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

A Smart Sensor Web for Ocean Observation: System Design, Modeling, and Optimization

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Agenda

- Introduction
- Technical Objectives
- Mooring Sensor System
- Acoustic Seagliders
- Acoustic Communications and Networking
- Satellite Sensors
- Ocean Modeling

Introduction

- As the effects of **global warming** and associated **climate change** become more pronounced, it will be ever more important to accurately know the state of the ocean and to be able to predict it significantly into the future.

- Earth's oceans however, are clearly **under sampled** and **unexplored (up to 90%)**. Over half the world's population lives within 200 km of a coastline.

- Efforts are underway to rectify this situation.

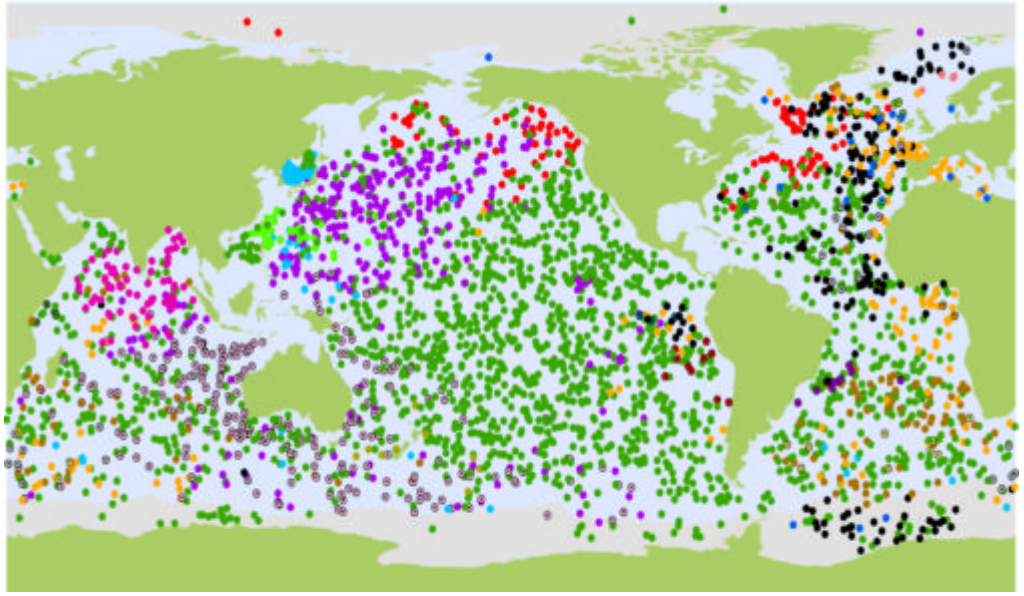
- On global scales, the Integrated Ocean Observing System (IOOS) within the Global Earth Observation System of Systems (GEOSS) is in the process of bringing together **satellite**, **in situ observations**, and **modeling** to provide products on various time and space scales.

GROUP ON EARTH OBSERVATIONS

Introduction

- Satellite observations include **sea surface height** altimetry (for heat content and near surface currents), scatterometry for **wind speed and direction**, and infrared radiometers for **sea surface temperature**.

- In situ elements include a near-global distribution of **3200+ Argo profiling floats** to provide sparse (incoherent, 300 km spacing) in-situ temperature and salinity data, volunteer **observing ships** (typically temperature profile data), and **arrays of moorings**, e.g., the TAO-TRITON array in the equatorial Pacific primarily for El Nino monitoring.



Introduction

- **Numerical modeling** is just now reaching the state of being able to assimilate with adequate resolution the satellite altimetry and in situ data, to **produce a 4-dimensional ocean state that is dynamically consistent.**

- However, there are still major discrepancies when one looks at the total heat and fresh water budget – **various models and independent data driven results** for the fraction of sea level rise attributable to ocean thermal expansion and to ice melting **are inconsistent within their respective formal error bars**.

- Even just for ocean heat content change, different analysis groups produce **estimates that differ by more than the formal error bars**, with a spread that is about half the nominal change in heat content over the last 5 decades.

Introduction

- In a research-oriented effort, NSF has initiated the Ocean Observatories Initiative to **provide leading edge infrastructure for long-term sustained observations** at a few selected sites.

- There are many other efforts to develop and sustain long-term ocean observing capability, to complement the satellite data collected by NASA and other space based Earth observing systems.

Project Summary

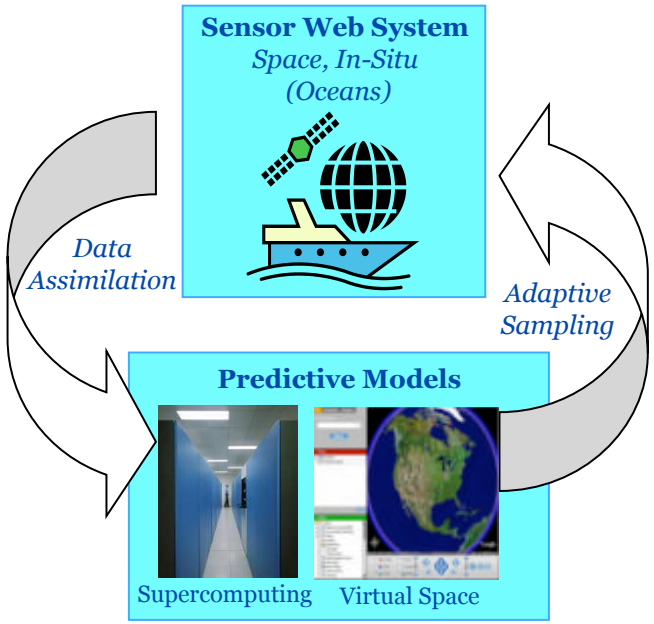
- We have been developing a smart sensor web that combines many of the essential elements of an ocean observing system: a mix of **fixed and mobile in-situ sensors and NASA satellite sensors** that perform a combination of spatial and temporal sampling; and an **ocean model**, embodying all our best and current knowledge of the physics, embedded in a data assimilation framework, that can be used in an adaptive sampling mode to jointly optimize sampling and resource allocation for improved science data.

- For all the pieces to work together, the **power**, **communications**, and **timing network infrastructure** must be in place, linking the web between the in-situ and space-based sensors.

We report here on the development of various elements of such a sensor web: **(a)** a cable-connected mooring system with a profiler under real-time control with inductive battery charging; **(b)** a glider with integrated acoustic communications and broadband receiving capability; **(c)** satellite sensor elements; **(d)** an integrated acoustic navigation and communication network; and **(e)** a predictive model via the Regional Ocean Modeling System (ROMS).

Technical Objectives

- Implement a **semi-closed loop dynamic sensor network** for ocean observation and modeling.
- 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.

Relevance to Decadal Missions

Tier 1

- ICESat-II
- DESDynI

Measuring ice sheet mass balance and predicting the response of ice sheets to climate change and impact on the sea level → sensor network for ice extent and thickness forecasting (DARPA)

Tier 2

- HyspIRI
- SWOT

Item of relevance in HyspIRI includes integration of terrestrial and aquatic (inland, coastal, and oceanic) ecosystem studies: strong data integration component of current task (space, surface ocean, underwater ocean) in the coastal zones.

