher than its normal operating temperature (Berg, 2012). Following proven and recognized material ageing techniques the sensors under test are exposed to temperatures of 50 deg C. The principle is that exposing the sensor to 50 deg C over one month is equivalent to two years of natural ageing at 5 deg C. The key performance attributes of the sensor are then measured at regular intervals. Figure 4 shows the frequency response (up to 400 Hz) of an optical hydrophone that has been subjected to the equivalent of 30 years of natural ageing at 5 deg C (15 months at 50 deg C). The frequency response is flat and the sensitivity has not varied beyond experimental uncertainties over that period. Similar results are also achieved when performing the same experimental procedure to optical accelerometers.
The Flexibility Within Fiber-optic Sensing Technology Increases “The Art of Possibility” When Applied to PRM Solutions

Because the use of fiber-optic sensing technology is relatively new, particularly for the PRM application, there is a perception of risk within our industry. However, it is precisely because it is relatively new, that it offers an increased opportunity. There is a greater degree of “The Art of Possibility” (Zander, 2000) principles available to the users of fiber-optic sensing technology. There is greater potential for flexibility and more innovative PRM solutions with fiber-optic technology compared with existing electrical technology.

As companies transition from working with electrical technology based seismic acquisition systems to fiber-optic sensing based systems, stakeholders experience a paradigm shift in thinking, as they are able to consider solutions outside the ‘electrical’ box. Users are able to expand the options and consider what is “yet to be invented”. A completely passive, subsea fiber-optic sensing array not only increases bandwidth and improves reliability; it also offers the potential for new system configuration alternatives to improve overall performance and efficiency in the PRM application.

In the authors’ experience, examples of how the possibilities and flexibility offered by fiber-optic technology can be used to benefit PRM projects fall into four key categories:

- Improved system design and layout solutions
- Greater levels of design, supply and installation integration
- Increased flexibility in connection options and repairability scenarios
- Expanded system redundancy options

Improved System Design and Layout Solutions. The initial survey design and system layout planning is a key activity within a PRM project, which has a major impact on overall project success. Utilizing the inherent flexibility of fiber-optic technology for PRM applications allows the consideration of a greater range of design and layout solution options during the project planning stage. The PRM system design and subsea layout have a large impact on the project costs, influencing both the equipment cost and, importantly, the installation cost. The design and layout also influence system reliability as well as overall system performance over the field lifetime. The ability to consider and explore a greater range of alternative options to maximize the potential from the flexibility afforded by the use of fiber-optic sensing technology results in a chosen design and layout solution that can significantly reduce the overall cost and risk of a PRM project.

Greater System Design, Supply and Install Integration Potential. Real value is added to PRM projects when the key advantages in design and layout afforded by fiber-optic technology are realized within an integrated project planning effort, which includes system supply and installation. In addition to translating into significant advantages during system installation, the increased flexibility in design and layout enables further optimization for both the field conditions and the particular expertise and preferred techniques of the selected installation provider. As one example, advanced optical architectures allow the use of longer individual receiver line lengths, which can be applied to a system design to reduce the number of lay initiation operations required during the system installation.

Working with the physics of light rather than electricity, there are fewer physical constraints in a subsea PRM system application with a fiber-optic sensing array compared to an electrical sensing array. This particularly applies to the power and weight constraints and associated limitations with electrical technology based cables. When the subsea PRM sensors are optically powered, the need for electrical cables is removed completely, providing new levels of design flexibility and simplicity, limited only by the capacity and low loss of optical fibres.

Combining the knowledge and specialist domain expertise of operators, optical system suppliers and installation providers during an integrated project planning effort enables a far greater potential for cohesive equipment supply and installation optimization during a PRM project. An integrated planning approach to assure the delivery of these benefits should be the model for all PRM project planning.

Increased flexibility in System Connection Options and Repairability Scenarios. Any underwater connection, either electrical or optical, is potentially a reliability weak point in a PRM system. The flexibility to optimize the number, placement and type of connection solution in the subsea array improves overall reliability and reduces both risk and cost during the system supply and installation. With fiber-optic sensing technology, there is greater scope to optimize the location and connection strategy for maximum project benefit.

Expanded Redundancy Options. The use of fiber-optic sensing technology also expands the options to implement system redundancy within a PRM solution. With the selection of an appropriate optical architecture, cost-effective implementations of Data Path Redundancy (DPR) allow bi-directional interrogation of the seabed optical sensors for continued operation in the event of a component failure or a physical disruption to the primary data path.
Fiber-optic Sensing is the Technology of Choice for the Future due to a Greater Ease of Expansion, Upgrade Potential, Lower Cost and its Suitability to Address PRM Market Trends

_Ease of Expansion._ When properly considered during the initial planning, any PRM array can be extended or expanded at a later date. In the authors’ experience, the ease of preparing for cost-effective expansion and extension is greater with fiber-optic sensing based systems for several key reasons. Adding expansion fiber capacity into the initial riser design attracts a low marginal cost and typically fits easily within the available space envelope. System extensions, which increase the step-out distance to the subsea sensing array, can typically be more readily accommodated within a fiber-optic sensing system compared to electrically powered sensing systems.

_Upgrade Potential._ One issue affecting the rate of uptake of PRM is the caution shown by companies before investing in a technology solution that will be installed and operating for a period of 25 years or more, during which timespan new and more advanced technologies may be developed that offer the potential for improved performance. However, one benefit of an optical system is that the system performance is driven to a large extent by the topside equipment. This is because the sensors themselves are passive in nature, and key performance parameters such as noise floor and dynamic range are driven by factors such as the laser noise and processing electronics. Because the topside system is readily accessible, there is a convenient upgrade path for the system when new technology becomes available. The introduction of improved technology in topside upgrade modules can give enhanced system performance without disturbing the existing subsea system.

