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Remote Real-Time Subsea Monitoring Systems

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Abstract

In Oct, 2014, installation of the largest North American scientific cabled observatory was completed. The Cabled Array portion of the Ocean Observatories Initiative, funded by the U.S. National Science Foundation and implemented by the University of Washington, consists of over 850 km of fiber optic and electrical cables, 7 primary nodes, 18 seafloor junction boxes, 3 mooring-mounted winched profiling systems, 3 rechargeable wire-crawling profiler systems and 140 science instruments. The primary nodes and backbone cables, installed using standard telecommunications industry practices and designed to last a quarter century, bring unprecedented power and bandwidth to remote seafloor locations. Meanwhile, the modular, ROV-serviceable secondary infrastructure branches power and communications in support of instrumentation throughout the water column. The modular design of the secondary infrastructure provides the capacity to expand the cabled network well beyond its initial footprint. To facilitate full shore-based operations, a suite of management software was developed for network configuration, power control, port monitoring, system condition monitoring, configuring alarms, and troubleshooting. These systems are part of a growing new trend of real-time remote ocean monitoring, or interactive observatory-class, systems.

The purpose-built observatory-class systems for the OOI Cabled Array's long-term sub-sea monitoring operations provide a modular framework capable of adapting to many applications and scales. All secondary infrastructure equipment, including cables up to 5 km, were deployed by a work class ROV and configured to fit multiple site geometries and environments, from soft sediments to volcanic crust. Seafloor nodes, or junction boxes, deliver up to 200 Watts to each of 8 instrument ports, and can be daisy-chained for expansion. Real-time controllable winched profilers routinely perform multiple 200 m vertical profiles daily, and can be docked as needed to accommodate operations in the water column above. A 3500-meter rated wire-crawling profiler samples the entire water column and recharges at a cabled seafloor docking station. While each system is tailored to its specific mission, all components of the secondary infrastructure: 1) enable remote shore-based operation of deployed equipment, 2) allow for real or near-real time data collection and system control, and 3) are synchronized to a GPS-based clock. These key attributes of interactive observatory-class systems unlock several possibilities for subsea systems, including immediate responses to detected events, accurate time-based comparisons of

spatially-varying data sets, synchronized operations over an extended area, and shore-based control of remote resident infrastructure.

Introduction

Ship-based monitoring of subsea sites and infrastructure can be costly, time-delayed, and dependent on local weather conditions. Intermittent measurements may result in delayed responses to changing and potentially hazardous environmental conditions. In the 1990s and early 2000's, the concept of a long-term cabled observatory that would provide power and bandwidth to arrays of instrumentation over large ocean regions began to take form (Delaney, 2000). This vision has come to fruition over the Juan de Fuca tectonic plate in the Northeast Pacific (Figure 1), first through Ocean Networks Canada's NEPTUNE observatory, collecting data since 2009 (Barnes, 2010), followed by the Ocean Observatories Initiative (OOI) Cabled Array, the installation of which was completed in 2014. With these two plate-scale observatories and several other global cabled systems online (Favali, ed., 2015), the maturity of cabled ocean observing systems now provides a proven approach to long-term, real-time monitoring of underwater infrastructure and its surrounding environment. Further, the substantial power and bandwidth delivered to the seafloor by interactive observatory-class systems is poised to extend beyond monitoring applications to operational possibilities including resident vehicles and offshore industrial installations, all monitored and controlled remotely from shore.

The OOI Cabled Array infrastructure was purpose-built to support the scientific objectives of the OOI program; however, its modular component designs provide flexibility to support a wide range of devices, from small, local systems all the way up to ocean basin-scale installations. System requirements that drove design considerations include a 25-year lifespan, high reliability, individual network addressing and power control of hundreds of instrument ports, support for a diverse set of instrumentation, precise GPS-based time synchronization, and the capacity for expansion.

