Earth Science Technology Office (ESTO)
Advanced Information Systems Technology (AIST)

A Smart Sensor Web for Ocean Observation: Integrated Acoustics, Satellite Networking, and Predictive Modeling

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P. Arabshahi, B.M. Howe, S. Roy, A.A. Gray, W.L.J. Fox
N. Parrish, L. Tracy, M. Grund, T. McGinnis
University of Washington

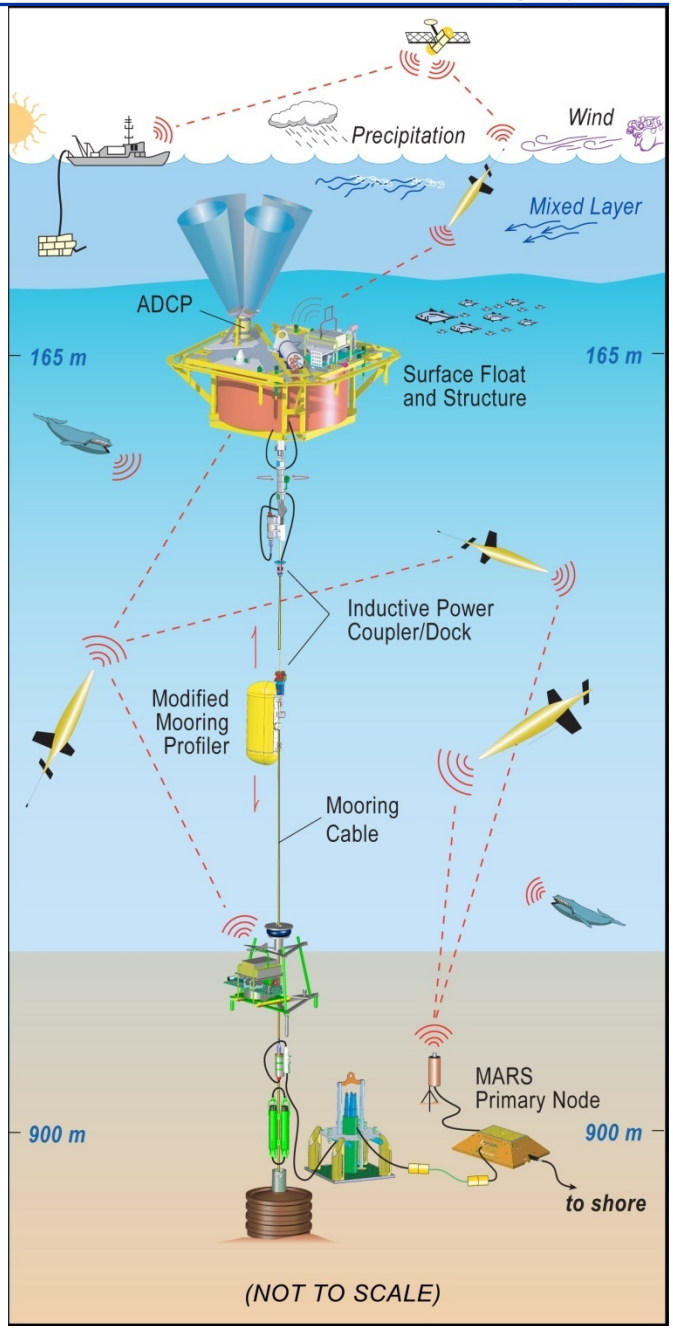
Yi Chao
Jet Propulsion Laboratory and
University of California, Los Angeles

Outline

- Technical Objectives
- Science Objectives
- Research Plan
- Technical Progress

Technical Objectives

- Implement a semi-closed loop dynamic sensor network for ocean observation and modeling.
- Design, develop, and test an integrated satellite and underwater acoustic communications and navigation sensor network infrastructure.
- Perform science experiments in Puget Sound and Monterey Bay, enabled by such a network, and evolve them to growing levels of sophistication over the period of performance (three years).



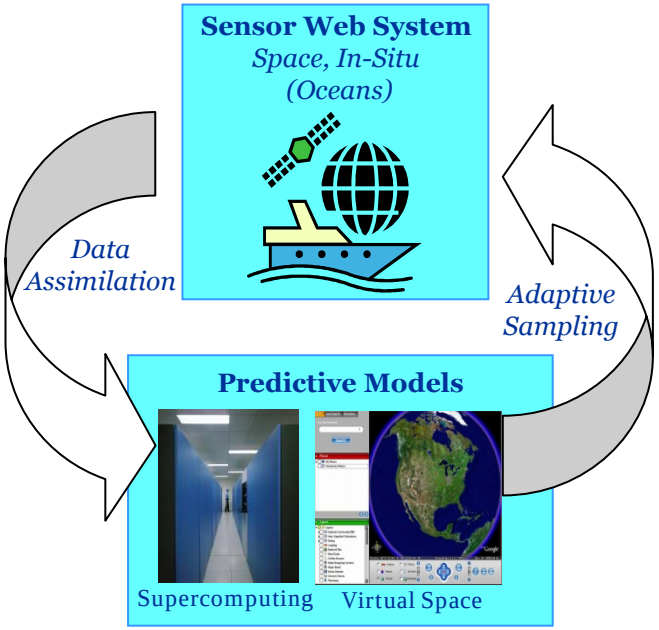
ALOHA-MARS Mooring (AMM) System

Technical Objectives

- **The Semi-closed Loop Dynamic Smart Ocean Sensor Web Concept**
  - Over half the world's population lives within 200 km of a coastline. Improving our physical understanding in coastal zones and ultimately having a predictive capability would have huge societal and economical impacts. Despite the recent success of NASA satellite missions in global weather and climate research, satellite data remain underutilized in coastal areas.
  - We will demonstrate the use and benefits of satellite data in prototyping a dynamic sensor web system in the coastal environment to improve our understanding and enable predictions.

Technical Objectives

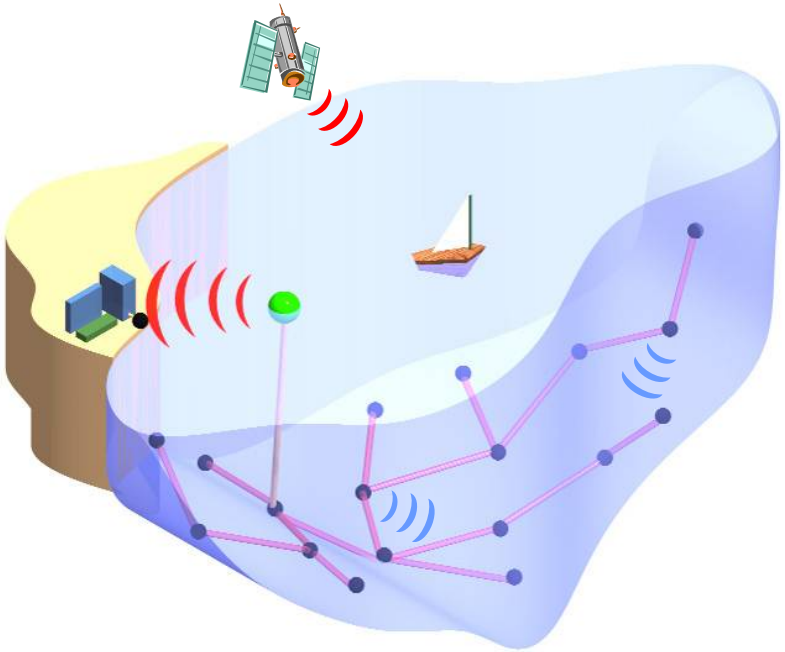
- **The Semi-closed Loop Dynamic Smart Ocean Sensor Web Concept**
  - One-of-a-kind integrated in-situ/space based Earth observation system, where data gathered locally by an underwater sensor network is fed back and combined in near real-time with global satellite data, appearing nearly instantaneously on scientist workstations.
  - This data is then used to augment, calibrate, and fine tune measurements made from space, increasing their accuracy and timeliness.



Two-way interactions between the sensor web and predictive models.

Technical Objectives

- **The Integrated Satellite and Underwater Acoustic Network Concept**
  - A first-of-its-kind ad hoc satellite/acoustic sensor network, incorporating: reconfiguration of sensor assets, adaptive sampling, autonomous event detection, targeted observation, location-aware sensing, built-in navigation on mobile Seagliders, high-bandwidth/high-power observation on cabled seafloor and moored nodes, and satellite networking.



Technology enabler for the smart ocean sensor web.

Technical Objectives

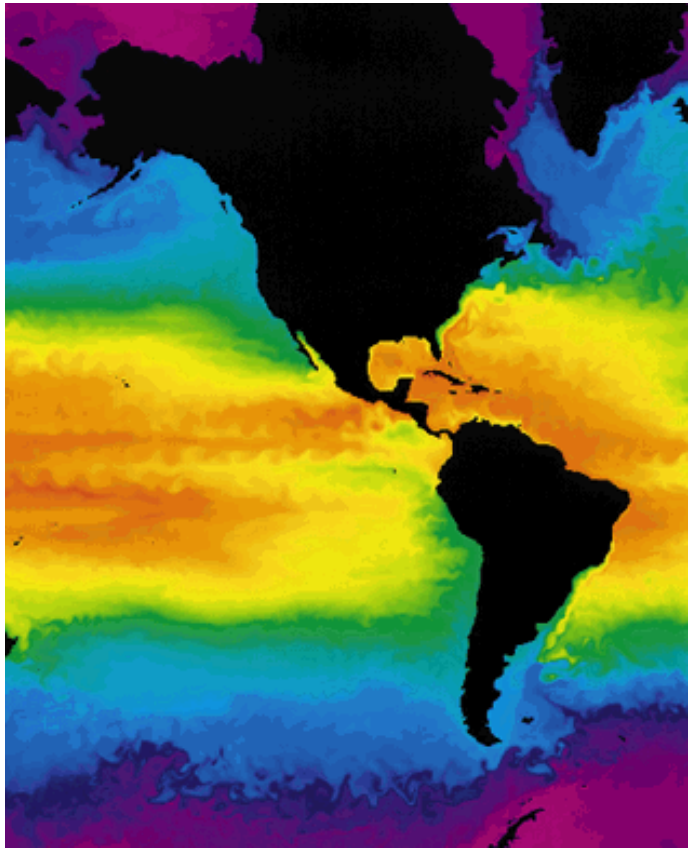
- **Science Experiments**
  - Mobile Seagliders "flying" around the fixed mooring system with the vertical profiler, sampling temperature, salinity, and ambient sounds, within the infrastructure provided by an underwater acoustic network.
  - In situ measurements, along with NASA satellite observations, will be assimilated into a Regional Ocean Modeling System (ROMS) to realize the goal of adaptive sampling.

Synergistic integration of in situ and remote sensing sensors in Monterey Bay.

Science Objectives

- Addressing two fundamental questions that drive Earth science research: *How does the Earth system respond to natural and human-induced changes?* and *How will the Earth system change in the future?*

- And in the process, …
  - Exploring interactions between the ocean and atmosphere.
  - Helping distinguish natural from human-induced climate change.
  - Aiding in understanding and predicting consequences of change.

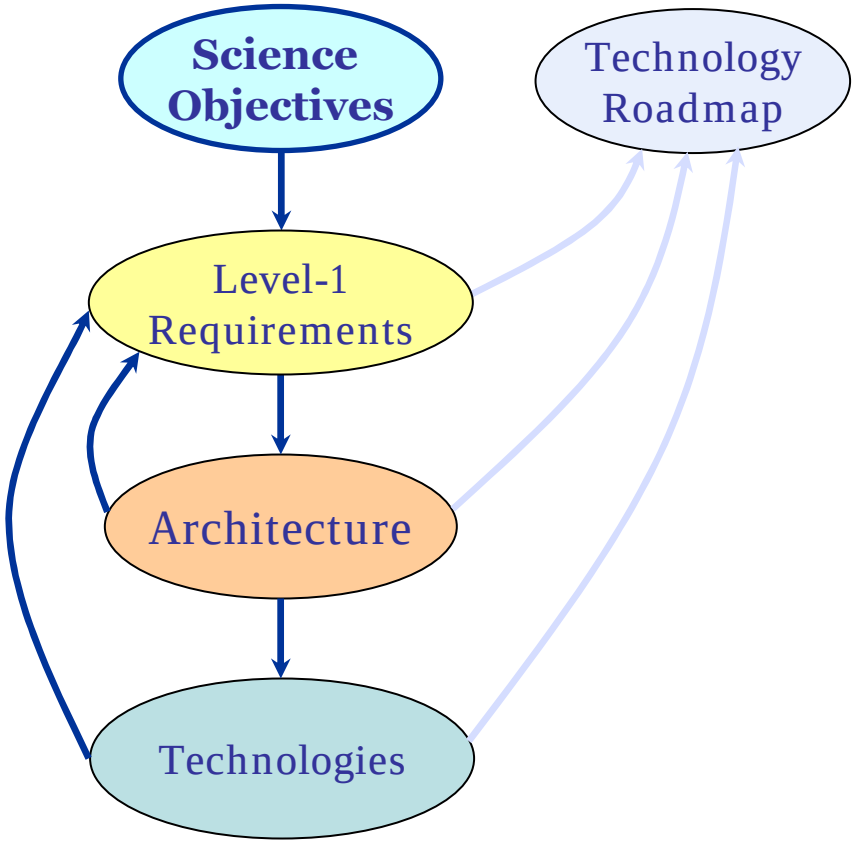


Sea surface temperatures produced by a global ocean model. Warm temperatures in the tropical oceans are shown in red, and colder temperatures in purple.

Research Plan

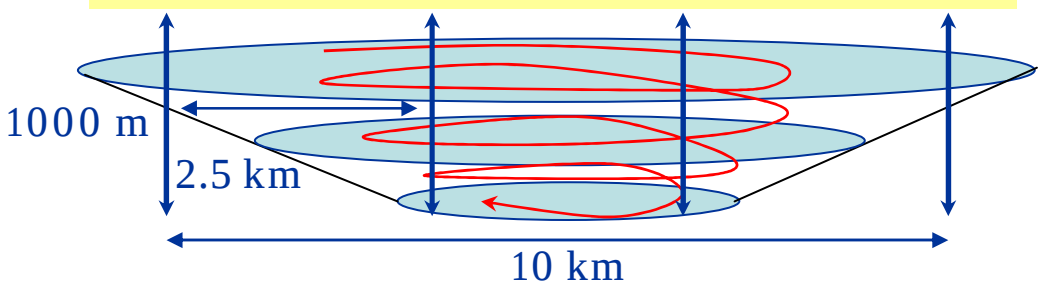
1 Science Objectives

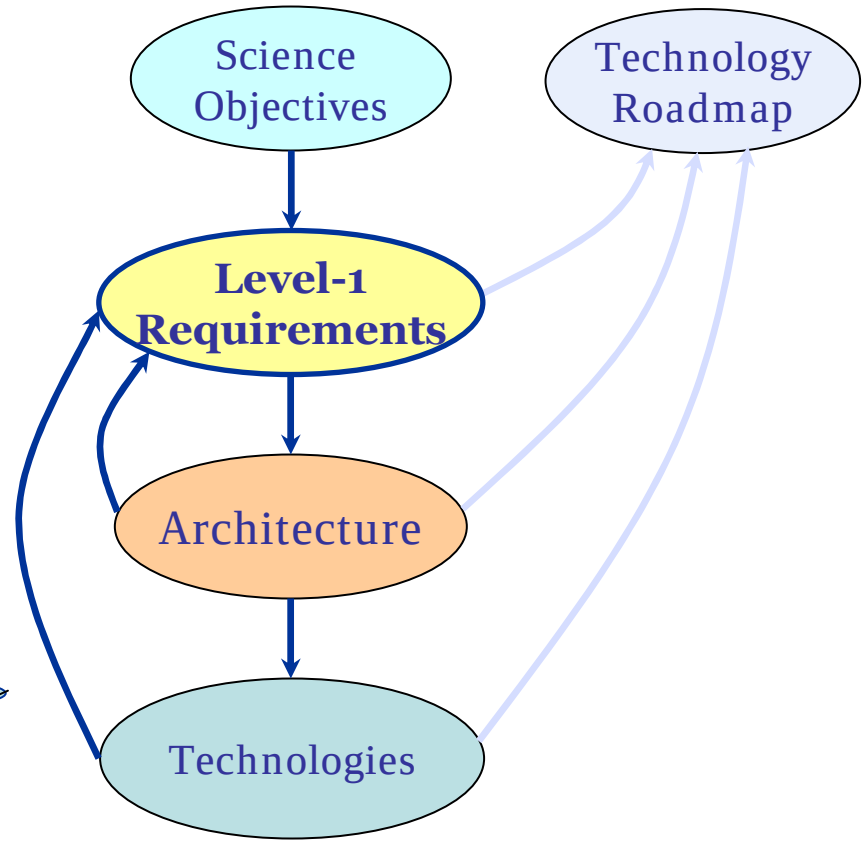
- Observe a finite volume (~1 x 10^{11} m^3) of the ocean and characterize dynamic processes (e.g., eddies).
- Assimilate sensor web data into predictive models in order to fill in the gaps where and when there are no measurements, with the goal of reducing uncertainties of the model simulation and predictions.
- The assimilated model will be used to guide the future observing strategy (i.e., adaptive sampling) of future experiments, thus closing the loop of an end-to-end autonomous sensor web from measurement to predictive modeling.