Tier 3

- XOVWM

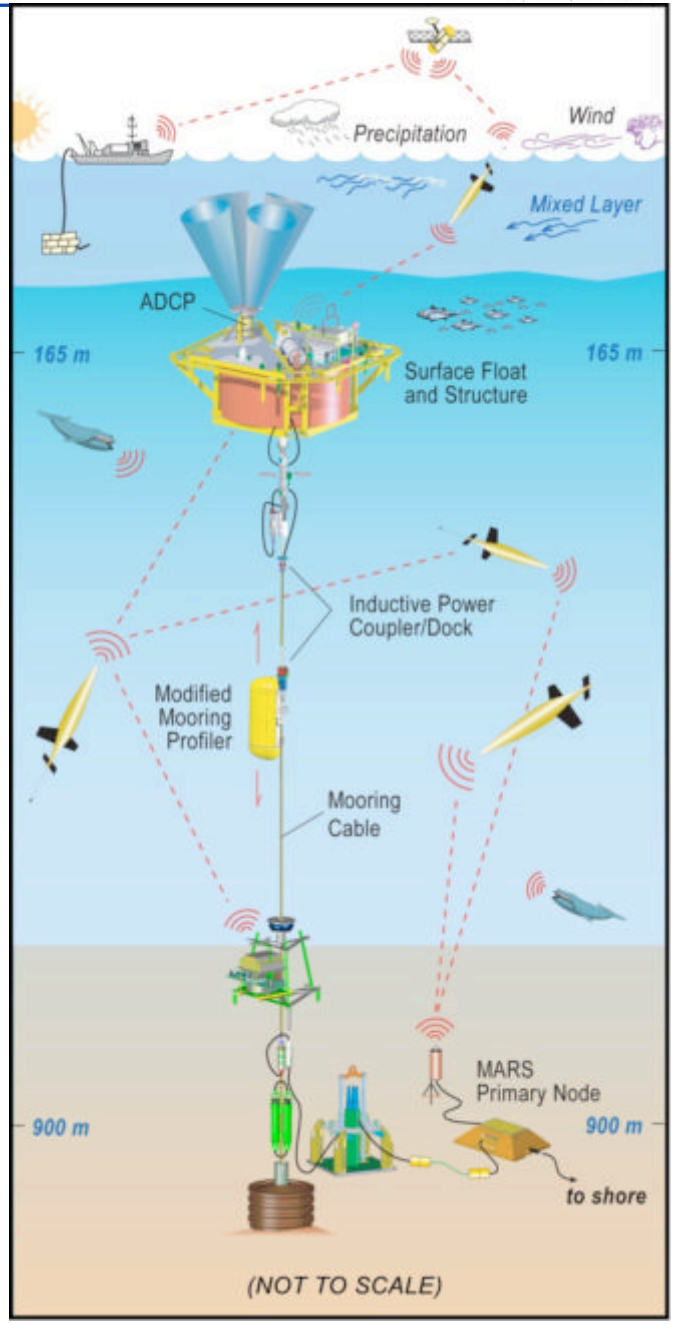
Strong Mission buy-in for SWOT and XOVWM (see AIST'08 proposal) → Virtual ocean observatory (VOO) 1) to support SWOT mission planning, 2) to serve as a vanguard for fusing SWOT, XOVWM, and in-situ data sets through fusion of OSTM (SWOT proxy) and QuikSCAT (XOVWM proxy) data with in-situ data, and 3) to serve as a feed-forward platform for high-resolution measurements of ocean surface topography in island and coastal environments utilizing space-based and in-situ adaptive sampling.

1 Mooring Sensor System

Mooring Sensor System

- **Status:** The current hardware implementation was deployed and operated on the Seahurst Observatory (a high school marine center) in 40 m water depth in Puget Sound, just west of Sea-Tac International Airport.

- In the future it will be deployed at the MARS cabled observatory in Monterey Bay in 1,000 m water depth and at the ALOHA Cable Observatory site 100 km north of Oahu in 5,000 m water depth.



ALOHA-MARS Mooring (AMM) System

Mooring Sensor System

The basic mooring concept is to provide the infrastructure to distribute power, communications, and precise and accurate timing throughout the water column.

- **Features**
  - Enables adaptive sampling
  - Distributes power, communications, time throughout the water column
  - ROV servicing

- **Major Components**
  - **A near-surface float** at a depth of 165 m with a secondary node and suite of sensors
  - **An instrumented motorized moored profiler** moving between the seafloor and the float that will mate with a docking station just beneath the float for battery charging
  - **A secondary node** on the seafloor with a suite of sensors.

Mooring Sensor System

Both secondary nodes have remotely operated vehicle (ROV)-mateable connectors available for guest instrumentation.

- The profiler has real-time communications with the network via an inductive modem that provides some remote control functions to allow the sampling and measurement capabilities to be focused on the scientific features of greatest interest.

- The **power**, **two-way real-time communications** and **timing** provided by cabled seafloor observatories will enable this sensor network, the adaptive sampling techniques, and the resulting enhanced science.

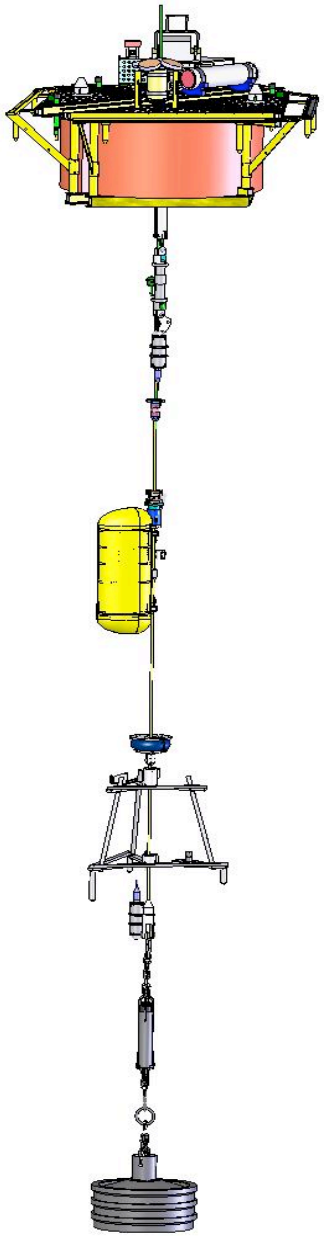
Puget Sound Deployment

- Identified "target of opportunity" to perform field demonstration of Seagliders in summer of 2007:
  - Helped mature architecture and con-ops concept.
  - Acquired initial data for ROMS facilitating early evolution of the model.
  - Learned about system integration problems.
  - Further refined requirements that are guiding technology development efforts.

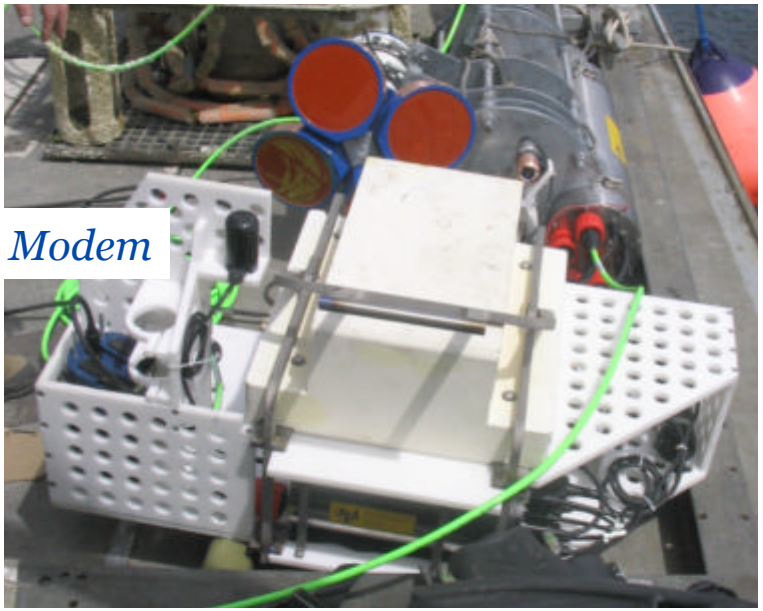
Puget Sound: Theater of Operations for Summer '07

