Development, Deployment, and Operation of Kilo Nalu Nearshore Cabled Observatory

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Abstract- **The Kilo Nalu Observatory, located on the south shore of the island of Oahu, supplies data and power connections to a suite of instruments over an array of stations extending from 12 to 20 m water depth which enable real-time extended time series observations, as well as individual user-specific interactive and automated experiments. The observatory power backbone includes a central distribution node at 12 m depth which controls DC power for up to four secondary nodes distributed across the reef; each node, in turn, provides isolated power for up to four experiment modules or ‘subnodes’. The shore cable also provides gigabit Ethernet data communications to the central node over optical fiber, with 100 Mb data bandwidth capability routed subsequently to each node. A monitoring system provides real-time diagnostic data on power system performance. Backbone data connections to remote nodes are achieved using underwater mate-able ‘micro-nodes’ that transmit Ethernet over fiber optic cable. Raw observational and diagnostic data are collected and archived at a shore station and transmitted via wireless link to the University of Hawai’i at Manoa campus where a database system provides products to a web interface (www.soest.hawaii.edu/OE/KiloNalu). Baseline observations include water currents and temperature versus depth, directional wave spectra, salinity, acoustic backscatter, turbidity, dissolved oxygen and chlorophyll fluorescence. Meteorological data is collected at the observatory’s shore station. Kilo Nalu is part of the broader Hawai’i Ocean Observing System (HIOOS), which includes observational and forecast components across the Hawaiian Islands.**

I. INTRODUCTION

The biogeochemical processes that occur in the benthic environment along coastal margins are strongly affected by, and to a large extent dependent on, forcing from episodic events such as freshwater runoff, storm winds, seasonal tides and surface and internal waves. Coastal ocean observatories enable real-time, long-term monitoring of these intermittent events and of the associated environmental response. Cabled systems further ease constraints on communications and power, opening the door to new instrumentation, adaptive sampling and manipulative experimentation. The Kilo Nalu Observatory, in operation on the south shore of Oahu, Hawai’i since August, 2004, aims to provide this sort of access to the tropical reef environment.

The broad goals of the observatory are to provide support for coastal ocean and tropical reef research, stimulate ocean technology development, obtain long-term time-series observations for validation of ocean prediction models and to enable ocean education and outreach opportunities. The observatory’s infrastructure provides baseline observations on the coastal ocean environment along with data and power connections at guest ports for user-specific experiment modules.

The observatory, whose name combines the Hawaiian words *kilo* meaning “to observe” and *nalu* meaning “ocean waves”, builds on a series of earlier cabled ocean observing efforts undertaken in and around Hawai’i, including HUGO [1], H2O [2], [3] and more recently the ALOHA cabled observatory (www.soest.hawaii.edu/GG/DeepoceanOBS/aco_home_page.htm). Kilo Nalu was initiated with funding from the US Office of Naval Research in support of a study on wave and current physics over coral reefs. The first generation of the observatory backbone was based on the electronics design of the Monterrey In Situ Observatory (MISO: www.oc.nps.edu/~stanton/miso/). The second generation KN backbone was developed and deployed as part of a National Science Foundation Coastal Oceans Processes (CoOP) project targeting benthic biogeochemistry and physics. Kilo Nalu now forms a core component of the broader Hawai’i Ocean Observing System (HIOOS: www.hioos.org).

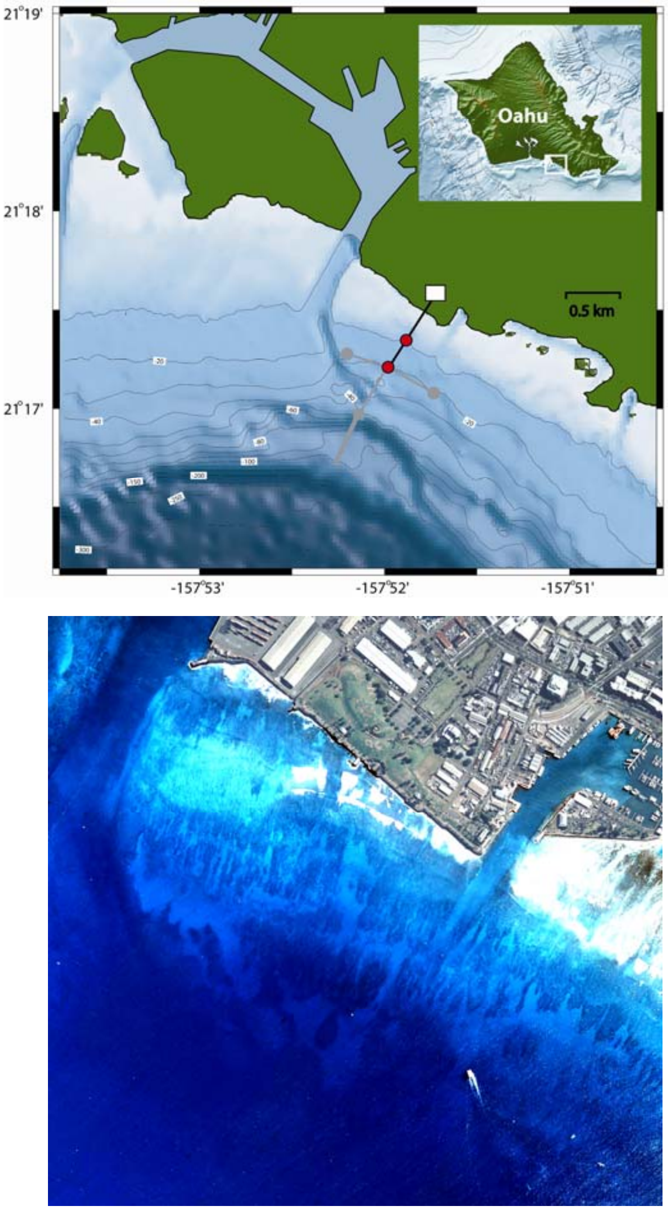

Figure 1. Top: South shore of Oahu, with Kilo Nalu site. Bottom: Aerial image of Kilo Nalu site (contrast enhanced over water to highlight reef morphology).

