



Using submarine cables for climate
monitoring and disaster warning

Engineering feasibility study



IOC



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Additional information and materials relating to this Report can be found at:
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Executive summary

Oceans store more than 90% of the heat and 50 times as much carbon as the atmosphere in the Earth's climate system. Ocean bottom waters originate in the northern North Atlantic and around Antarctica. Global warming causes polar waters to be less capable of sinking, reducing thermohaline circulation and impacting the ocean's capacity for heat and carbon storage. A time series of data that provided detailed information on changes in the deep ocean over decades would significantly improve our ability to quantitatively evaluate the rate and degree of changes in climate and in the Earth climate system.

Long-time series data requires a very stable and reliable platform. Such a platform exists in the deep ocean: the subsea fibre optic cable systems that join continents and form the fabric of the Internet. These cables, which have repeaters (optical amplifiers) in housings approximately every 50-75 km along the cable and have a design life of 25 years, appear to offer a low cost support mechanism for the placement of instruments to obtain time series data. This study considers the implications for telecommunications companies and for scientists of placing instruments on repeaters. For the purposes of this study, a repeater equipped with science instruments is termed a "Green Repeater".

The conclusion reached in this study is that it is feasible to support a modest number of low power instruments in repeaters. One of the principal manufacturers of subsea telecommunications cabled systems, TE SubCom, made an announcement in February 2012 that it has a cost effective solution to integrate scientific instruments into trans-oceanic telecommunications systems. TE SubCom has entered into an exploratory partnership with Scripps Institution of Oceanography at University of California, San Diego, and National Oceanic and Atmospheric Administration (NOAA)'s Pacific Marine Environmental Laboratory (PMEL) and is in the formative stages of seeking funding for engineering for its solution.

However, the greatest impediment to the Green Repeater is that instruments of the required longevity do not exist. Existing instruments will need to be further developed for long life, small size, robustness, and stability; their housings must be redesigned out of materials which are compatible with repeater housings, and then they must be qualified to subsea telecommunications industry standards of practice. This effort will parallel similar programmes being undertaken for cabled observatories, including Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET), NEPTUNE Canada and the Ocean Observatories Initiative (OOI) Regional Scale Nodes (RSN). Instrument development will take some time, and require significant funding. Before this effort can begin, science goals must be clearly defined and realistic, and specifications for the instruments and instrument interfaces must be agreed on by both the science community and the subsea telecommunications manufacturers.

Monitoring long term changes in the deep ocean is an important endeavour that, if successful, will significantly increase our understanding of climatic processes. Developing suitable instruments is the next step along the path towards that goal. Regular interaction with both the science community and the subsea telecommunications manufacturers should continue during the instrument development and qualification stages. After suitable instruments are designed, tested, and have a history of use on existing scientific arrays, the details of how to integrate them into telecommunications repeaters should be turned over to the subsea telecommunications manufacturers. These manufacturers have the experience and capability to perform the necessary integration tasks while achieving the levels of system reliability and performance required by the telecommunications industry and system owners.

1 Introduction

1.1 *Introduction to subsea telecommunications cables*

Subsea telecommunications cables have a long and rich history beginning with the earliest telegraph cables in the late 1850s, through the development of coaxial analogue cables after the Second World War, followed by the transition first to digital coax and then to optical fibre. Today's systems employing Erbium Doped Fibre Amplifiers (EDFAs) are capable of carrying several Terabits per second. All continents except Antarctica, and most populated islands are linked by subsea fibre optic cables which provide the foundation for the global Internet.

Telecommunications cables are designed for one specific purpose: to move data from shore terminal to shore terminal with the highest possible degree of reliability. Signals are boosted by means of in-line optical amplifiers contained in pressure resistant housings; these are still termed "repeaters," nomenclature derived from terrestrial and subsea telegraph cables. Data processing within a repeater, if it is present at all, is limited to rudimentary control and monitoring functions using four-bit words.

Subsea cable systems have also been built specifically for monitoring and data gathering. Countries around the world have deployed arrays of hydrophones for intelligence gathering. Japan¹ and a few other nations² employ cable systems for seismic measurements and tsunami monitoring. More recently, general purpose "cabled observatories"³ have been installed in both coastal and deep ocean environments. These systems are most often purpose built, incorporating some of the technology used for telecommunications cables while adding capabilities such as electrical power conversion, data switching, and underwater connectors. The unique functions and relatively high cost of these systems has so far limited their role to coastal or regional deployments.

1.2 *Introduction to the science goals regarding instrumenting cables*

The oceans, bounded by the atmosphere, lithosphere and shore, and covering 70% of the Earth's surface remain a poorly understood component of the Earth system. Oceans store more than 90% of the heat and 50 times as much carbon as the atmosphere in our Earth climate system. The changing climate, ocean circulation and chemistry, and depletion of ocean life are increasing at an alarming rate, largely as consequence of human activities. Ocean bottom waters are formed in the northern North Atlantic and around Antarctica. Global warming causes polar bottom waters to be less capable of sinking, reducing their capacity of heat and carbon storage.

There is an imperative for improved public understanding of these environmental changes, consequences and possible future options, and for the development of responsive and informed public policies that will better protect societies through this century and beyond. Many of these issues are particularly acute for developing nations and challenge priorities for resource allocation and international aid programmes. To support future planning and policies, a more quantified, detailed and continuous scientific database is required for the ocean realm than the limited, short period data sets which are the outcome of the last century of investigations which drew on data from buoys, battery-operated instruments and ship-based investigations. Instruments to gather data for such a database require permanent seabed infrastructure for support. One option for such infrastructure is to provide a cable from the instruments back to shore, to power the instruments and deliver real-time data to the users. However, such cabled instrument arrays have a high capital cost, and are generally restricted by cost to a few hundred kilometres from a shore landing.

An intriguing solution to both the high costs and limited scale of purpose-built science arrays has been proposed: enabling the next generation of telecommunications cables to gather scientific data by modifying repeaters to support scientific instruments. A typical trans-ocean cable system spans 5 000 to 8 000 km and has repeaters spaced every 50 to 75 km. Equipping each repeater with temperature, depth, and conductivity-

ty sensors would allow continuous time series data to be collected across entire ocean basins. Data from such a system could provide valuable insight into issues such as climate variation, tsunami propagation and sea level change.

1.3 *Purpose of this study*

This study examines the technical feasibility of modifying repeaters to support science instruments (“Green Repeaters”) for incorporation into commercial telecommunications cable systems. First, the elements of a conventional telecommunications cable are briefly reviewed. Then, the science objectives for the Green Repeater are identified. A baseline design is proposed and several alternatives considered. Design and deployment issues are identified and addressed. The feasibility of the baseline design and alternatives are examined. Information gathered from suppliers of subsea cable systems is presented. Finally, the key study results are presented and summarized.

2 Existing technology

Before considering what modifications to a subsea cable system are necessary to support a Green Repeater, it is worthwhile to review the essential components of existing trans-oceanic telecommunications systems. These components are the cable itself, which must protect the transmission media, in this case optical fibres, and provide an electrical power conductor; repeaters, which amplify the optical signals to overcome loss in the transmission media; branching units, which allow branching of either the power conductor, the fibres or both; terminal equipment, and power feeding equipment. Line monitoring or system supervisory functions are typically included, but are not essential for system operation.

2.1 *Cables*

Cables designed for deep sea deployment utilize a central tube containing optical fibres; existing designs can generally support a maximum of twelve fibres, though some can support sixteen. This central tube is surrounded by a matrix of steel wires which create a strength member and are nested in such a way as to form a pressure resistant vault. This matrix is in turn surrounded by a welded copper tube which prevents Hydrogen ingress. The steel vault and copper tube together form an electrical conductor for power feeding. This electrical conductor is overlaid with medium density polyethylene (MDPE). In benign environments, including most of the deep ocean floor, this “lightweight” cable is sufficient. Where the cable must be buried, armour wires and layers of tar coated yarns are added to the outside of the cable. Where the risk of damage is high, further layers of armour may be added. As with any commercial product, variations exist between manufacturers, but the general design elements are similar.

2.2 *Repeaters*

The term “Repeater” originates in the days of telegraph cables and refers to a device which amplifies, re-shapes, or otherwise boosts the signals in a cable. A repeater consists of pressure housing, typically 250 to 300 mm in diameter and 1 000 to 1 600 mm long. This pressure housing is constructed either of steel or Beryllium Copper. At each end of the pressure housing, a penetrator or gland permits the fibres and power conductor to enter the housing. External to the pressure housing, mechanical elements and couplings carry mechanical loads from the cable through the pressure housing, and back to the cable. The internal structure of the repeater houses the circuit boards which perform power conversion and optical amplification. Like cables, repeaters have a number of common design elements, although the variation between suppliers is somewhat greater.

2.3 Branching units

Some cable systems include branching units, to allow multiple geographically diverse landings or to serve communities adjacent to the cable route. Branching units are similar to repeaters but employ a larger housing to accommodate three or four cable ends. Branching units may be entirely passive or may include components for switching the power conductor and regenerating optical signals.

2.4 Submerged plant

Cables, repeaters and branching units together make up the “submerged plant.” Both the cable and repeaters are designed to withstand pressure up to 80-100 MPa (or, equivalently, 8 000-10 000 m depth). Branching units are generally designed to withstand 50 MPa. Cable and repeater designs have been proven through many years of development and experience, beginning with the coaxial cable systems in the 1960s.

