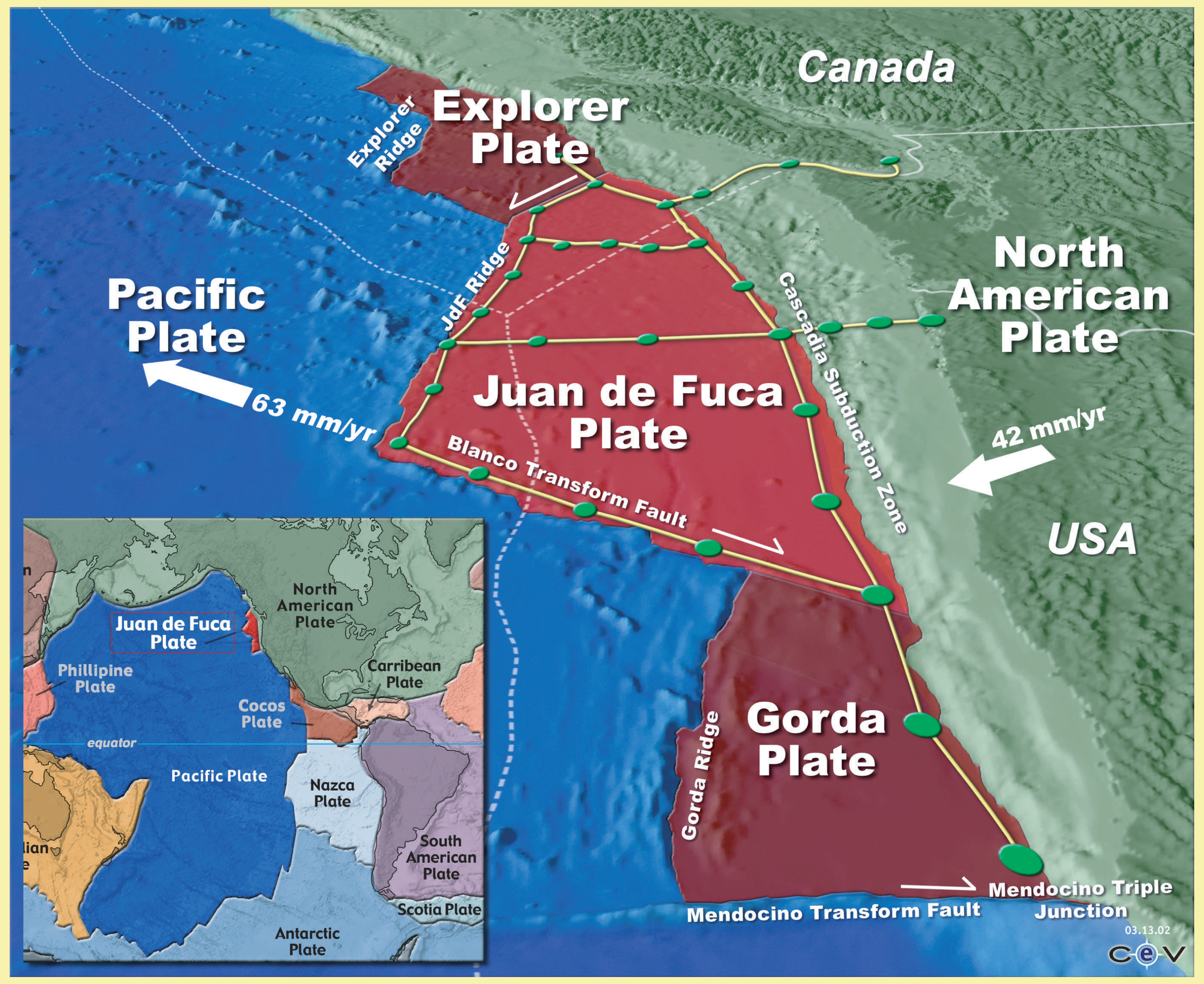
Development of a Power System for Cabled Ocean Observatories

Bruce M. Howe[1], Harold Kirkham[2], Vatché Vorpérian[2], Tim McGinnis[1], Chen-Ching Liu[3], Mohamed El-Sharkawi[3], Kevin Schneider[3], Aditya Uphadye[3], Shalini Gupta[3]

