COMMISSIONING OF A SYSTEM THAT TERMINATES ON THE SEAFLOOR

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Abstract: Ocean observatories introduce demanding requirements and a variety of new complexities in the commissioning phase of a program. For the Regional Scale Nodes (RSN) observatory program, the backbone telecommunication cables were first installed in 2011. The in-water nodes and shore terminal equipment were successfully installed in 2012, followed by the installation of the in-water secondary infrastructure later in 2013. When the commissioning phase occurred, the primary infrastructure was already installed but connections to the secondary infrastructure had yet to be made. The RSN system test plan mitigates risk with a stepwise verification process maximizing end-to-end post installation testing possibilities.

This paper reviews the test processes required to assure successful optical performance, power distribution, and network integrity after system installation.

1. OVERVIEW OF RSN OBSERVATORY

The RSN is a component of the National Science Foundation's (NSF's) Ocean Observatories Initiative (OOI). The construction and early operation of this Northeast Pacific Ocean cabled ocean observatory is being lead by the University of Washington (UW). L-3 MariPro is the prime contractor for the design, manufacture, installation, and test of the overall system. The primary infrastructure network consists of a single shore facility in Pacific City, Oregon, connected to two backbone cable lines, with over 850km of fiber optic cable and seven primary science nodes. The system is located on the southern portion of the Juan de Fuca tectonic plate in the Northeast Pacific Ocean. The capacity of the RSN system is up to 170kW of power and 240Gbps of TCP/IP Internet data. The initially installed system capacity of seven nodes provides 60kW of power and redundant 60Gbps of TCP/IP science data. The RSN 25-year life system allows for expansion[1] to serve future science needs and technological advances with minimal impact to the initially installed primary infrastructure. RSN compliments the NEPTUNE Canada[2] cabled ocean observatory project as shown in Figure 1, which depicts both systems.

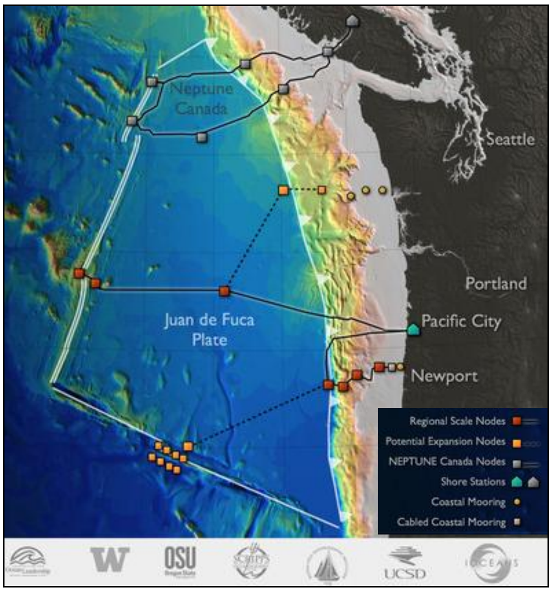

Figure 1: RSN and NEPTUNE Canada Systems (Figure courtesy UW)

1.1. Key RSN Requirements

- 25-year life, redundant, fault-tolerant, expandability, serviceability
- Seven Wet Mateable Connector (WMC) science ports; 375V and 20A, 1/10GbE data, 1 micro-sec precision timing accuracy, status-control link

- 10kW per node, 10A cable line, 10kV constant voltage operation, seawater return
- Integration of COTS and custom optical components, 10GbE DWDM operation
- 3,000m depth, shallow water trawler (fishing) resistant frames, WMCs

1.2. Submarine Cable Plant

The submarine cable plant for the RSN system is repeatered, employing standard telecommunications cable line and repeater technology provided by TE SubCom. The repeaters were upgraded to support an operational current of 10A to meet RSN's full power capabilities. Each cable line is connected to Primary Nodes that are powered from shore and support 10GbE fiber optic communications using a DWDM transport mechanism. Figure 2 shows Nodes during the manufacturing phase at L-3 MariPro's facility.

Figure 2: Primary Nodes

Primary Nodes have two main assemblies.