There have been no significant design changes since the 1990s when optical amplification replaced electro-optical regeneration as the means of boosting signals. The presently used cable designs also date from the early 1990s when the fibre tube design replaced fibres embedded in Hytrel. For the last fifteen years, change has been incremental, with new amplifiers, new fibre types, and new terminal equipment providing steady advances in the total system capacity.

This cautious approach to design changes is validated by the extremely high reliability achieved. Nearly all cable faults are caused by external factors ranging from fishing gear, anchor drags, to seismic activity and underwater landslides. The failure rate of repeaters during their 25-year design life is typically 10 to 20 per 10E9 hours of operation (FITs), equivalent to one failure per several thousand years.

Some of the general design constraints for submerged plants are discussed below.

2.4.1 Marine handling requirements for submerged plants

All submerged plants are designed to withstand the rigors of installation from the deck of a vessel in the type of weather that may be encountered in winter in the world’s oceans. Each assembly is tested to significant impact and vibration, including a 40 × force of gravity impact test. Cable housing entries are protected by substantial cable bend restrictors that are designed to accommodate loads that exceed the cable breaking strength. The cable and repeaters are designed for the tension and snatch loads that occur during deployment of repeaters in bad weather.

In addition, all submerged plants are designed for deployment through cable engines, over capstan wheels and along cable ways, chutes and over stern ways. To meet this requirement, the exterior of all submerged plants is clean of protrusions and extremely robust.

Marine handling requirements will be a significant constraint on the design of any science instruments.

2.4.2 Installed conditions for submerged plant

Submerged plant includes any equipment designed for installation underwater. Submerged plant has to work in any seabed conditions. It may be buried, either by plough or by natural sedimentation. Cables may be in suspension off the seabed in areas where the seabed has more relief than anticipated. Where the seabed is jagged, the cable may lay across protrusions.

No attempt is made to control vertical or radial orientation of submerged plant, except for branching units. Branching Units are installed such that the cables are not twisted; however, in many instances the branching unit turns over during deployment.

Science instruments must be designed for this variance in as-laid conditions, since it is very unlikely that monitoring during or after lay will be feasible.

2.4.3 Pressure seals, material selection and external grounds

Pressure seals on submerged plant are designed to seal against Hydrogen migration for the design life of 25 years. Due to its small atom size, Hydrogen tends to bypass conventional elastomeric seals, and over time may pressurize subsea housings. For subsea systems, Hydrogen poses a risk of attenuation caused by fibre darkening and of danger to maintenance personnel. Submerged plant seals therefore tend to include a metal-to-metal component, either using a malleable metal such as Lead or by welding.

Pressure seals for science instruments, and for cables to science instruments, must be compatible with the seals used by the subsea industry, and be similarly qualified.

Material selection for any submerged plant housing designed to be exposed to seawater for 25 years is critical. Materials must be corrosion resistant, or protected from corrosion. Materials must be compatible, and not create corrosion in adjacent materials. Housing materials must be uniform, and not subject to local corrosion such as crevice corrosion.

Material selection for science instruments must take into account the materials used in the adjacent repeater housing, and be compatible with them. Failure to meet this requirement could result in sacrifice of either the repeater or the instrument housing through galvanic action.

Submerged plants use external grounds, often placed along the cable some distance from the repeater. This method avoids off-gassing of Hydrogen near the repeater, and restricts ground currents to a sacrificial electrode. No grounding to the housing, even reference grounding, is permitted. Science instruments to be put on a repeater must meet this ground isolation requirement.

2.4.4 Maintenance interval

No maintenance is scheduled, or expected, for the submerged plant during its 25-year design life. The operating history of cable systems confirms that the modern submerged plant meets or exceeds this design life objective. Accordingly, it is desirable that science instruments attached to telecommunications cables be capable of performing over a similar period without the need for intervention or maintenance.

2.5 Terminal equipment

Terminal equipment for subsea cable systems is designed to transmit and receive optical signals through the submerged plant. Dense Wavelength Division Multiplexing (DWDM) combines up to 120 signals on each optical fibre. As of 2012, most existing systems carry 10 Gbit/s on each optical signal; although 40 Gbit/s and 100 Gbit/s systems are now being planned and installed. The overall capacity of a system is the product of the number of fibre pairs, the channels per fibre pair and the bit rate per channel. Total capacities from 1 to 4 Tbit/s are common, with new systems being designed for 10 Tbit/s or more.

Power feeding equipment delivers a constant current into the cable which powers the repeaters. The power feed current typically ranges from 300 mA to 900 mA; voltages up to 10 kV are necessary to drive this current through thousands of kilometres of cable. The Earth is used as a return path. Within repeater housing, a simple Zener diode bridge provides a constant voltage to power an optical amplifier. The power feed equipment is controlled so that the load is normally shared by the two ends of the cable. If one power feed unit should fail, the other is capable of powering the entire cable. If the cable is damaged and the electrical conductor shorted to ground, the current path is split into two loops with each cable end feeding as far as the point on the cable which is grounded. The total power that can be delivered into a cable is limited by the maximum voltage which can be sustained; as the power feed current increases, so does the necessary voltage. On some long systems, especially those in the Pacific, the cable design may be modified to reduce the resistance of the power feed conductor and increase the amount of available power.

2.6 System supervision

The final element of subsea system design is the line monitoring and system supervisory functions. Line monitoring is performed using optical reflectometry. Each repeater contains fibre Bragg gratings which reflect specific wavelengths and direct the reflections' signals onto the fibre transmitting in the opposite direction. This allows a subsea cable system to be measured in much the same way as a conventional Optical Time Domain Reflectometer measures a single fibre span. This method allows faulty repeaters and fibre breaks to be identified. Some manufacturers incorporate digital monitoring and control functions into their repeaters. A low speed data signal is used to query and send commands to each repeater in a system. Using this method, the input and output optical powers, laser diode bias current and intermittent faults can be identified. Commands to increase the optical output power of a repeater may also be sent. Repeaters which do not have a digital supervisory channel may be controlled by changing the power feed current; the amplifier modules measure this current and adjust their output point accordingly.

3 Green repeaters

All of the design elements discussed in Section 2, with the exception of the Terminal Equipment and System Supervision, have some bearing on the design of a Green Repeater. The cable must accommodate additional fibres to transmit science data. The repeater housings must have space for additional circuit boards and any sensors. The science functions must be powered using the power feed current. The science instruments must be designed for the forces inherent in installation on a cable. The instruments must be designed to survive and provide useful data in a variety of seabed conditions. Seals, materials and grounds must be compatible with industry standards.

The design elements discussed in Section 2 which do not have bearing on the design offer no benefits or necessary functions. Line monitoring is an analogue function and provides no method of collecting digital data from the repeater. The supervisory signalling channel has a very low data rate, is not universally available, would entail a high degree of integration with the existing amplifier design and therefore cannot be recommended for data gathering without further study.

3.1 Science objectives

For the purposes of this study, the science objectives for the Green Repeater have been defined to be the measurement of temperature, pressure and conductivity on the seabed at locations distributed across oceans. Such measurements should be reliable, unaffected by drift or lack of calibration, and should provide a continuous time series of data over a 25-year life.

3.2 Science instruments

While review of instruments was not part of the scope of this study, the following observations are offered as means to furthering the overall discussion.

3.2.1 Instrument specifications

The following instrument specifications are proposed for review, and are used in this study. Comments from the science community should be sought to define the instrument requirements, within the overall parameters proposed in this study.

These performance parameters in Table 1 are representative of commercially available instruments. For a number of reasons (discussed in Section 7), these instruments are not immediately suitable for use on the Green Repeater, so the fact that these instruments are listed in Table 1 should not be used as an indication that these products are in any way recommended.

Table 1: Typical Science Instrument Performance Parameters

Measurement	Range	Accuracy	Resolution	Specifications taken from:
Pressure	0 to 70 MPa	±2.0 KPa	0.70 Pa	Paro Scientific Series 8CB
Conductivity	0 to 7.5 S/m	±0.005 S/m	0.0002 S/m	Aanderaa 4319
Temperature	-5°C to 40°C	±0.1°C	0.01°C	Contained in both Pressure and Conductivity Sensors

3.2.2 Precision

The goal of the Green Repeater is to provide reliable and useful data over its 25-year design life, without intervention. The accuracy and precision of the sensors must be sufficient that small changes in the ocean environment over long periods of time can be reliably identified, and separated from any instrument drift or local instrument status changes that may occur.

3.2.3 Stability

The long-term stability of the instruments is a concern, particularly for the Conductivity sensor. There will be no opportunities for calibration once the sensors are deployed; methods of calibrating or validating the data will need to be considered.

Stability issues are not only internal to the instrument. Over time the environment around the instrument may change; sediment may build up on the instrument; marine or bacterial growth, or corrosion by-products may build up around the instrument; the heat output of the repeater may change as redundant components go out of service; etc. An instrument on the Green Repeater has to be able to reliably isolate these local issues in order to provide valid data on larger scale conditions throughout the design life.

3.2.4 Polling rate and time stamps

A polling rate of 0.1 Hz (one sample per 10 seconds) is adopted as a baseline for the purposes of this study; considerations for increasing or decreasing this rate are reviewed.

Time stamps will be generated on shore; no provision is made within the instruments or repeater for time stamping.