1–University of Washington, Applied Physics Laboratory and School of Oceanography
2–Jet Propulsion Lab, California Institute of Technology
3–University of Washington, Electrical Engineering

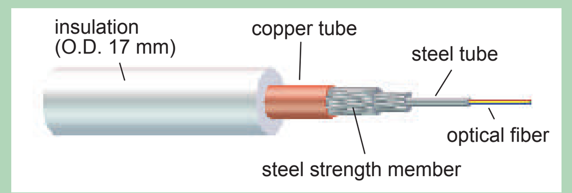
Abstract

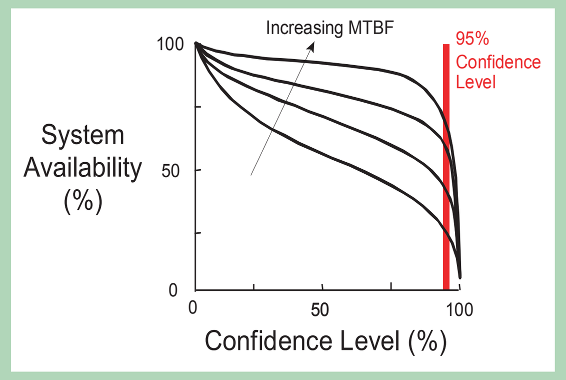
Cabled Ocean Observatories offer the potential to deliver unprecedented amounts of power to remote instruments and sensors. The availability of sufficient power will enable new instrumentation and methods. Here we describe the present NEPTUNE power system design which will be capable of delivering an average of approximately 4 kW or a maximum of 10 kW to over 40 seafloor node locations spread over approximately 500 km x 1000 km of seafloor. The system will have a backbone of 3500 km of standard seafloor telecommunications cable connecting the nodes in a mesh topology. The network will have 10 kVdc parallel feed, distributed stochastic load, and constant voltage output. A network of secondary extension cables will be developed that will allow the network to be extended up to 100 km from the backbone. The backbone cable has a single power conductor so a seawater ground return will be used. High availability and reliability over the 30 year life of the system is an important consideration in design and construction of the system. It is anticipated that faults will occur in the node electronics, cables, etc., so a protection system is being incorporated to allow faulted sections to be isolated and then to utilize the ring/mesh topology to minimize impact on the rest of the system.



The NEPTUNE Power System Challenge

Design a power delivery system, using conventional submarine telecom cable





- ~40 Science Nodes, peak power at each ~10 kW; total ~100 kW
- Extreme reliability–Maximum of 4 repairs per year over 30 year lifetime; MTBF node ~10^6 hr
- Fault tolerant
  - minimize downtime, maximize continued operation
  - Cable or node faults—no collateral damage
- Maintainable with UNOLS vessel

Power to area the size of New York state ~ a few houses.

The Solution:

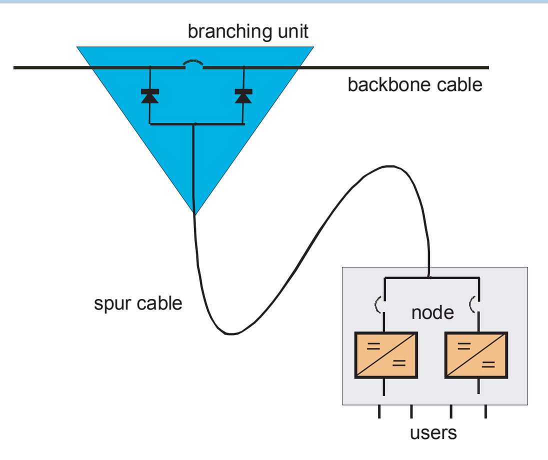
Transmit power from shore at 10 kV dc and step it down via a dc/dc converter at the Science Nodes. Use a parallel distribution sytem, with features borrowed from the utility world:

- Redundancy of construction
- Use of hi-reliablitiy parts only
- A protection system for detecting and isolating faults
- A power management system

However, The Design Job Is Difficult

DC networks are new. DC is used today to transmit power over large distances, at 500 KV, not 10 kV.