The backbone of the Cabled Array, originating from a shore-based power and communications terminal building, was developed and installed by L-3 MariPro. It consists of a telecom-grade cable with unique primary distribution nodes used to convert 10 kVDC input to 375 VDC science port outputs and provide networked communications to the scientific, or secondary, infrastructure. The secondary infrastructure, designed and built by the University of Washington's Applied Physics Lab (APL-UW), is a network of sub-sea nodes that distributes power and communications to scientific instrumentation. Each of 18 seafloor junction boxes hosts up to 8 instruments ports, which are optimized to suit the communication protocols and power requirements of connected instruments. Also parts of the secondary infrastructure are three undersea moorings anchored at depths up to 2900 m. These moorings provide subsurface platforms to support custom-designed winched profilers. Additionally, rechargeable wire-crawling profilers are deployed adjacent the three mooring sites. Together, the winched and wire-crawling profilers enable long term full water column measurements in areas that have previously been sparsely sampled.

This paper focuses on the features and early operations of the secondary infrastructure of the OOI Cabled Array.

Description and Application of Equipment

The secondary infrastructure of the OOI Cabled Array was designed and built for flexible and expandable coverage over diverse oceanic areas of scientific interest covering the Juan de Fuca tectonic plate in the northeast Pacific Ocean. Deployment locations range from the continental shelf (80 msw), to areas rich in gas hydrate deposits (800 msw), the continental shelf slope base (2900 msw), and the active caldera of a submarine volcano (1500 msw). To survive in these challenging conditions, cabled infrastructure systems are packaged in grade 5 titanium housings with rugged bulkhead connectors and are rigorously tested under freezing temperatures and high pressure. Pressure housings are closed in a clean room and nitrogen purged for optimal sealing and low internal humidity. All secondary infrastructure systems were designed to be deployed and recovered by a work class ROV.

In addition to adopting uniform hardware design practices across the different node types, configurable system management software provides a common operational interface for each node. In the deployed network, each individual instrument port is assigned a unique IP address, with all nodes supporting multiple VLANs, remotely-manageable internal switches, and remote firmware updates.

Junction Boxes

Seafloor junction boxes can connect directly to 8kW, 375 VDC, 1 GigE fiber science port outputs of the primary infrastructure, or they can be daisy chained to fit site geometry and instrumentation requirements. All junction boxes are deployable by working class ROVs and connections are made with Teledyne ODI Nautilus wet-mate connectors. Figure 2 shows daisy chained junction boxes.

Using the same basic architecture and components, including Atmel microcontrollers, Moxa network switches, Vicor DC-DC converters, APL-UW-designed instrument interface boards, and control firmware, each junction box can be optimized for maximum expansion capability (Low Voltage Node), maximum instrument ports and a single expansion port (Medium Power Junction Box), or as a low-power end-point node servicing up to eight 50 W instrument ports (Low Power Junction Box), as described in Table 1.

Within a junction box, each instrument port is optimized to the power, voltage, and communications protocol of the instrument that is connected to it. To date, over 30 diverse types of instruments have been powered and operated by junction boxes, including low power serial devices like pressure sensors and CTDs, camera systems complete with lights and pan/tilt, and Ethernet hydrophones capable of continuous output of up to 256 kSamples/s. Table 2 shows available instrument port pinout options, supporting multiple communications protocols and time synchronization outputs that include differential 1PPS and NMEA time of day signals, synchronized via IEEE-1588 Precision Time Protocol to within microseconds of a shore-based GPS clock.

Several internal monitoring capabilities enable operators and users to remotely monitor all aspects of system operations. Internal junction box sensors include input voltage, humidity, temperature, pressure and pitch/roll. Also, each isolated instrument port can be monitored for output voltage, current draw, and isolation faults on power and ground lines. These internal sensing modalities, coupled with system management software, offer critical troubleshooting functionality, allowing for small faults to be detected before hard failures of instrumentation occur.

Two-legged Mooring, Platform, and Winched Profiler

Each of the three two-legged moorings incorporates two anchors with tethers that meet at a large floating platform stationed 200 m below the surface. One tether is an electro-optical-mechanical cable for power and communications, and the other is high molecular weight polyethylene line. The mooring platform supports the winched profiler and a dedicated mooring controller, both of which share many of the modular components of the seafloor junction boxes, including instrument interface boards, node controller boards, and a suite of internal sensors. The platform structural elements are titanium for weight and corrosion resistance, and the flotation is syntactic foam.