3.2.5 Marine handling requirements

Every instrument to be mounted on a repeater must be tested to significant impact and vibration, including a 40 × force of gravity impact test. To ensure successful deployment, the instruments should meet or exceed the handling requirements for repeaters.

It is understood that it is not normal practice for manufacturers of scientific instruments to subject their products to this type of testing.

3.2.6 Installed conditions

Instruments installed on repeaters will have to work in any seabed conditions. They may be buried, either by plough or by natural sedimentation; they may be in suspension off the seabed, in areas where the seabed has more relief than anticipated; they may be sitting up off the seabed in areas of hard or rocky seabed. Over time, their condition will change as sediment builds up.

The vertical orientation of the instruments will be unknown, and will vary from instrument to instrument.

Science instruments must be designed for this variance in as-laid conditions, since it is very unlikely that monitoring during or after laying will be feasible.

3.2.7 Pressure seals, material selection and external grounds

Science instruments normally use conventional elastomeric seals, which over time will be bypassed by Hydrogen. These should be supplemented to include a metal-to-metal component, either using a malleable metal such as Lead or by welding, and the housing and seals should be qualified to the same extent as industry products. A typical specification requires the penetrator to limit the ingress of Hydrogen to less than $5\text{E-}9\text{ cm}^3/\text{s}$ for an external gas pressure of 5 MPa.

Science instruments generally use materials such as anodized aluminium, uncoated 316 stainless steels and Titanium. These materials are dissimilar to the materials used in repeaters, and may not be suitable for 25 years deployment. Significant effort will be required to either qualify them for use on the repeaters or redesign the instruments with housings made of different materials.

Experience suggests that science instruments commonly use their housing as an external reference ground. It is likely that instrument re-design will be required to qualify or redesign the grounding plan.

Finally, instrument housings must be upgraded to a pressure/depth rating of 100 MPa/10 000 m which is commensurate with the repeater design depth.

3.2.8 Instrument design life

For maximum benefit for the investment, all parts of Green Repeaters, including the instruments, should have a design life of 25 years to match the submerged plant design life.

Science instruments are not built based on a 25-year design life. A normal deployment would likely be one year, with a maximum predicted deployment of around 5 years. Designing for a 25-year life will require a change in approach, taking into account issues such as sensor life, sensor stability, and calibration requirements.

3.2.9 Instrument size

An instrument to be deployed on a repeater must fit within the outline of the repeater housing to allow the repeater to continue to present a smooth featureless profile to the cable handling equipment, cable drum and engines, stern sheave and chutes found on modern cable laying vessels. This requirement presents a significant limitation on instrument dimensions. It also means that the instrument will be part of the repeater shell, albeit a part at ambient pressure, and exposed to seawater. The instrument will therefore be subject to the heat output of the repeater, and over time the ambient space within the repeater shell may be filled with sediment. These conditions are likely to require purpose built instruments.

3.3 Scope

The baseline scope of a system equipped with Green Repeaters is taken to be a 5 000 km system equipped with 100 repeaters. A system length of 5 000 km is representative of a North Atlantic system; trans-Pacific systems can be much longer. To ensure that all possible scenarios can be met, representative systems of 10 000 km with 200 repeaters and 12 500 km with 250 repeaters will also be considered. A 12 500 km system represents the longest system that would be reasonably built; this is roughly the distance from Hong Kong to the west coast of North America. For all system scenarios, the number of repeaters is greater than would actually be required; however, accounting for extra repeaters ensures that any design has some margin.

Table 2: Typical Telecommunications Systems

System A	5 000 km	100 repeaters
System B	10 000 km	200 repeaters
System C	12 500 km	250 repeaters

Branched systems are not considered in detail in this study. Branches (or “spurs”) are typically used to connect additional landing points to a primary cable route and may be only a few hundred km long. The value in equipping the branches with Green Repeaters, many of which would be on the continental shelf, remains to be determined. If a branch is equipped with Green Repeaters, some method of connecting these to the rest of the system would be needed. In principal, a data switch could be placed in the branching unit, but this is likely to have an adverse effect on overall reliability. Alternatively, the repeaters in the spur would communicate only with the shore station at the end of the spur.

4 Shared infrastructure assumptions

4.1 Assumptions regarding instrument design

Assumptions regarding the sharing of telecommunications infrastructure are made as follows. These design assumptions are, in the judgment of the authors, necessary to make the Green Repeater acceptable to system owners and suppliers, but do not impair the effectiveness of the science operations.

1. The performance and reliability of the telecommunications functions of the repeater must be unaffected by the presence of science functions;
2. The Green Repeater must require no modifications to the existing methods of system assembly, cable handling, laying, burial or maintenance; the science module and any instruments must withstand transport, laying, plough burial and possible recovery;
3. Cable routing is determined by telecommunications needs;
4. Faults or failures of the science functions will not be repaired;
5. Faults or failures of the science functions will have no impact on the telecommunications functions;
6. The science modules or instruments do not include battery backup or data storage; when the cable is out of service, so are the science instruments.

4.2 Required system elements (baseline design)

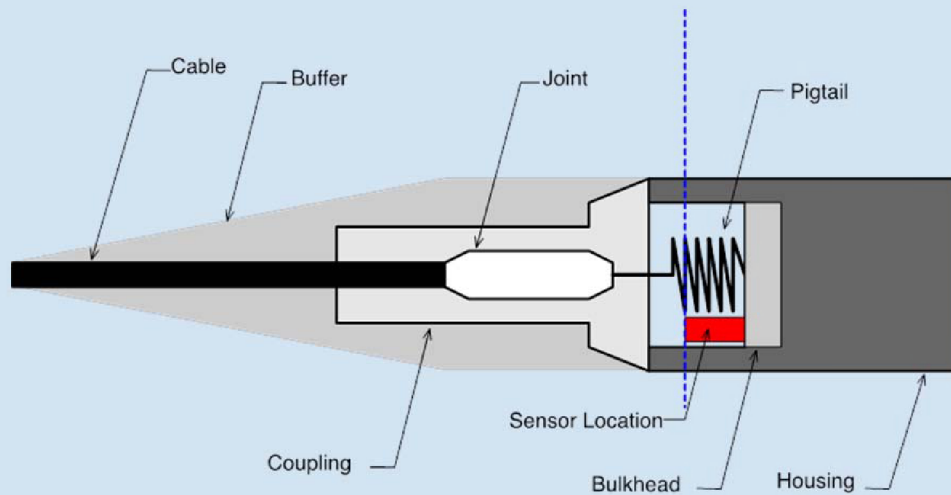
The baseline design elements needed to support the science functions are identified as:

1. The repeater housing length is increased to accommodate one or more additional opto-electronic science module;
2. One fibre pair is added to the entire system, linking the science modules in adjacent repeaters;
3. The power delivered to the science module is the same as that delivered to one line amplifier module;
4. The repeater housing bulkhead design is modified to include an electrical penetrator with six electrical conductors;
5. A science module is added to each repeater, taking the space normally occupied by one line amplifier module;
6. Each science module incorporates bidirectional optical transmission to science modules in each of the adjacent repeaters;

7. The science instruments are mounted outside the pressure housing between the repeater bulkhead and coupling.

This baseline design is provided as a basis for discussion and may be altered or extended by the system manufacturers during detailed development. The feasibility of each of the elements of the baseline design is discussed in the following sections.

Figure 1: Possible Instrument Location



4.3 Repeater housing modifications

Repeater housings may be modified for two purposes: to increase the internal capacity and to provide additional space outside the pressure housing in which to mount the instruments. The resulting modified housing must still have dimensions which can pass through a linear cable engine and over the sheave of a cable ship.

Repeater housing designs for two, four, six, and eight fibre pairs are available. System owners typically choose either a two- or a four-fibre pair designs. To accommodate an additional fibre pair, the repeater housing would be increased to the next available size.

The section of the repeater outside the pressure housing between the bulkhead and the cable coupling is the proposed location for mounting sensors. A similar approach has been employed on some of the purpose-built seismic systems and may also be necessary for the Green Repeater. This section cannot be an arbitrary length, but is limited by the overall housing dimensions which must still allow for passage of the repeater around a cable drum and over a stern sheave.

As a result, the instruments under consideration will need to be relatively compact. Dimensions of 90 mm long × 40 mm in diameter are assumed. This is based on representative, commercially available instruments.

The combination of a longer housing to accommodate an additional fibre pair and some increase in the area outside the bulkhead will result in a repeater housing approximately 2 m long.

4.4 Adding one fibre pair

All conventional cable designs can accommodate up to twelve fibres. Most subsea systems use four-fibre pairs, though some use six. Manufacturers have designs for cable and repeaters to support eight-fibre pairs, but eight-fibre pair systems are rarely found to be economically optimal.

There are two limits on the number of fibre pairs. The first is the size of the fibre tube within the cable; the second is the length of the repeater required to house the optical equipment to support the fibre pairs. However, unless a system owner needs six or more fibre pairs, additional fibres can be provided for science using existing cable designs.

4.5 Electrical power limitations

The maximum power which can be delivered to the science module is limited by the system power feed current and allowable voltage drop. Total science power consumption per repeater (including module(s) and instruments) of 4 W should be targeted. Up to 7 W can be provided, although this will result in higher power feed current than is required to operate the telecommunication equipment.

4.6 Repeater bulkhead modifications

Modifications to the repeater bulkhead to accommodate the penetration of electrical lines from the sensors are required and are seen as the highest risk element of the Green Repeater design. Existing bulkhead designs are well proven and known to meet the requirement to withstand 80 MPa, but have no spare penetrators.