- Reliability/availability is a challenge for such a novel and complex system
- Strong reliability driver–large amount of sub-sea energy storage ruled out
  - Power system must start up from a "black start," with no power available at the node until after the node's own converter is operating
  - Fault tolerance and protection system challenged by the lack of energy storage
- Converter design–large number of modules in series but with lower component stresses
- Separate the hi-reliability backbone infrastructure from the science node
  - Problems in one node will not affect the operation of any other node
  - Some control equipment for the backbone will be located in a pressure housing that has no communication with the outside world, and is powered only when the system is operating

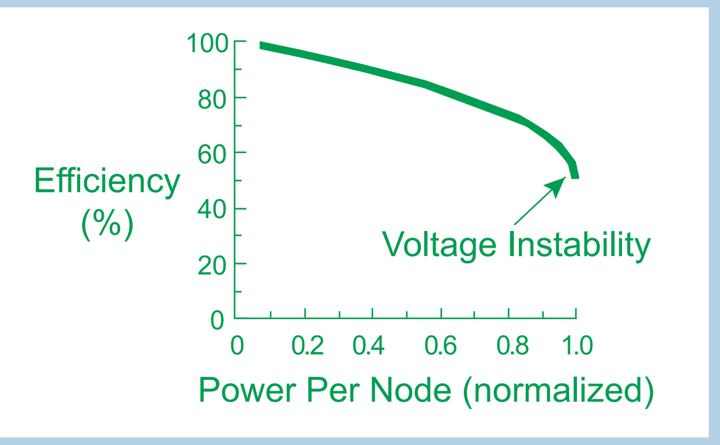


- Short-circuits in the sub-sea portion of the network are expected to be rare, but must be allowed for. With the parallel system proposed for NEPTUNE, a short circuit must be accommodated by isolating the fault, as in a conventional utility.
- Any short circuit in the cable network will result in a momentary shut down of the entire system, as a result of the way the shore stations are operated. Rather than allow a high fault current to flow, as in an ordinary power system, NEPTUNE will operate in a current-limited mode, to protect equipment.
- Operation can resume shortly after the circuit breakers nearest to the fault have opened, clearing the fault. However, while full power can be reapplied at the shore station, the location of the fault is not known unless some special detection means is incorporated.
- Control will be particularly challenging. There is an *observability* problem caused by the fact that some of the system is unmonitored . . .
- There are several inherent *instability* modes in the system
  - Voltage instability, a result of the maximum power transfer capability of the network
  - Operating stability, coordination of the multiple power sources
  - Converter stability has two aspects: the negative resistance question posed by the constant-voltage nature of the output, and the voltage/current balance question posed by the modular nature of the design

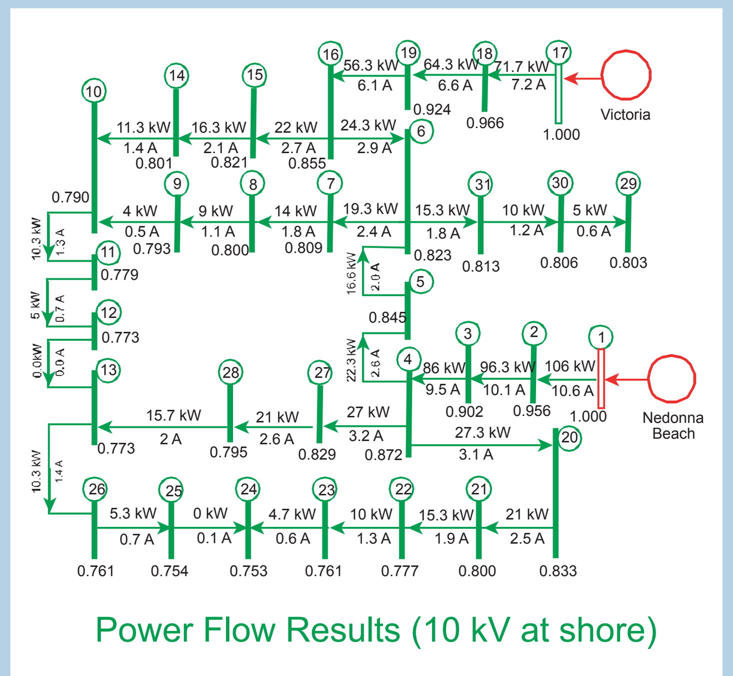
Voltage Instability

Voltage instability occurs when the power transfer capability of a power network is approached. The approach to the limit is characterized by the inability of the control systems to maintain voltage.