The present Kilo Nalu site sits within the boundaries of the former J.K.K. Look Laboratory Ocean Engineering Test Range. The OE Test Range was deployed in the mid 1980's and made use of a shore cable to provide power and data connections to two underwater platforms at 50' and 80' depth. The Kilo Nalu shore cable uses the same Look Laboratory conduit as the earlier Test Range cable, extending from the former lab site through the Kakaako Waterfront Park seawall. The system also makes use of the older cable as a structural support through the surf zone.

From a research perspective, the observatory site offers a dynamic, highly permeable and biogeochemically active seafloor in close proximity to the deep ocean, which provides regular exposure to offshore geochemistry and variable physical forcing driven by internal tides and mesoscale eddies. The south shore is further subject to a wide and predictable range of surface wave conditions. The ability to forecast the arrival of significant surface wave events greatly aids the planning of experiments, deployment of instruments and implementation of event-driven sampling. The site is also located midway between Honolulu Harbor and the two of the state's most important beaches, Ala Moana and Waikiki.

II. General Environment

A. *Reef Morphology*

Kilo Nalu is located off of Kakaako Waterfront Park in Mamala Bay, on the south shore of the island of Oahu, midway between downtown Honolulu, to the west, and Waikiki Beach to the east (see Figure 1). The shoreline at Kakaako Waterfront Park consists of a seawall extending from Honolulu Harbor to the Kewalo Basin Boat Harbor. The depth at the base of the seawall is roughly one meter at MLLW. Offshore, the bathymetry (Figure 2) slopes steadily at a rate of 1:30 to roughly 40m depth, beyond which the slope increases dramatically, reaching depths of 250m within a little over 2 km from the shoreline and 400m within 3.5 km.

The substrate along the south shore is comprised largely of Holocene limestone reef [4], with regions of extensive live coral coverage interspersed with patches of carbonate sands. At the KN site, the reef is dominated by encrusting algae and corals with sparse coverage by branching corals (*porites lobata* and *porites meandrina*) over very rough fossil reef from the shoreline out to approximately 12 m depth. Beyond this, a band of relatively flat reef deepens to approximately 15 m where dense coverage by branching corals extends out to about 20 m depth. Seaward of 20 m depth, coral coverage is sparse.

The seabottom roughness in the Kilo Nalu vicinity was examined by [5] using boat, diver and AUV surveys to measure scales from tens of centimeters to 25 meters. Their observations indicated that the roughness over this range could be described by a red spectral distribution with spectral slopes of -3 +/-0.7. The spectral energy varied locally over the reef consistent with qualitative estimates of roughness 'texture' from AUV sidescan imagery.

The alongshore variations in morphology are primarily associated with characteristic spur and groove morphology with scales of meters to tens of meters. The KN central node (CN) and 12 m node (N12) are located on the edge of one such feature, along the boundary between reef substrate and a large cross-shore sand channel, enabling access to both substrates.

B. *Local Environment*

Baseline data on the general oceanographic conditions at Kilo Nalu has been collected nearly continuously since March 2007 with further incomplete data records dating back to 2003, including observations on tide, current and wave characteristics, and basic water properties.

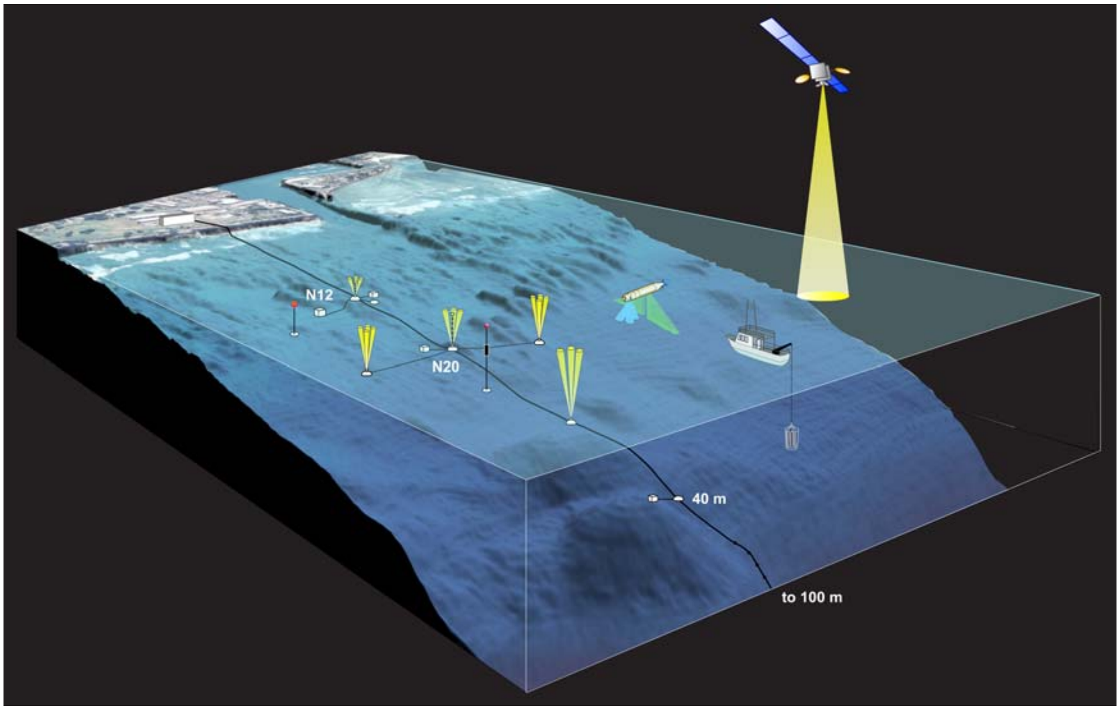

Figure 2. Kilo Nalu Observatory array, with N12 and N20 node locations including baseline observational components. Alongshore ADCP sites at N20 and deeper cable extension are presently under development.