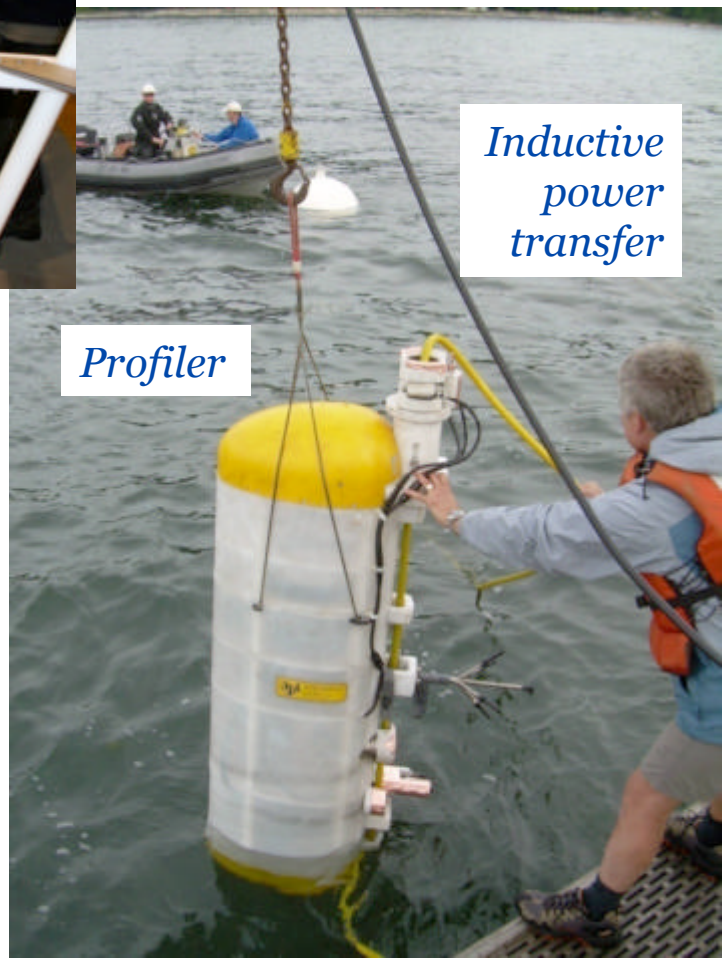
Mooring Sensor System

AMM components



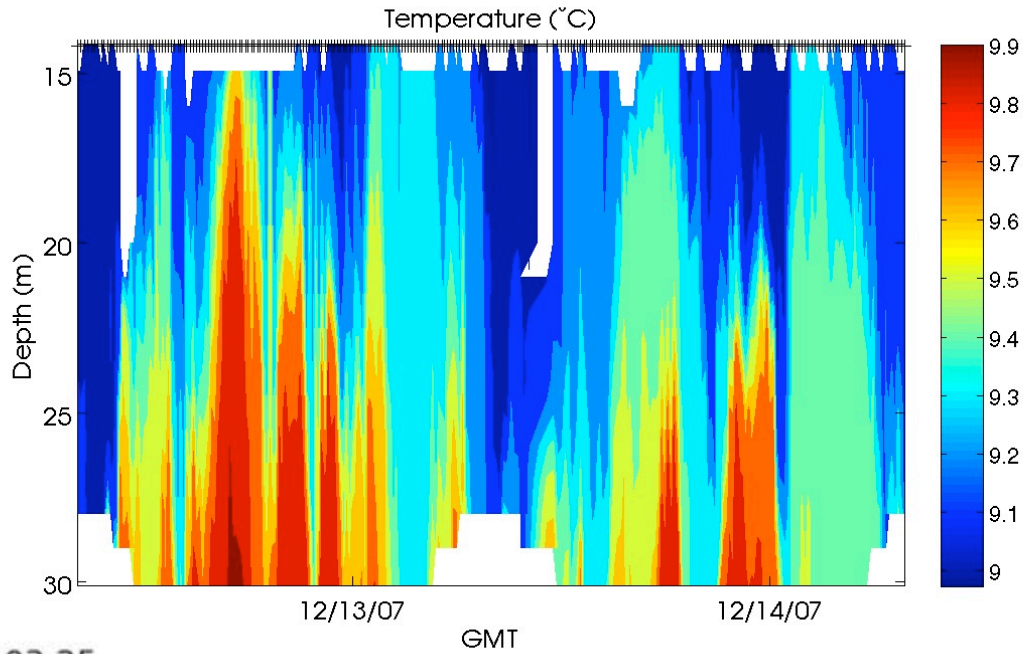
Modem

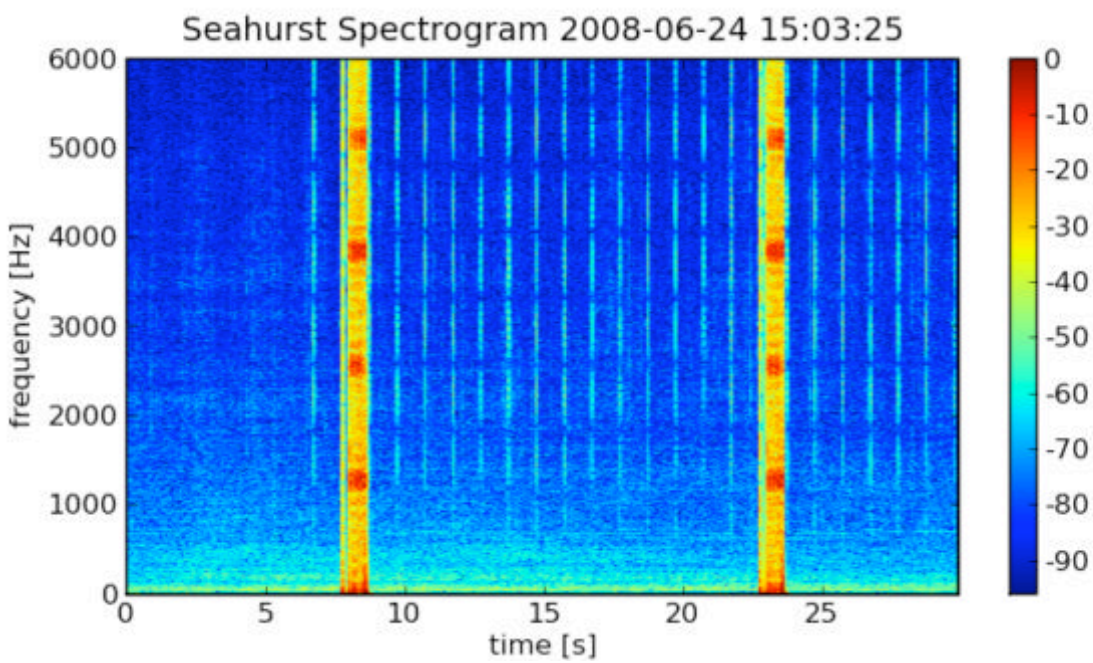




Mooring Sensor System

Temperature as a function of depth (vertical axis) and time (horizontal axis). Warm (and salty) bottom intrusions associated with tidal flow are clear.





Hydrophone spectrogram showing two strong modem signals (saturated, aliased here) and the ADCP transmissions at 1 second intervals.