This happens when the efficiency is approaching 50%, instability is being approached (vertical slope)



The constant voltage characteristic of the dc/dc converters conceals the onset of voltage collapse. The fact that we can get a solution to the power flow problem means that stable operation can be achieved.

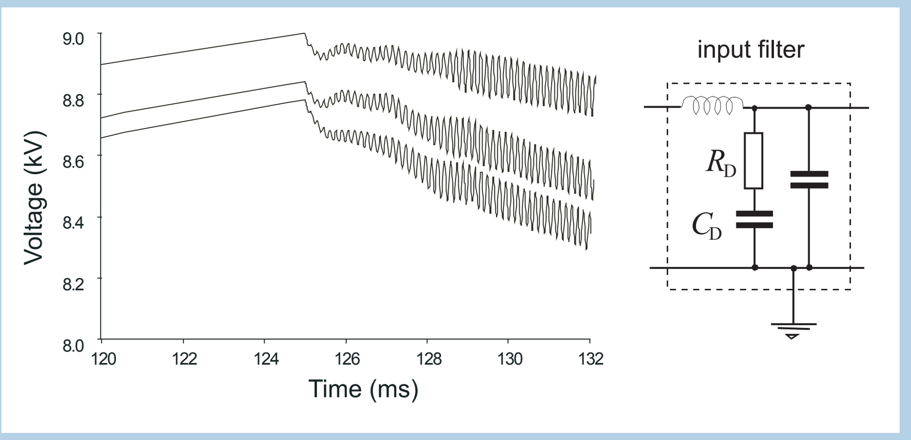


Operating Stability

- Coordinating the multiple shore stations supplies
- Assume 2 shore stations set to produce the same voltage. Each is a "slack" generator. While utility practice is to have only 1 slack machine in any area, our simulations show that having 2 should not be a problem. Power will be drawn from each according to Ohm's law.

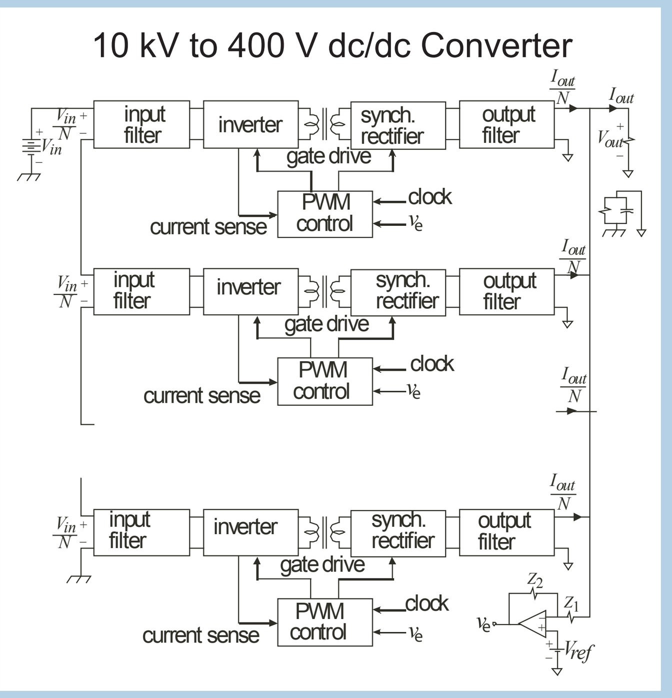
Converter Stability

1. Output of the dc/dc converter is a constant voltage (400 V) and load power is constant in spite of variations in the input voltage. Thus, input current increases when the voltage decreases, i.e. the converter presents a negative resistance to the system. Normally, a negative resistance in a circuit implies instability. The negative resistance appears because of the control action of the converter. The effect is present only over the bandwidth of the control system (a few kHz). The solution is to damp out oscillations with appropriate input filter.



Simulations show that with the filter installed, the converter is stable even for step changes in load or input voltage. That is not the case when the filter is removed, shown here.

2. Second converter stability question arises from the modular nature of the design. Plan on a stack of converters with inputs in series and outputs in parallel.