Backbone Interface Assembly (BIA). The BIA is jointed to the cable line and contains a 10kW Medium Voltage Power Converter (MVPC) provided by Diversified Technologies Inc. (DTI). The MVPC steps down the cable line voltage from 10kV to a more commonly usable 375V. The MVPC also includes switching circuitry, controlled from shore, to detach the downstream cable or the Node itself from the backbone cable and isolate failures on a particular cable line. Switching only occurs when power is not applied to the cable line. The BIA separates the optical and power from the cable line and provides them to the SIA via two individual optical and electrical WMCs.

Science Interface Assembly (SIA). The SIA contains the optical and power subassemblies to bridge between the cable line BIA and Science Port interfaces. The SIA provides low voltage (375V) distribution, science data Ethernet network switch, and Out Of Band (OOB) status-control link/Precision Timing (PT). A Remotely Operated Vehicle (ROV) is used to disconnect the two BIA WMCs allowing the SIA to be removed from the BIA frame and recovered to the surface for servicing. The SIA being moved into a BIA is shown in Figure 3.

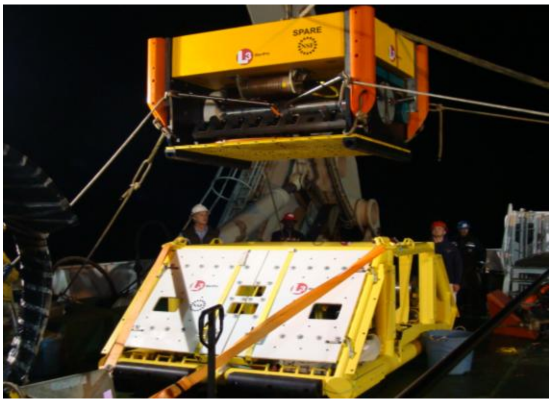

Figure 3: SIA Being Installed into a BIA

SIAs provide hybrid electrical/optical WMC interfaces for a maximum of seven Science Ports. Figure 4 shows the SIA WMC panel interface for six of seven possible Science Ports and BIA power and optical connections.

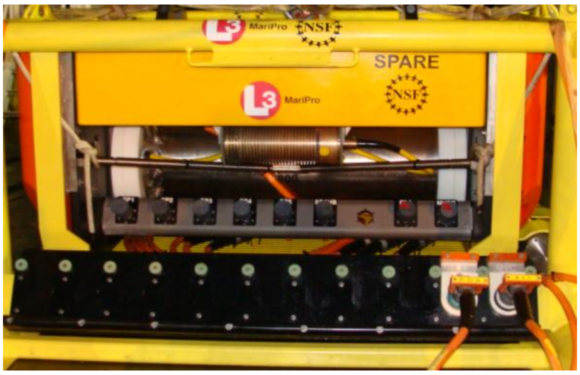

Figure 4: SIA Wet Mate Connectors

1.3. Commissioning Support Hardware (CSH)

The CSH was developed specifically to allow post-installation testing during commissioning and acceptance phases of the RSN program. CSHs connect to a Node's Science Port to simulate future secondary infrastructure assemblies (low-voltage Nodes, medium power junction boxes, or scientific instruments). CSHs provide the interfaces to exercise and test Science Port connections. CSH functionality includes: a 1kW load and selectable leakage currents, science data 1GbE or 10GbE loopback with variable optical attenuation, and OOB status-control link / PT interfaces (see Figure 5).

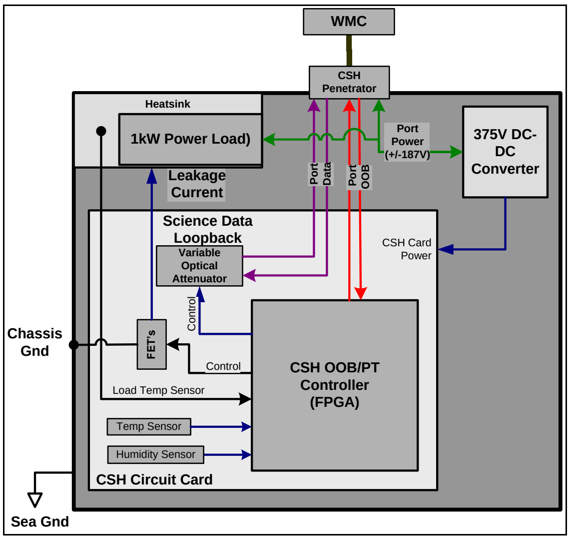

Figure 5: CSH Simple Block Diagram

CSHs are packaged in a titanium pressure housing with an ROV compatible WMC to allow subsea connection and disconnection to/from the Science Port. Currently, six CSH test fixtures are currently installed on the six of the seven deployed Nodes. They are all connected to Science Port Number 1 (SP1) and mounted on the Node frame allowing future removal by an ROV, see Figure 6