2 Level-1 Requirements

- Measure the characteristics of coastal eddies
  - Spatial horizontal scale on the order of 10 km).
  - Spatial vertical scale on the order of 1000 meters.
  - Temporal scale on the order of days to weeks.



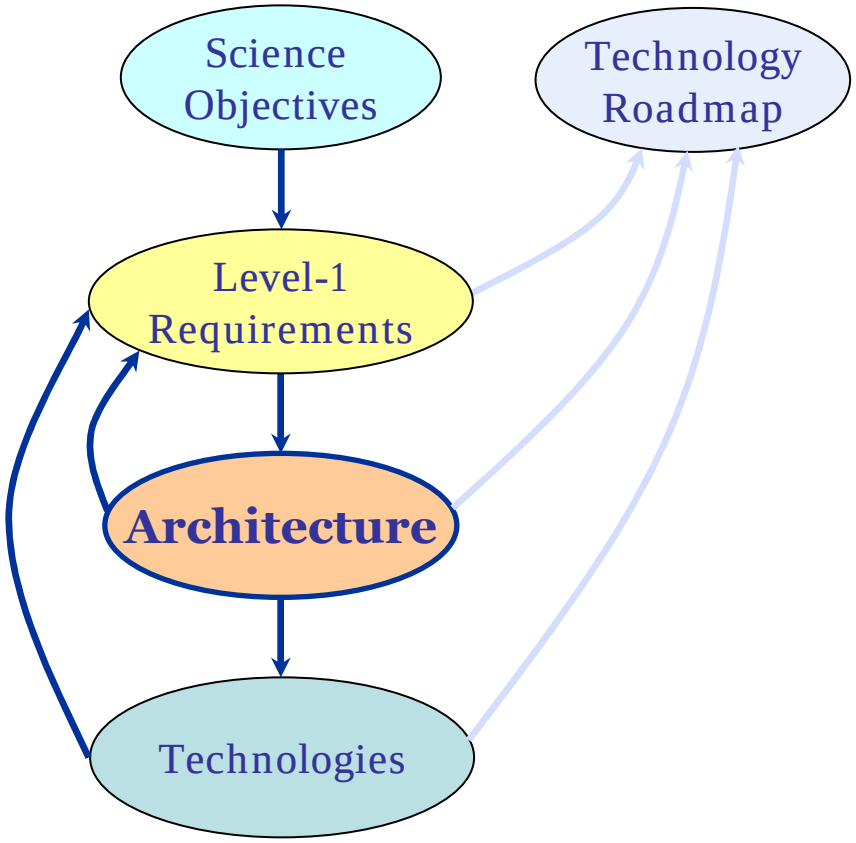


Primary Challenges

- Developing requirements that satisfy science objectives within the constraints of baseline capabilities, hardware, budget, and schedule.
- Iterative development.

3 Architecture

- **Systems view**
  - 3-4 in-situ sensors
  - Deployment infrastructure
  - Processing resources
  - ROMS models and simulations
- **Subsystems view**
  - Platforms (Seagliders, TRL 8)
  - Sensors (entire suite TRL 9)
  - Acoustic network (TRL 3)
  - ROMS (TRL 5)
  - Several technologies require further development.
- **Con-ops view**
  - Sequence of operations of all system elements, to be developed.

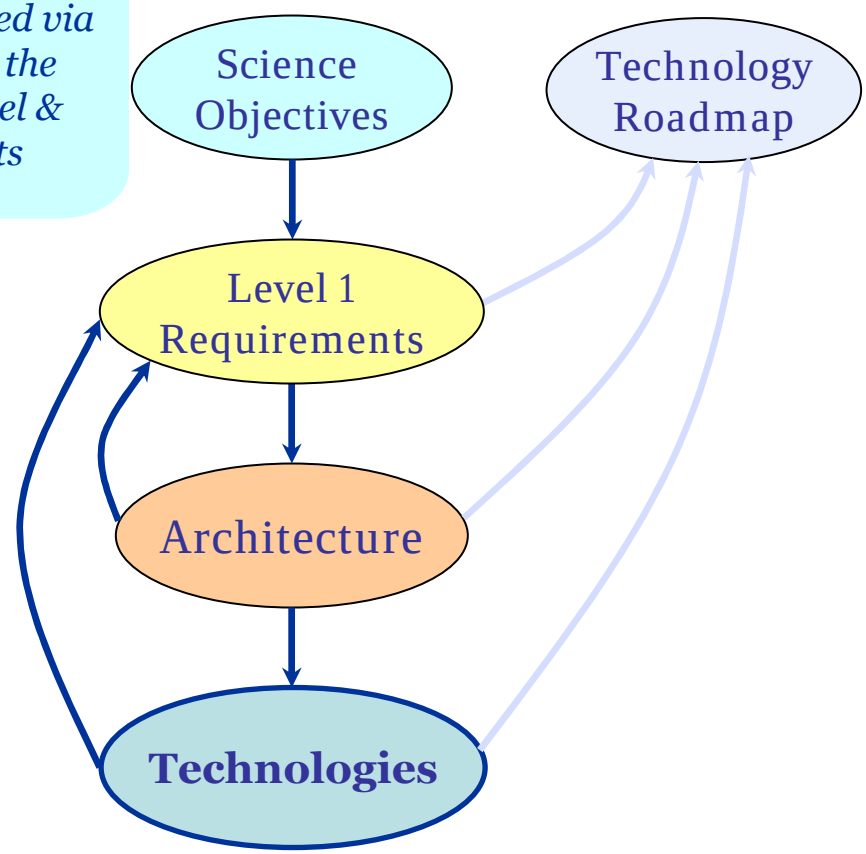


Research Plan

4 Technologies

- **ROMS ocean model**
  - Data Preparation
  - Interface with sensor web
- **Micro-modem + Gumstix**
  - Baseline transceiver + controller
  - Further development required
  - FDMA vs. CDMA
- **MAC layer protocols**
  - Under development
  - FDMA vs. CDMA
  - Number of users versus complexity
- **Seagliders**
  - Baseline mobile node
  - MAC layer to be implemented in each
- **Moored profilers & other sensors**
  - Baseline stationary, powered nodes
  - Acoustic communication capability

Network topology design performed via trade studies at the architecture level & L-1 requirements



Primary Technology Challenge

- The **acoustic channel** is very dynamic and requires significant improvements or re-design in physical layer and media access control (MAC) layer algorithms.

ROMS: Technical Progress

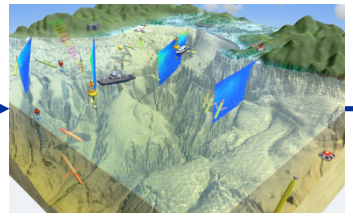
1 Regional Ocean Modeling System

- ROMS is a modeling infrastructure developed at NASA JPL, Rutgers, UCLA, ..., funded by ONR and the NASA Oceanography Program.
- It solves the three-dimensional oceanic equations of momentum, temperature and salinity. It also includes a 3-D data assimilation subsystem comprised of data quality control, model initialization and analysis, and forecasting components.
- ROMS contains state-of-the-art parameterizations for surface boundary layer, turbulence mixing, and side boundary conditions.
- ROMS can be implemented in a multi-nested grid configuration that allows for telescoping from the large-scale down to local region at very high resolution (on the order of 1 km).
- The Monterey Bay ROMS modeling and forecasting system has been tested during two field experiments in 2003 and 2006.
- ROMS is capable of assimilating glider data and providing real-time forecasts back to the glider operators for adaptive sampling and decision making.

ROMS: Technical Progress

Virtual Ocean Design and Test

Design, Testing and Deployment



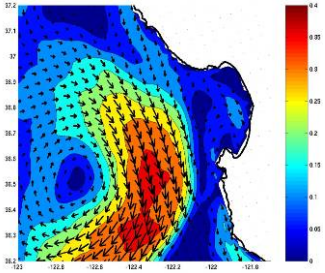
Observatory data

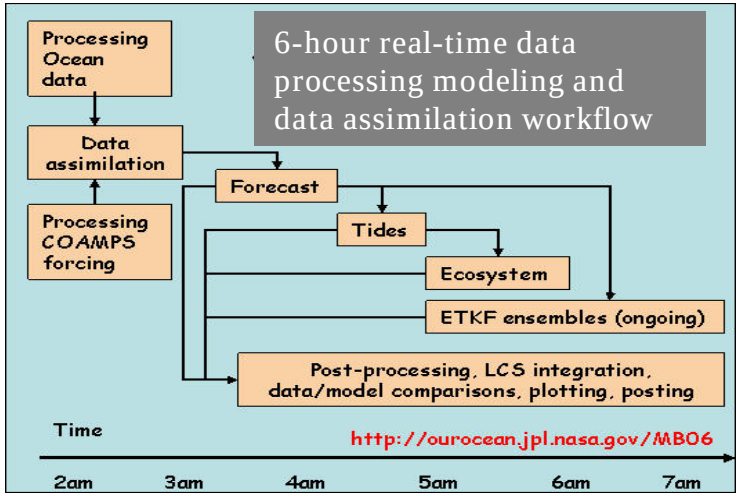
Sensor & Platform

~3 km

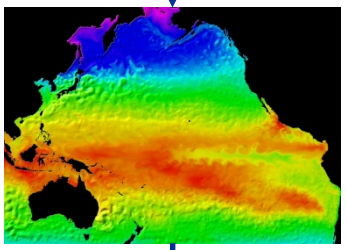
~ 500 m

Observatory or Virtual Ocean

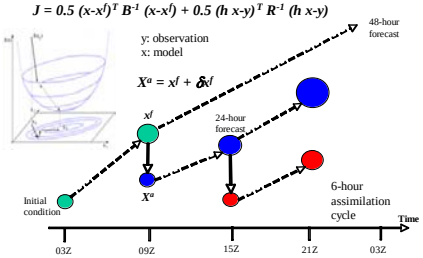


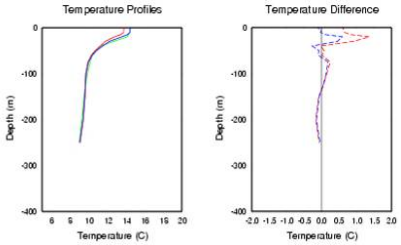


3-D Ocean Models



Data Assimilation





Data Analysis

Science Questions & Drivers

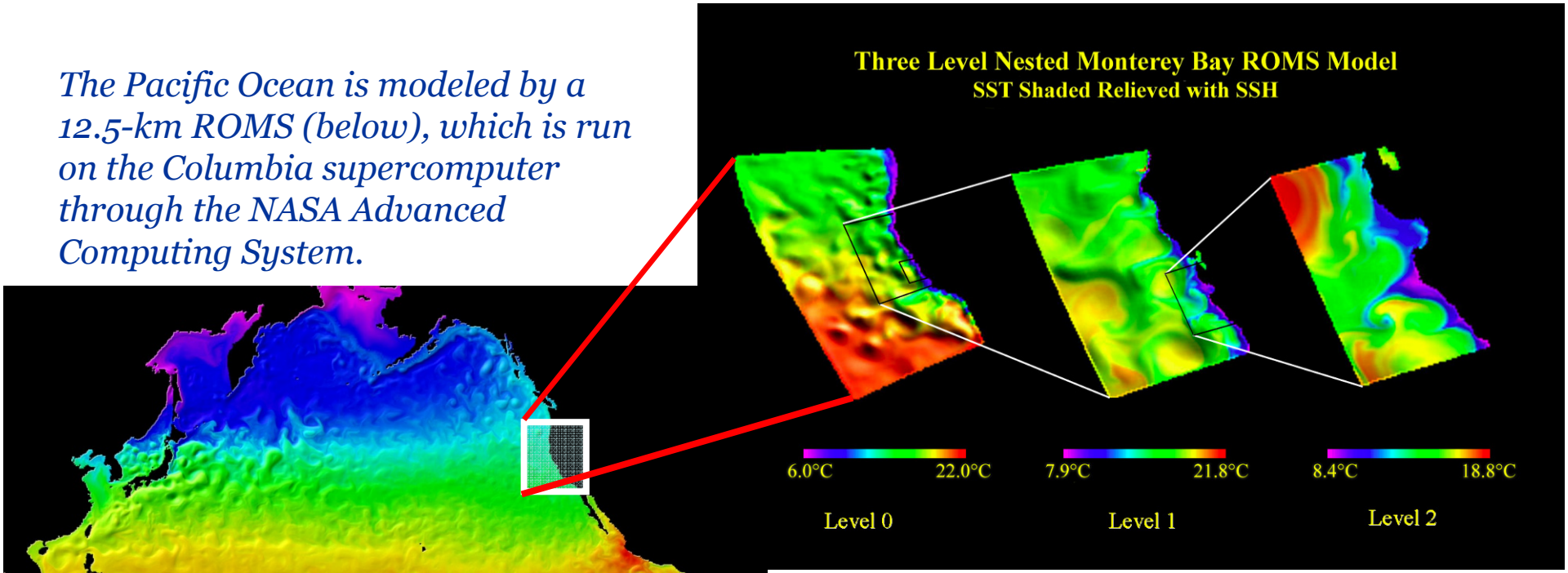
Data Synthesis: Forecast & Data Impact

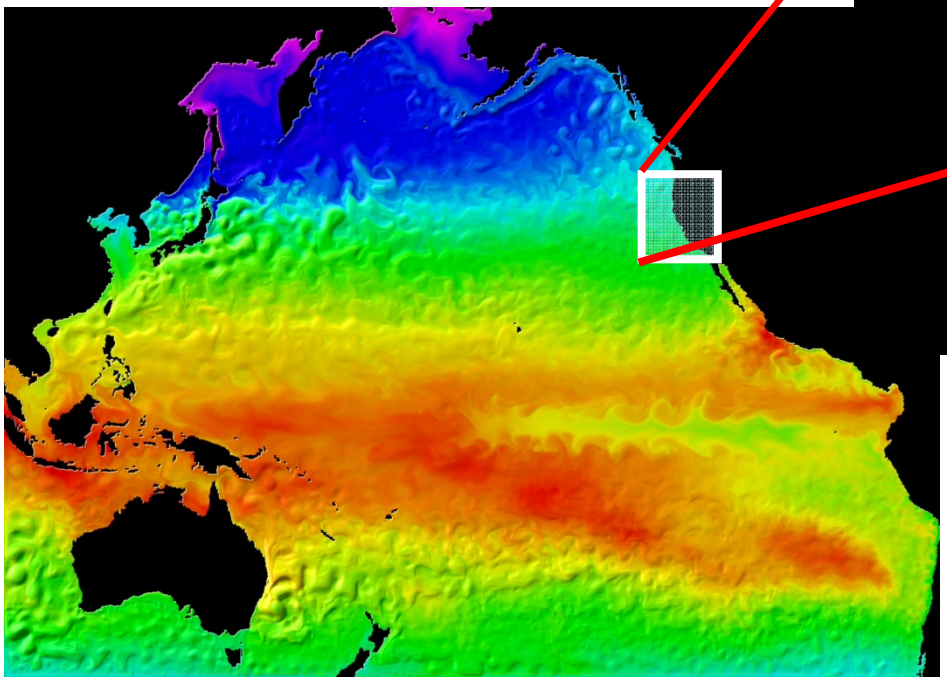
An iterative feedback loop to design and test the end-to-end network before field deployment; demonstrate the data impact and success (or identify deficiencies if any) after the deployment.