If all components perfect, pulse width modulation control monitoring the output voltage would produce identical drive pulses for the switching transistors, and each converter would drop the same input voltage.

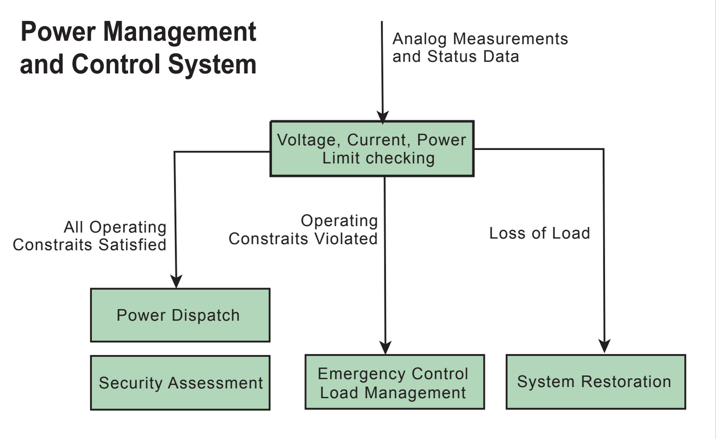
Real components have values subject to uncertainty. A control mechanism is needed so that the input voltage is evenly divided. This is achieved by a current sense system that adjusts the PWM drive of each stage relative to the others.

Operations

Startup

- Backbone powered up sequentially. Breakers in branching units closed autonomously, with only local control information
- Nodes powered up as soon as power is available on the backbone
- Special diode arrangement allows node to be powered from either direction, without energizing other side
- Backbone will be energized in milliseconds; nodes ~20 s to full power
- Startup circuit for the main converters *has to work*–extremely simple using only a few robust parts. Trade-off: takes 10 s to start converter
- When converter starts, startup supply disconnected, protection system on, and communication system energized
- After a minute, communication system operational, and power management and control system available
- As outbound circuit energized, it is monitored for faults. Energization takes place through series resistor, so no large current spike even if cable is faulted
- If communication system fails, node power system enters safe mode. The circuit breaker is closed, allowing power to be transmitted farther

Normal operation is controlled by a Power Monitoring and Control System (PMACS). The Node Power Controller makes voltage and current measurements and transmits values to shore. The shore-based PMACS performs a number of functions on a continuous basis.



- Security Assessment checks that all system voltage, current and power constraints are satisfied
- Dispatch adjusts the relative outputs of the shore stations
- Emergency Control adjusts voltages or loads when constraints are violated (e.g., load-shedding)
- Restoration re-energizes system when protection system has acted to shut all or part of it down

Protection

Protection is more the ambulance at the bottom of the cliff than it is the fence at the top. Nothing can prevent faults– all one can do is react appropriately

- Faults may occur in the cable and in node electronics
- Protection acts to isolate faulted parts and leave remaining parts operating

Cable Protection

Cable faults can be caused by manufacturing defects, fishing activity or anchors. NEPTUNE will use overcurrent protection in the branching units. This approach obviates the need for communicaton and for voltage meaurement. Normally it is considered that the protection system itself may develop a fault, and so must be designed with redundancy. NEPTUNE plans instead to make the protection scheme simple and reliable.

Node Protection

Faults within a node are easier to detect, as the measurements needed are all close together. Clearing a node fault may mean shutting the node down. In this case, the node must signal adjacent nodes to isolate it, as the individual nodes do not have breakers they can operate to isolate themselves. A challenging aspect of node protection is to detect small leakage currents from the backbone circuit. In general, such a leakage may signify incipient insulation failure inside the node. Since there will normally be a significant ground (ocean) current at the node, the technique depends on directly measuring the sum of the currents in the two backbone cables and the ground connection.

Restoration

Faults will inevitably result in the entire network being shut down. This aspect is unlike the terrestrial power system, and is a result of the current-limiting nature of the shore station power supplies. However, while faults may occur, and the network may go down, it will only be down for a short time.

Faults cleared by opening backbone circuit breakers. Cannot act fast enough to prevent the effect of the fault reaching the shore station. Will isolate fault in ~20 ms.

All breakers will open after a fault. Not effective from reliability viewpoint to keep them closed with stored energy. When fault cleared, voltage on shore will return to normal, and restoration can begin. However, the operator may decide first to perform a fault location sequence.