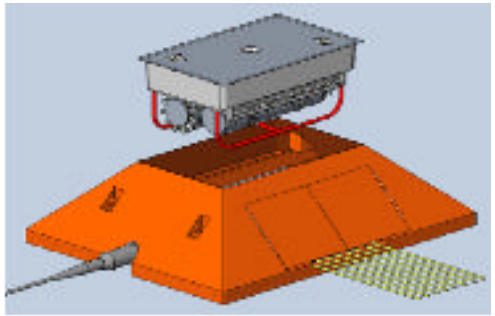
MARS System

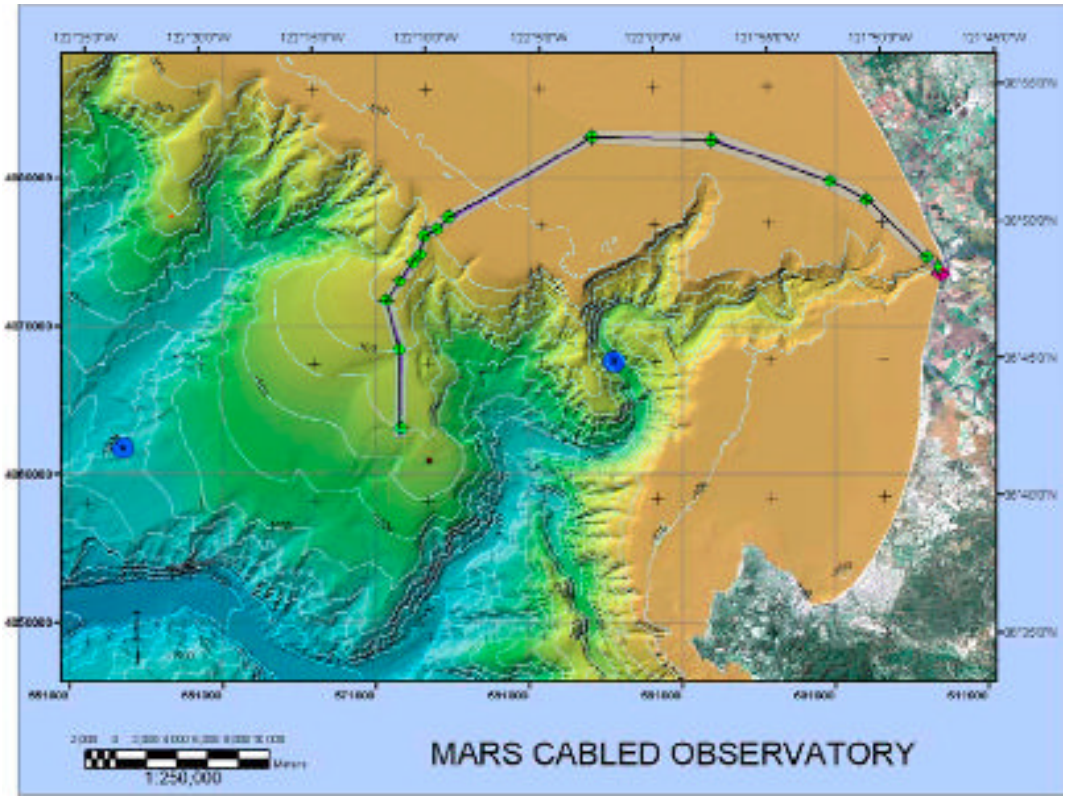
- Original intent was to deploy the NSF-funded ALOHA-MARS Mooring (AMM) system, with NASA funded modems on the MARS cabled observatory system in April 2008, and then execute the end-to-end demonstration with gliders (with modems) and modeling/ data assimilation
- The MARS system suffered a major setback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

Mooring Sensor System

MARS System

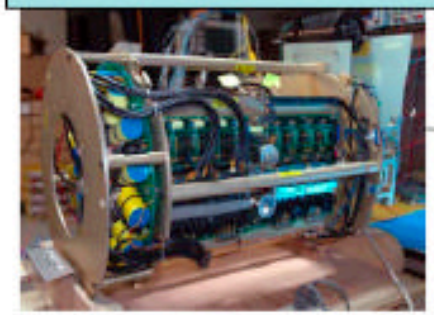
- Monterey Bay Aquarium Research Institute
- Part of NSF Ocean Observatories Initiative
- Monterey Bay
- Node on Smooth Ridge at 870 m
- Delivers nominal 9 kW of power
- Fibers providing bandwidth of 2 Gb/Sec per fiber pair: 2 fiber pairs
- 8 science ports for science instruments
- Electronics in a removable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





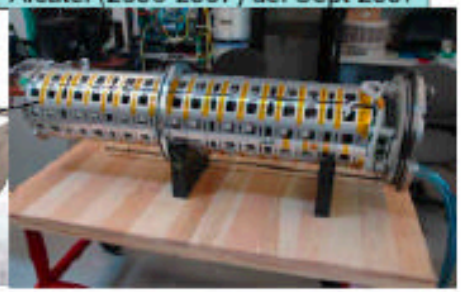
Mooring Sensor System

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

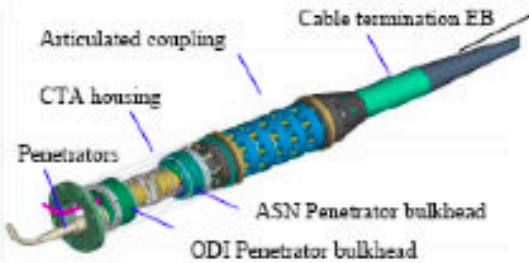


Status: MARS Sub-Systems

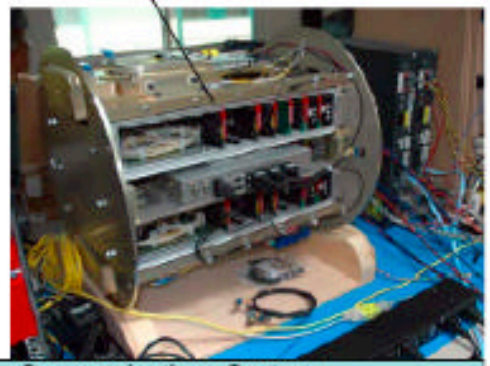
MV 10kV Power Converters
JPL (2003-2005)
Alcatel (2006-2007) del Sept 2007



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

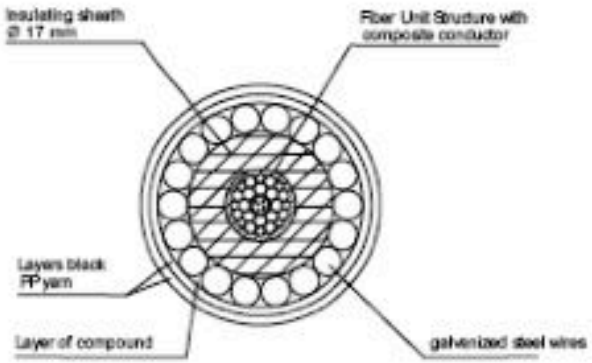


Cable Termination Assembly
Alcatel: delivered Jan 2005



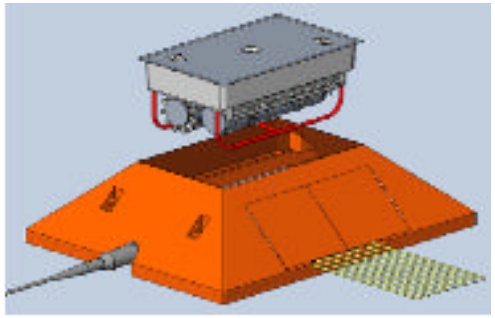
Communications System
Woods Hole: Del July 2005: accept test June 2007