At least, two suppliers have indicated they have an existing design with a spare penetrator which could be used to support science needs.

4.7 Science module in the space occupied by amplifier module

Building a science module to fit in the space normally occupied by an amplifier module will pose constraints on the designers. However, meeting such constraints appears to be realistic. Fitting the science module into a standard repeater space will simplify the manufacturing of the Green Repeater.

4.8 Bi-directional optical transmission to adjacent repeaters

Bidirectional optical transmission to adjacent repeaters is viable using today's technology, and appears to improve overall reliability.

4.9 Science instruments mounted outside pressure housing

The sensors for the science instruments must be exposed to ambient seawater. However, they must be protected from damage by being within the repeater shell. Therefore, the obvious place to mount the science instruments is within the shell of the repeater, but outside the pressure housing. This protects them from direct impact during deployment, and gives them some measure of exposure to seawater.

The coil of the small diameter cable that provides flexibility to the bend restrictor is also in this area. Care will need to be taken to avoid contact between the instrument and the cable.

Instruments in this area will not have access to free circulating water. Over time, this space may be filled with silt. It may be possible to provide windows in the shell for the science instruments, provided they do not protrude.

5 Supplier responses

Four potential suppliers were queried regarding their ability to design and supply Green Repeaters. The questions are provided in the Annex. The suppliers contacted are Alcatel-Lucent Subsea Networks (ASN), Fujitsu, NEC Corporation (NEC), and TE SubCom (SubCom).

Responses were received from ASN, SubCom and Fujitsu. NEC did not respond. Supplier comments are taken into account throughout this study.

The fifth known supplier of repeaters, Huawei Marine Networks (HMN) was not contacted because their repeater design is made to fit in a standard joint housing and could not accommodate either the instruments or science module functions.

Only one supplier, Fujitsu, responded in writing with a brief response indicating that the concept appeared feasible and noting the availability of a two-penetrator bulkhead. ASN and SubCom both responded by stating that additional specific information was required before any useful response could be provided. This additional information could take the form of a clear list of the parameters and variables that need to be measured, or specifications of the interface between the instruments and the subsea system.

While this response is disappointing, it is not unexpected. Industry is used to resolving well defined problems. A lack of specificity in defining a problem may lead to inappropriate solutions being offered. However the verbal responses, and Fujitsu's written response, make it clear that the manufacturers do not reject the idea of instrumenting repeaters out of hand.

NEC already provides in-line instrumentation for the cabled seismic systems that it has built off Japan⁴. The most recent of these systems is the Dense Ocean Floor Network for Earthquakes and Tsunamis (DONET). DONET demonstrates that telecom technologies can be adapted for scientific purposes. The cable, in-line housings, and power feed for the DONET arrays are all similar if not identical to those employed in the telecom systems. However, DONET does not demonstrate that telecom and science can share a single cable. With DONET, all the available housing volume and all available power can be used for science functions. A trans-oceanic telecom system can provide only limited space and power for science purposes. More importantly, the DONET pressure sensors are designed for tsunami detection, and hence are not subject to the long term stability requirements that are needed to measure climate change. A high resolution pressure sensor can still detect tsunamis even if its absolute depth measurement has drifted by tens of metres. However, if a sensor is required to detect long term changes in sea level, any drift will negatively impact the data from that sensor.

The hesitation from the suppliers in providing responses must be taken into account when considering the most appropriate next step for the Green Repeater. Ongoing feedback from suppliers will be invaluable in ensuring that any design solution is viable when considered in light of the existing equipment.

6 Possible green repeater design solution

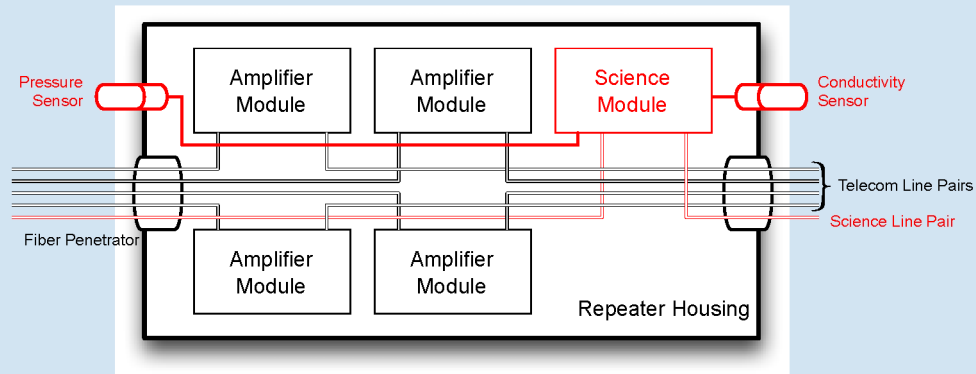
It is not the intent of this study to provide a detailed solution for the Green Repeater. Rather, this section is intended to demonstrate that there are solutions available, and to set out the types of constraints that such solutions will impose on the instruments and the system.

It is anticipated that, once provided with detailed interface specifications for qualified instruments, the suppliers will be free either to adapt this proposed design or to adopt a different approach for the implementation of the Green Repeater.

6.1 Science module functions

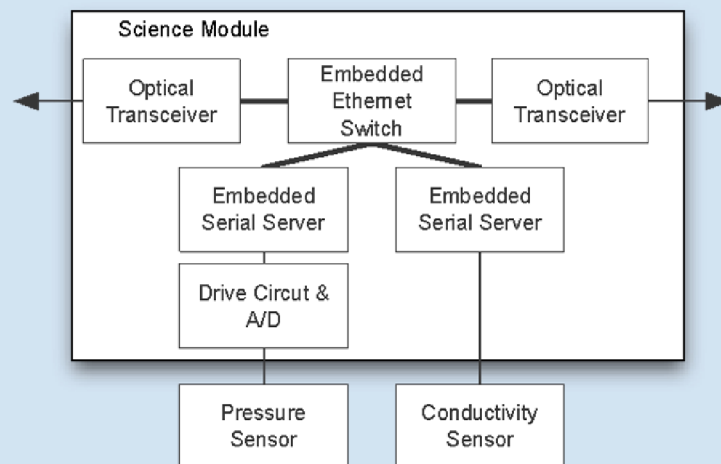
The conceptual design includes a science module as an interface between the instruments and the telecommunication line. The science module must have the same physical dimensions and mechanical properties as the repeater amplifier modules.

Figure 2: Block diagram of repeater



The science module must include an embedded processor, two optical transceivers, and any circuitry required to drive the instruments. There are no “off-the-shelf” designs. However, there are no particularly innovative functions required. Design and development of a suitable module are within the capabilities of all the suppliers of subsea telecommunications systems.

Figure 3: Conceptual block diagram of science module



6.2 Bi-directional optical transmission

The conceptual design uses a dedicated fibre pair for optical transmission of the science data. Data on the line is regenerated (as opposed to “amplified”) at each repeater, allowing local data to be added to the stream. In this design, each science module includes two optical transceivers, one communicating to each adjacent repeater. Each science module is thus accessible from either of the two shore stations. The science modules will form a series of point-to-point links, so optical amplification is not required. Each science module is effectively an optical-electrical-optical regenerator, so performance impairments will not accumulate over the length of the system.

The optical transmission link between each science module may use off-the-shelf transceivers. One option is to use those commonly employed for 100 Mbit/s or 1 Gbit/s Ethernet transmission; this solution has the advantage of using proven, standards-based equipment. However, the power requirements of these modules may be too great. Alternatively, a custom design using a lower bit rate could be used.

6.3 Data Channel Capacity

The data channel capacity required by each Green Repeater is estimated using these assumptions.

Table 3: Data Channel Capacity Estimate

Protocol used	TCP/IP over Ethernet	This is not the most efficient protocol for collecting small data packets, but will provide a conservative estimate of bandwidth needs.
Number of sensors	[4]	Both pressure and conductivity sensors incorporate a temperature sensor.
Data per poll, bytes ¹	[64]	Most sensors will collect between 24 and 48 bits (3-6 bytes); 64 bytes is the minimum size of an Ethernet packet; assumes one packet is sent for each sensor.
Polling rate	0.001 to 1 Hz	Data can be collected as often as once per second or as infrequently as once every 1 000 seconds (about 17 minutes).
Link utilization	[20%]	This is to allow headroom for packet collisions and idle time between packets.

The data channel capacity needed for a single repeater being polled once per second is thus about 10 Kbit/s.

Table 4: Data Channel Capacity per Repeater

Number of sensors	4
Data per poll, bytes	64
Data per poll, bits	512
Polling rate, Hz	1
Bit rate required, bit/s	2048
Link utilization	20%
Link data rate, bit/s	10240
Link data rate, kbit/s	10.24

¹ 1 byte (B) = 8 bits (b)

The data channel capacity needed for various polling rates and system lengths is shown below.

Table 5: Data Channel Capacity vs Polling Rate and System Length

Data Channel Capacity, kbit/s		Number of repeaters			
		1	100	200	250
Polling Rate, Hz	0.001	0.01	1.0	2.0	2.6
	0.01	0.1	10.2	20.5	25.6
	0.1	1.0	102.4	204.8	256.0
	1	10.2	1024.0	2048.0	2560.0

As shown above, the maximum data channel capacity required under any circumstances is 2 560 kbit/s or 2.56 Mbit/s. A 10 Mbit/s Ethernet link between each repeater would provide more than sufficient capacity. However, since 10 Mbit/s optical modules are not commonly used, it may be more practical to move to 100 Mbit/s or even 1 Gbit/s, as optical modules for these data rates are mass produced and provide the required optical power budget.