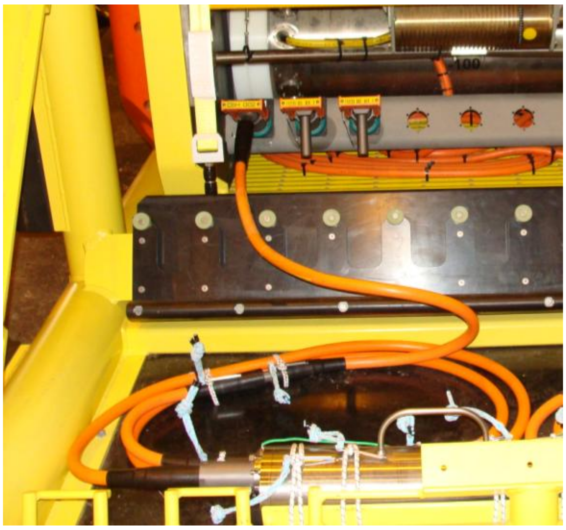

Figure 6: CSH Mounted on Node and Connected to SP1

One variant of the CSH also includes a video camera and lighting system addition, and is installed on Node 3B at the Axial site location. The camera and lights allowed inspection of the area in front of the Node during installation to ensure no obstructions were around the Node. This was determined to be necessary since the seafloor in this area has significant volcanic rock structures. After initial deployment, the Node could have been repositioned if an obstruction had been present. Figure 7 shows the camera and lights mounted on the Node frame near the top.

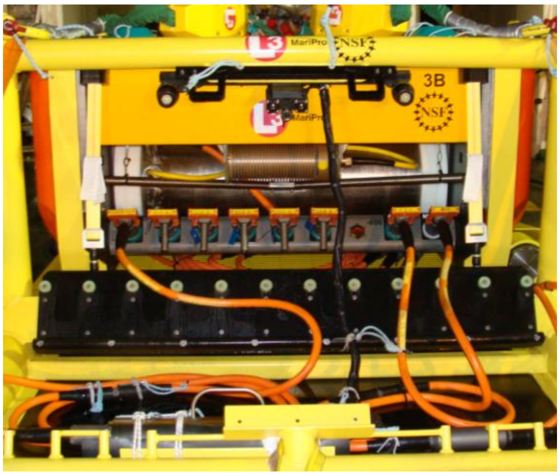

Figure 7: CSH with Camera System

1.4. Shore Facility

Before RSN, the shore facility was originally used for the North Pacific Cable (NPC) landing in Pacific City, Oregon. The shore terminal subsystem equipment consists of power feed, line and transmission terminating, line monitoring, and network management.

DTI provided the Power Feed Equipment (PFE) subsystem, consisting of a pair of redundant 170kW high voltage (HV) power supplies which allow different powering configurations (i.e. both supplies connected to both cable lines for redundancy), or single supply providing power to both cable lines allowing high voltage supply maintenance, or isolated, with each supply providing power to a single cable line. Isolated supplies allow potential repairs to one cable line with the other cable line still operational. The PFE also includes the controller subsystem to command the MVPC switching circuit to isolate the cable line from the downstream cable or the Node itself.

The Submarine Line Termination Equipment (SLTE) subsystem provided by TE SubCom comprises the Line Terminating Equipment (LTE), Line Monitoring System (LMS), and TE SubCom's Element Management System (TEMS). LTE components include Wavelength Termination Equipment (WTE) and Terminal Line Amplifiers (TLAs) with redundant EDFA pumps. The LMS provides in-service undersea cable line performance monitoring and out-of-service fault locating. LMS consists of the Line Monitoring Equipment (LME) and software that runs on the TEMS. The TEMS server and client are deployed at the Pacific City cable station to manage the TE SubCom-supplied equipment in the station.