If this process is automated, system operation should be reusmed in less than a second.

Maintenance

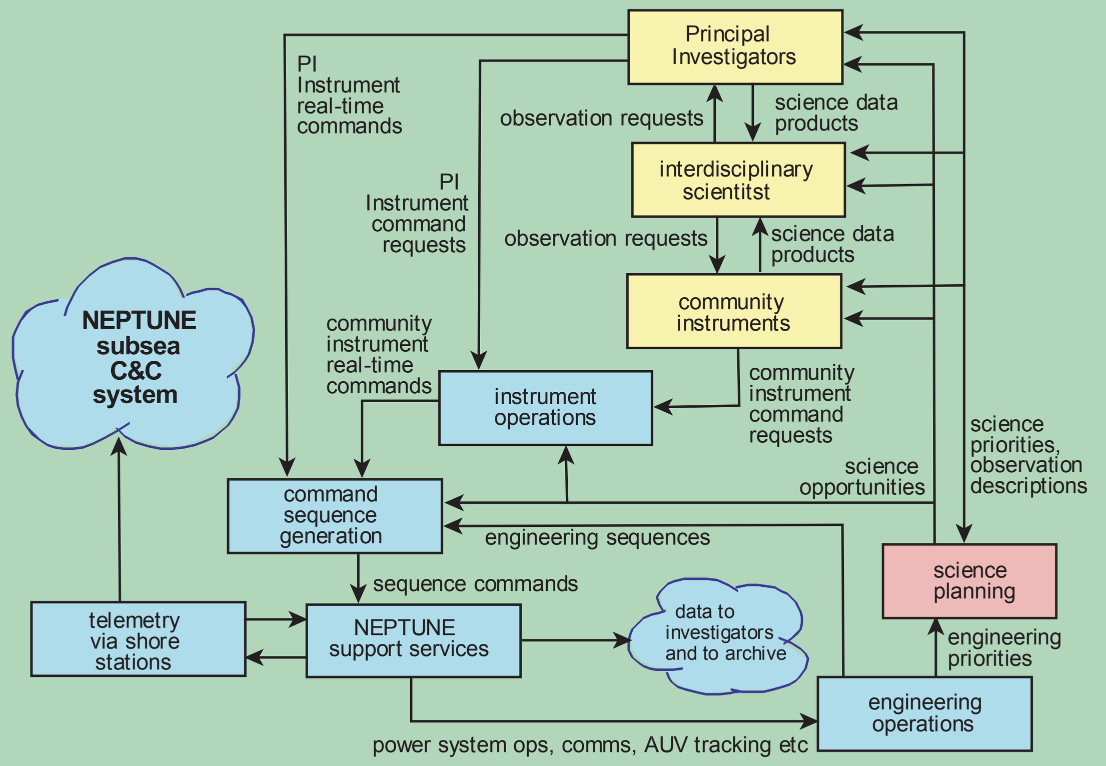
Even though we plan on an extremely reliable system, some maintenance must be allowed for. A UNOLS vessel will likely service the nodes (on spurs) while a cable ship will be required for work on a branching unit.

Actual repairs would probably not be performed at sea, as most of the power system will require clean-room assembly to achieve the required MTBF figures.

User Considerations

User "Contract"

- Schedules and profiles for expected autonomous changes in power loads
- Schedules for planned power cycling or other interactions
- Interactions accomplished through observatory management system



Proposed User Categories

- **General** – most science loads. Energized if no problem or power shortage.
- **Deferrable** – lighting, battery charging, big power users may be disconnected to allow other critical loads to be served
- **Essential** – *internal* loads such as the communication system, the protection system. Powered any time the converter is operating
- **High-Priority** – science loads that warrant an extra effort to keep them energized

User Interface and Sensor Requirements

- 48V and 400V available on separate pairs of pins
- Isolation of all circuitry (electronics, cables, connectors) from case/sea water is required
- Ground faults will result in instrument being disconnected
- User will need to incorporate energy storage if required for power outages

Concluding Remarks

While the work presented here is being done within the framework of NEPTUNE, it will be generally applicable to all cabled ocean observatories using similar cable.

Science community input is needed to review engineering requirements.