Alternatively, by using a lower polling rate, the data channel rate could be reduced to as low as 10 kbit/s. A more efficient protocol could be used to reduce this requirement further. The only practical benefit to reducing the data rate would be to reduce the power requirements of the science module. Until detailed design is undertaken, it is not clear if this step will be necessary.

6.4 Science module electrical power consumption

The repeater power bridge will provide from 2.5 to 5W of power to the science module. The line feed current will typically be 600 mA; but may range from 300 mA to 1.6 A. A Zener diode is used to regulate the voltage delivered to each circuit module, typical values range from 9 to 12 V. To ensure compatibility with power feeding, the science module, including the instruments and instrument power supplies, should be designed to consume no more than 600 mA at 9 V or 5.4 W.

A preliminary estimate of the science module power requirements is provided.

Table 6: Science Module Power Consumption

Circuit Element	Power, mW	Quantity	Total, mW
Optical Transceiver	700	2	1400
Embedded Ethernet switch	300	1	300
Conductivity Sensor	300	1	300
Pressure Sensor	20	1	20
Embedded Ethernet/Serial Server	900	2	1800
Total, mW			3820

Note that the Conductivity and Pressure sensors each incorporate a thermocouple, so no separate temperature sensor is listed.

The presence of the science module will increase the end-to-end system voltage. The voltage drop across each line amplifier or science module is constant; this is then multiplied by the total number of units present. If this voltage drop is taken as 10 V, then a system with 100 Green Repeaters will require an end-to-

end voltage 1 000 V higher than a system with standard repeaters. This is not likely to be an issue on a 5 000 km system, but could pose problems on longer systems, particularly trans-Pacific.

A 10 000 km system with 200 repeaters will now require a power feeding voltage 2 000 V higher than otherwise required. System owners have a strong preference for designs which can be single end fed, that is the total voltage that can be delivered from one end of the system. This allows the system to tolerate both power feed outages and shunt faults in the shore ends. To reduce the required voltage, cable designs with a lower resistance centre conductor may be used; however, this incurs additional cost. If the presence of the science functions requires the use of lower resistance cable, then this cost would have to be borne by the science users. Another solution that could be considered for long systems would be the inclusion of a Green Repeater at every second repeater, thus halving the power requirement. Table 9 suggests that in most cases, there will be sufficient optical power to accommodate the increased link distance. However, the impact that this solution would have on the science should be considered.

6.5 Diversity and redundancy

The Green Repeaters all share a single, unprotected fibre pair. This fibre pair can be accessed from both ends of the cable, so a single science module failure in one repeater will not impact data transmission from any other repeaters. A second failure, however, may isolate a set of repeaters between the two failures. Therefore, a single science module failure can be allowed, whereas two or more failures are considered a failure of the system.

The reliability of the sensors themselves is not considered and may be much less than the reliability of the science modules. Even if many of the sensors fail, the science modules must continue to function so that data can be retrieved from the working sensors. Science modules must protect themselves from damage due to all modes of instrument failure.

6.6 Reliability

An initial estimate of reliability shows that commodity components may be inadequate to achieve the desired reliability.

The core components of the science module are two optical modules, a micro-controller, and a power supply. Using data from previous scientific systems, the failure rate of a single science module can be estimated. These are conventionally calculated using Failures in 10E9 hours (FITs).

Table 7: Component FIT Rates

Optical module 1	150
Optical module 2	150
Controller	150
Power supply	20
Total FITs	470
MTBF, hours	2.13E+06

The probability of a single unit operating without failure for time t is given by:

$$P(0) = \exp\left(-\frac{t}{MTBF}\right)$$

The probability of zero failures in N units is given by:

$$P(0) = \exp\left(-\frac{Nt}{MTBF}\right)$$

The probability of one failure in in N units is given by:

$$P(1) = \frac{Nt}{MTBF} \exp\left(-\frac{Nt}{MTBF}\right)$$

Finally, the probability of the system working with zero or one failures is given by:

$$P(\text{success}) = P(0) + P(1)$$

$P(\text{success})$ is calculated for several scenarios.

Table 8: FIT rates versus Failures

Total FITS per science module	470	47	4.7
MTBF	2.13E+06	2.13E+07	2.13E+08
Operating life, years	2	10	25
Operating life, hours	17 520	87 600	219 000
Number of repeaters	100	100	250
P(0 failures)	44%	66%	77%
P(1 failure)	36%	27%	20%
P(<2 failures)	80%	94%	97%

Using the baseline assumptions regarding reliability, the system has only an 80% probability of operating for two years. If the reliability can be increased by a factor of ten (second column), then the system has a 94% chance of operating for ten years. If the reliability is improved by a factor of 100, then the system has a 97% chance of operating for 25 years.

These calculations indicate that the science module must be designed and manufactured to the same standards as repeater line amplifiers if a twenty-five year operating life is to be achieved. If a shorter operating life or higher probability of failure can be accepted, then there is more scope for the use of commodity parts. Experience has shown that the manufacturer's FIT figures are often conservative, so a system based on commodity parts may have a reasonable expectation of operating for ten years.

6.7 Optical power budget

The spacing between repeaters will be chosen based on the requirements of the telecommunication system. This distance can vary from as low as 40 km to as much as 100 km, depending on the system requirements. The optical link between two science modules must operate over this distance, with margin for repairs and aging. The worst case repair margin occurs when a repair is conducted in deep water, which may entail adding as much as 15 km of cable. Optical fibre attenuation is typically in the range of 0.19 to 0.22 dB/km. Based on these assumptions, the minimum and maximum optical losses between two repeaters are estimated to be about 8 and 26 dB. Off-the-shelf optical modules are capable of providing up to 30 dB of optical gain and would be compatible with this link distance.

Minimum attenuation may be more of a problem than optical losses for the optical links, because the receivers can saturate at power levels greater than -9 dBm. However, saturation can be avoided by adding fixed attenuators if the repeater spacing for a system is short.

Table 9: Attenuation Considerations

	Minimum	Maximum
Link Distance, km	40	115
Fibre Attenuation, dB/km	0.19	0.22
Estimated Link Loss, dB	7.6	25.3

6.8 Shore station equipment

Minimal equipment is needed at the shore station to terminate the science pair. A single optical transponder of the same type as employed in the science modules is needed to receive the signals. A small data server can be installed in the shore station to collect and store data. A connection to the Internet or other suitable data link is needed to transfer data to the end users. Overhead capacity on the telecommunication system can be used to transfer data between shore stations or, alternatively, transmission capacity on the system could be purchased for this purpose.

A test module consisting of an optical transponder and laptop PC is needed on board the cable laying vessel to monitor the science pair during installation.

6.9 Repeater power dissipation

Each repeater dissipates 10 to 40 W of residual heat from the operation of the power circuits and electronics. This heat is transferred into the environment through the repeater housing. This effect, however small, may impact the temperature measurements. Further study is required to quantify the impact of heat dissipation on temperature measurements.

7 Science instrument design constraints

The science requirements for instruments are undefined. However, in a general review of instruments as part of this study, no suitable instruments have been identified that meet the engineering requirements. These engineering requirements include a 25-year operational design life with no intervention under any circumstance, material compatibility with the repeater, external ground and that the instruments be built to subsea telecommunications quality standards.

For the purposes of this study, it is therefore assumed that all instruments will be purpose built. In this section, some of the constraints to the design of these instruments are discussed.

7.1 Electrical power consumption

Electrical power that can be made available for the instruments at a repeater will depend on the power draw of the science module that supports the instruments. As stated in Section 6.4, the combined power draw for science module and instruments must be less than 5.4 W. However, at this stage, it is reasonable to set a maximum limit on the sum of all the instrument power at a repeater to 350 mW.

7.2 Material compatibility

Repeater housings may be manufactured of Beryllium Copper or steel. Steel housings are coated with a complex matrix of epoxy resins while Beryllium Copper is left exposed to seawater. Science instruments mounted on these housings should ideally be of the same material and material treatment as the housing to avoid galvanic corrosion of the least noble metal. Titanium is often used for science instrument housings. However, Titanium may not be an option for instruments on the Green Repeater since it would drive galvanic corrosion of the repeater housing.

Alternatively, the sensors may have galvanic isolation from the repeater housing. However, this approach is less desirable because it is difficult to ensure that no contact will occur under all possible conditions.