The mooring controller feeds power to the controller of a variable frequency drive-controlled winch. Winch motion is carefully orchestrated with an on-board level wind system for precise layering of over 200m of cable. The winched profiler, pictured in Figure 3, is equipped with an on-board inertial measurement unit and a pressure sensor. Large accelerations in the profiler body indicate storm conditions and are utilized to automatically limit the upper bound of travel. Custom profiler “missions” were generated for optimal sampling of the 10 onboard instruments, and include continuous up/down profiles at controlled speeds as well as stepped sampling in which the profiler stops for a predetermined period at different depths throughout a profile. In response to detected events, the operating mission can be changed on the fly. Control software in each winched profiler maintains safe operation regardless of network connectivity to shore. Additionally, a network protocol supports instrument coordination based on the state and activity of the profiler.

Deep Wire-Crawling Profiler

A McLane wire-crawling profiler was modified by APL-UW to support long-term cabled operations. The profiler drives up and down a fixed mooring line that doubles as an inductive modem interface for continuous real-time communications. The battery-powered profiler recharges after several profiles at a custom-built cabled docking station located near the seafloor, where a WiFi link provides higher bandwidth communications for full data retrieval and mission downloads.

For ease of maintenance, the wire crawling profiler, shown in Figure 4, and deployed at depths up to 2900 m, uses a custom release mechanism that allows a working class ROV to remove the profiler from the mooring line and replace it without recovering the entire mooring. The crawler, host to 6 instrument ports, follows customized missions which cover all or part of the mooring line from the seafloor to a ceiling of 150 m water depth, providing overlap between the wire-crawling profiler and the winched profiler.

Management Software

System management software was developed with the capacity to scale along with the deployed scientific infrastructure. At the lowest level, the Element Management System (EMS) provides direct control and monitoring of each deployed infrastructure node. A common EMS node configuration format allows customization of each node interface, and permits error levels, including ground fault thresholds, port temperature and over current limits, to be set individually for each instrument port. Figure 5 shows the basic node power interface EMS screen. The EMS interface has a plotting function for trend analysis of all node parameters monitored by the EMS.

At a higher level, the Observatory Management System (OMS), collects and stores all array infrastructure management parameters, and provides a robust interface for viewing network wide status, events and alarms. Built on the commercial Zenoss platform and customized for the OOI Cabled Array, the OMS is modular and scalable with the network infrastructure. Figure 6 is an overview image of data flow in the deployed network, as viewed through the OMS.

Operational Results

All seafloor infrastructure has remained 100% operational through its first 18 months. At least one junction box has endured heavy external aggression, likely from fishing gear that pulled the frame onto its side, with no loss of function. Mooring-mounted instrument platforms and winched profilers, swapped annually for instrument calibration and maintenance, have proved capable of 12 month operations, profiling up to 9 times per day (see Figure 7). Wire crawling profiler moorings have successfully demonstrated water column profiling from 150m to 2900m water depth. The OMS and EMS software management systems stream real-time system status, alerting operators to changed conditions as well as maintaining a archived status parameters.

Most importantly, the Cabled Array has delivered on its promise. Data from over 140 instruments have flowed seamlessly to the OOI's Cyberinfrastructure, where shore based data servers collect, in real time, over 1 terabyte of data each week, including diverse data sets ranging from high definition video to seafloor pressure. Additionally, operators on shore routinely interact with remote instrumentation, controlling camera systems, in situ mass spectrometers, and remotely controlled physical samplers.

Less than one year into the cabled array's operation, on April 24, 2015, a major volcanic eruption was detected at Axial sea mount (Delaney, 2015). For the first time ever, the eruption was observed, as it happened, by a time-synchronized and diverse array of sensors. This allowed researchers to better plan research operations directly following the eruption, and is giving new insights into to mechanisms that govern mid-ocean-ridge processes and the impact of eruption events on the surrounding ocean.

Conclusions

A decades-long vision in the ocean science community was realized with the installation of the OOI Cabled Array. In its second year of operation, the system infrastructure is fully functional, having already captured data in real time from an eruption on a submarine volcano 350 km away from the western United States. But this is just the beginning for this system, designed for 25-years of operations. Built for expansion, the OOI Cabled Array will grow to include new and novel instrumentation, which may include resident autonomous underwater vehicles, and data connections to networks of wireless systems, communicating through acoustic and optical modems.