Mooring Sensor System



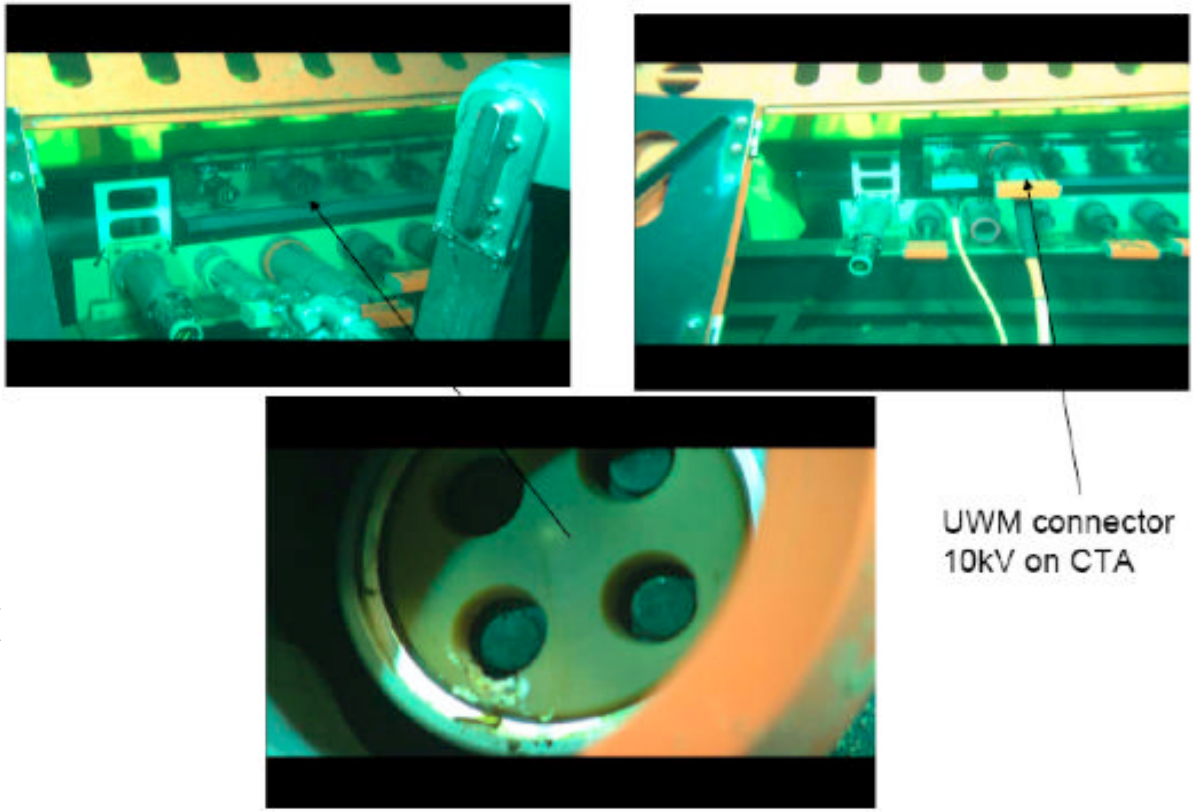
Cable installation in Monterey Bay
March 2007

Mooring Sensor System



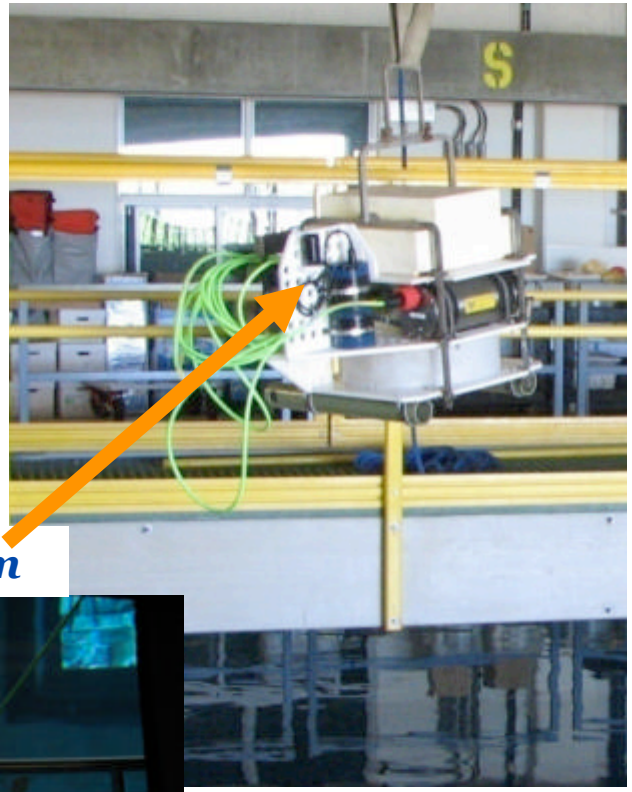
MARS - Node Installation
26 February 2008

- 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



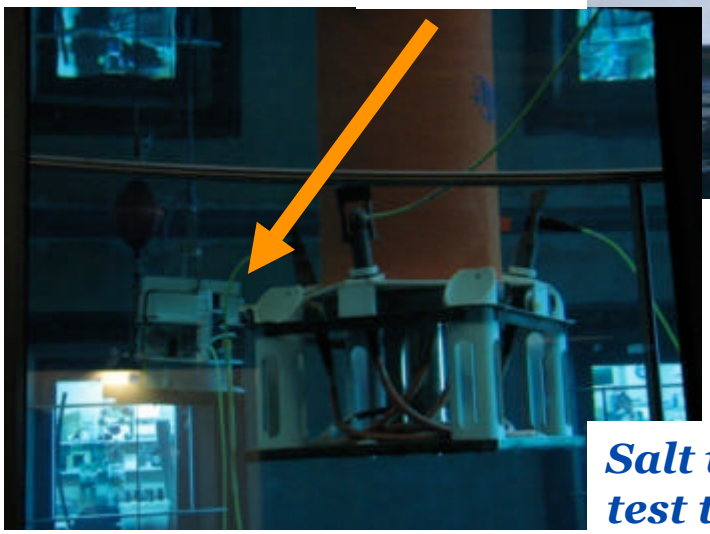
Mooring Sensor System

- 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

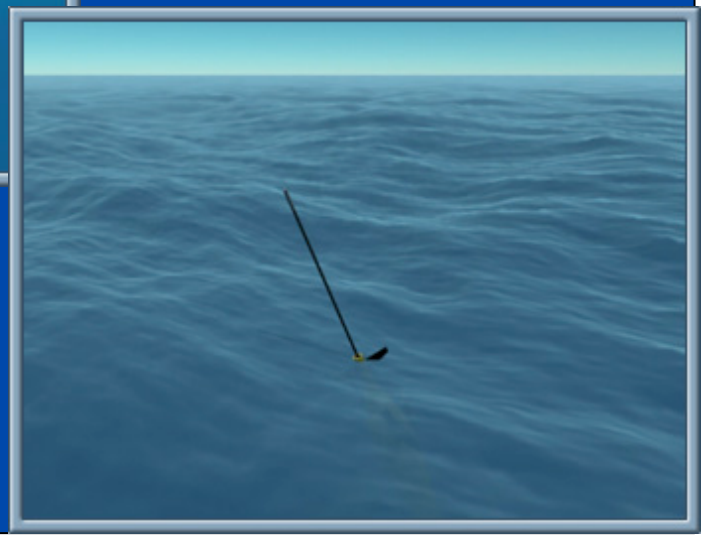
Field Plans

- In the future AMM will be deployed at the MARS cabled observatory in Monterey Bay in 1,000 m water depth and at the ALOHA Cable Observatory site 100 km north of Oahu in 5,000 m water depth.