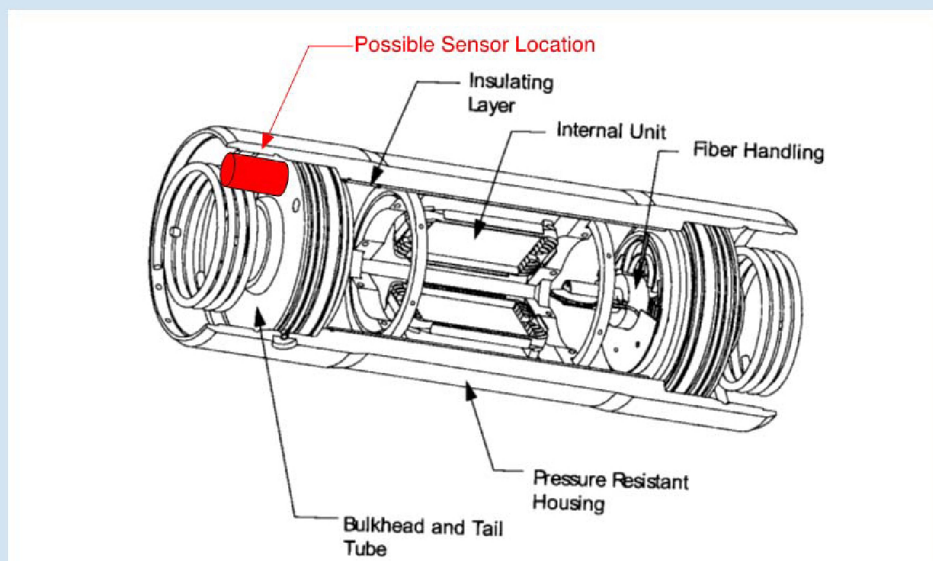
7.3 Marine handling requirements

The instruments must be qualified and tested to withstand the same impact and vibration limits as subsea telecommunication system suppliers require for their repeaters.

7.4 Installed conditions

The instruments will be inside the shell of the repeater, in the ambient pressure end of the housing. Water circulation will be limited. It is likely to be possible to machine a small opening in the repeater shell for an instrument. However, no part of the instrument can be permitted to protrude beyond the shell.

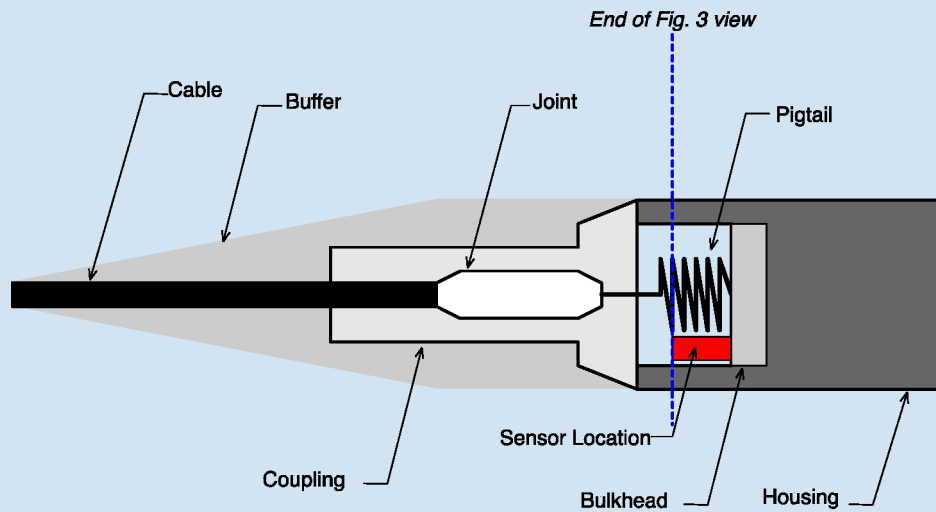
Figure 4: Possible sensor location



Central housing of a two-fiber-pair repeater, showing the disposition of the two amplifier pair assemblies within the internal unit.

Source: Chesnov José (2002) *Undersea Fiver Communications Systems*. London: Academic Press, p378

Figure 5: View of Repeater Coupling



The repeaters on which instruments are installed may be buried, either by plough or by natural sedimentation; they may be in suspension off the seabed, in areas where the seabed has more relief than anticipated; they may be sitting up off the seabed in areas of hard or rocky seabed. Over time, their condition will change as sediment builds up. In some areas, sedimentation may fill the ambient pressure end housings of the repeater. The vertical orientation of the instruments will be unknown, and will vary from instrument to instrument. The instruments must be designed so as to be unaffected by these varying conditions.

7.5 Pressure seals and depth rating

The instrument housing seals should be supplemented to include a metal-to-metal component, either using a malleable metal such as Lead or by welding and qualified to the same extent as industry products.

The instrument housings must be designed for a pressure/depth rating of 100 MPa/10 000 m which is commensurate with the repeater design depth.

7.6 External grounds

Instrument housings must not be used as either a reference or a power ground. Separate grounds must be provided, and isolation within the instrument confirmed.

7.7 Instrument design life

Instruments shall have a 25-year design life. Instruments shall be designed to provide reliable data without calibration or any other activity that would require subsea intervention.

7.8 Instrument size

A reasonable size limit per sensor external to the repeater pressure case is a cylinder 90 mm long × 40 mm diameter.

7.9 *Compatibility between table 1 instruments and section 7 design constraints*

7.9.1 **Digiquartz paroscientific depth sensor series 8cb**

The Paroscientific depth sensor is a robust and reliable instrument. It meets the requirements of Section 7.1, Electrical Power Consumption. However, it does not meet the requirements of: Section 7.2, Material Compatibility; Section 7.3, Marine Handling Requirements; Section 7.4, Installed Conditions; Section 7.5 Pressure Seals and Depth Rating; or Section 7.8, Instrument Size. There is insufficient information to indicate if it meets the requirements of: Section 7.6, External Grounds; and Section 7.7, Instrument Design Life, but it seems likely that it does not.

The depth sensor itself will require design verification (or re-design) to ensure compliance with Sections 7.3, 7.4, 7.6 and 7.7. The depth sensor will then need to be re-housed in compliance with Sections 7.2, 7.5 and 7.8.

7.9.2 **Aanderaa conductivity sensor 4319**

The Aanderaa sensor meets the requirements of Section 7.1, Electrical Power Consumption and Section 7.8, Instrument Size. However, it does not meet the requirements of: Section 7.2, Material Compatibility; Section 7.3, Marine Handling Requirements; Section 7.4, Installed Conditions; or Section 7.5, Pressure Seals and Depth Rating. There is insufficient information to indicate if it meets the requirements of: Section 7.6, External Grounds; and Section 7.7, Instrument Design Life, but it seems likely that it does not.

The conductivity sensor itself will require design verification (or re-design) to ensure compliance with Sections 7.3, 7.4, 7.6 and 7.7. The conductivity sensor will then need to be re-housed in compliance with Sections 7.2 and 7.5.

8 **Product development and quality assurance**

Quality Assurance (QA) is fundamental to any successful subsea deployment with a 25-year design life. The subsea telecommunications industry has a well-developed QA system which is similar to the QA systems used for building equipment for space exploration.

8.1 *Repeater modifications*

Product development will be required for the science module inside the repeater, and for the various penetrations and cable types used to service the science instruments. This product development should be done within the laboratories of a subsea telecommunications provider, and under the controls of subsea telecommunications industry quality assurance.

Although the requirements are straightforward, the detailed design and development of the Green Repeater will entail considerable effort on the part of the supplier. The science module must be designed and bench tested. The repeater housing design modifications will require extensive finite element and thermal analyses. Two or more prototypes of the entire repeater must be built and tested. All the necessary processes and procedures required to integrating the Green Repeater into the manufacturing, system assembly, cable loading, laying, and commissioning programmes must be developed.

Given the scope of the changes to the repeater, sea trials will almost certainly be required. Ideally, this would be followed by a low-risk deployment on a demonstration system, perhaps 500 to 1 500 km in length, before the Green Repeater is offered for general availability. Based on experience with previous development efforts, this process can be expected to take from three to five years from inception to completion. This entire effort, including a substantial fraction of the demonstration system deployment, is likely to re-

quire external funding, as telecommunications suppliers carefully manage their Research & Development budget to provide the greatest rate of return on that investment.

8.2 *Science instrument development*

Science instruments are not normally developed or built to the standards set by the subsea telecommunications industry. They tend to be built with limited budgets, and some possibility of failure is accepted as part of doing science in the deep ocean. Science instruments are rarely built to recognized standards, but usually follow the requirements of the specific science programme, science institution or funding agency, and are not subject to any specific standards. However, for this project, science instruments that match the reliability of telecommunications equipment will be required, both to provide a 25-year time series and to ensure that premature failure does not jeopardize the entire effort. As such, it will be important for the instruments to be built to well-developed and adopted standards.

Both the Japanese and Canadian experience with cabled ocean observatories suggests that current levels of instrument longevity and reliability are insufficient to really make use of the benefits of cabled observatories⁵. Rates of failure soon after deployment are high, and production of continuous time series data sets is disappointing. The instrument manufacturers will require significant technical support to meet the challenge posed by Green Repeaters. There may, however, be an opportunity to cooperate with cabled science observatories in the development of long-term reliable instrumentation for Green Repeaters. Any advances would benefit the whole community. However, to be adopted by the telecommunications industry, instruments will have to meet standards that are agreed to by all interested parties. In particular, the reliability and fault outcomes will have to be standardized to demonstrate that the telecommunications functions are not put at risk by the instrumentation.

9 Alternatives

Three potential design alternatives have been identified during the preparation of this report. These alternatives are considerably different than the base design presented above and entail more than a simple modification of the design parameters.

9.1 *Separate housings containing instruments*

The first alternative is to place the science functions in separate housings from the telecommunications repeaters; these “science housings” would be interspersed between the repeaters and equal in number to the repeater housings. The fibres for the telecommunications system would pass through the science housing and vice versa. At first glance, this solves a number of problems, since no modifications are required to the telecommunications repeater. The science housing can be designed specifically for science, with less internal space and more volume outside the pressure housing in which to mount instruments. However, in reality, the design challenges are simply moved to the new housing, and several new problems are created. The science housing must have a re-designed bulkhead with two penetrators. Since it is an in-line part of the system, the science housing must have the same integrity and mechanical reliability as a repeater. Additional housings must be managed during system assembly, loading and laying. The entire cost of the science housings must be considered part of the science system cost. The end result is that this approach will be even more costly than modifying each repeater.