The Transmission Terminal Equipment (TTE), provided by L-3 MariPro, consists of the Network Management System (NMS), Communications (COMMS), and OOB/PT subsystems. The NMS subsystem provides the user interface, generates system commands and provides system data logging. The NMS features redundant servers employing a 3-way voting scheme to ensure continuous operations under fault conditions. The COMMS subsystem receives and transmits redundant 10GbE DWDM in-band streaming science data and aggregates the multiple Ethernet data channels to the customer backhaul. The OOB/PT subsystem supplies real-time information to the RSN shore equipment and PT to Nodes via redundant DWDM channels. This channel multiplexes PT data with Science Port status/control link information, Node commanding and reception of status and health data.

The shore subsystems are supported by dual redundant Uninterruptible Power Supplies (UPS). The UPS' provide back-up power to the shore equipment during facility power interruptions, before the main generator is fully engaged.

Figure 8 shows the line-up of shore cabinets; UPS rack nearest, next South and North TTE provided by L-3 MariPro, then TE Subcom's SLTE and at the far end DTI's PFE - seven cabinets.

Figure 8: RSN Shore Cabinet Line-up

2. TESTING PHASES

RSN testing phases encompassed qualification and design verification, factory acceptance, field installation, commissioning, and system acceptance. The test plan was tailored specifically to address the fact that system acceptance could not occur until after deployment, when the system would be fully integrated and available for final testing.

2.1. Qualification

Qualification*:* A qualification plan was developed and executed for the RSN program. Qualification consisted of test, analysis, demonstrations, inspections, and design verification tests. The first group of production Node and CSH optical/ electrical housing assemblies were subjected to qualification testing. Tests included operation verification (OpVer), acceptance tests, environmental stress screening tests (ESS), and repeated acceptance tests (see a typical Qual test flow in Figure 9). In addition, a 30-day burn-in was completed on a fully assembled qualification Node with power loading on all Science Ports, maximum Ethernet traffic loop-back at all Science Ports and A/B side operation was confirmed.

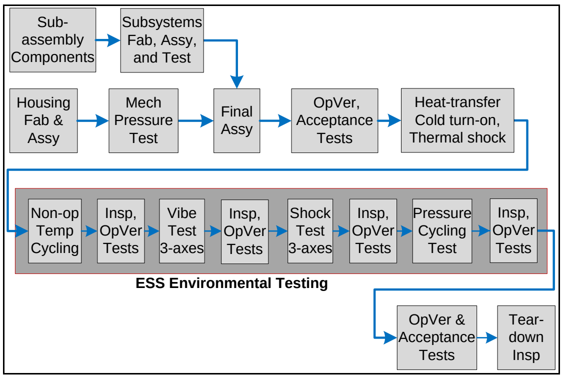

Figure 9: Typical Qualification Test Flow

Demonstrations*:* Several of the RSN key cable line optical and power requirements required early design verification and demonstrations to confirm compatibility and risk mitigation. A sea trial was also conducted to demonstrate compatibility of Node design with ROV operations.

Two optical demonstrations were performed by TE SubCom. An initial demonstration successfully characterized 10GbE DWDM optical transceiver performance and proved its compatibility with the candidate optical fiber and optical repeater configuration chosen for the cable line. A second demonstration was conducted on an expanded RSN optical configuration with the number of repeaters representing a fully built-out system. The results from this testing showed that the optical line was tolerant to cable line failures[3] (loss of a Node or cable segment) and provided the characterization data required to finalize the cable line optical design.

Power demonstrations were performed on a prototype Node MVPC at DTI's facility. A multi-stage cable model was produced to replicate the impedance of the cable line. MVPC operation was confirmed over a variety of static and dynamically changing load conditions, 6kV-10kV extremes and with minimum and maximum cable lengths. This power demonstration also integrated the 10A high current repeater to ensure no interactions occurred between the powering subsystem and the repeater.