Tides on the south shore of Oahu are mixed semidiurnal with maximum amplitudes on the order of one meter [6]. Currents at the 12 m Kilo Nalu site (Figure 3) are predominantly alongshore and tidally driven with amplitudes on the order of 20 cm/s. Primary tidal constituents are M2 and K1 accounting for 72% of the variance in surface height over the data record extending back through 2007. Mean currents are typically westward at 3-5 cm/s based both on Kilo Nalu observations and from earlier observations by [7].

The south shore of Oahu is subject to highly energetic internal tide forcing [7], [8], [9], [10] with vertical displacements of up to 200 m observed during spring tides in water depths of only 300 m. Model simulations suggest that these internal tides are generated at a number of “hotspots” along the Hawaiian chain [10], [11], [12] as the barotropic tidal flow interacts with the offshore ridge topography. The nearshore component of the internal tide off Oahu is characterized by broad-banded variability that is largely decorrelated with the harmonic surface tides [9]. Similarly, analyses of depth-averaged currents at Kilo Nalu also indicate a weak correlation with surface tidal amplitude. Harmonic analysis of hourly averaged currents at 12 and 20 m at Kilo Nalu from June 2008 to February 2009 using M2 and K1 tidal frequencies accounts for only about 30% of the total variance. This is consistent with analysis offshore in Mamala Bay by [8] which could only account for 60% of the semidiurnal internal tide energy using tidal frequencies.

Flow velocities at Kilo Nalu are generally dominated by surface wave forcing. Wave climate statistics for Kilo Nalu are summarized in Figure 4. The wave environment on the south shore of Oahu is subject to forcing from a range of sources [13]. Short period (6-8 sec) wave energy associated with refracted easterly trade-wind-generated swells provides fairly consistent background forcing at significant wave heights of up to 1 m. Between May and October, long period (12-20 sec) southerly swells associated with distant southern hemisphere sources can generate waves with significant wave heights of up to 3 m. Local ‘Kona’ storms, associated with winter low pressure fronts, are often accompanied by strong southwesterly winds and can generate short period swells (6-12 s) with significant wave heights of 3 m. In addition to these primary sources, hurricanes, occurring between June and November, can generate very strong wave energy with significant wave heights of up to 7 meters [14].

Water temperatures over the period of observations have ranged between 23 and 28 ^{o}C, with a seasonal modulation (Figure 5). Diurnal temperature variations of a few tenths ^{o}C are common. Thermal stratification is typically weak although daylight radiative heating and nighttime convective cooling has been observed to drive a diurnal stratification cycle [15]. In addition, shoaling internal tides intermittently result in periodic cold water intrusions near the bed (Figure 6) at N12 and N20. Sporadic warm events have also been observed at both sites, often accompanied by strong, internal bore-like flow structure.

Salinity, measured by a bottom-mounted sensor at N12, is typical of larger scale, regional open ocean values, although strong rainfall events can temporarily result in salinity reductions at 12 m depth. Lower frequency salinity variations

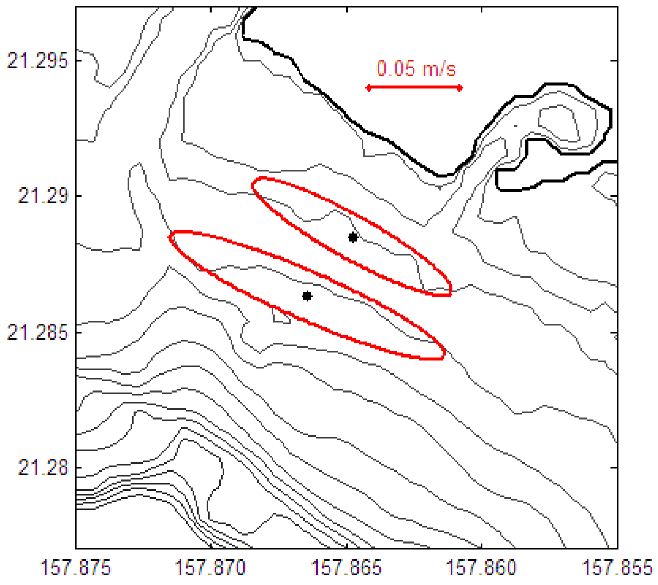

Figure 3. Kilo Nalu tidal current ellipses (2008-2009).

have been observed at the observatory associated with mesoscale eddy activity [15].

Winds on the south shore of Oahu are dominated by north-easterly trades, associated with the North Pacific Anticyclone. Trades average about 6 m/s and vary in frequency between roughly 45% in winter to 95% in summer months [6], [16].

III. KILO NALU INFRASTRUCTURE

The observatory's cabled infrastructure, summarized in Figure 7A, includes a shore cable which carries data and power from the shore station, located in a utility building in Kakaako Waterfront Park, to a central node (CN) located at the 12 m site. The central node, in turn, provides connections to two secondary nodes, one adjacent to the CN at 12 m depth (N12) and a second, remote node at 20 m depth (N20). Each of these secondary nodes provides data and power to a number of baseline and user subnodes distributed across the observatory domain.

The KN shore cable was originally deployed in June 2004 along the route of the original OE Test Range cable. After unspooling a section of cable from a small boat moored offshore and pulling the section through the seawall conduit, the cable was laid out to the 12 m site and secured by divers. A new cable was deployed using the same method in October 2006 following damage to the cable at the shore side access point. The second generation backbone CN and N12 components were deployed later that month with full operation of baseline instrumentation beginning in March 2007. The remote N20 cable was deployed along with the N20 electronics package in December 2007.