Separate science housings might be more useful if only a few such housings were to be added to a system at spacing of several hundred kilometres. That spacing would require optical amplification on the science fibre pair in the intervening repeaters, potentially increasing the size and cost of those repeaters.

9.2 *Separate housings containing connectors*

It is understood that the systems designed and installed by Lighthouse R & D Enterprises, Inc. off the coast of Oman in 2005 and 2007 utilize wet mate ROV connectors within a repeater shell. The orientation of the repeater shell is established by a weight on the lower side of the shell. By using this approach, it might be possible to install wet mate connectors at points on the line.

The benefits of this installation are that instruments can be away from the repeater, and can be removed or replaced if necessary. However, instrument installation would be a costly, separate operation, requiring the use of an ocean ship with deep water Remotely Operated Underwater Vehicle (ROV). The need to deploy a second vessel and the long times involved in ROV deployment to ocean depth make it unlikely that this approach would be cost effective.

9.3 *Use of supervisory channel*

Some system suppliers employ a supervisory channel to communicate with the repeaters. This channel can collect performance measurements from the repeater and control the repeater output current. The data channel may also be used to control branching units. The data channel is provided by modulating the power of the entire optical signal. To avoid impacting the operation of the main telecommunications traffic, this modulation must be very low, with the result that the supervisory channel data capacity is very low, in the order of a few hundred bits per second.

In principle, the supervisory channel could be used to carry data from the science instruments. However, a number of factors make this inadvisable:

1. The data capacity is limited, so instruments would be polled at most a few times per day.
2. The supervisory channel does have a small impact on system performance; some system owners use it only when necessary.
3. The effort required to integrate the science module with the supervisory channel is unknown and cannot be determined.
4. The supervisory channel is employed by only some suppliers, so a solution relying on the supervisory channel would not be applicable to all systems; a solution using a separate fibre pair would still need to be developed.

Based on these considerations, a solution which employs the repeater supervisory channel is not recommended.

9.4 *Support for seven sensors*

A proposed option for the Green Repeater in the scope of work for this study is to include seven sensors: temperature, sea current, salinity/conductivity, pressure, seismic, hydroacoustic and cable voltage. Let us consider these sensors one at a time, related to the basic Green Repeater design proposed in Section 6 above.

9.4.1 **Temperature**

Temperature measurement is included in the base design. Temperature measurement will have to overcome the challenges of proximity to a heat source (the repeater) and possible shielding of the water flow by the repeater shell and by any sediment that may bury the repeater. Note that the extent of burial of a repeater is unknown at deployment, and is likely to vary over time.

9.4.2 Sea current

Current measurement in the ocean is often made acoustically, using an instrument such as an ADCM. These instruments are relatively large (typically larger than a 200 mm cube) and their power consumption is measured in Watts, not mW. They also require a near vertical deployment, and an unobstructed water column above them. They are not suitable for burial in sediment.

A different technology, possibly non-acoustic, will be required to measure ocean currents from a Green Repeater.

9.4.3 Salinity/conductivity

Salinity/Conductivity measurement is included in the base design. Salinity/Conductivity measurement will have to overcome the challenge of the possible shielding of the water flow by the repeater shell and by any sediment that may bury the repeater.

9.4.4 Pressure

Pressure measurement is included in the base design. Pressure measurement should be possible, provided the instrument can be made sufficiently small and robust.

9.4.5 Seismic

NEC has developed an in-line seismometer for the Japanese observatories that may be suitable. However, no details are available. There may be an issue with power consumption. Due to the surface deployment, the data will likely not be as high quality as the data from a buried seismometer.

Conventional seismometers are very vulnerable to shock during deployment.

9.4.6 Hydroacoustic

Hydrophones are generally low power instruments. It is not clear what issues there will be for the data in the hydrophone being close to the seabed and potentially partly buried.

9.4.7 Cable voltage

It is understood that the desire to measure voltage at certain points along the cable is related to the theory of electromagnetic induction by ocean water currents. It is likely to be possible to measure voltage.

9.5 Acoustic modems

Dr. Kim Juniper of University of Victoria has proposed an alternate solution using acoustic modems on each repeater, and providing battery-powered instrument packages that would communicate with the cable acoustically.

This solution would allow all repeaters to be identical, and would overcome the problem of placing instruments inside the repeater case. Instruments could be more appropriately positioned within a cage on or above the seafloor some distance from the cable. Acoustic modem power could be kept to a minimum provided the instrument packages were close to the cable.

Instrument packages would be lowered from a vessel, and the acoustic link confirmed prior to releasing the lift line. Recovery would be via acoustic release, avoiding the need for an ROV.

A drawback of this alternate is that regular vessel cruises would be required to replace batteries in the instrument packages. If instrument and acoustic modem power was limited, a cruise every 5 years could be

possible. In addition, various means would have to be considered to minimize the power draw of the modem on the instrument package.

10 Cost estimate

A rough order of magnitude cost estimate in USD has been developed based on experience both within the telecommunications industry and with the scientific array systems. Costs are divided into fixed costs, unit costs and operating costs.

10.1 Fixed costs

Fixed costs are those that are incurred once to develop the Green Repeater into a deliverable product. Note that fixed costs will be incurred separately by each supplier, since each must modify its own repeater design. Fixed costs do not include the cost of a demonstration system. Fixed costs are the most difficult to estimate; a development programme that goes smoothly will cost less than one that encounters difficulties. A rough estimate is provided based on the cost to develop previous scientific observatory systems and the associated underwater components.

Development cost, up to and including sea trials, are estimated to be in the range of 15 to 25 million USD.

Development costs do not include the cost to develop suitable instruments or modified instrument housings. These instrument development costs will depend on the instrument requirements, and the extent to which the instrument is a new development as opposed to a modification of an existing instrument.

10.2 Unit costs

Unit costs are the cost for each repeater, plus the cost of additional fibre which must be added to the cable. Unit costs are driven by the modified housing cost, which is estimated based on the cost differential between a repeater and a branching unit, which is an equivalent change in complexity. The cost of instruments, the science module, integration and testing are small compared to the cost of the housing.

Modifications to repeater housing	USD 200K
Instruments	USD 20K
Science module	USD 5K
Integration and testing	USD 10K
Contingency	USD 15K
Total cost per repeater	USD 250K
Fibre	USD 200/fibre/km

10.3 Operating costs

Operating costs are assumed to be zero, there are no direct costs associated with the science instruments once deployed. The cost of collecting, storing and analysing data is not considered.

10.4 Total cost to implement system

The total cost to implement a system of varying lengths is provided below. Note that the development costs would be incurred once by each supplier.

Table 10: Order of Magnitude Cost Estimates

Number of repeaters	100	200	250
Approximate length	5 000-6 500 km	10 000 km	12 500 km
Development Costs	USD 20 M	USD 20 M	USD 20 M
Repeater	USD 25 M	USD 50 M	USD 62 M
Fibre	USD 2 M	USD 4 M	USD 5 M
Total	USD 47 M	USD 74 M	USD 87 M

11 Ownership issues

Most of this study deals with the technical aspects of constructing and deploying a system. However, a number of commercial, ownership and operational issues have been identified:

- Development funding will likely come in the form of grants from national agencies such as the United-States National Science Foundation (NSF), Advanced Research Projects Administration (ARPA), Japan's JAMSTEC, Australian Institute of Marine Science (AIMS), Industry Canada, among others. What stake or ownership in the completed system will accrue to the grantees?
- Can the entire system be owned by the commercial operator, with rights to the science functions being passed on through an Irrevocable Right of Use (IRU), as is commonly done when several owners wish to share a commercial cable?
- What happens to the system if it is taken out of commercial service but is still potentially viable for science? Although arrangements have been made to transfer commercial systems to scientific use, this process can take years. To avoid interruptions in data gathering, it may be worth addressing this issue at the start of the system life so that an orderly transfer can take place.
- The operation and presence of the science instruments must be completely transparent to the system owner. In particular, the owner will look to the supplier to warrant and support the system as though it were a fully commercial system.

Further discussion of these and related topics is encouraged, as this discussion can take place in parallel with the necessary development work. Addressing these issues early will avoid delays or missed opportunities later. The ITU/WMO/UNESCO-IOC Task Force provides a suitable existing multi-stakeholder platform where these discussions could take place.

12 Legal issues

Presentations were made at the Workshop on Submarine Cables for Ocean/Climate Monitoring and Disaster Warning in September 2011 in Rome regarding possible legal and regulatory issues for telecommunications cables that host science instruments^{6,7}. These issues should be addressed, since, if not resolved, they may impact the viability of the Green Repeater.

The paper "Using submarine cables for climate monitoring and disaster warning , Opportunities and legal challenges" (Kent Bressie, 2012) details the issues to be considered.

13 Military issues

The standard set of temperature, pressure and salinity instruments is unlikely to cause concerns for the world's navies. However some of the proposed supplementary instruments, in particular hydrophones, are likely to be of significant concern, since they could potentially be used to pinpoint military asset positions.