ROMS: Technical Progress

The virtual 3-D ocean is simulated by ROMS. Our project uses a nested ROMS configuration with increasing spatial resolutions for the region of interest (i.e., Monterey Bay, California or Puget Sound).

The Pacific Ocean is modeled by a 12.5-km ROMS (below), which is run on the Columbia supercomputer through the NASA Advanced Computing System.





The Monterey Bay (above) is modeled by a 1.5-km ROMS, which is influenced by the 5-km ROMS off the central California coast and subsequently a 15-km ROMS off the U.S. west coast.

2 Acoustic Networking

Focus

- Development of link & multiple access protocols for Underwater Networking (UWN)
  - Capacity analysis and link design for underwater channels.
  - Media Access Control Layer (MAC) design principles for UWN.
  - MicroModem implementations.
  - Next generation underwater acoustic modem development.

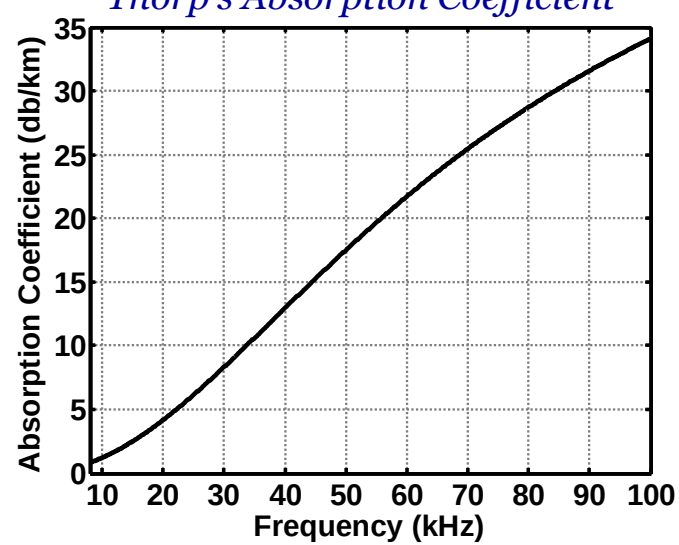
Accomplishments (07-08)

- ✓ Computed theoretical limits of communication for realistic underwater models using Bellhop.
- ✓ Analyzed FH-FSK link layer performance.
- ✓ Created a link layer model for integration into a MAC layer simulation tool.
- ✓ Successful CDR for new fully network capable acoustic modem.

Transmission Loss in Underwater Channels

- Transmission loss is the ratio of source power to receive power
- Transmission loss in an underwater channel is environment dependent:
  - Bottom composition determines forward losses,
  - Surface roughness determines scattering losses,
  - 'Bending' of sound waves by the channel sound speed profile (SSP).
- Frequency dependence
  - Frequency dependent absorption of acoustic sound.
  - Noise is also frequency dependent.

Thorp's Absorption Coefficient



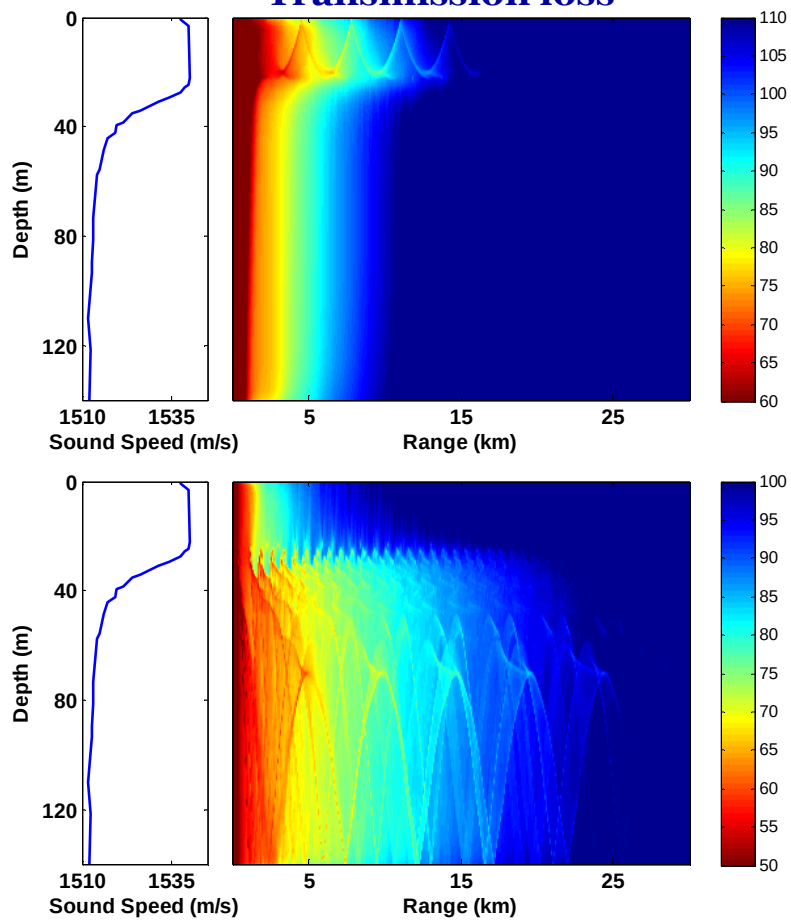
Acoustic Modeling Tool: Bellhop

- Uses Gaussian ray tracing
  - Source is assumed to emit a fan of rays.
  - Energy of each ray falls off in a Gaussian manner.
  - Energy at a receiver is the incoherent or coherent superposition of all the rays.
- User specifies
  - Sound speed profile,
  - Surface and bottom conditions,
  - Channel geometry,
  - Source and receiver locations.
- Generates transmission loss profiles and impulse responses.
- Can be used to compute link capacity and to predict performance of acoustic modems.

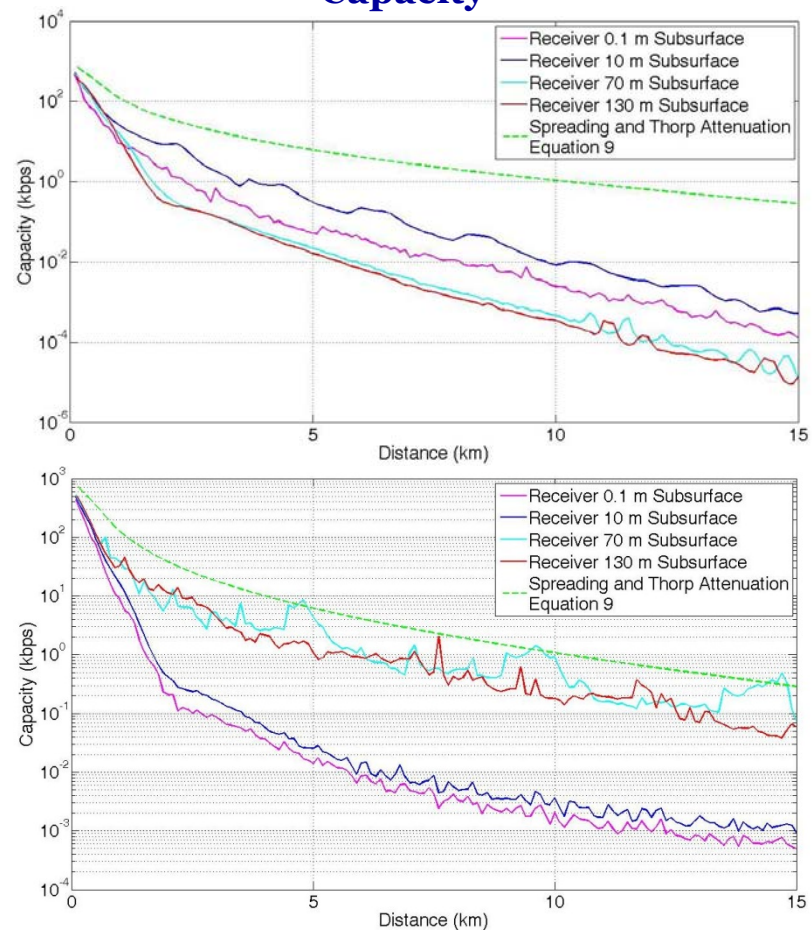
Link Capacity

- Capacity varies greatly based on source location.
- Capacity of two receivers at different depths varies greatly in some channels.

Transmission loss



Capacity



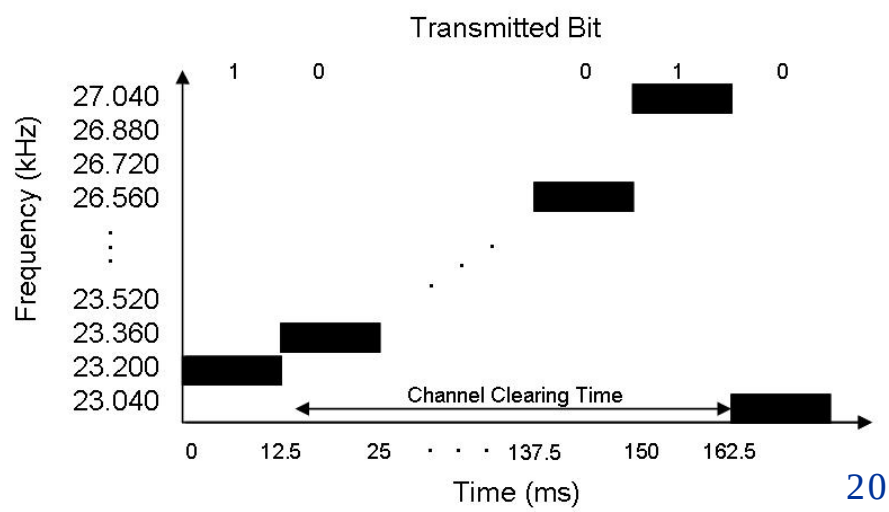
Link Modeling with Bellhop

- Realistic receiver limitations make achieving capacity difficult.
- Wide variety of underwater channels dictates the need for physical layer performance in a *specific channel*.
- Technique: apply MicroModem link layer specifics to the channel impulse response created by Bellhop.

MicroModem Link Layer Specifics

- Non-coherent frequency hopping, frequency shift keying.
- Channel clear time mitigates inter-symbol interference.
- Convolutional coding with bit interleaving.
- Receiver matched filter window is open for 12.5 ms.

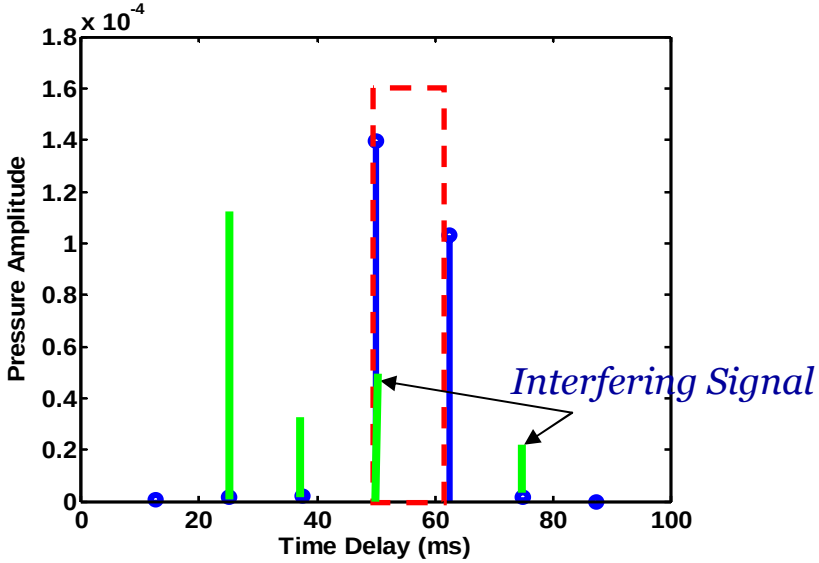
FH-FSK Design in the Micro-Modem



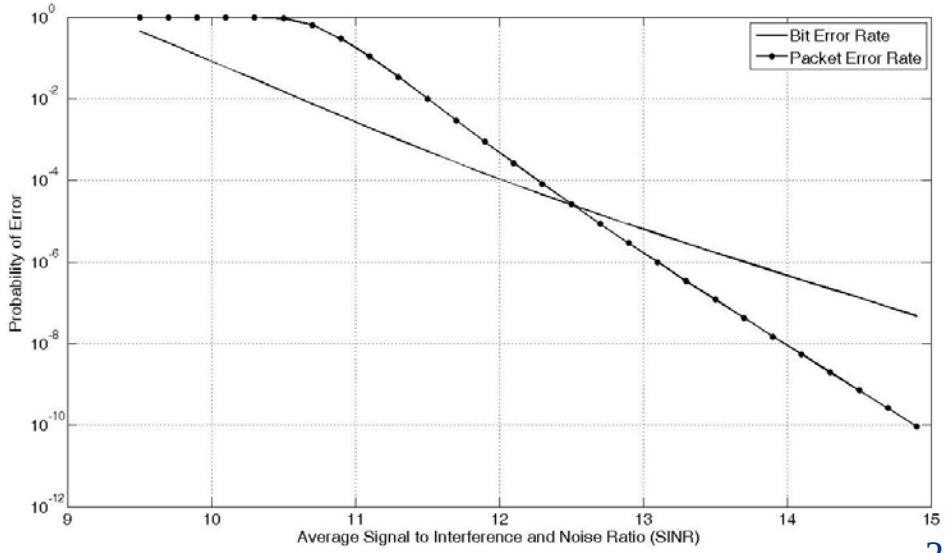
Computing the Packet Error Rate

- Assumption: arrivals at the receiver are Rayleigh distributed.
- Interfering signals are treated as additional noise.
- Bit error rate determined by average receive SINR.
- Average SINR is determined from the signal and interferer arrivals within the receiver window from the Bellhop impulse response.