A. Power System

The shore cable provides 300V DC (4A maximum) from a power supply in the shore station to the central node (CN) located at the 12 m site. The positive and negative voltage lines are balanced (+/-150V) relative to seawater using resistive connections to a seawater ground (SWG) at the CN. The 300V input is locally stepped down using switching DC:DC converters (Vicor Inc.) to power CN internal power and data hardware. Power to four secondary node connections at 300V is managed in the CN via a series of MOSFET switches controlled remotely via an ADAM (Advantec Inc.) Ethernet data acquisition and control module. I/O lines on ADAM modules can be set remotely through a GUI interface, and input voltage channels remotely recorded and displayed, providing a simple remote control and monitoring facility for the power infrastructure. Current flow to each secondary node along with the voltage balance at each port relative to SWG is monitored by additional ADAM modules in the CN.

Secondary nodes (N12, N20) receive 300V SWG-reference (max 4A) power from the CN. In each node, the input power

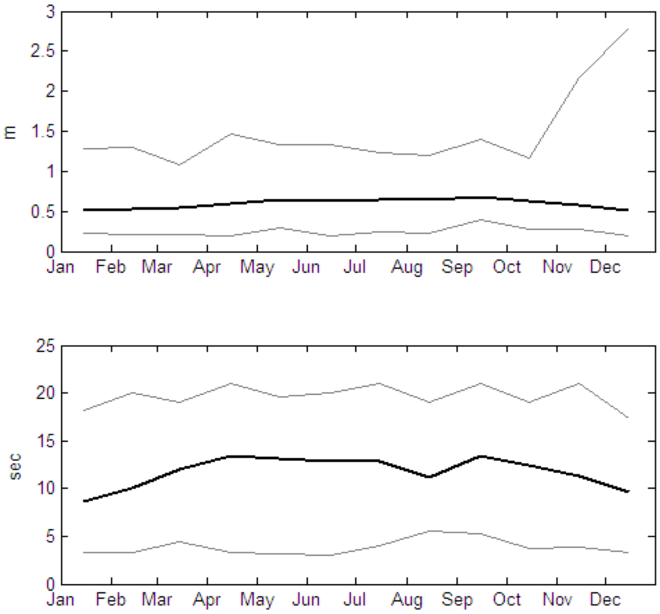

Figure 4. South shore Oahu wave climate 2004-2009: Top:significant wave height vs month with maximum/minimum monthly values in gray; Bottom: Wave period vs. month

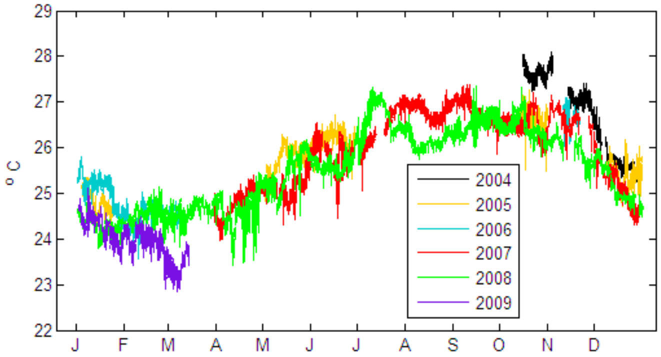

Figure 5. Seasonal temperature variation at Kilo Nalu, 12 m depth, 2004-2007.

is stepped down locally to power internal hardware. The 300V input is also stepped down via galvanically isolating, switching DC:DC converters (Vicor Inc.) to provide power to four subnode ports (three 24V, 250W and one 48V, 250W) at each secondary node. Power to each of the four ports is controlled remotely via ADAM modules. The voltages at each port are also referenced to a SWG at each secondary node via high resistance in the same manner as the high voltage line in the CN and voltage balance and current flow is monitored via ADAM modules. Internal temperature is measured at 3 locations within CN and in the secondary nodes and monitored via ADAMs. In addition, leak sensors are included in each component.

Baseline instrumentation subnodes receive SWG-balanced 24V or 48V from the secondary nodes which can be stepped down internally as needed using DC:DC converters to power internal electronics and external instruments. The power to each output port is typically controlled remotely via ADAM modules. This independent control is critical for power systems troubleshooting and for routine instrument maintenance when full subnode shutdown is not desirable. In general, a capacitive connection to the input power is desirable to enable ground-fault monitoring at each instrument port. This is achieved using a high resistance shunt with the output voltages balanced via a capacitive connection to a local SWG.

B. Data System

The data system is shown in schematic form in Figure 7B. The fiber optic data link from the shore station to the CN is converted to standard cabling using 1 Gb fiber-to-Ethernet converters on both ends. The secondary node ports in the CN are in turn connected via a 1 Gb Ethernet switch. Downstream, the maximum data bandwidth reduces to 100 Mb, due to the limitation imposed by the design restriction of four data wires per underwater bulkhead connections. The Ethernet data stream is distributed to individual subnodes in the secondary nodes via 100 Mb switches. Baseline subnodes are linked to N12 and N20 via copper connections which limit their distance from nodes. Reliable connections have been maintained with maximum distances of 30 meters. In practice we can expect less than 100 Mb bandwidth due to losses at multiple connection points, among other sources, but bandwidth limitations have not yet been noticeable despite significant data loads.

Baseline subnodes make use of Ethernet serial port servers (Digi, Inc.) to connect to most instruments since these are typically limited to serial communications. The port servers are remotely configurable and can communicate using multiple serial protocols (i.e. RS-232, RS-422, RS-485). Ports can be mapped to PC COM ports on shoreside computers or accessed directly via TCP to enable remote access to instruments, which can then be operated using command-line driven interfaces or vendor-supplied GUI interfaces. Custom drivers have been developed for a number of Kilo Nalu baseline instruments to interface with the data management system discussed further below.