Parties need to be cognisant of military sensitivities in this area. However, provided no hydrophones or other similar instruments are deployed, it appears unlikely that the Green Repeater will be seen as a threat to national security for any nation.

14 Need for international standards

The subsea telecommunications industry is international by its nature, and also, to a large extent, uses interchangeable technologies. There are many examples of manufacturer collaboration on the implementation of large systems, even to the extent of two manufacturers providing components for a single trans-oceanic system. This degree of interchangeability is brought about by the negotiation and adoption of international standards. Any instrumentation or associated equipment that is to be deployed on subsea telecommunications facilities will be expected to meet similar standards.

The objective of standardization is to provide the same utility regardless of supplier. End users will expect consistent, traceable and defensible data. Standardizing the instrument performance and possibly the data formats would help achieve this result. Details such as the mechanical size of the housing, circuit board operation, or even communication protocol have no impact on the quality of the data gathered and do not require standardization.

This standardization effort will need to be directed towards the science community. Ongoing input from the system suppliers is required, but is not in itself sufficient to achieve the standardization of data gathering.

15 Summary of study results

The key study results are summarized here:

15.1 *Advantages and disadvantages of each option*

Only one viable option has been identified. The science functions will be supported by a single fibre pair and sensors integrated into the repeater in the space between the bulkhead and coupling. The alternatives considered were placing the instruments in a separate housing, including a separate housing with wet mate connectors and using the supervisory channel for data collection. None of these alternatives is considered viable.

15.2 *Power requirements of each option*

The base design assumes a maximum power consumption of 5.4 W for science at each repeater (see Section 6.4). The PFE voltage must be increased by approximately 12 V for each repeater present in a system. Repeater line current will be approximately 600 mA. The alternatives considered would have similar power requirements.

15.3 Heat dissipation for each option

All power will be dissipated as heat; thus the heat dissipation from the science module and science instruments is 5.4 W or less.

15.4 Physical size for each option

The base design requires a repeater housing which is one fibre pair larger than used for commercial systems plus additional length between the bulkhead and coupling. The resulting repeater will be approximately 2 m long.

15.5 Data rate

The data rate required depends on the polling frequency. Possible data rates range from as low as 100 kbit/s to 2.5 Mbit/s. This is substantially less than what can be delivered over a fibre pair and is not expected to limit the system design.

15.6 Power limitations

The total power consumed by the instruments must be less than 350 mW; the remaining power is consumed by the communications functions of the science module.

15.7 Physical size limitations

Sensor dimensions are assumed to be no greater than 90 mm long × 40 mm diameter.

15.8 Specific issues relating to measurements

Design life, survivability, and stability of all the sensors require further scientific review.

15.9 Required sensor resolution

The required sensor resolution must be determined by the science community and ICT industry and is outside the scope of this study.

15.10 Need for standards

Standards regarding the measurements to be made and the quality of data collected would be beneficial.

15.11 Cost estimate

Costs are in the range from USD 50 to USD 80 M for the first system and would decline thereafter.

15.12 Seven sensors

The seven sensor types described above are not all compatible to be an attachment to a repeater. Some of these instruments will require dedicated scientific systems.

16 Considerations

Based on a review of the available information, the Green Repeater is potentially feasible, insofar as some power is available from the cable in most cases, and with additional fibre data that can be transmitted to shore. The components required for the design proposed for the science module are generally available, and the assembly longevity and reliability goals appear to be achievable with some effort.

However, before any more work can be done on the repeater itself, the instruments must be specified. Following the specification of the instruments, the design, prototyping and qualification must take place before manufacturing can begin. This process will pay particular emphasis to:

- 25-year design life
- Sensor stability over 25 years
- Sensor reliability
- Sensor physical size
- Ability of sensor to provide reliable data in variable deployments
- Design of sensor housings that are compatible with repeater materials, deployment methods and operating environment

The uncertainty of the type and availability of the sensors raises considerable doubt in the minds of the system suppliers and, as a result, the suppliers are unlikely to pursue the concept further until these uncertainties are resolved. In principal, the telecommunications industry can deliver the necessary supporting infrastructure, but it has little or no experience with scientific sensors. Development and qualification of suitable sensors and long-term trial deployment on existing science arrays (as opposed to commercial telecommunications cables) will be the first step towards making the Green Repeater a reality.

In summary, the next step in the iterative process to develop the Green Repeater is to develop suitable long life instruments compliant with the science goals and the criteria specified above.

17 Conclusions

Based on this review, it appears that telecommunications repeaters have the ability to support a modest instrument load such as the base instruments proposed in the request for this study. In addition, it appears that the technology for a reliable science module exists, but would need further development and qualification to meet telecommunications requirements.

Telecommunications industry suppliers can deliver the communications capabilities; however, they have little or no capability with regard to sensors and instruments.

Based on the information gathered, no sensors currently exist that can meet the 25-year design life without intervention. Unless long life and stability issues can be addressed, the utility of deploying instruments as part of repeaters is questionable. Development of suitable instruments must be a priority if the Green Repeater is to proceed.

Based on their responses to the authors of this paper, potential system suppliers have limited commercial incentive to pursue the Green Repeater until instrument designs are fully developed and qualified. Even when this is done, ownership issues, legal and permitting issues and lack of commercial incentives may continue to be impediments.

At the end of February 2012, it was announced² that an exploratory partnership between Scripps researchers, NOAA and TE SubCom was in the formative stages seeking funding for engineering and operations and looking at new approaches to collect high-bandwidth ocean data from the seafloor. An initial project was envisioned to focus along a cable route spanning 12 950 km from Sydney to Auckland and across the Pacific Ocean to Los Angeles. Initial efforts were announced as exploring the use of seismometers, pressure gauges and temperature sensors for hazard warning and mitigation. TE SubCom states that it has a solution for ocean connectivity (instrument support) with unprecedented performance-to-cost ratios, and together with Scripps and PMEL, that it has the right ingredients to make cable-based ocean connectivity a reality in every major ocean.

The statement by TE SubCom (formerly Tyco), a major supplier of subsea telecommunications systems, that it has a solution to use telecommunications systems to collect high-bandwidth ocean data from the seafloor, and believes that its solution offers a good performance to cost ration, is very positive. The solution that TE SubCom is proposing appears to address the interface between the instruments and the cabled system, as opposed to the viability of the instruments themselves for long-term deployment. Although no details are available at this time, this independent effort offers valuable opportunities for collaboration and promises an interesting future for collection of data from the deep sea environment.

² http://ucsdnews.ucsd.edu/pressreleases/cables_spanning_pacific_ocean_seafloor_to_give_ocean_science_a_new_edge/


Annex

Questions to suppliers:

1. Please comment on the overall feasibility of the Green Repeater.
2. The single largest risk area appears to be modifications to the bulkhead design. Please comment on the feasibility of adding an electrical penetrator to the existing repeater bulkhead.
3. Can a modified bulkhead be qualified to full ocean depth (8 000 m)?
4. If a modification to the existing repeater bulkhead is not possible, are there other alternatives which may be feasible, for example, using a branching unit housing?
5. Please comment on the feasibility of mounting sensors in the area between the bulkhead and coupling. What is the maximum size of the sensor which could fit in this area?
6. Please comment on the science module design parameters, in particular, the maximum power that can be delivered to the science module using normal line feed current.
7. Please comment on the feasibility of isolating the science module such that failure on the module, whether open or short circuit, cannot cause repeater failure.
8. Please comment on any other alternatives which may exist or other means of achieving the objectives based on your repeater technology.

Glossary

ADCM	Acoustic Doppler Current Meter; an instrument to measure ocean currents acoustically
ASN	Alcatel-Lucent Subsea Networks, a manufacturer of subsea telecommunications systems
Branching Unit	A subsea housing on a subsea telecommunications system that supports a branch in some or all of the fibres and/or the power conductor
Design Life	The period of time during which the item is expected by its designers to work within its specified parameters. For Submerged Plant, the Design Life is normally 25 years
DONET	Dense Ocean Floor Network for Earthquakes and Tsunamis; a Japanese cabled observatory operated by JAMSTEC and primarily interested in seismic monitoring.
DWDM	Dense Wavelength Division Multiplexing, which is a way to combine multiple signals on each optical fibre
Erbium Doped Fibre Amplifier (EDFA)	A type of optical amplifier that uses a doped optical fibre as a gain medium to amplify an optical signal
FIT	Failure in time. Units are 10^9 hours.
Fujitsu	Fujitsu Limited, a manufacturer of subsea telecommunications systems
Green repeater	A repeater fitted with science instruments
Intervention	The deployment of marine equipment to service or repair Submerged Plant or science instruments
HMN	Huawei Marine Networks, a manufacturer of subsea telecommunications systems
MDPE	Medium density polyethylene
NEC	NEC Corporation, a manufacturer of subsea telecommunications systems
Optical amplifier	A device that amplifies an optical signal directly, without the need to first convert it to an electrical signal
Regenerator	A device that amplifies and/or modifies an optical signal by first converting it to an electrical signal
Repeater	A subsea housing containing optical amplifiers and associated equipment as manufactured for use in subsea telecommunications systems, as more fully described in Section 2.2
ROV	Remotely Operated underwater Vehicle
Science Module	An electronics module that provides power and data transmission for science instruments in a Green Repeater



Submerged Plant	Cable, repeaters and branching units which are deployed on the seabed and make up a communications system
TE SubCom	A manufacturer of subsea telecommunications systems, formerly known as Tyco.

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