Receiver window and Bellhop Impulse Response



Probability of Error vs. Average SINR

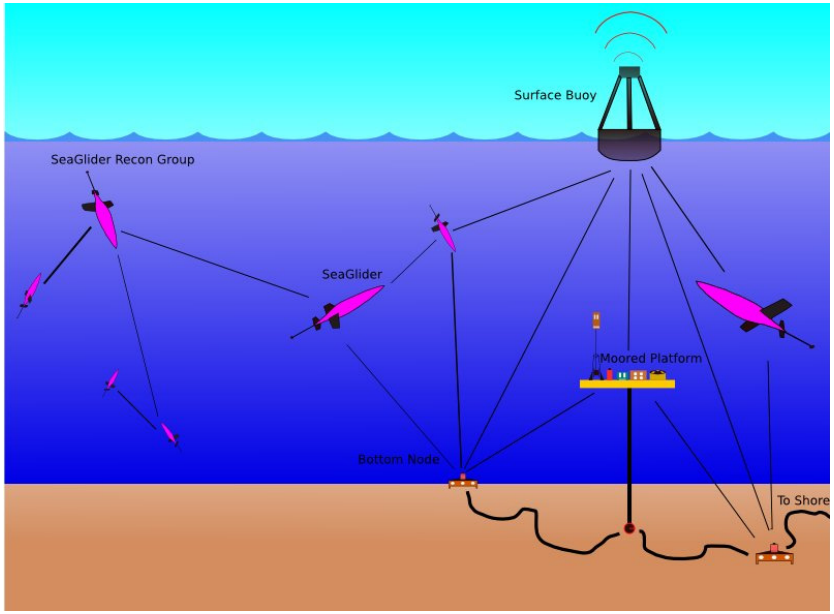


Next Steps in Link Design

- Compare the performance predictions to experimental test-data
- Implement modeling for other modulations/hardware types
  - Orthogonal Frequency Division Multiplexing (OFDM) Modem
  - Multichannel physical layer
  - MicroModem Phase Shift Keying (PSK)

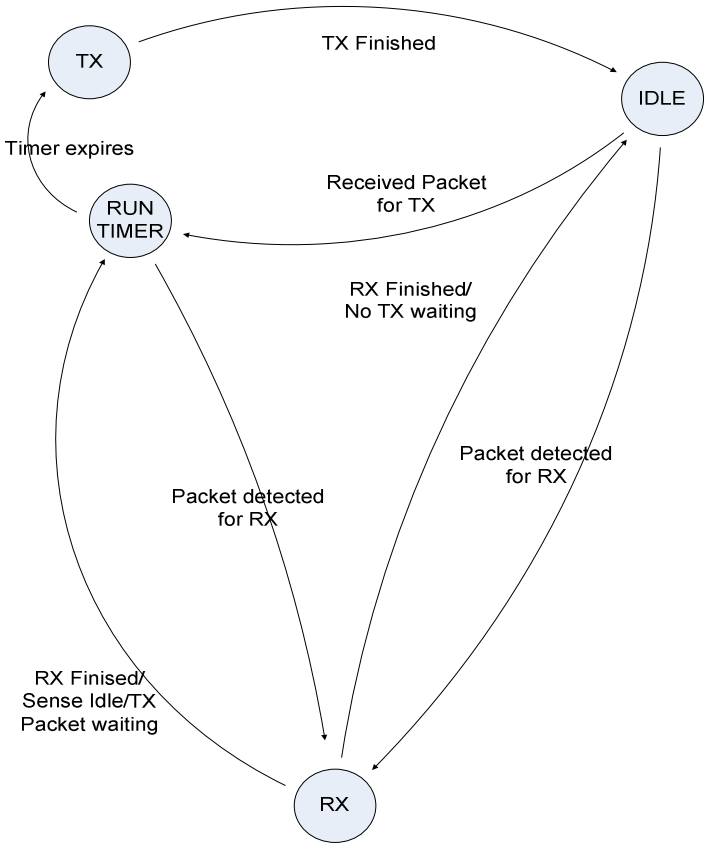
UWN MAC Protocol Design Principles

- MAC Protocols developed for terrestrial networks are not suited for underwater networks
  - High propagation delays (approx 1.5 s per 1 km)
  - High TX/RX power, low idle power
    - WHOI MicroModem: 5-10W TX, 3W RX, 80mW idle
- Typical underwater network topology
  - Mix of fixed and mobile nodes (gliders)
- Desired new MAC should be
  - Distributed and Self organizing
  - Delay tolerant
  - Energy efficient



A MicroModem MAC

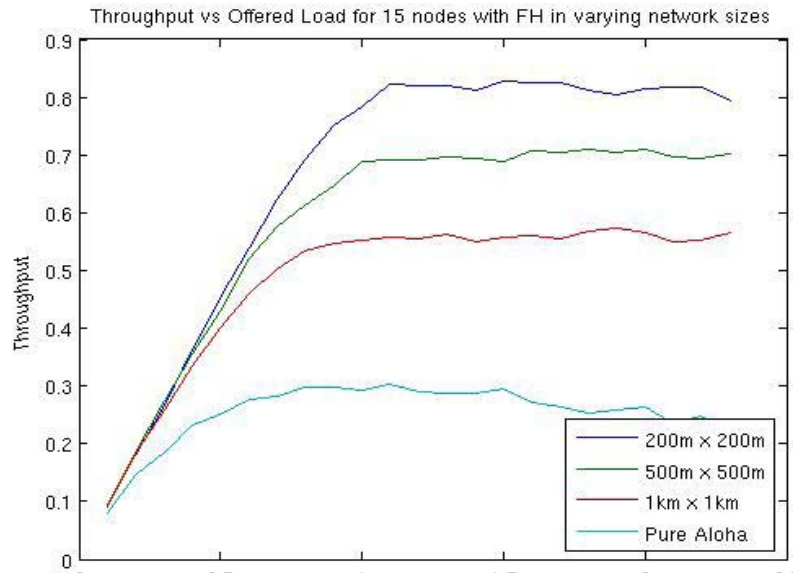
- MicroModem Challenges
  - All packets heard on channel are received and processed by all nodes.
  - No multiple access possible.
  - No carrier sensing.
  - FSK packet lengths are not configurable.

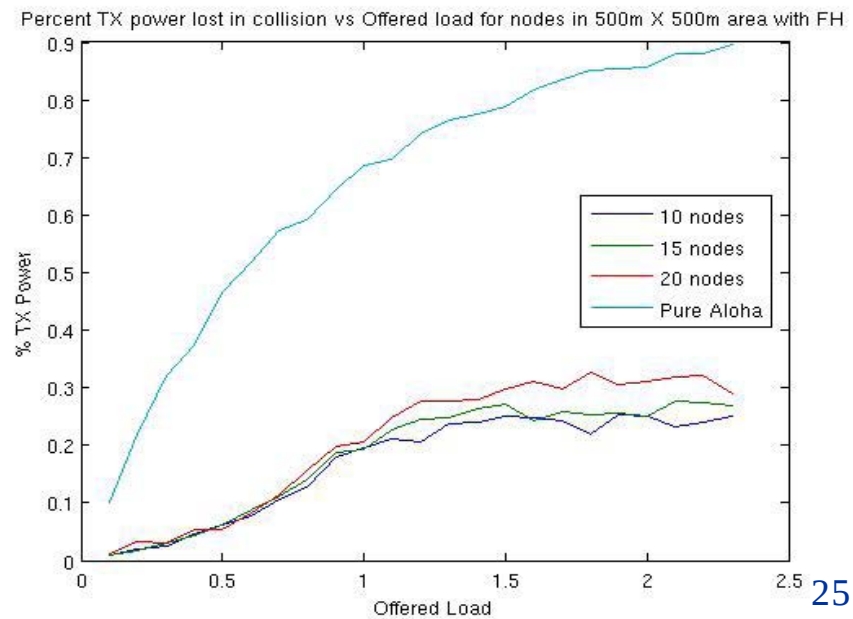


- New MicroModem Compatible MAC (Aloha with Random Backoff)
  - Node chooses slot CW (contention window).
  - Set timer to CW × slotsize.
  - Countdown timer while not in RX mode.
  - TX when timer reaches 0.

MicroModem MAC Simulation Results

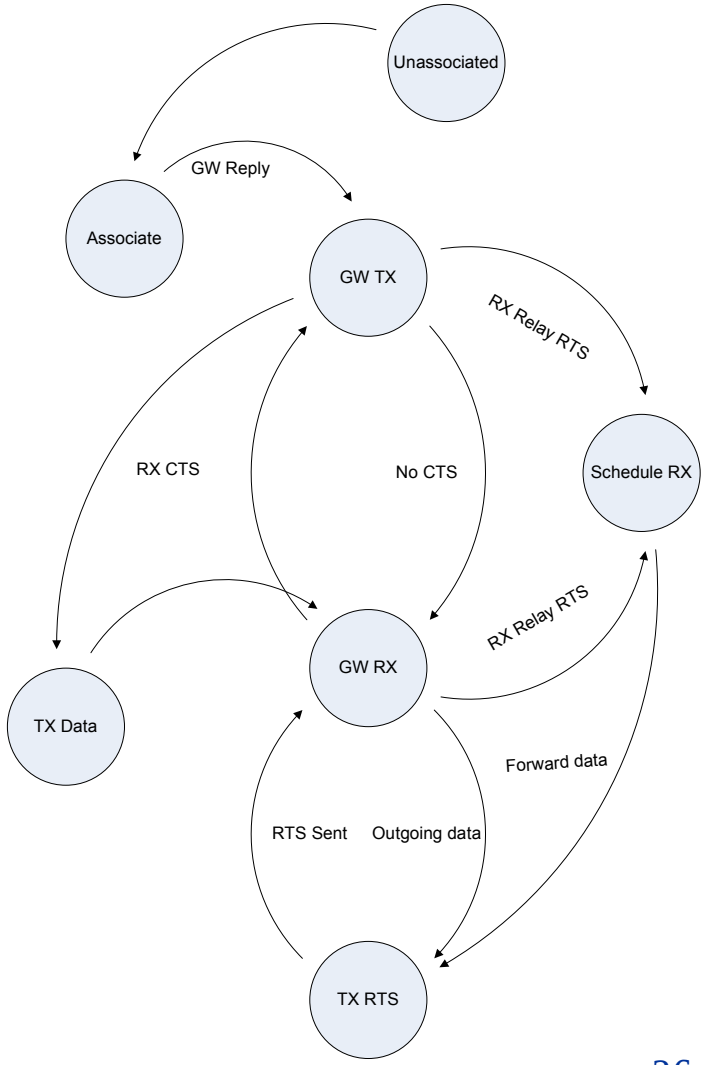
- ns2 simulations
  - Used PHY model from Bellhop
- Results
  - Improved throughput
  - Better power efficiency
- Drawbacks
  - Reduced throughput for large networks
  - Fixed CW size (must adapt to changing network load)





Future MAC Design I

- **Goal:** Enhanced power efficiency and channel utilization
- Proposed solutions
  - Use Multiple channels
    - Dedicated CTRL channel using Aloha with random backoff
    - Data channel scheduled via CTRL channel
  - Optimize CTS/RTS handshake
    - Use a dedicated channel for CTRL packets
    - Allow multiple frames per RTS
    - Schedule multiple sessions
  - Optimize for common underwater network traffic flow
    - Data flows to gateways
    - Often few hops from gateway to outlying nodes



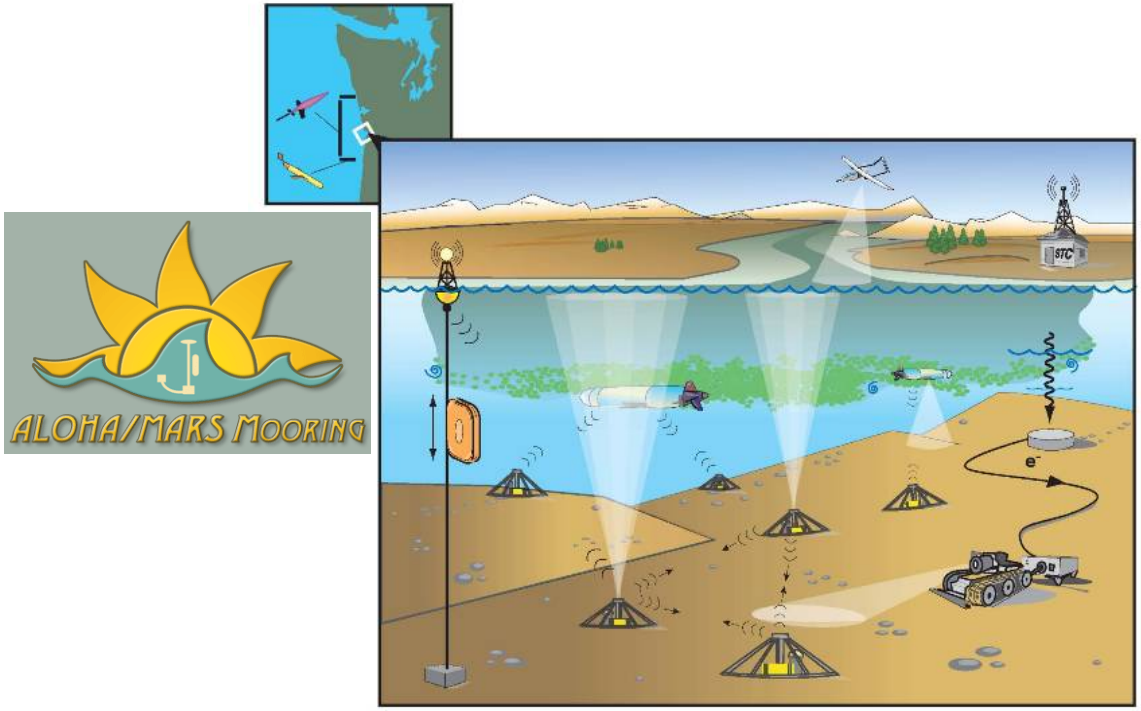
Future MAC Design II

- Implement Multichannel MAC in ns2
- Analyze optimal parameters vs. network characteristics
  - Number of hops and number of gateways
  - Channel BW ratio vs. network load
- Develop hardware platform to allow for in-water deployment

3 Field Experiments

Goals

- Power, timing, navigation, communications: $f(\mathbf{x},t)$
- Fixed cabled nodes with high power and bandwidth
- Mobile/fixed hybrids – profiler, ROVs, docking, etc
- Mobile/autonomous
- Fixed autonomous
- Role of acoustics



Outline

- Milestones
- Seahurst Results – mooring and modem
- Puget Sound testing in Port Susan, and Dabob Bay
- Lake Washington testing
- MARS
- Plans