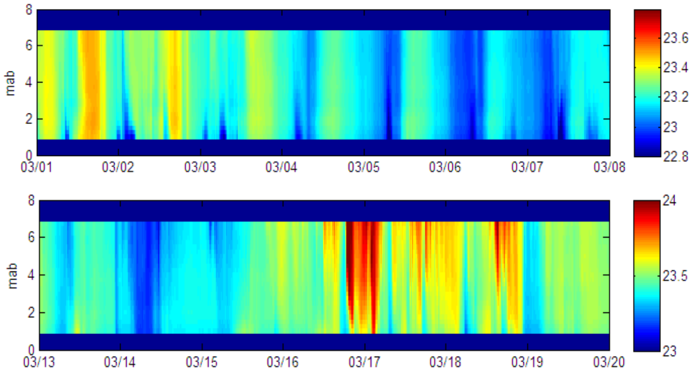

Figure 6. Temperature profiles from N12 thermistor chain for March 2009. Top panel illustrates diurnal cycle with intermittent cold intrusions near the bottom. Lower panel (one week later) shows occurrences of sudden warming events in the upper water column.

Ethernet-ready instruments connect directly to the network in subnodes, enabling direct socket connections from shore. Examples in use at Kilo Nalu include webcams and hydrophones.

Instrument cabling from subnodes is limited to 20-30 m for RS-232 and Ethernet instrumentation. RS-485 serial protocol is used where more remote instrument deployment is required.

The shore station is connected via 802.11a wireless Ethernet to the roof of the nearby UH John A. Burns School of Medicine (JABSOM) which is connected via high bandwidth connection to the Ethernet backbone. The Kilo Nalu meteorological station is also located on the roof at the JABSOM wireless access point.

The KN array is connected to the UH campus via a virtual private network (VPN) enabling direct access to observatory hardware. External users can connect to individual subnodes via secure shell (SSH) connections.

C. Cables, Connectors and Housings

The shore and remote node cable connections consist of two single-conductor, four-fiber, double-armored cables. The choice of cable was made primarily due to the availability of surplus cable from an earlier project. The shore cable connection to the CN uses a custom-designed molded cable termination (Figure 8) which provides strain relief on the connection and mates with the CN end cap via a double o-ring bore seal. This dry connection to the CN was made aboard a boat moored at the 12 m site.

The majority of underwater connections make use of standard and micro 8 pin, wet-pluggable cable and bulkhead connectors (Impulse, SeaConn). While these are typically used for topside wet connections and are not generally recommended for underwater mating, these have performed adequately for low voltage underwater connections. In some instances, particularly for the microconnectors, the connections have been subject to current leakage, as detected by voltage imbalances in the ground fault monitoring system. These leakages have most often been resolved by reseating the connections, but in a small number of instances have required replacement of the connectors or bulkheads.

For higher voltage connections (48V, 300V), the wet-pluggable connections were found to be unreliable, with deteriorating current leakage occurring in a majority of underwater-mated cases. To resolve this issue, high voltage connections at Kilo Nalu now employ penetrator-type bulkheads which include a wet-pluggable connector on the end of a length of cable molded directly to the bulkhead. These connections are then made in a small air-filled diving bell in which the two cable connectors can be mated by a diver. Connections made in this manner have been generally reliable over long-term deployments (one year or longer).

Ethernet communications between the CN and N12 and between the secondary nodes and the subnodes are transmitted over polyurethane-jacketed category-5 cable with standard 8 pin wet-pluggable connectors. The cable-pair twist is maintained as near to the connector as possible during the potting process to minimize fluctuations in the Ethernet cable impedance.

Underwater housings for the CN, N12 and N20 components are 10-in diameter cylinders constructed from anodized aluminum. The internal electronics chassis (Figure 8) is mounted on aluminum fins that connect thermally (but not galvanically) to the outer housing to facilitate dissipation of heat from the electronics components. Housing endcaps are constructed from PVC and connected to the aluminum housings using double o-ring bore seals. Micronode and baseline subnode housings and endcaps are constructed from PVC since electronics heat production is not substantial.