The RSN power system was required to be tolerant to short-circuit and open-circuit cable line fault conditions while still allowing Nodes to operate properly, when possible. An additional capability was added to the PFE and MVPC designs whereby the local Node or seaward cable segments could be commanded to disconnect from the shore cable. A low voltage, reverse polarity, low data-rate commanding scheme was developed to open or close relays within the MVPC to disconnect or re-connect to the cable line. This feature also had to operate in current mode (short circuit condition) and voltage mode (open circuit condition). The commanding scheme was successfully demonstrated by DTI in both modes of operation using a low-voltage version of the cable line simulator.

ROV Compatibility: Early in the manufacturing phase, an ROV compatibility sea trial was conducted using a Primary Node. The trial occurred in the spring of 2012, off the coast of Oregon, at a location with over 700m of water depth. The test objective was to ensure that an ROV would be able to manage the doors on the BIA, access all wet mate connectors and remove/install an SIA. Testing was successfully performed from the RS THOMPSON using the Canadian Scientific Submersible Facility Remotely Operated Platform for Ocean Science (ROPOS) ROV. Figure 10 shows the ROPOS manipulator connecting a wet mate connector. The ROPOS ROV was able to successfully perform all operations including removing and installing the SIA into the BIA.

Figure 10: Subsea ROV Compatibility Testing

2.2. Factory Acceptance Tests

Cable Lines: TE Subcom fabricated and tested cable sections, cable joints, and high current optical repeaters. Afterwards, the cable lines were fully assembled and system optical testing was performed at TE SubCom's cable factory. During this testing, production optical components of the Nodes and shore equipment were integrated with the cable lines. Complete end-to-end system tests were performed and optical cable line performance was validated to meet system Optical Signal Noise Ratio (OSNR), Q-factor, Bit Error Rate (BER) and optical budget requirements at both start and end of life.

In-water Nodes: Testing was performed at all levels of integration: circuit cards, sub-assemblies, pressure vessel assemblies and final Node assembly levels. All Nodes were subjected to operational verification and acceptance tests including 72 hours of burn-in under full power loading conditions with Ethernet traffic looped-back and A/B sides operating. CSH fixtures were assembled, integrated, and acceptance tested. Next, CSHs were connected to SP1 and tested together with the Node. CSHs remained connected in place after the completion of all tests; ready for next phase - installation.

Shore Terminal Equipment: Similar to the Nodes, shore equipment circuit cards, Commercial off the Shelf items, and sub-assemblies, were integrated, set-up and tested. Sub-assemblies were then inter-connected with the remaining components of the racks, and operations and interfaces were verified. The finalized rack assemblies were lastly subjected to performance verification, acceptance testing, and burn-in tests.

2.3. Installation and Tests

Backbone Cable Line: Independently of all other elements of the RSN system, the backbone cable lines were installed by TE SubCom using the cable ship CS DEPENDABLE. After installation, the backbone cable line was inspected and, for protection, cables were buried in water depths of less than 1,500m. Installation occurred in the summer of 2011, approximately one year prior to primary Node installation.

Shore Terminal Equipment: During the third quarter of 2011 to the second quarter of 2012 the shore terminal station subsystems were installed in the shore facility. Shore subsystem cabinets (power feed, transmission terminating, line monitoring, and network management) and support equipment were assembled, set-up, connected, and underwent a series of individual subsystem installation tests. Next, all the shore subsystems were inter-connected and integrated. Operational checks were performed on the finalized shore terminal subsystems, followed by in-station site acceptance tests and a 2-day confidence trial.

Primary Nodes: Nodes were installed in the summer 2012 using the cable ship CS DEPENDABLE. Loading and laying tests were conducted throughout Node installations. Initial tests consisted of cable segment integrity checks from the ship. Next, Node-cable line optical/power performance was confirmed by temporarily connecting the Nodes to the shore and applying HV power. Nodes were then permanently jointed to the cable line and power re-applied to confirm joint integrity. Lastly, the Nodes were deployed; checks were made during the descent, upon reaching the seafloor, and prior to release. Figure 11 shows a shallow water Node being deployed.

Figure 11: Node Installation from TE SubCom Cable Ship CS DEPENDABLE

CSH test fixtures were used to validate the connections to SP1 and were left in place after deployment to support later test phases. Similar to the backbone cable installation, after Node installation, the cables connecting to the Nodes were inspected and re-buried in water depths of less than 1,500m, as necessary.