- Perform end-to-end test/demonstration with updated ROMS models

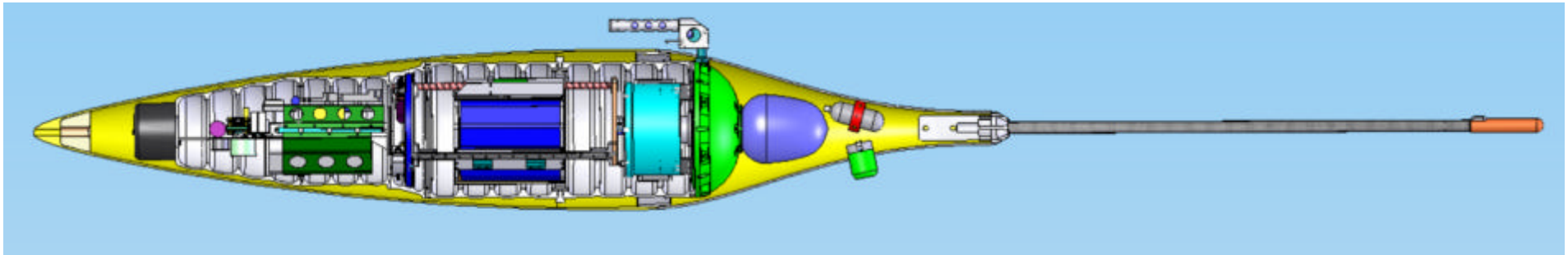
- **Important to note that the failure at MARS was very unique: first ROV deployment at 930 meters of a one-of-a-kind. complex, high-tech connector, only 2 or 3 of which have been manufactured. The ocean community is pushing the envelope with this new infrastructure.**

2 Acoustic Seagliders



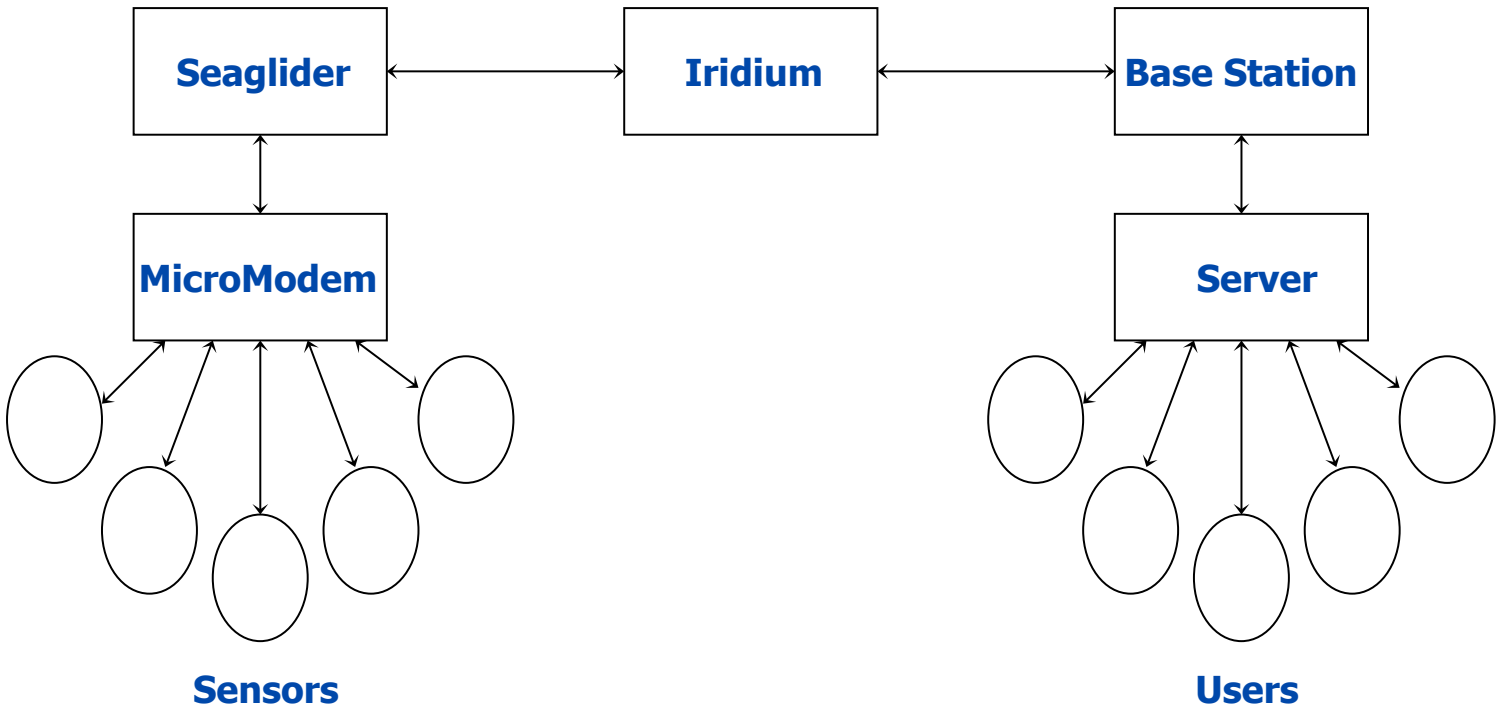
Acoustic Seagliders

- ½ knot at ½ W
- Up to 1,000 m dives
- > 6 months; 3,000 km; 600 dives
- Temperature, salinity and other measurements
- Now with a broadband hydrophone (10 Hz – 30 kHz) and a WHOI acoustic micromodem, operating in the 23 – 27 kHz band.



The acoustic Seaglider. The hydrophone is in tail cone at the top, the acoustic modem transducer beneath it. The body contains (left to right) an acoustic emergency locator transponder/altimeter, electronics and low voltage batteries, high voltage batteries on a mass shifter for changing pitch and roll, buoyancy engine (oil pump) with internal and external oil bladder, and GPS and Iridium antenna.

Communications Reachback System



Reachback Example: HTML

Added communications to Seaglider Base Station

- Live updating, just as traditional code
  - Glider-by-glider summaries
  - Sensor message counts
  - Latency monitoring
  - CCL Message decoding
- Password protected pages

Seaglider sg116 Telemetry

Connectivity

Log Starts: **2007-09-26 16:15:20Z**
Log Ends: **2007-10-11 12:04:40Z**
Duration: **355.8** hours.

Active Polling

Total: 3850 cycles.

- Rate **80 bps FSK: 3850** cycles.

- From **"Seahorse": 290** cycles.
- From **"Unicorn": 298** cycles.
- From **"Macrura": 297** cycles.
- From **"Kelp 1": 294** cycles.
- From **"Slocum SSC": 292** cycles.
- From **"UT Bottom Node VS 1": 632** cycles.
- From **"UT Bottom Node VS 2": 640** cycles.
- From **"Seaglider 106": 48** cycles.
- From **"Seaglider 107": 258** cycles.
- From **"Seaglider 116": 280** cycles.
- From **"Seaglider 117": 269** cycles.
- From **"Seaglider 118": 252** cycles.