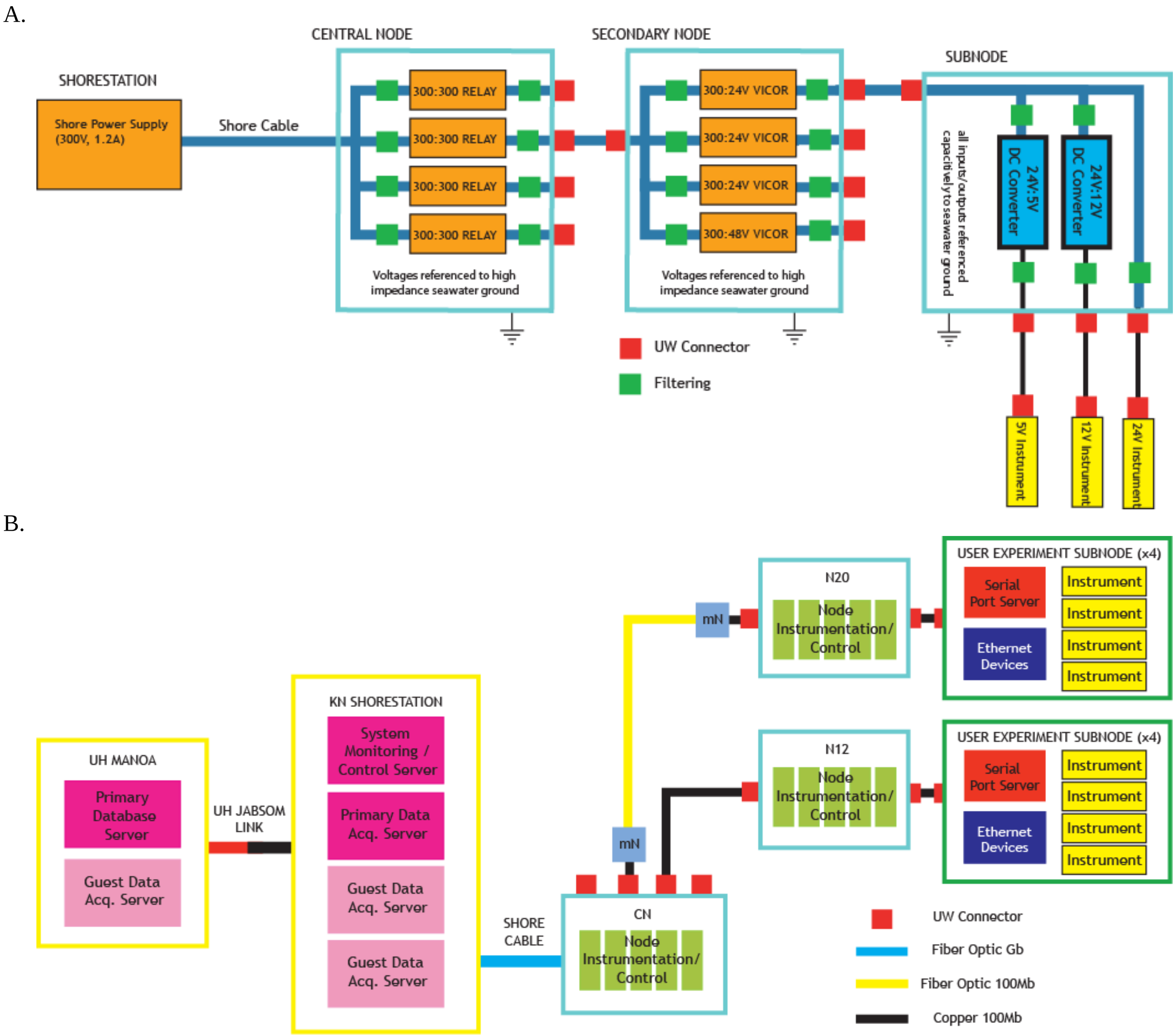

Figure 7. A) Kilo Nalu power system overview. B). Data system

D. Micronodes

Since Ethernet communications are not practical over standard copper cabling over the distances between remote nodes, conversion back to optical fiber was necessary to connect to the remote N20 to the CN. Commercially available underwater fiber connections are primarily targeted towards deep-water, ROV mate-able applications and are at least an order of magnitude more costly than underwater mate-able copper connections. Instead, we designed and built 'micronode' packages for both ends of the secondary-node cables (Figure 9); these packages convert the standard Ethernet signal to optical fiber and also feed through the 300V SWG referenced voltage. The micronodes comprise of PVC housings connected to the KN-standard dry-mate molded cabled termination, also used for the shore-cable-to-CN connection. The micronodes connect to the CN on one end and to the remote secondary node (N20) on the other, via one 8 pin wet-pluggable penetrator for Ethernet and 300V and a second 4 pin connector which provides power for the Ethernet-to-fiber converters. In case of component failure, either cable end can be brought to the surface for troubleshooting and component replacement. This design then provides a modular, wet-pluggable copper-to-fiber solution for long cable runs.

IV. DATA ACQUISITION, ARCHIVING AND DISTRIBUTION

The observatory includes a comprehensive data management system for collecting and archiving data from instrumentation and engineering systems. The overarching strategy is to use modular, near real-time streaming software that can scale to hundreds of sensor connections and that can provide duplex communication with standard oceanographic instruments. The data management architecture includes a replication system that mirrors data streams to a UH campus server in order to maintain the integrity of the data. Data are also backed up to remote disk storage for fault tolerance. The core component of the data acquisition system is the RBNB DataTurbine software [17], which provides a centralized data streaming mechanism that can handle binary or text-based observations, as well as streaming audio or video. The primary DataTurbine is deployed at the shore station on a multi-core Linux-based server, and archives streaming channels of data in near real-time to in-memory and on-disk ring buffers. Each instrument in the water has a corresponding 'source' software driver, which is a customized Java client that communicates with the instrument, parses the proprietary data formats, and commits the data observations into the onshore DataTurbine as data channels. Both raw and interpreted data channels can be loaded into the DataTurbine, depending on the desired features of the source software. The drivers allow for two-way communication, and commands can be sent to the instruments to alter sensor settings or to poll

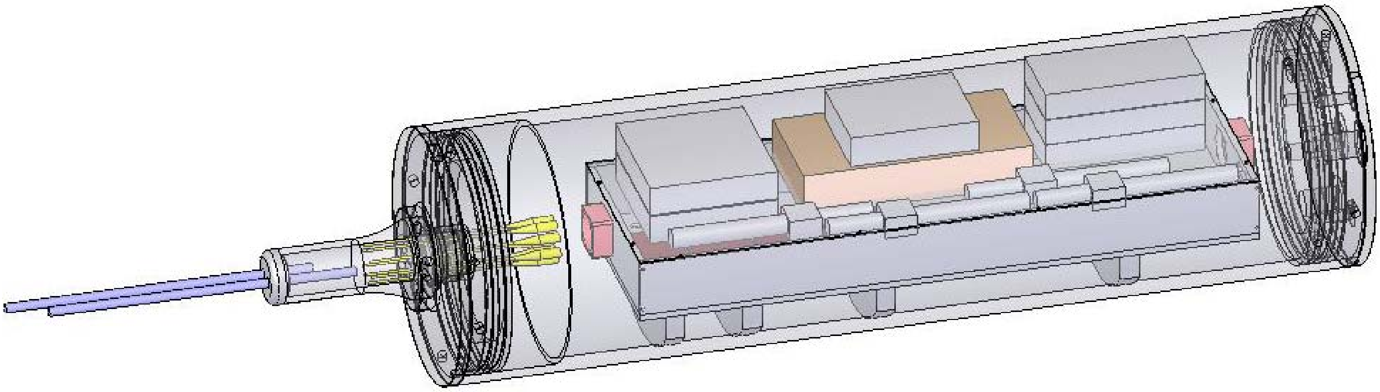

Figure 8. Central node internal detail, including electronics chassis, and dry-connect power/fiber bulkhead.