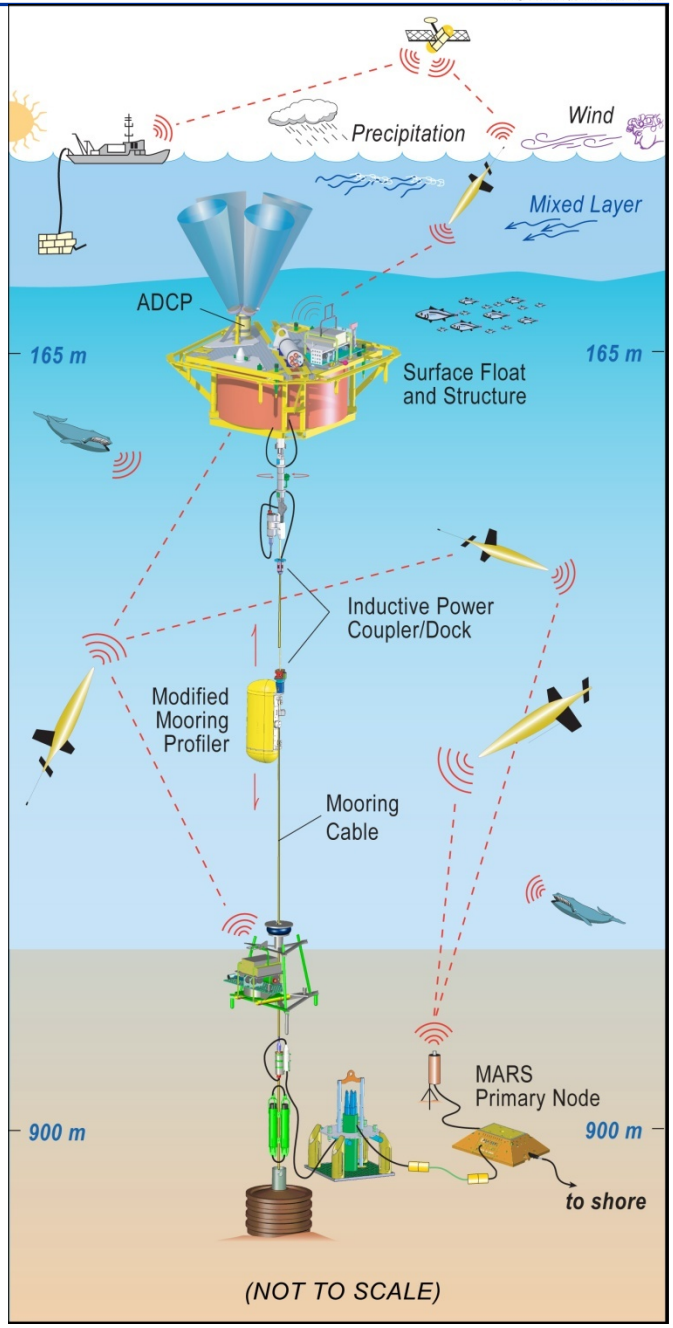
Field Experiments: Technical Progress

- **Year 1.5 Milestones**
  - Modems deployed on test mooring at Seahurst in Puget Sound
    - in 30 m water depth
    - Tested, power supplies improved to reduce noise
    - Tested again, ranges to 2.5 km
  - Modems used on gliders in Puget Sound as part of ONR program
    - Ranges to 7 km
    - Part of larger experiment - gliders performed as communications gateways for 2 weeks, ~50,000 packets, two-way
    - Glider - surface gateway
      - PSK at 240 and 5200 b/s
      - Command to glider to surface
      - Generalized communications stack
  - Modems on AMM prepared for deployment on MARS cable system in Monterey Bay – latter failed
- **Plan for Demonstration:**
  - Execute at Seahurst in Puget Sound – modems on short mooring plus gliders
  - Investigate possibility of gliders and seafloor modems at MARS in 2009

Field Experiments: Technical Progress

- Moorings called for in many NSF Ocean Observatories Initiative plans
- **Features**
  - Enables adaptive sampling
  - Distributes power, communications, time throughout the water column
  - ROV servicing
- **Major Components**
  - Subsurface float at ~165 m depth with sensor suite and junction box
  - Profiler with sensor suite that can "dock" for battery charging, continuous two-way communications via inductive modem
  - Electro-optical-mechanical mooring cable
  - Seafloor sensor suite and junction box
- **Deployments**
  - June – December 2007 on Seahurst Observatory in Puget Sound, 30 m depth
  - April 2008 on MARS in Monterey Bay, 900 m depth, 6 months

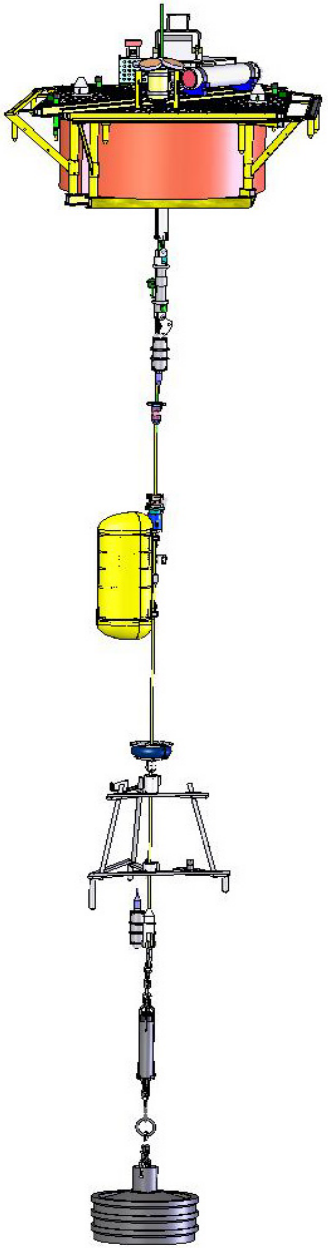
NSF funded – OTIC - Lukas and Boss co-PIs



ALOHA-MARS Mooring (AMM) System

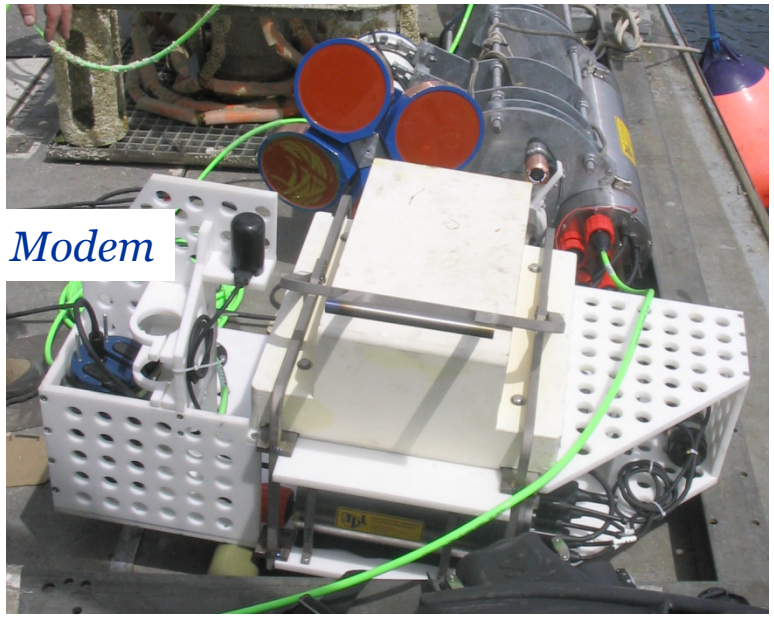
Field Experiments: Technical Progress

AMM components

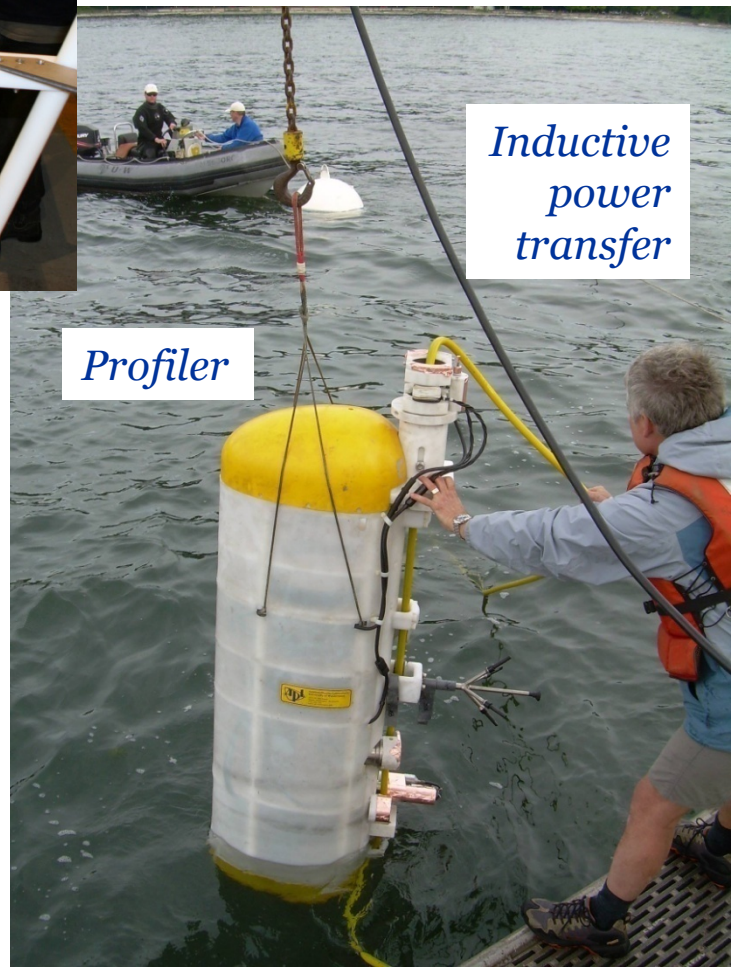


Subsurface float

Modem



Modem



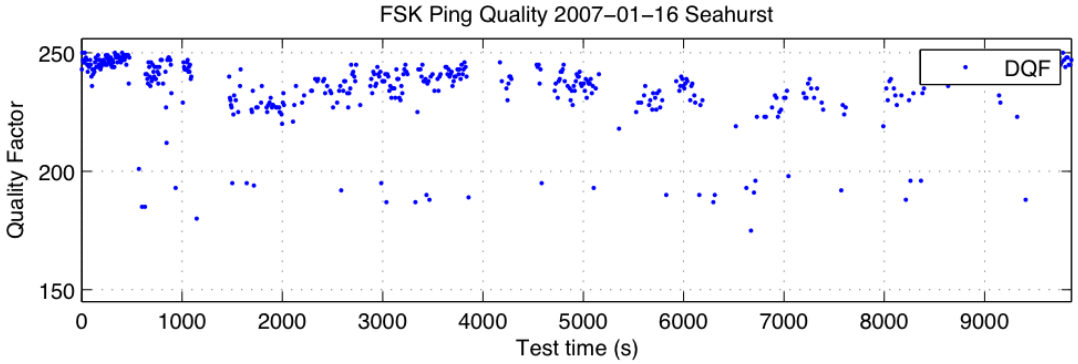
Inductive power transfer

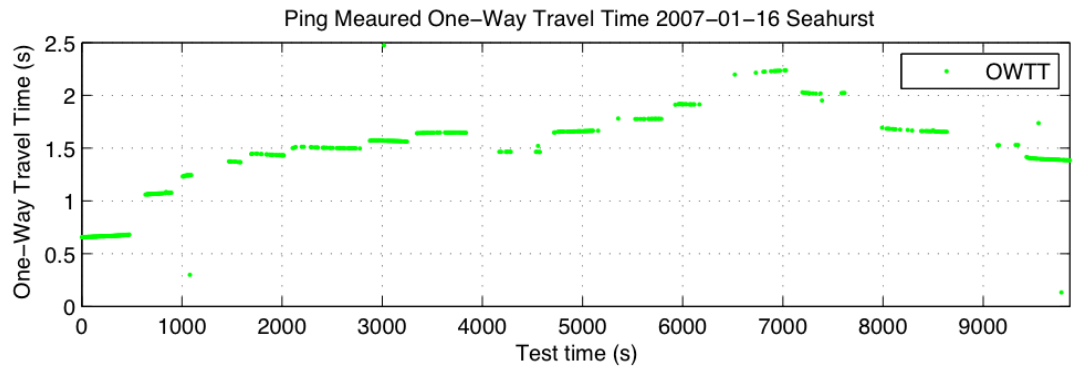
Profiler

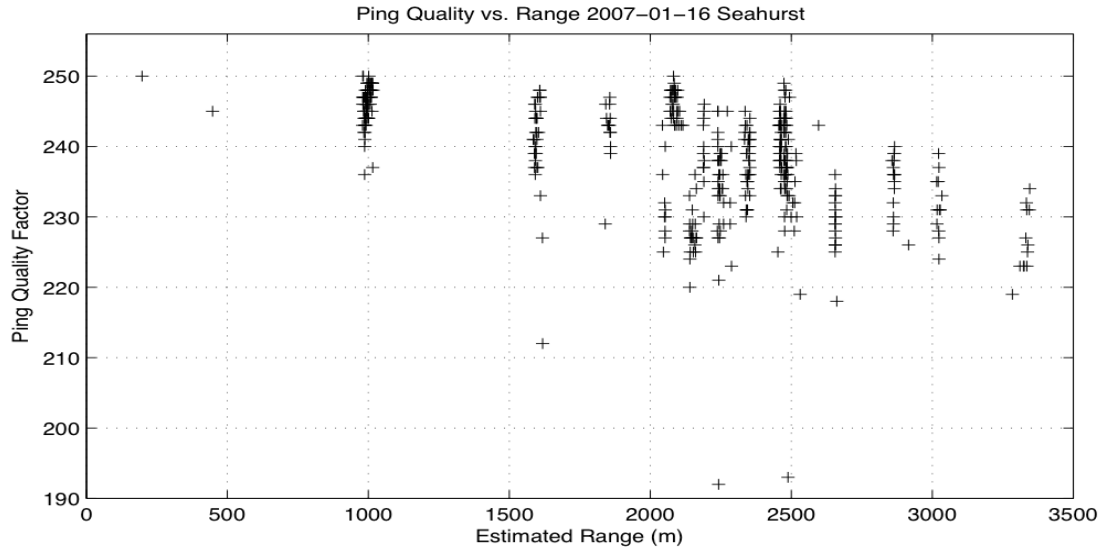
Field Experiments: Technical Progress

Modem Tests at Seahurst

- 18 January 2008
- Modem on bottom instrument package, 30 m depth
- Boat/deck unit moving into deeper water 200 m depth
- Ranges up to 3500 m
- "Good" to 2500 m