Throughput: Received Data

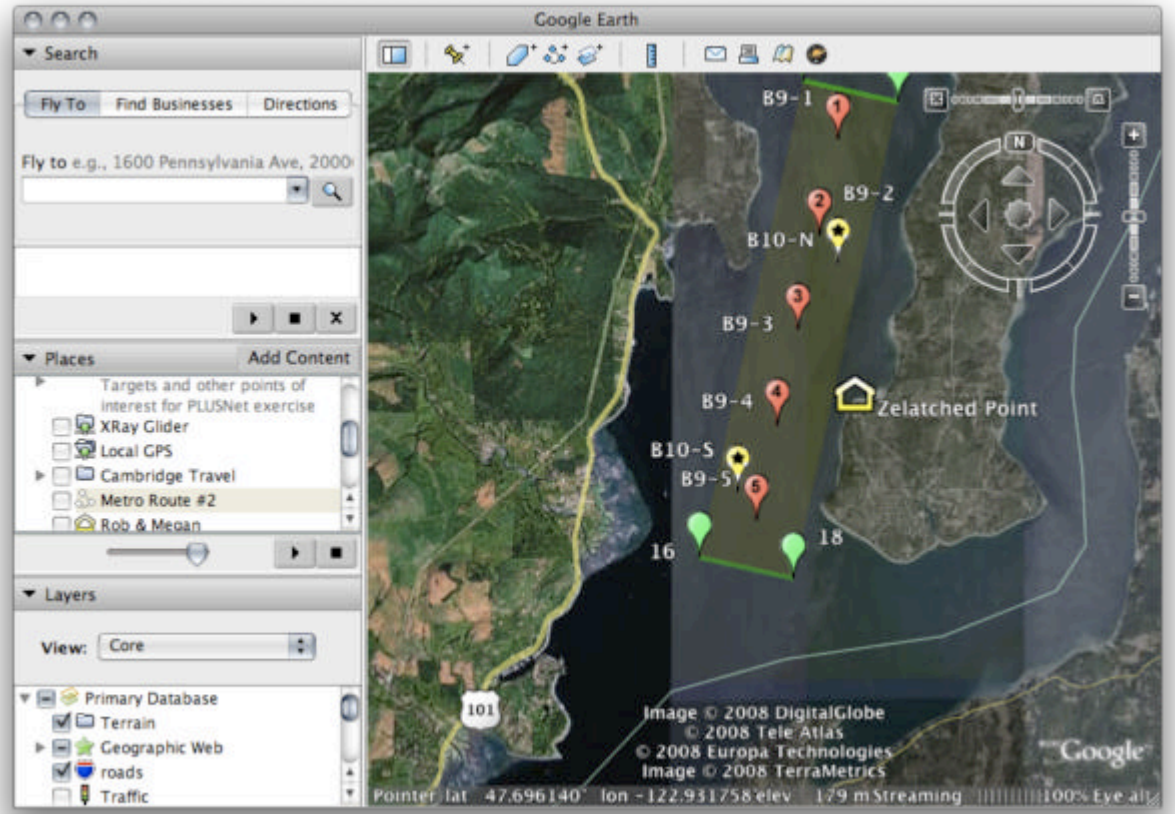
Total: 5863 packets. **183.2** KB.

- From **"Surface Vessel": 1** packets. **0.0** KB.
- From **"Seahorse": 263** packets. **8.2** KB.
- From **"Unicorn": 108** packets. **3.4** KB.
- From **"Macrura": 132** packets. **4.1** KB.
- From **"Kelp 1": 358** packets. **11.2** KB.
- From **"XRay": 1** packets. **0.0** KB.
- From **"Unknown Platform (src=8)": 3** packets. **0.1** KB.
- From **"Kayak Dee": 50** packets. **1.6** KB.
- From **"WHOI Gateway Buoy 2": 215** packets. **6.7** KB.
- From **"WHOI Gateway Buoy 3": 53** packets. **1.7** KB.
- From **"Slocum SSC": 253** packets. **7.9** KB.
- From **"Kelp 2": 254** packets. **7.9** KB.
- From **"Unknown Platform (src=16)": 26** packets. **0.8** KB.
- From **"R/V Defender": 8** packets. **0.2** KB.

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
- Server files can be password protected