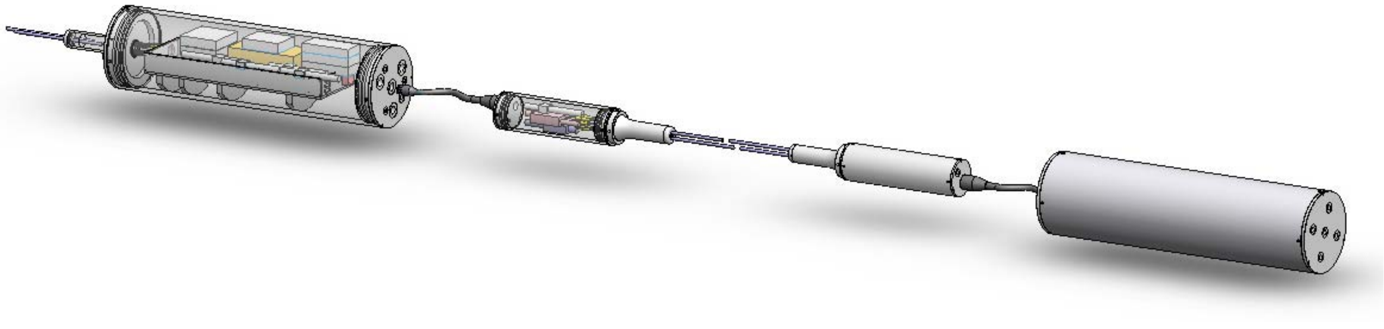

Figure 9. Schematic of central node, micronode and remote secondary node connection.

instruments that do not provide autonomous sampling mechanisms.

The DataTurbine provides a robust routing mechanism for the data streams, and each DataTurbine installation is capable of replicating streams to other DataTurbines. In the Kilo Nalu network, an on-campus DataTurbine has been deployed on a multi-core Linux system that maintains an instant mirror of the shore station system as each observation is collected. This is a specialized version of a 'sink', or software that retrieves data from channels stored in the DataTurbine.

Likewise, the DataTurbine provides a time-based query mechanism filtering the data streams. Sink clients written in Matlab leverage the DataTurbine's Matlab toolbox, periodically querying the data channels to produce web-based summary graphics of the observations. For a persistent data archive, a Java-based sink program also writes the data to a file store, available to researchers via the webDAV [18] protocol directly on their desktops. Many sink clients ship with the DataTurbine, including a configurable client that allows data to be directly transferred into a SQL database for further querying.

The unique feature of the DataTurbine system is that both streams of scientific observations and engineering diagnostic information can be handled through the system, and can be viewed in near real-time using viewers such as the Realtime Data Viewer (RDV) (it.nees.org/software/rdv). The system supports realtime monitoring of data streams, rewind and fast-forward for quick examination of historical data, and the ability to add markers to specific events for later reference. Future work on the source drivers for each instrument will take advantage of these features, and all of the data streams will have this real-time viewing capability.

Software drivers written for oceanographic instruments have leveraged the work of open source projects such as the Network for Earthquake Engineering Simulation (nees.org) and are likewise made open source for further community development.

A. *Data System Monitoring*

Engineering systems are monitored via ADAM control modules as described earlier. Data from the ADAMs are streamed via the DataTurbine interface and are accessible via a web-interface in near-real-time (several seconds) for monitoring, including plots of node internal temperatures, leak sensors, node and subnode current draws and ground system voltages. An email alert system is being implemented to provide notification of system faults.

V. BASELINE INSTRUMENTATION AND OBSERVATIONS

Kilo Nalu baseline observations target comprehensive characterization of the general oceanographic conditions, including waves, currents, tides and basic water properties as discussed earlier in section IIB. Baseline instrumentation is summarized in table 1.

In addition to the cabled instrumentation, the observatory includes an autonomous automated moored profiler, which telemeters data from its location along the 20 m contour. A telemetered surface mooring located near the N12 site, funded by NOAA Coastal Services Center (CSC) as part of HIOOS, collects near-surface water quality data to complement the bottom data collected by the cabled array. In addition, the HIOOS mooring also includes air and water O_2 and CO_2 concentration measurements, which contribute to NOAA/PMEL global CO_2 monitoring program. The observatory's time-series data is also augmented by regular (monthly) autonomous underwater vehicle (AUV) surveys using a REMUS AUV (Hydroid, Inc.). Meteorological data is collected from a station co-located with the JABSOM wireless link.

Kilo Nalu baseline data is presented on the observatory webpage (www.soest.hawaii.edu/OE/KiloNalu) in tabular and graphic form including 3 day and 1 week plots of currents, directional wave conditions and water quality. Historical data of up to 3 months is available on the website. In addition, Kilo Nalu data is also uploaded to the NOAA NDBC website where it appears as station KNOH1.

VI. OBSERVATORY OPERATIONS

Regular observatory field operations make use of the R/V *Kilo Kai*, a 25' Force Marine twin-outboard motorboat based in Kewalo Basin, just inshore of the Kilo Nalu site. In addition, the observatory has access to vessels from the UH Marine Center which include the 57' R/V *Klaus Wyrtki* and smaller motorboats. Kilo Nalu staff access observatory infrastructure using SCUBA, following scientific or commercial dive safety protocol, as appropriate.