3. COMMISIONING AND SYSTEM ACCEPTANCE

After Node installation and deployment, system acceptance testing was completed including: transmission segment tests, confidence trials and system integration tests. During these testing periods, the NMS provided: control of operations, display of information and recording of logs and data. Throughout all phases, key operational and performance parameters were tracked.

- *Power transmission:* Cable line current and voltage at each Node and shore power feed performance.
- *Optical transmission:* Cable line BER/Q-factor, OSNR, receive power levels and repeater performance.
- *Node operation:* Power delivery, Science Port operation, Ethernet traffic, PT, and status-control link, Node telemetry and redundancy confirmation.
- *Network management:* Node and shore equipment monitoring, control and display, data logging and back-up.

3.1. Transmission Segment Tests

After Node installation was completed, a series of AC/DC electrical and optical tests were conducted, including LME optical cable line measurements. Tests were repeated for different configurations of Nodes and cable line. The PFE-MVPC commanding scheme was used to disconnect or re-connect a Node or cable segment to/from the backbone cable. For each configuration, power and optical signatures were captured and characterized. This data-set will be used as a baseline reference performance of the RSN system, against which future performance will be compared. Subsets of the same transmission segment tests were then repeated by UW to replicate measurements performed earlier for completeness.

3.2. Out of Service (OOS) Confidence Trial

In the OOS confidence trial, the shore and in-water system was continuously monitored for a 7-day period. Key performance parameters including: optical line transmission, power subsystem, communications, Ethernet traffic, and OOB/PT were verified. Any alarms or irregularities were recorded and daily logs were kept. During this period, the CSHs were used as the main tool to prove Node Science Port operations and verify interfaces. Both redundant halves of the Nodes were exercised and operation on A and B sides were confirmed. An Ethernet traffic generator/checker (SmartBits) was used on the shore to demonstrate end-to-end error-free transmission via optical loop-back within the CSH connected to SP1. OOB/PT operation was verified and round-trip delay accuracy to/from the CSH was confirmed. Port power interface was checked using the CSH 1kW load and current monitoring circuits were verified.

3.3. System Integration Test

System integration tests were then conducted to further demonstrate correctness of operation and verify transmission and power sub-systems. In addition, management functionality, remote access, fault localization and system restoration tests were also performed.

3.4. System Test – Buyer

System test periods allowed the Buyer an opportunity for their own testing. The Buyer performed a series of agreed upon tests over a 30-day period. During this testing phase, the Buyer operated the system assisted by L-3 MariPro.

3.5. System OOS Confidence Trial

Finally, the system OOS confidence trial of the shore and in-water system was performed with portions of the OOS confidence trial repeated. The system was continuously monitored, key performance parameters and operational status checked, and alarms/irregularities recorded. Node SP1 operation and interfaces were confirmed using CSH assemblies. Node redundancy was verified, error-free Ethernet transmission was demonstrated, OOB/PT operation was checked, round-trip delay accuracy confirmed, and power interface monitoring circuits were tested. This phase lasted three days and ensured there were no changes in performance from previous test periods.

3.6. System Acceptance Report

Results recorded over the various testing phases were gathered together and collated into a final acceptance test report and delivered to the customer.

4. CONCLUSIONS

The overall RSN testing strategy has proven successful. As initially outlined in the proposal phase and executed over the course of the program, technology risks were mitigated early on through demonstrations. A successful qualification test program verified both the design and provided workmanship assurances. A two-phased approach to in-water installation, with the backbone cable lines successfully installed in the summer of 2011 and Nodes successfully installed in the summer of 2012 minimized schedule risks that may have occurred due to the well known

Oregon coast bad weather. And finally, during the commissioning and system acceptance phases, the CSH proved to be an exceedingly useful test tool in simulating the secondary infrastructure connections to a Science Port.

5. REFERENCES

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ACKNOWLEDGEMENTS:

L-3 MariPro wishes to acknowledge the following companies for making the RSN installation and operation a success.

TE SubCom: cable line, repeaters, SLTE, optical demos, cable factory testing, installation of backbone and Nodes.

Diversified Technologies, Inc. (DTI): power feed equipment and MVPC, power demonstrations