As an example, laser noise performance, which is one of the key influencers of overall system noise, has improved dramatically over the last 5 years, and is likely to improve further in the future. This will make possible further reductions in system noise, especially at very low frequencies, which can be achieved with a simple topside upgrade. As another example, it is well known that the speed of digital signal processors (DSPs) has been, and continues, to increase dramatically. The size and power consumption of the topside unit is highly influenced by the DSPs used and, in future, the size, weight and power consumption of the topside unit are likely to be significantly reduced as DSP technology continues to improve.

Use of a fiber-optic based solution therefore allows access to the latest technology throughout the 25 year lifetime of a PRM system.

_Reduced Cost._ The cost of PRM systems is a frequently debated topic between customers and suppliers of such systems. Today, it is fair to say that respective electrical and fiber-optic based systems are at different points along the relative technology maturity/volume versus cost scale. There is little doubt that the use of fiber-optics offshore is increasing rapidly and will continue to do so for some time. As more operators adopt the use of fiber-optic technology offshore, for PRM and other applications, the direct equipment supply costs for fiber-optic sensing solutions will continue to decrease over time. The potential for further direct cost savings is greater with fiber-optic based systems moving forward.

As discussed above, when noting the benefits of reliability and flexibility afforded by fiber-optic sensing systems, the indirect costs associated with the technology choice, those of through-life maintenance and of the initial installation, are also positively impacted by fiber-optic sensing systems. Improved reliability reduces the through-life cost and increased flexibility can be intelligently used to reduce system installation cost.

_Greater Suitability to Address Future Trends._ From an analysis of the PRM market and observation of the industry, it is possible to identify several developing trends which need to be considered when making a technology choice for PRM projects. The trend towards production in deeper waterdepths is already well established. As of today, a visible trend is starting to emerge towards larger scale system installations as more operators adopt PRM for seismic 4D monitoring of the reservoir (Figure 5). We also note that consideration is being given to extending the size of some of the earlier PRM systems already in the field.
Observing current trends in offshore field development, it is also possible to anticipate there will be a growing need for PRM systems to facilitate longer step-out distances to reach satellite production targets as field development over producing assets matures in the future.

A further logical progression is for the PRM system technology to support the drive to reduce the number of surface facilities with the move towards subsea to shore configurations. It is anticipated PRM systems of the future will need to operate over long distance tie-backs to onshore locations.

All of these trends favor the use of fiber-optic technology in today’s PRM applications due to the capability of fiber to (a) operate efficiently over greater distances as a result of the inherently lower propagation loss over distance, and (b) to provide very high bandwidth transmission, allowing transfer of very large amounts of data.

Low propagation loss is an intrinsic feature of optical fibres, where light is confined within a small (≈9um diameter) crystalline strand of glass. In contrast, electrical cables have a stronger interaction with the electric field as it propagates, leading to resistance, or loss of energy.

Figure 6 contrasts the energy lost through propagation along 2 km of optical fiber compared with the same propagated along coaxial and twisted pair electrical cables. After just 1 km, 0.001% energy remains in the twisted pair cable, 1.7% in the coaxial cable, but 96% in the optical fiber.

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**Figure 5: Approximate PRM System Receiver Area Size in sq.km.**

**Figure 6: Illustrating Energy Loss Through Media Propagation. Optical Fiber - Corning SMF288 [2], Coaxial Cable LMR-1200-FR @ 750MHz [3], Twisted Pair CAT5e [4]**
During the last 40 years, high data transmission capacity (>100 Gbit.s⁻¹) and low (<0.2 dB.km⁻¹) propagation loss have driven worldwide adoption of optical fibres for telecommunications, where large quantities of data can be easily transferred over >100km distances without need for any amplifications or regeneration. In the same way as the drive for transatlantic communications made electrical cables impractical for telecommunications, so the trends towards deeper waterdepths, larger system sizes, longer step-out distances and, ultimately, tie-backs to shore, will increasingly drive the technology choice further towards optical fibers for PRM applications.

Conclusions

The inherent reliability of fiber-optic technology provides a great foundation for building a PRM system. As presented here, a focused, four-pronged approach during the system design and qualification effort provides the added structural framework to fully realize the reliability benefit in the delivered system. System development must optimize the architecture and the mechanical design, make careful material selections and perform rigorous qualification testing. Suppliers can validate the success of the approach with independent reliability verifications. Suppliers and operators can, and should, work together to maximize the benefits of the flexibility afforded by fiber-optic technology during an integrated project planning effort. The combination of significantly increased reliability and improved solution flexibility reduce risk and cost and make fiber-optic sensing the technology of choice for PRM applications today.

However, the selection of technology for a PRM system must also consider the future and the suitability of the technology to efficiently address potential expansion, efficiently incorporate new technology advances and to provide sufficient compatibility to enable the growing trends for satellite field developments and tie-backs to shore. With its intrinsic low propagation loss, fiber-optic technology is ideally suited to deliver on these future benefits throughout the life of the system. The combination of a greater ease of expansion, ease of technology upgrade, lower costs and suitability to address current and anticipated trends reduces lifetime risk and cost and makes fiber-optic sensing the technology of choice not only today, but also for PRM applications in the future.

The future is bright for “listening with light”.

References

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