Power systems are shutdown whenever dive operations occur in the vicinity of observatory components. For this reason, considerable effort has gone towards the development of robust instrument data interfaces that can reacquire data streams on power up.

The observatory maintenance cycle calls for regular (monthly) dives to maintain baseline infrastructure and instrumentation. In addition, the backbone hardware is presently on a replacement cycle of two to three years, facilitated by the modularity and accessibility described earlier.

A. *Ongoing Research and Experiments*

A wide array of projects presently makes use of Kilo Nalu infrastructure for ocean research. A central theme of much of the research effort at the observatory is the study of benthic exchange processes between the sediment and reef bed and the water column. This has been the central focus of the NSF CoOP project that funded the development of the 2nd generation Kilo Nalu backbone. This work has thus far included deployment of an array of automated measurement technologies and interactive experiments targeted at quantifying benthic fluxes [19]. This work builds on an earlier NSF-funded project targeting measurement of sediment porewater dispersion rates. Observations in sandy beds at Kilo Nalu found positive correlations between enhanced dispersion

Table 1. Kilo Nalu baseline instrumentation

Instrument	**Platform/ Location**	**Measurement**	**Sampling Scheme**
1200KHz Acoustic Doppler Current Profiler (RD Instruments)	N12 (bottom), N20 (bottom)	3D water velocity profile, pressure: mean currents, directional wave spectra; acoustic intensity	Full water column profiling, 1/s
Seabird Electronics (SBE) 37	N12 (bottom)	Temperature, salinity (conductivity)	1 / 15 s
FLNTUS (WETLabs)	N12 (bottom)	Fluorescence, turbidity	1/15s
Anderaa Optode	N12 (bottom)	Dissolved oxygen concentration	1/3 s
Thermistor chain (Precision Measurement Engineering)	N12 (mooring), N20 (mooring)	Temperature profile at discrete vertical intervals	1/3 s
Seahorse Profiler (Brooke Ocean Technology): SBE 19, SBE-43, WET Star, C-Star (WETLabs)	Profiling mooring; W of N20	Temperature, salinity (conductivity), pressure, fluorescence, light transmission, oxygen	Full water column profiling, 1/hr
Davis ProVantage 2 Plus	UH JABSOM roof	Air temperature, relative humidity, UV, solar radiation, wind speed / direction, barometric pressure, precipitation	1/ 5 s
LI-COR model 820 Non-Dispersive Infrared (NDIR); Maxtec MAX™-250; Sensirion model SHT71; SBE 16, SBE 43; FLNTUS (WET Labs). Iridium Telemetry (gas data), Satlantic Telemetry (water quality parameters)	Surface buoy; N12	CO_2 and O_2 in air and water, air temperature, relative humidity, surface seawater salinity, temperature, dissolved oxygen, chlorophyll-a, turbidity	CO_2, O_2: 1/3 hrs, (telemetered 1/dy); other parameters: 1/ 20 mins (telemetered each sample)
REMUS Autonomous Underwater Vehicle (Hydroid Inc.): 2x1200 KHz ADCP, SBE 49, BB2F Ecopuck (WET Labs), Sidescan sonar	AUV; South shore surveys	Temperature, salinity (conductivity), optical backscatter (2 wavelengths), fluorescence, 3D water velocity profile, acoustic intensity, bottom acoustic imaging	Spatial surveys, near-surface, offshore depth sections; 1/mon

and increased wave activity [20]. A complementary NSF-funded project led by B. Glazer (UH) is developing voltammetry methods [21] using the Kilo Nalu cabled array, to resolve benthic biogeochemistry across the sediment-water interface [19].

As part of the NSF-funded benthic dynamics work and in continuation with the earlier ONR funded efforts that first motivated the observatory, there is a significant focus on physical processes associated with wave and current dynamics over highly inhomogeneous boundaries, such as those presented by coral reefs. This work has included high resolution, spatial profiling of the near-bed flow that has identified changes in boundary layer structure with varying orbital amplitude, suggesting that the relevant roughness scales over reefs change with varying wave forcing [22]. This dynamical response is consistent with the spectral roughness paradigm reported by [5].

A further research emphasis at the observatory, funded by ONR, is on resolution of the transfer process between the strong, internal tides offshore (as discussed in section IIB) and nearshore dynamics. These internal tides can influence the nearshore region directly via cold, near-bed intrusions (Figure 6) [23] or indirectly by increasing nearshore current variability. More recent NSF funded work at the observatory is targeting stratified mixing processes associated with cold internal tide bores.

In addition to the focused efforts described above, the time-series data at Kilo Nalu has also yielded important research. Analysis of observations in November 2006 of a small tsunami which impacted Oahu identified tsunami-generated coastal trapped waves as an important mechanism in generating high-frequency motions and surface displacements [24].

The Kilo Nalu data time series also forms part of the HIOOS observational network for waves, currents, and water quality and provides valuable model validation data. As part of HIOOS, UH researchers (W. Au, M. Lammers) have deployed a hydrophone at N20 which forms the real-time part of a broader network of Ecological Acoustic Recorders (EARs) that aim to monitor biological acoustics and vessel traffic in marine protected areas. In addition, Kilo Nalu observations are also a key component in a project led by Sea Engineering, Inc. and funded by the City and County of Honolulu, to develop a monitoring system for the Sand Island Wastewater Outfall.

The NSF CoOP-funded work also includes a significant educational outreach program under development in collaboration with Bishop Museum (www.bishopmuseum.org), a leader in local science and cultural outreach. The program aims to make the research accessible to the local community and to exploit the real-time access to ocean data for educational purposes.

B. Future Observatory Expansion

The observatory is presently funded to expand the baseline array to include two alongshore current profilers and to add a bottom thermistor chain extending from N20 to the 100 m isobaths. These additions are expected to come online in late 2009. The CN design can also accommodate two additional secondary nodes that can be placed remotely or at N12.

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