Field Experiments: Technical Progress

PLUSNet07 Experiments at Dabob Bay, September – October 2007

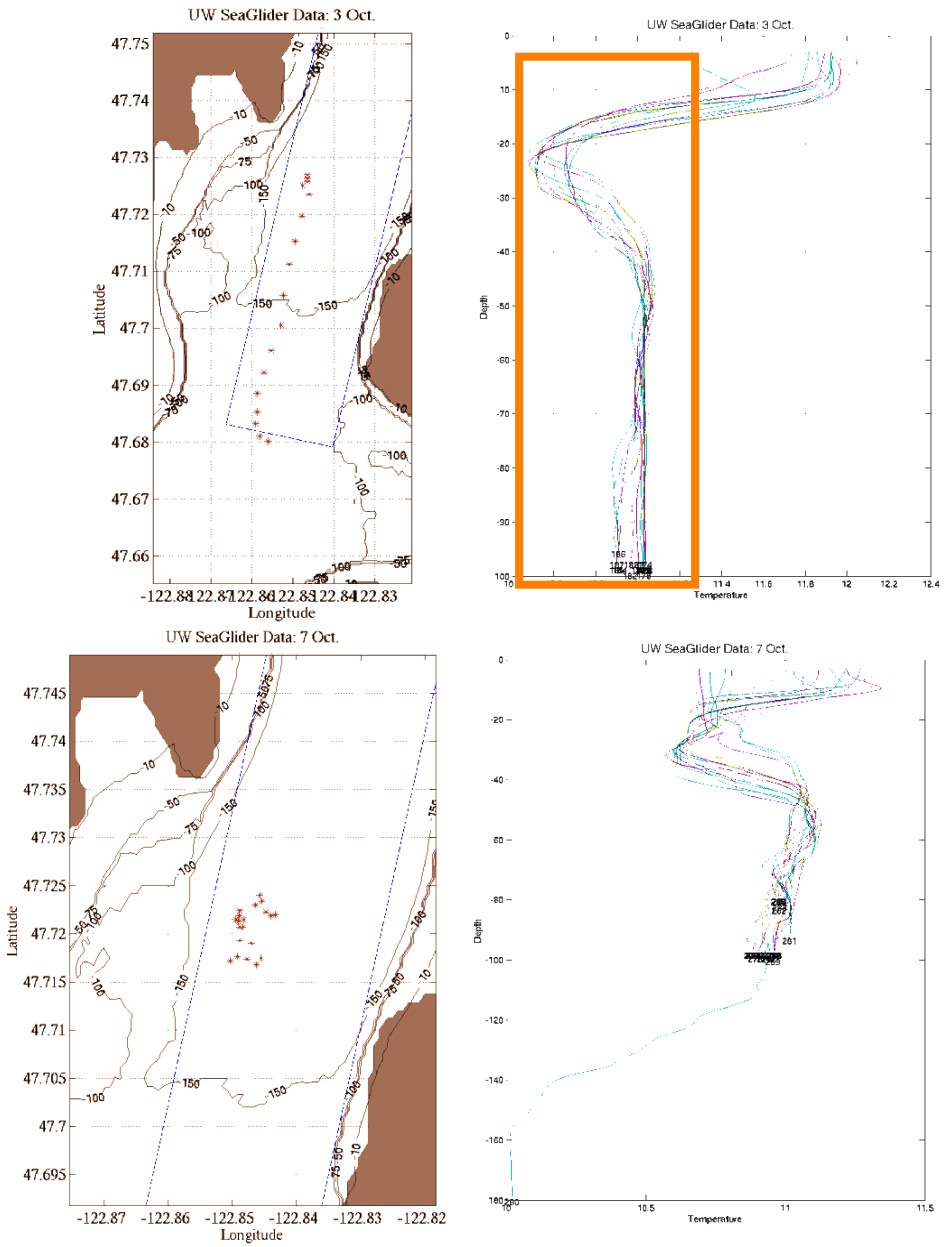
Zelatched Point

Dabob Bay

Seattle APL

Acoustic Seaglider Preparation, 19 September 2007

Field Experiments: Technical Progress

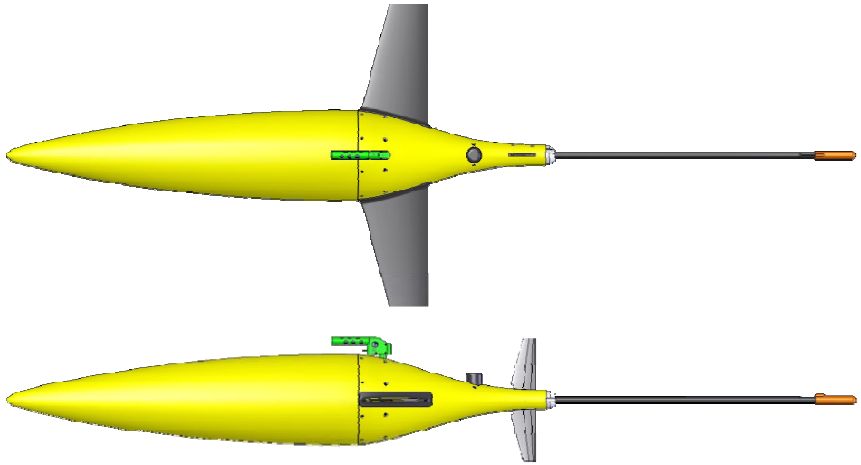


Profile Data

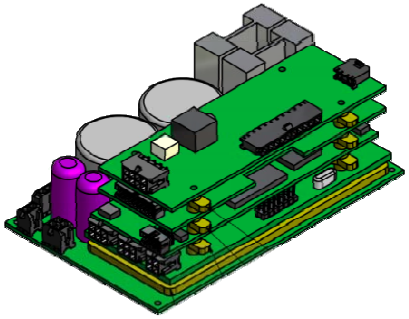
- Seaglider data assimilated by MIT
- Over 3000 profiles total
- Here show change from 3 to 7 October

Acoustic Communication Seagliders

- 5 Seagliders from UW Seaglider Fabrication Center

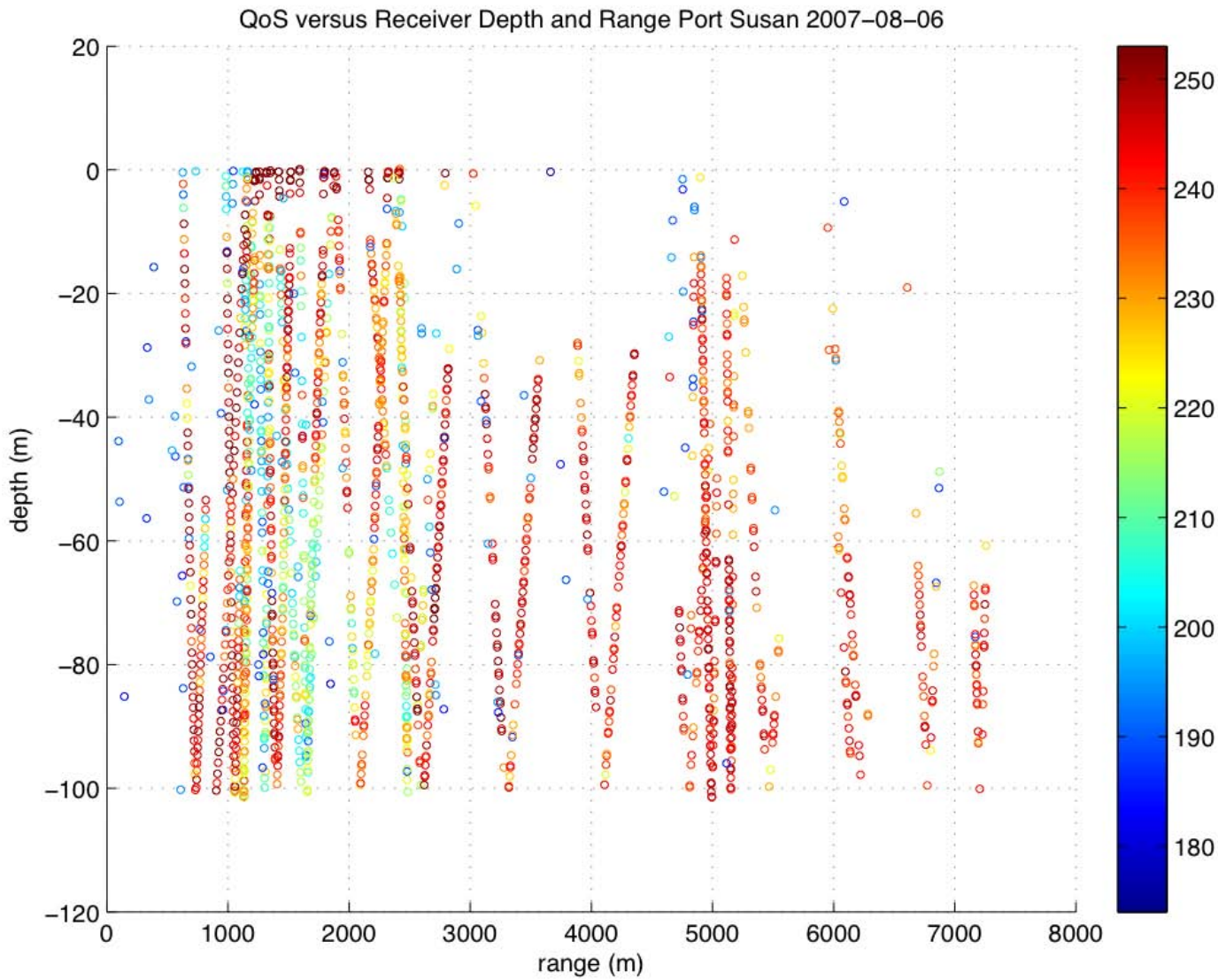


- Installed WHOI Micro-modem
  - Band C 25KHz
  - 1 channel
  - PSK capable
  - WHOI BT-1 transducer
  - ~10 Watt transmit power
- Installed Gumstix coprocessor
  - acts as Micro-modem controller & logger
  - embedded Linux platform
  - many peripherals available
  - WHOI provided interface electronics



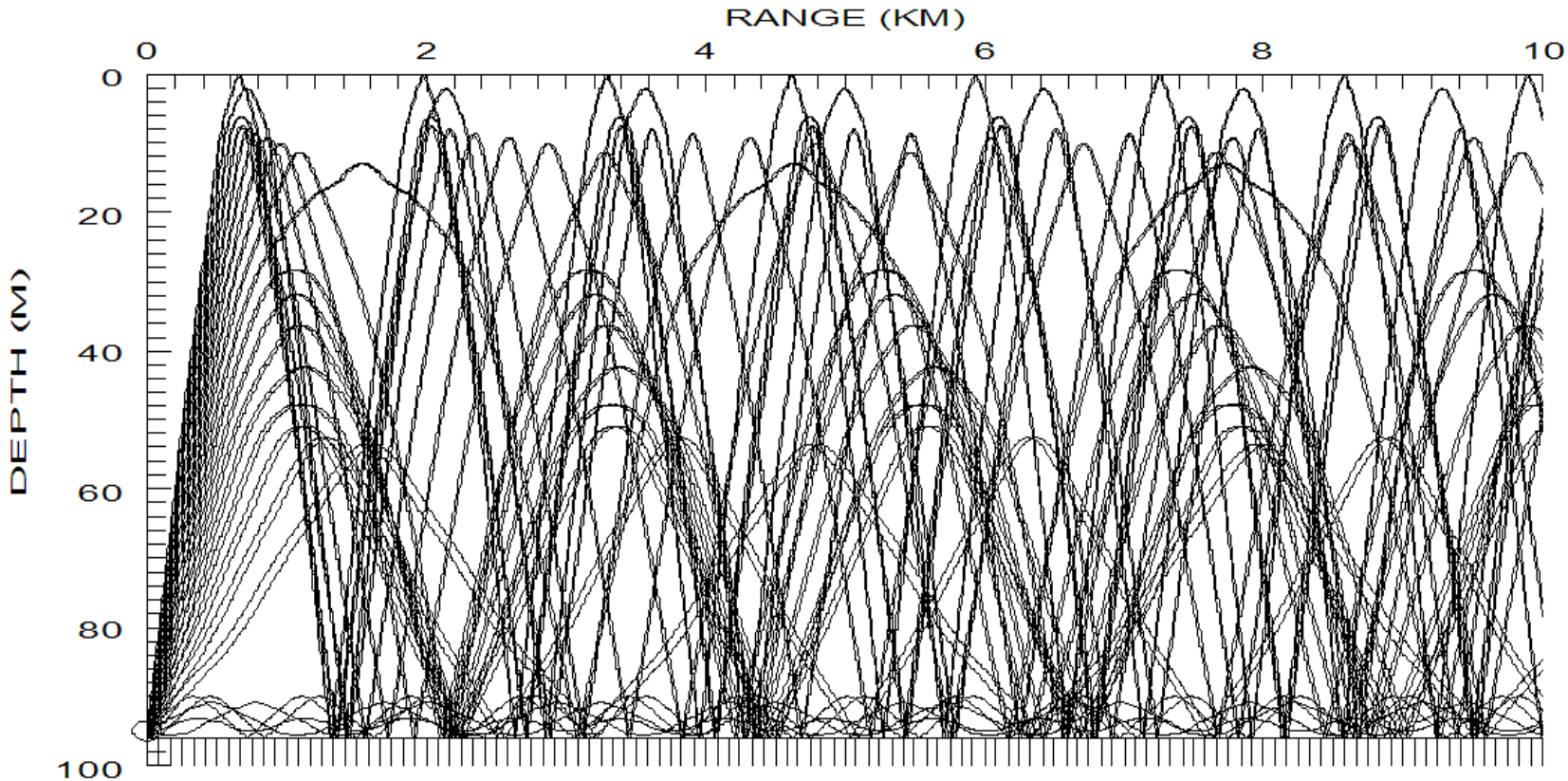
Communications Performance: Range.