Because the cabled array infrastructure components are robust, modular and configurable, they are well-suited to use in developing applications for remotely-managed subsea infrastructure. Despite their mission specific designs, each of the cabled array nodes possesses three key attributes of interactive observatory-class systems:

1) Remote shore-based operation of deployed equipment
2) Real time or near real time data collection and system control
3) Synchronization to a GPS-based time source

These attributes are the basis for a generation of systems that will grow both industrial presence and environmental monitoring in our ocean environments by enabling immediate response to detected events, accurate time-based comparisons of spatially-varying data sets, synchronized operations over an extended area, and shore-based control of remote resident infrastructure.

Applications for interactive observatory-class systems will continue to grow as the high costs of vessel-based operations drive the need for remote real-time operations and monitoring. As the robotic systems that conduct remote operations mature, no longer requiring close proximity to shore-based resources, these same remote systems will enable intelligent expansion into new ocean regions while closely monitoring impacts on delicate underwater ecosystems.

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A detailed view of the 2014 Cabled Array deployment cruise may be found at: http://www.interactiveoceans.washington.edu/story/VISIONS_14.

Tables

Table 1. Configurations of seafloor junction boxes

	Inputs	Number of Output Ports	Maximum Power per Output Port	Maximum Total Output Power	Output Protocols
Medium Power Junction Box	375 VDC 1 Gb/s fiber	8 instrument (12/24/48 VDC) 1 expansion (375 VDC)	Instr.: 200 W Exp.: 8 kW	8 kW	**Instr.** 10/100BASE-T EIA-232 EIA-422 EIA-485 **Exp.** 1Gb/s fiber
Low Power Junction Box	48 VDC 10/100BASE-T copper	8 instrument (12/24/48 VDC)	50 W	150 W	
Low Voltage Node	375 VDC 1 Gb/s fiber	4 instrument (12/24/48 VDC) 2 expansion (375 VDC)	Instr.: 200 W Exp.: 8 kW	8 kW	

Table 2. Junction Box port pinout options

	1	2	3	4	5	6	7	8	9	10	11	12
Enet	PGND	PPS+	DGND	TX-	RX-	TOD-	TOD+	RX+	TX+	24/48V	PPS-	12V
232	PGND	PPS+	DGND	TX	CTS	TOD-	TOD+	RX	RTS	24/48V	PPS-	12V
422	PGND	PPS+	DGND	TX-	RX-	TOD-	TOD+	RX+	TX+	24/48V	PPS-	12V
485HD	PGND	PPS+	DGND	DATA-	-	TOD-	TOD+	-	DATA+	24/48V	PPS-	12V
485FD	PGND	PPS+	DGND	TX-	RX-	TOD-	TOD+	RX+	TX+	24/48V	PPS-	12V

Figures

Figure 1. Map view of Ocean Network's Canada NEPTUNE observatory and the OOI Cabled Array

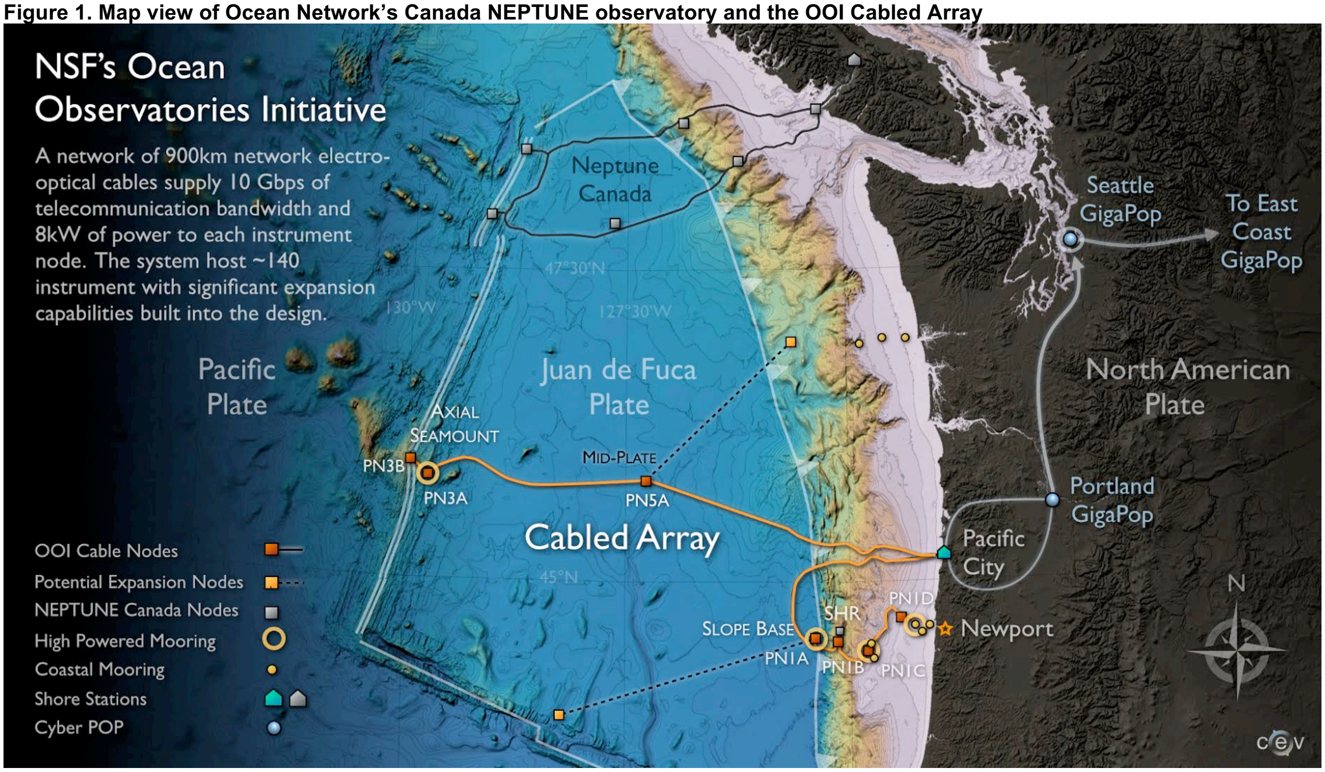

Figure 2. Daisy chained seafloor junction boxes with installed instrumentation (ADCP, hydrophone, CTD, Optical Attenuation and Absorption)