Port Susan testing: glider on bottom to moving glider

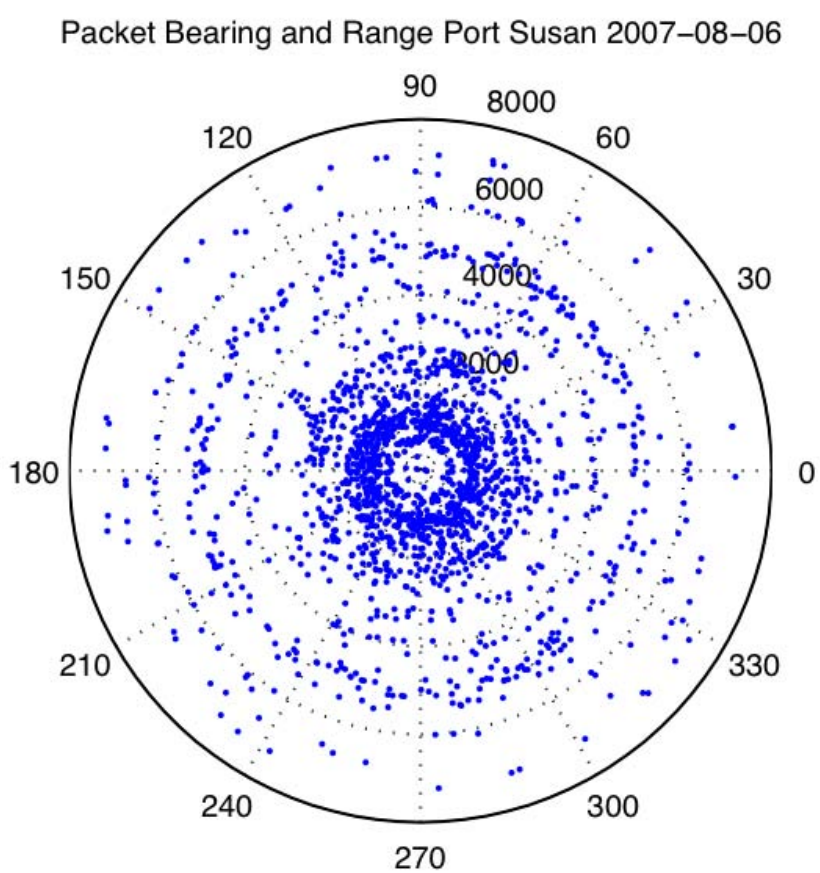


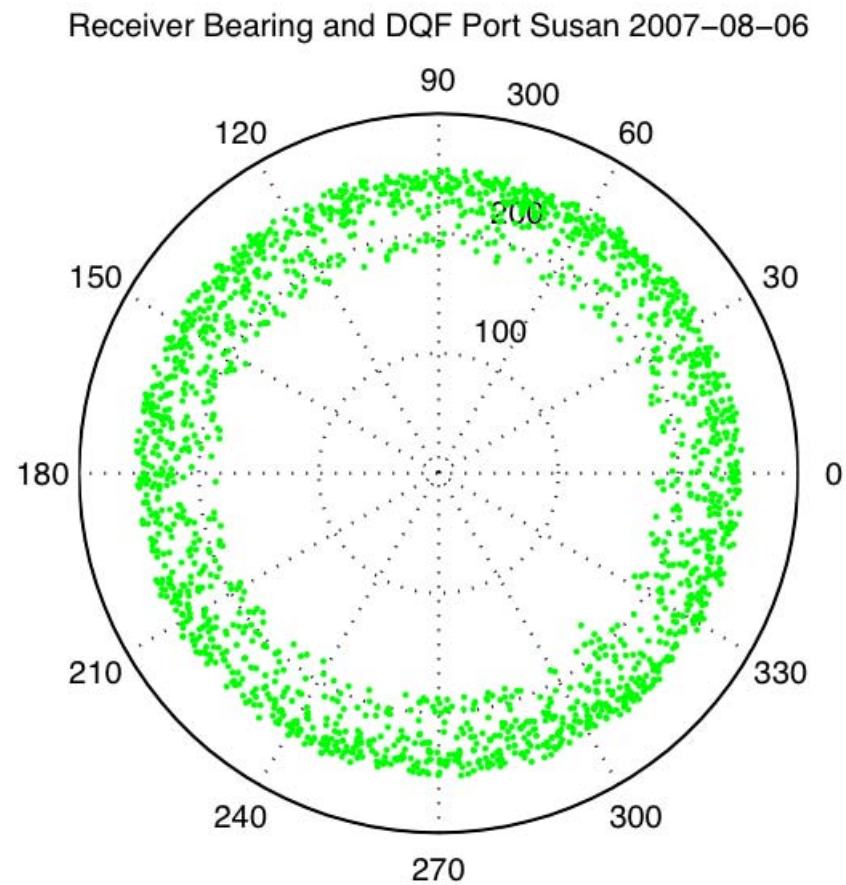
Communications Range: Ray Diagram

Port Susan testing: glider on bottom

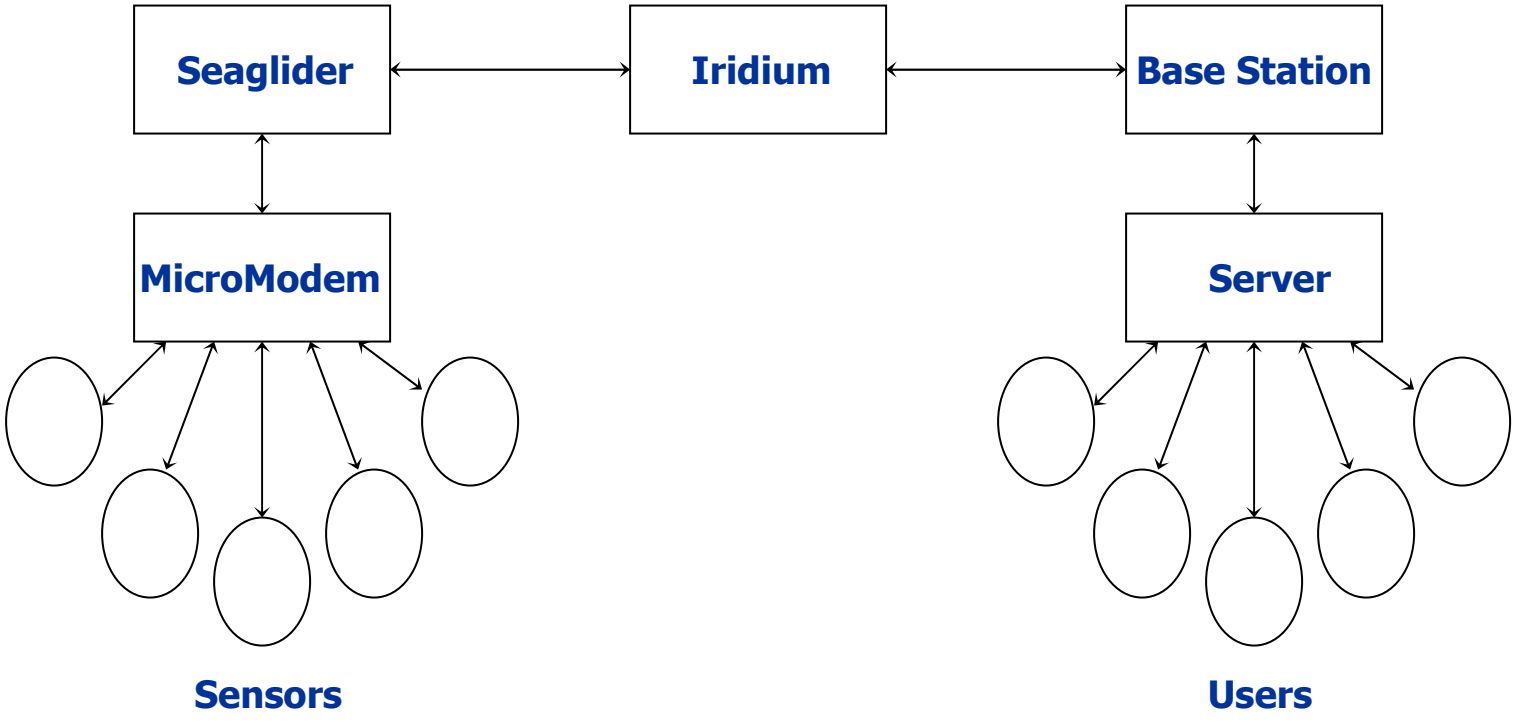


Communications Performance: Bearing





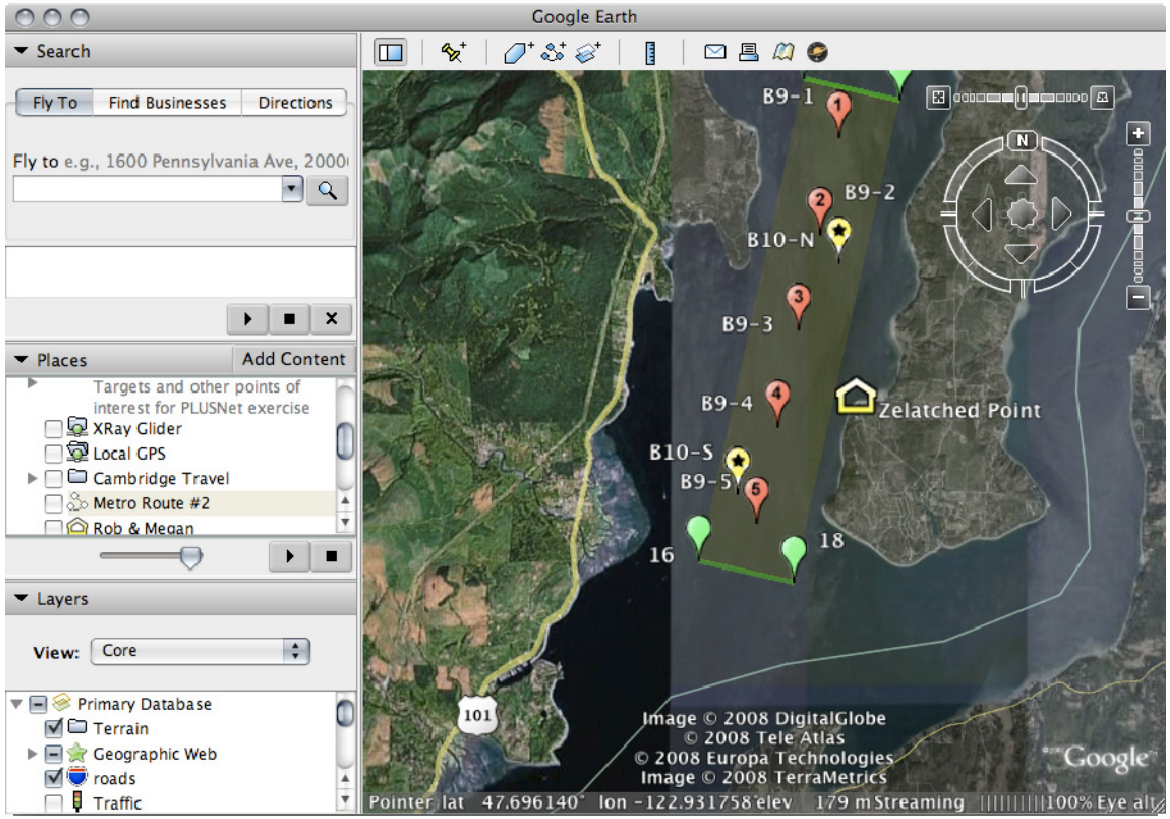
Communications Reachback System



Reachback: KML Viewer

Google Earth

- open file format (KML)
- platform portable
  - Linux
  - MacOS
  - Windows
- HTTP interface
  - KML files served by any server
  - GE is HTTP client
- Quick prototyping possible

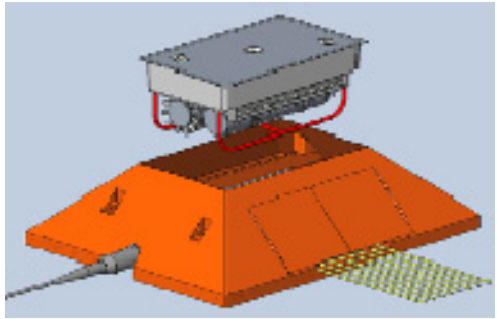


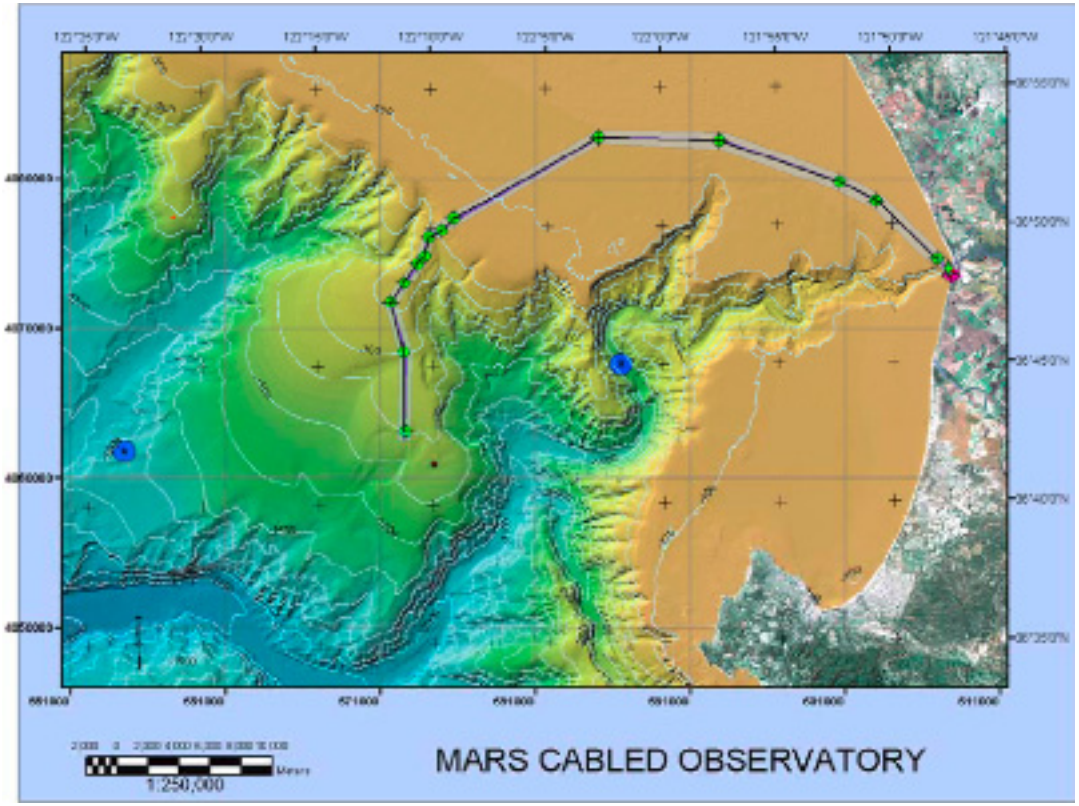
MARS System

- Original intent was to deploy the NSF-funded ALOHA-MARS Mooring (AMM) system, with NASA funded modems on the MARS cabled observatory system in April 2008, and then execute the end-to-end demonstration with gliders (with modems) and modeling/data assimilation
- The MARS system suffered a major setback in February 2008, forcing the cancellation of the AMM deployment
- The AMM will be deployed again at Seahurst in April 2008
- Next – a brief description of MARS and status
- MARS is a major NSF project: $7M + $5M from MBARI/Packard Found

MARS System

- Monterey Bay Aquarium Research Institute
- Part of NSF Ocean Observatories Initiative
- Monterey Bay
- Node on Smooth Ridge at 870 m
- Delivers nominal 9 kW of power
- Fibers providing bandwidth of 2 Gb/Sec per fiber pair: 2 fiber pairs
- 8 science ports for science instruments
- Electronics in a removable node





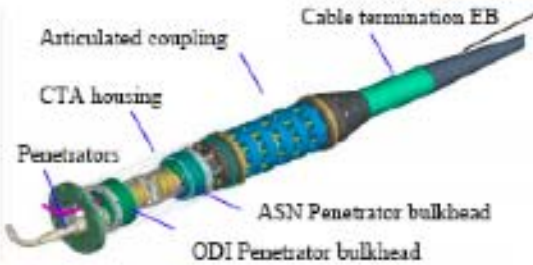
Field Experiments: Technical Progress

Low voltage power system:
Applied Physics Lab: del 1/07
accept test Apr 2007

Status: MARS Sub-Systems

MV 10kV Power Converters
JPL (2003-2005)
Alcatel (2006-2007) del Sept 2007

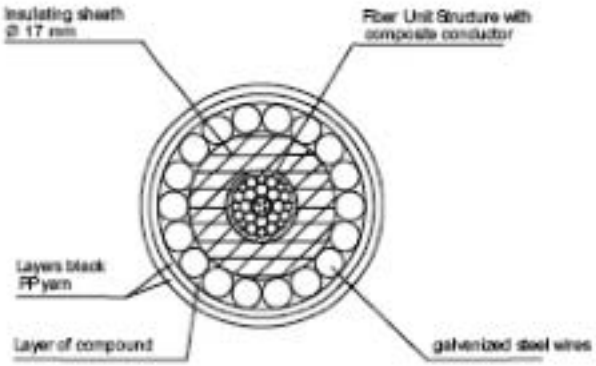
Node and Trawl Resistant Frame
L3 Com MariPro; delivered May 2005



Cable Termination Assembly
Alcatel: delivered Jan 2005

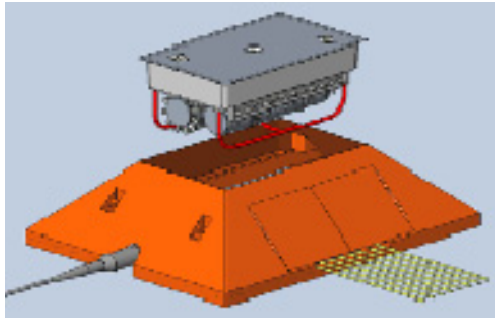
Communications System
Woods Hole: Del July 2005: accept test June 2007