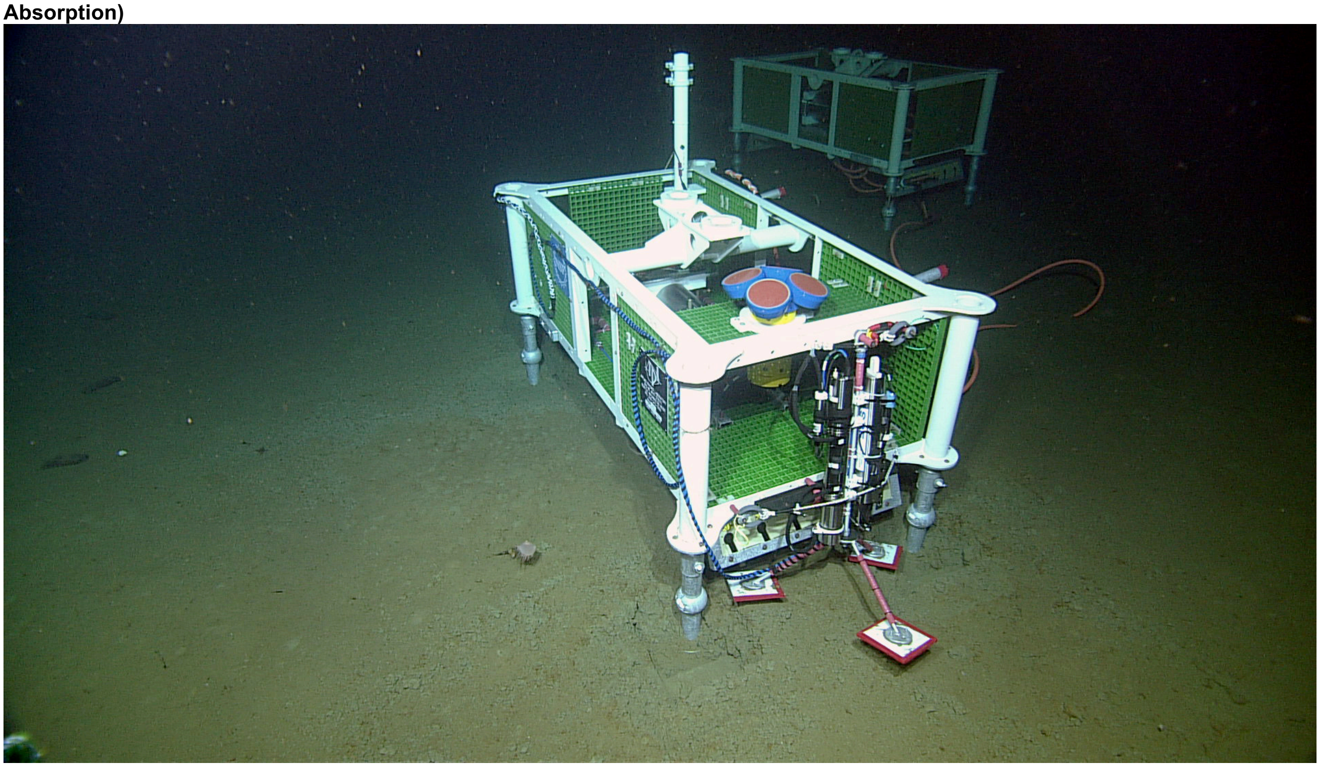

Figure 3. Instrumented winched profiler emerging from mooring platform at 200m

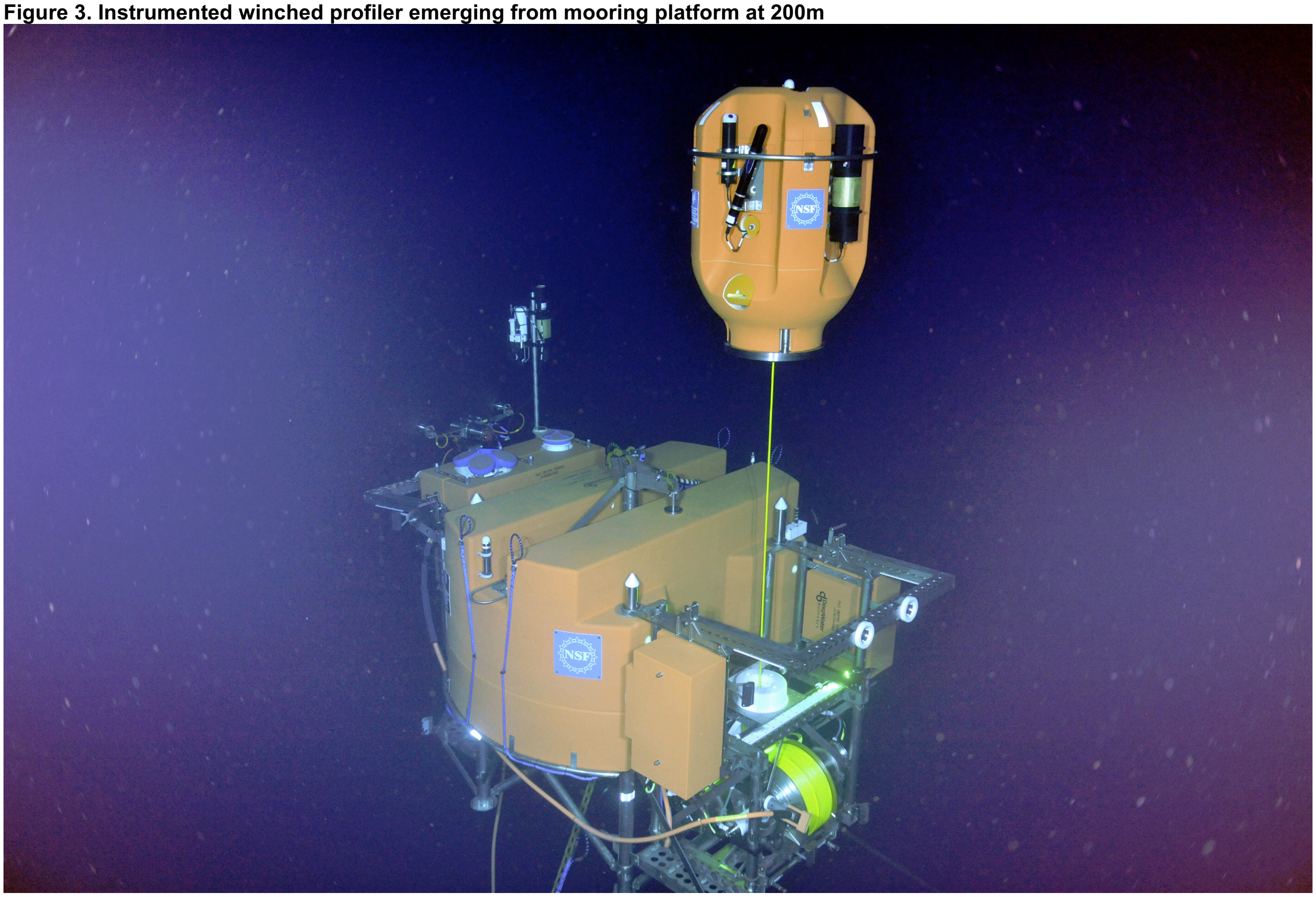

Figure 4. Deep winched profiler with 6-instrument payload

Figure 5. Secondary Node Element Management System (EMS) for control and monitoring

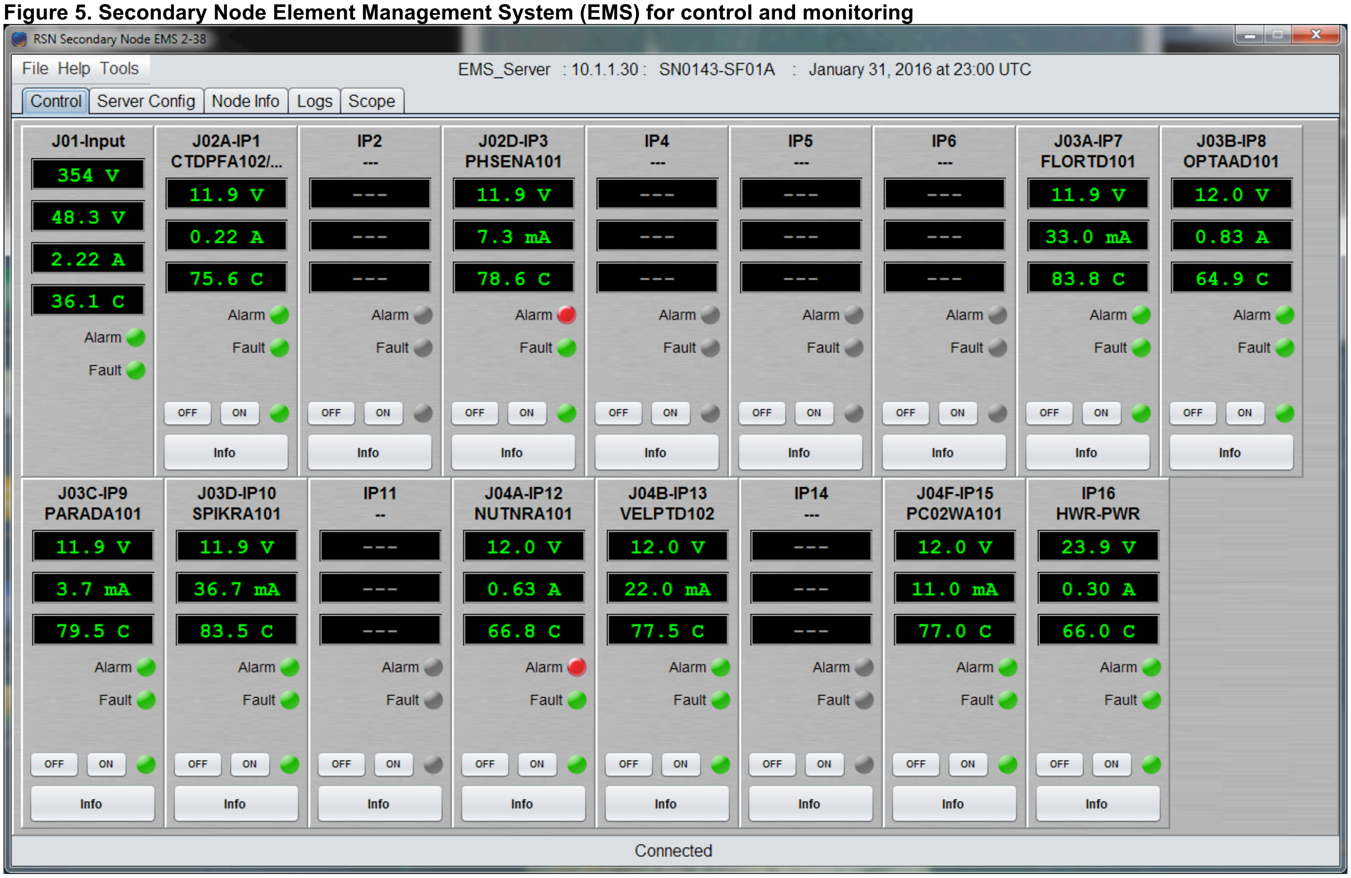

Figure 6. Observatory Monitoring System (OMS) for monitoring system level network traffic and status

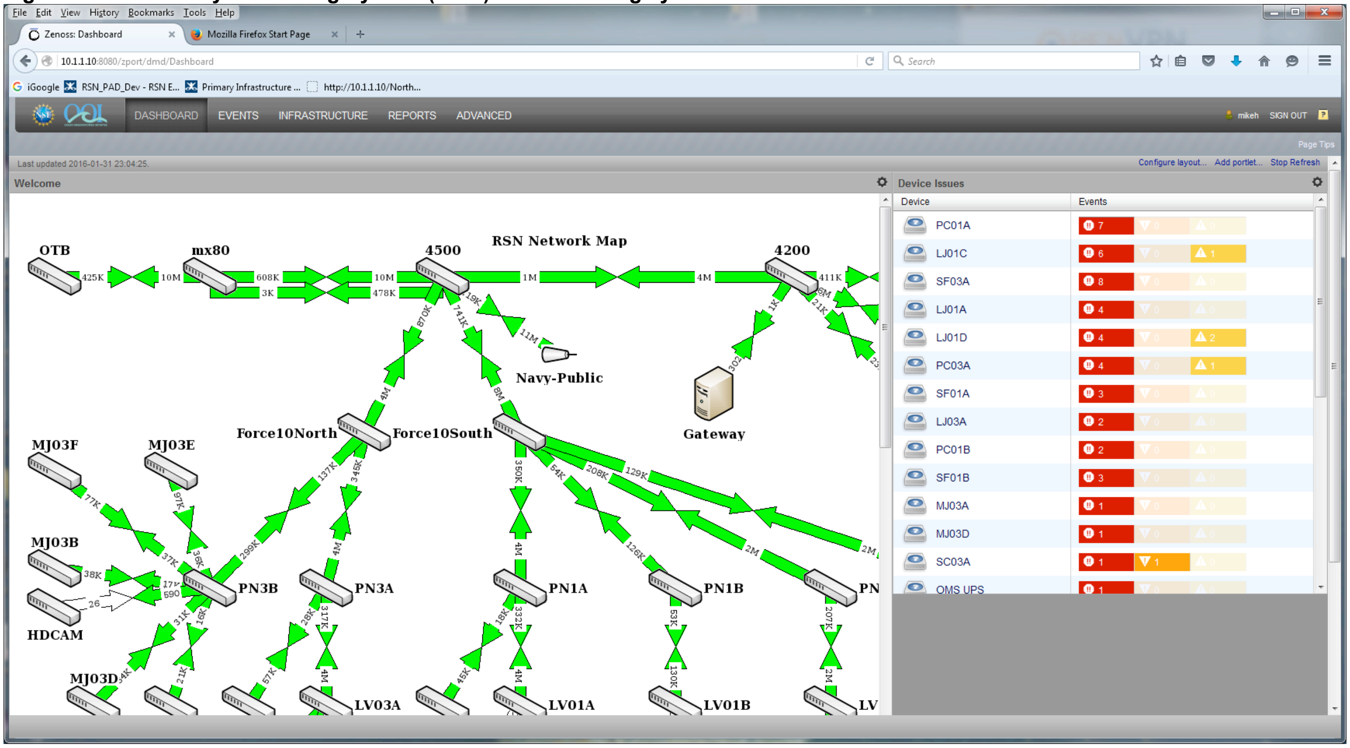

Figure 7. Plots of winched profiler system sensor readings during 9 profiles completed over 24 hrs