Field Experiments: Technical Progress



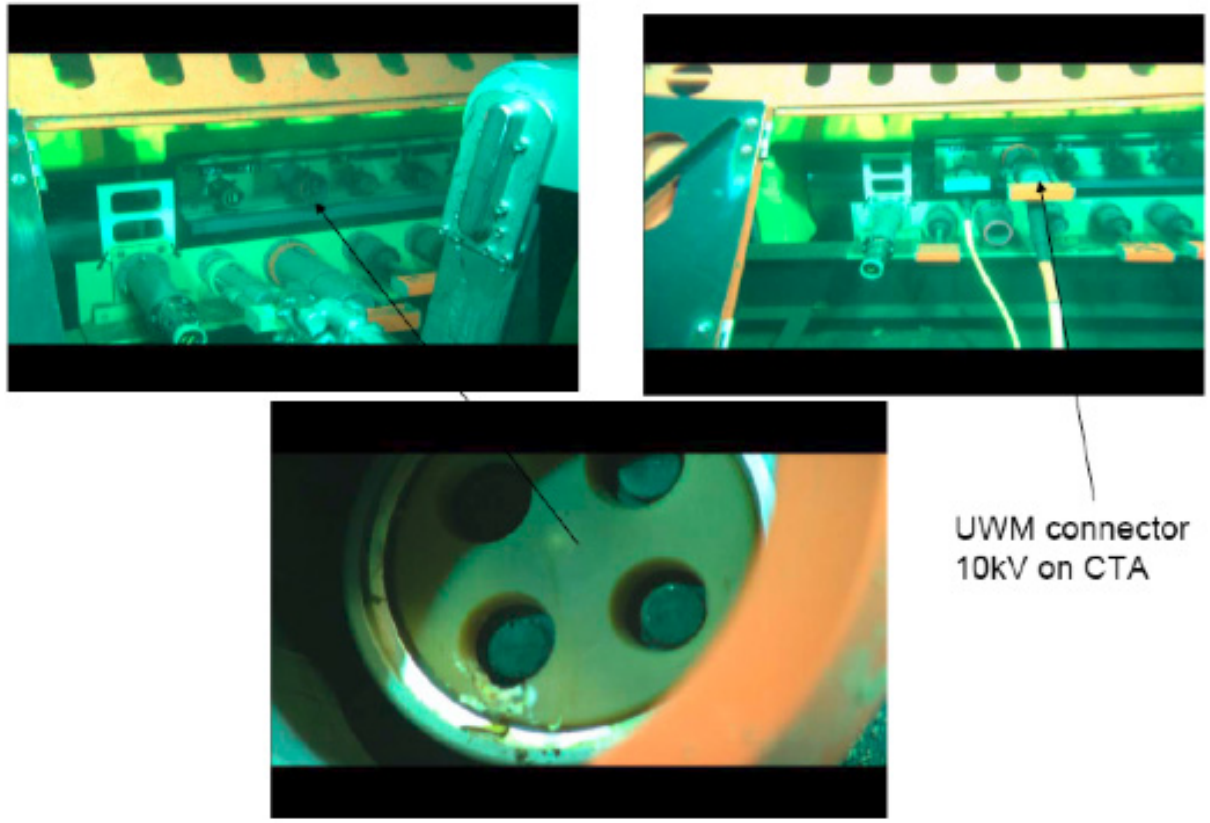
Cable installation in Monterey Bay
March 2007

Field Experiments: Technical Progress



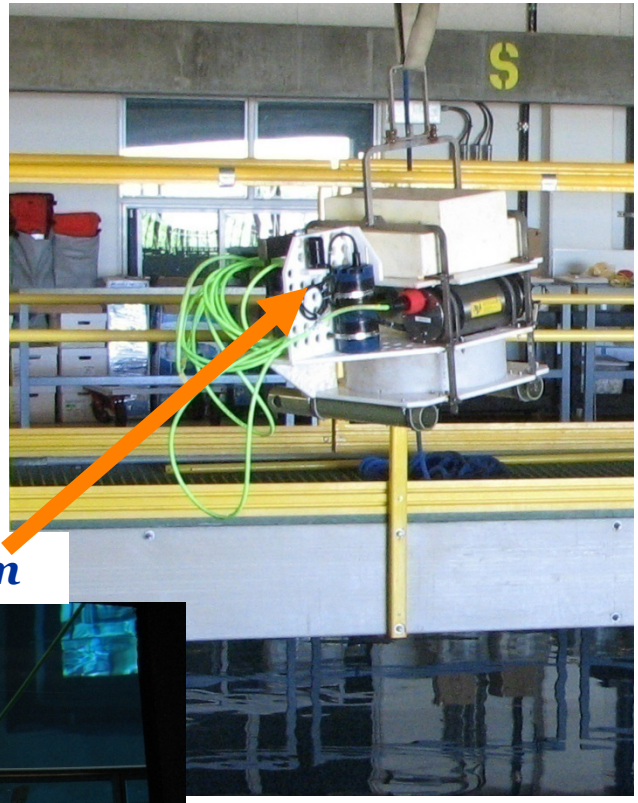
MARS - Node Installation
26 February 2008

- Node insert installed 26 Feb 2008
- Remotely operated vehicle (ROV) mated connectors
- Worked for 19 minutes
- High voltage (7.5 kV) connector failed
- Repair - > 6 months, $1M
- Parties committed to bringing to operations



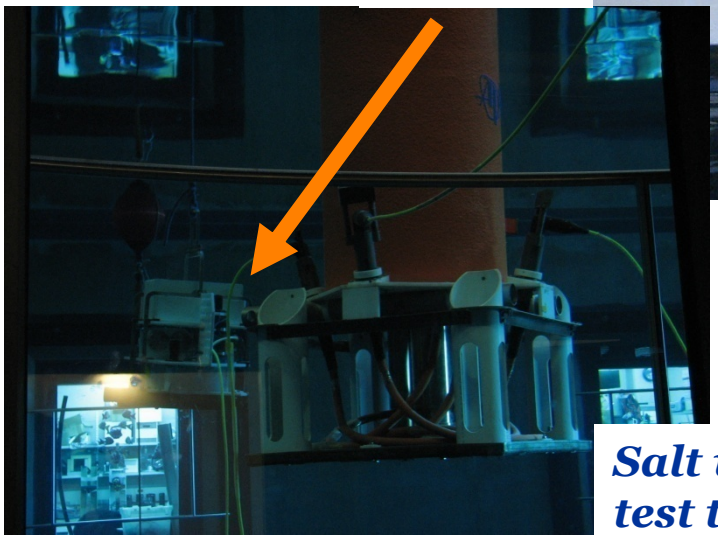
Field Experiments: Technical Progress

- Preparation of seafloor secondary cable and node, and bottom instrument package with modem at MBARI, February 2008



Seafloor cable and node

Modem



Salt water test tank

Field Plans

- AMM mooring will be re-installed at Seahurst, Puget Sound, April 2008
  - in somewhat deeper water (130 ft, 40 m)
  - including the large subsurface float
  - using the R/V Thompson
  - Service cruise August 2008
  - Perform end-to-end test/demonstration with updated ROMS models
- For 2009:
  - Seahurst deployment will be left in place for further, more complex experiments/final demo in 2009
  - At MARS, deploy seafloor secondary cable, node, instrument package with modem
  - Deploy other modem(s) on seafloor
  - In collaboration with L. Freitag at WHOI
  - Pending availability of funding from other sources, demo at Monterey in addition to Puget Sound

Field Experiments: Planning

- Task schedule and milestones fully accommodate this updated plan
  - Spring/Summer 2008 deployment was early attempt ("target of opportunity") – not originally planned – hence no time has been lost
  - Lessons learned in Spring/Summer 2008 will prove useful for experiments in 2009, as well for other programs leveraged by our task

- Important to note that the failure at MARS was very unique: first ROV deployment at 930 meters of a one-of-a-kind. complex, high-tech connector, only 2 or 3 of which have been manufactured. The ocean community is pushing the envelope with this new infrastructure.

- Final note: we have received a permit for using gliders and modems in the Monterey Bay National Marine Sanctuary – this may come in useful later, and does set a positive precedent for us and others.

Field Experiments: Leveraging

Leveraging

- The entire AIST task significantly leverages ongoing ocean observation, monitoring, target tracking, and anti-submarine warfare tasks funded by the US Navy, NSF, and internal UW/APL R&D funds.

- By way of an example, just the rental of the cable laying ship in Monterey Bay costs on the order of $100,000 a day. Repair/replacement cost for the high voltage connector will be greater than $1M.

- Significant other costs are also involved in various other equipment (moorings, floats, junction boxes, connectors, ...), as well as crew, planning team, and ship time.

- Without such leveraging, cross-team coordination, and planning, deployment of the main infrastructure for a real sensor web in the Pacific ocean or Puget Sound would have been impossible.

Publications

1. N. Parrish, L. Tracy, S. Roy, W. Fox, and P. Arabshahi, "System Design Considerations for Undersea Networks: Link and Multiple Access Protocols," *IEEE J. Sel. Areas Comm.*, 2008 (submitted).

2. W.L.J. Fox, P. Arabshahi, S. Roy, and N. Parrish, "Underwater Acoustic Communications Performance Modeling in Support of Ad Hoc Network Design," *Proc. IEEE Oceans Conference*, Vancouver, Canada, Sept. 29 - Oct. 4 2007.

3. Y. Chao, Z. Li, J. Fararra, K.J. Park, and X. Wang, "Development, Implementation and Evaluation of a Real-time Ocean Forecasting System off the California Coast", *Proc. 2007 Joint Assembly of the American Geophysical Union*, Acapulco, Mexico, 22-25 May 2007.

4. N. Parrish, S. Roy, W.L.J. Fox, and P. Arabshahi, "Rate-Range for an FHFSK Acoustic Modem," *Proc. Second ACM Workshop on Underwater Networking* (Mobicom 2007), Montreal, Canada, Sept. 14, 2007.

Publications

5. B.M. Howe, P. Arabshahi, W.L.J. Fox, S. Roy, T. McGinnis, M.L. Boyd, A. Gray, Y. Chao, "A Smart Sensor Web for Ocean Observation: System Design, Architecture, and Performance," *Proc. NASA Science Technology Conference*, College Park, MD, June 19-21 2007.

6. B.M. Howe, T. McGinnis, and M.L. Boyd, "Sensor network infrastructure: moorings, mobile platforms, and integrated acoustics", *Proc. Intl. Symposium on Underwater Technology*, Tokyo, Japan, 17-20 Apr. 2007.

7. B.M. Howe, et. al., "Elements of Sensor Network Infrastructure: Moorings, Mobile Platforms and Integrated Acoustics", *Proc. American Geophysical Union Fall Meeting*, San Francisco, CA, Dec. 11-15, 2006.

8. S. Roy, P. Arabshahi, D. Rouseff, W. Fox, "Wide Area Ocean Networks: Architecture and System Design Considerations", *Proc. First ACM International Workshop on Underwater Networks* (ACM MobiCom 2006), Los Angeles, CA, USA, Sept. 25, 2006.

Publications

9. Inclusion of our NASA sponsored research as one of a few selected ones to be highlighted in UW APL's *Biennial Report*, 2007.
http://www.apl.washington.edu/about_apl-uw/biennial_reports.php

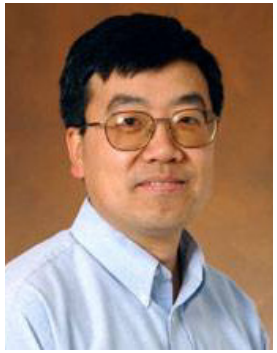
Team

At UW APL

- Payman Arabshahi
- Warren L.J. Fox
- Bruce M. Howe
- Matthew Grund
- Tim McGinnis
  + many engineering R&D staff members

At UW EE

- Sumit Roy
  + 3 students



At AGCI

- Andrew A. Gray
- Chung Hsieh

At JPL/UCLA

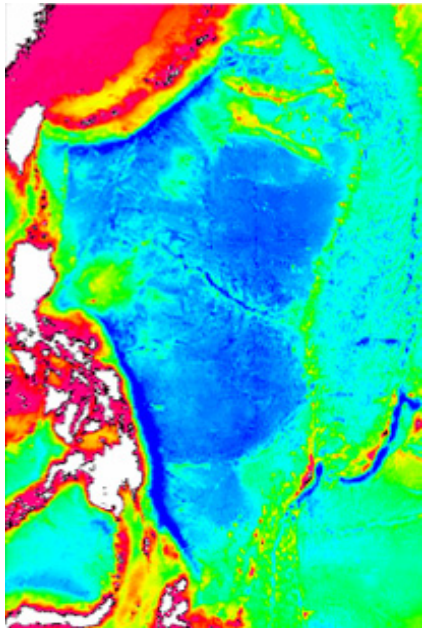
- Yi Chao
  + 1 assistant researcher and a part-time visiting scientist

Students

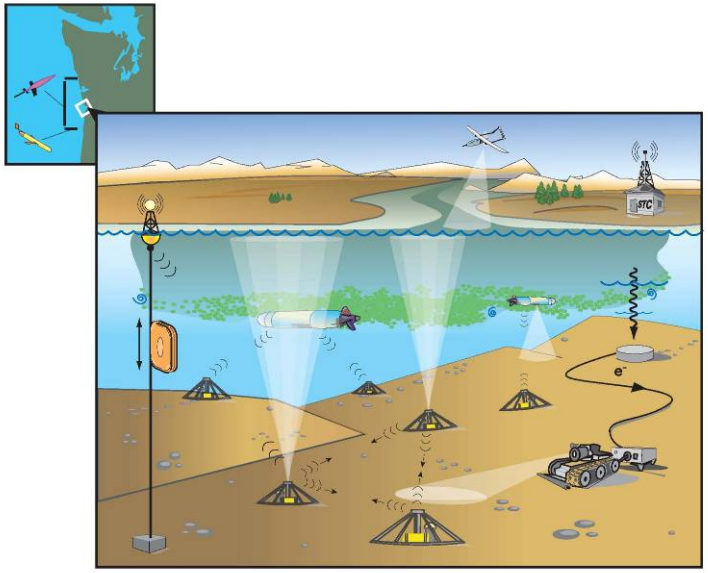
- Nathan Parrish – Ph.D. student at UW Electrical Engineering. He received his B.S.E.E. from the United States Military Academy in 2001. Nathan served as an officer in the U.S. Army from June 2001 – June 2006 and was honorably discharged at the rank of Captain. He is a recipient of the NDSEG Fellowship award. His research Emphasis is on link layer design aspects of acoustic modems.

- Leonard Tracy – Started his PhD in Electrical Engineering at the UW in Fall 2007. His research emphasis is on MAC layer design of acoustic modems.

Related Projects



- ONR Philippine Sea 2009 – Ocean acoustics deep water, QPE DRI (many)
- ONR: Acoustic Seaglider in the persistent surveillance context



- NSF STC Coastal Margin Observation and Prediction (OHSU, OSU, UW)
- NSF ORION …

Resources

On the Web …

- http://www.ee.washington.edu/research/funlab/uan
- http://seahurst.apl.washington.edu
- http://seahurst.apl.washington.edu/mars.php
- http://aloha.apl.washington.edu/wiki/index.php/PMACS_Data
- http://new-ssds.mbari.org/ssdsdata/ssds/generated/qc/device/index.htm
- http://alohamooring.apl.washington.edu

Sponsors

- NASA – National Aeronautics and Space Administration
- NSF – National Science Foundation
- ONR – Office of Naval Research

Thanks to many!

Glossary

A/D: Analog to Digital
ACK: Acknowledgement
ACM: Acoustic Current Meter
AMM: ALOHA-MARS Mooring
AMSR-E: Advanced Microwave Scanning Radiometer - EOS
ARQ: Automatic Repeat-Request
ASIC: Application Specific Integrated Circuit
AS-Modem: Application Specific Modem
AVHRR: Advanced Very High Resolution Radiometer
BPS: Bits per Second
CDMA: Code Division Multiple Access
COCMP: Coastal Ocean Currents Monitoring Program
CRC: Cyclic Redundancy Check
CSMA: Carrier Sense Multiple Access
CTD: Conductivity-Temperature-Depth
CW: Contention Window
DQF: Decision Quality Factor
DSP: Digital Signal Processor
FDMA: Frequency Division Multiple Access
FH-BFSK: Frequency Hopping Binary Frequency Shift Keying
FH-FSK: Frequency Hopping Frequency Shift Keying
FIFO: First In First Out
FPGA: Field Programmable Gate Array
GIS: Geographic Information System
GOES: Geostationary Operational Environmental Satellite
HF: High Frequency
MAC: Media Access Control layer
NEPTUNE: North East Pacific Time-series Undersea Networked Experiments
NS-2: Network Simulator version 2
PO-DAAC: Physical Oceanography Data Active Archival Center
PSK: Phase Shift Keying
RF: Radio Frequency
ROMS: Regional Ocean Modeling System
ROV: Remotely Operated Vehicle
SNR: Signal-to-Noise Ratio
SSP: Sound Speed Profile
SST: Sonar Simulation Toolset
TDM: Time Division Multiplexed
TDMA: Time Division Multiple Access
TL: Transmission Loss
TMI: Tropical Rainfall Measuring Missions Microwave Imager
WHOI: Woods Hole Oceanographic Institution