Acoustic Seagliders

PLUSNet07 Experiments at Dabob Bay, September – October 2007

Zelatched Point

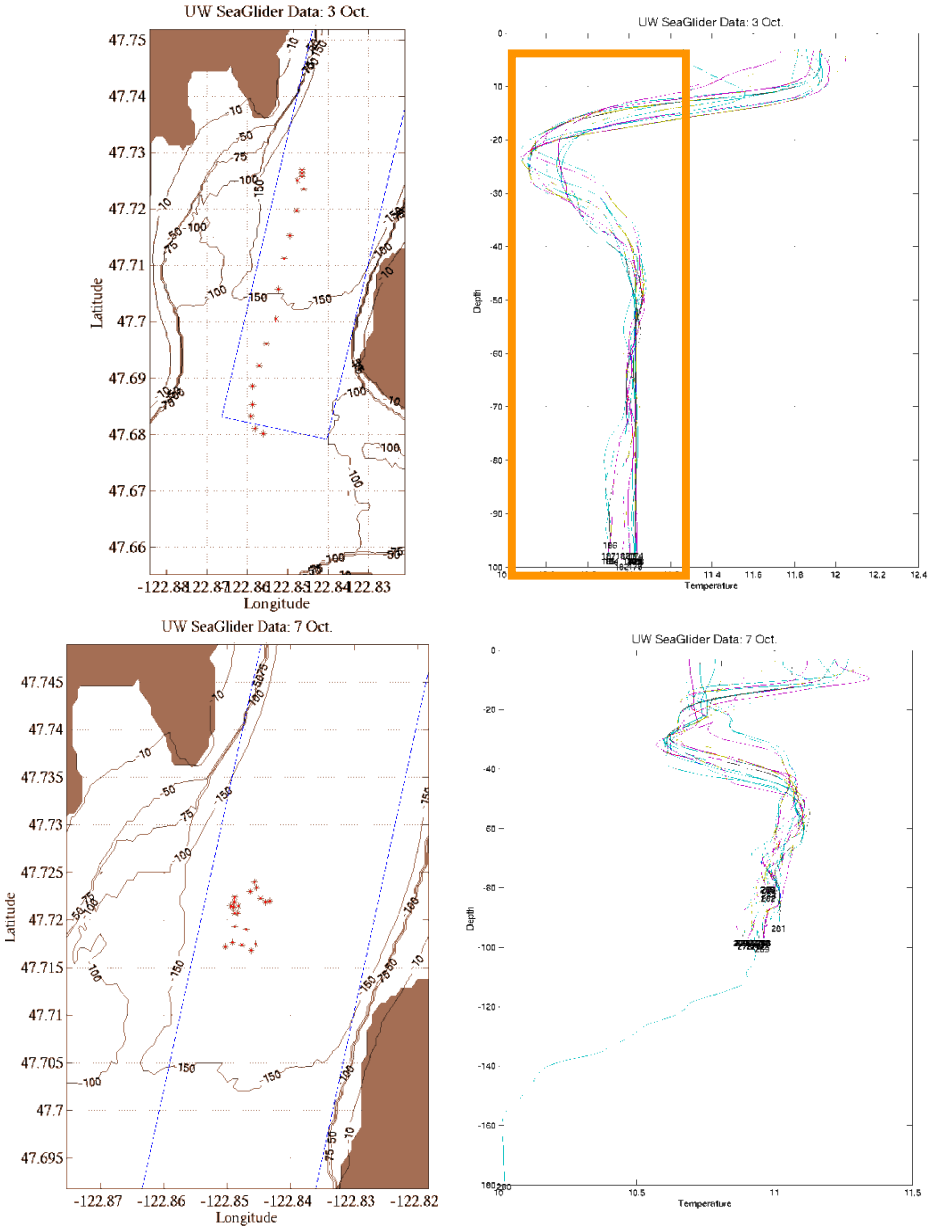
Dabob Bay

Seattle APL

Acoustic Seaglider Preparation, 19 September 2007

Google Earth views

Acoustic Seagliders

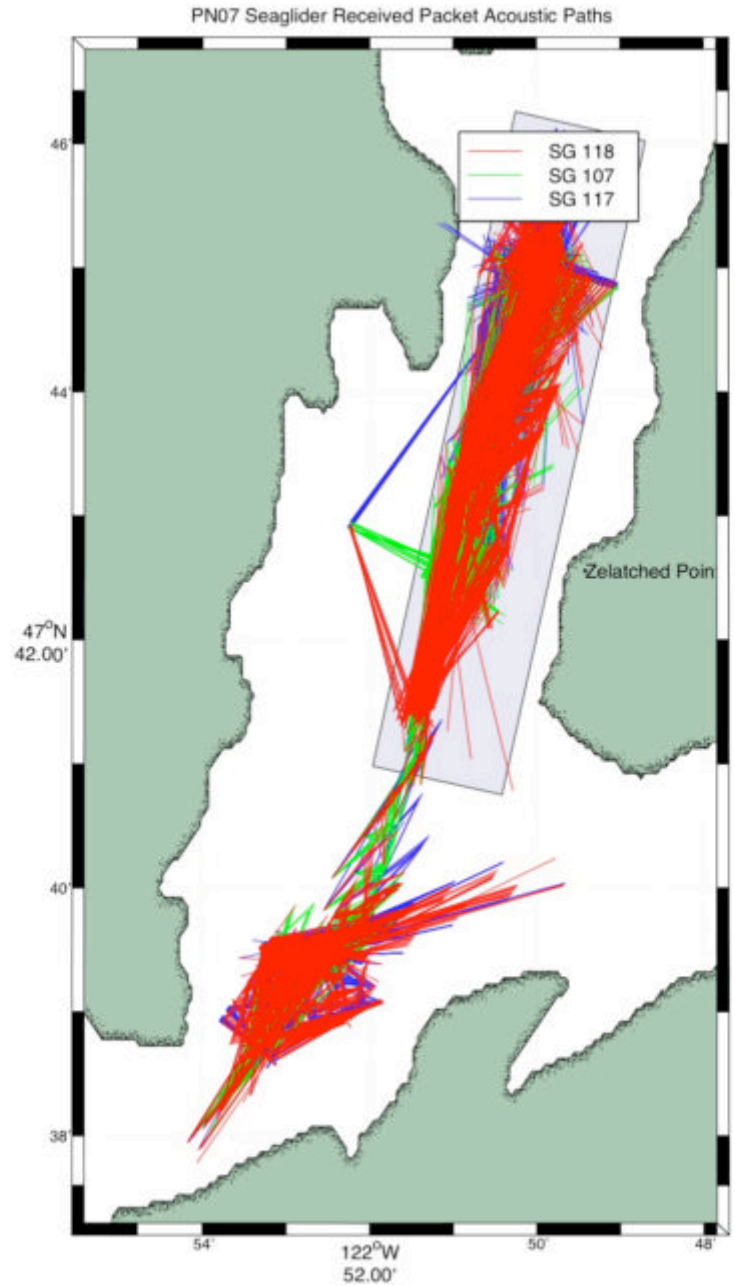


Profile Data

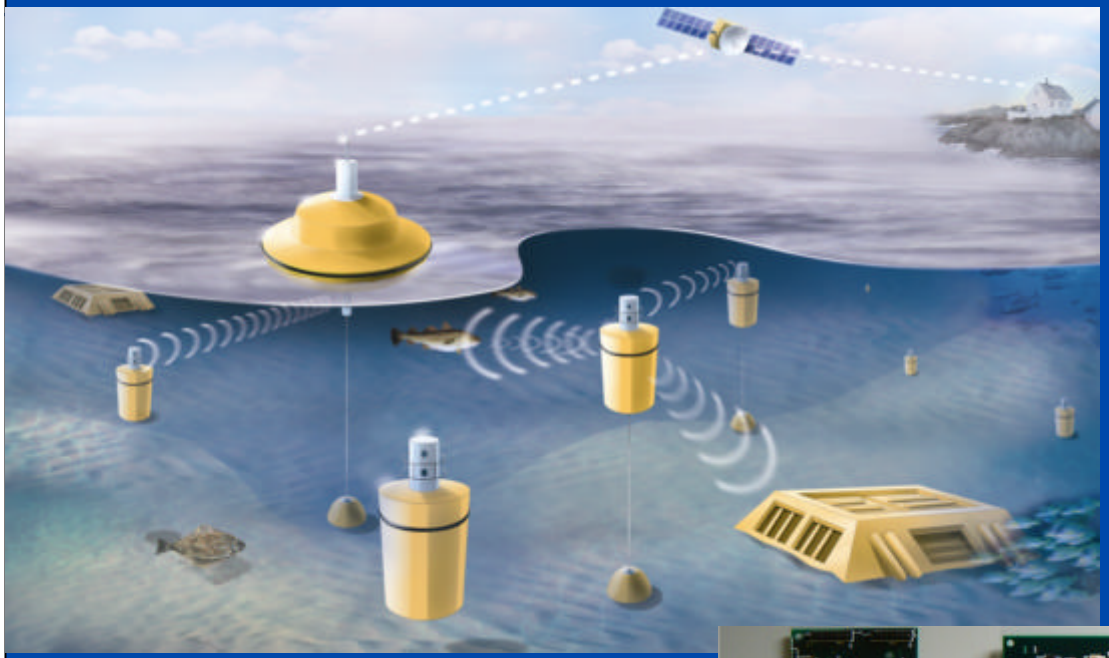
- Seaglider data assimilated by MIT
- Over 3000 profiles total
- Here show change from 3 to 7 October

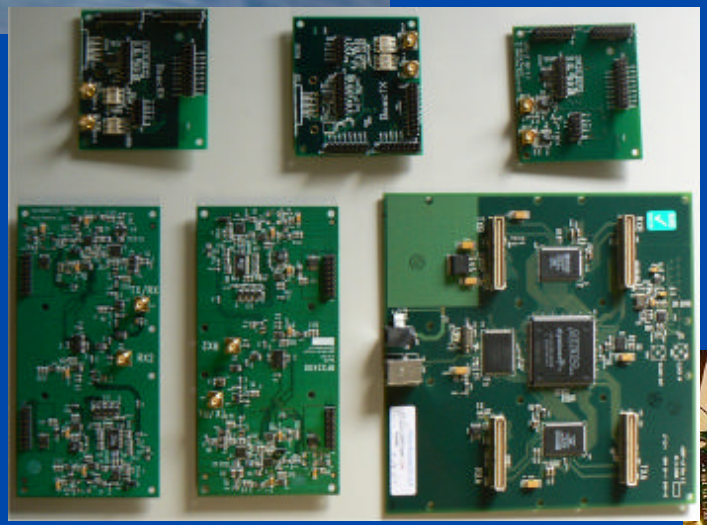
Acoustic Seagliders

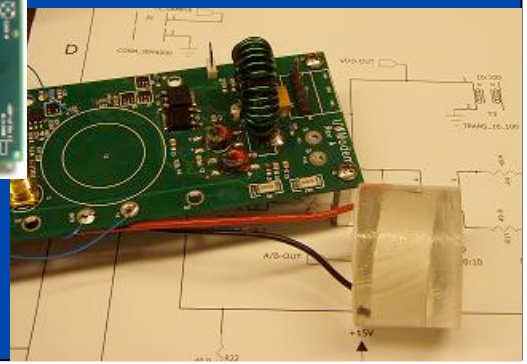
Acoustic Communications Coverage



3 Acoustic Communications and Networking







Acoustic Communications and Networking

- The underwater ocean environment, especially in shallow water, is a very challenging medium for reliable communication.

- Since radio frequency (RF) waves attenuate extremely rapidly underwater, **acoustic signaling** is preferred.

- Low acoustic sound speed (1,500 m/s) introduces **long propagation delays and extensive time spreading** of the received signal.

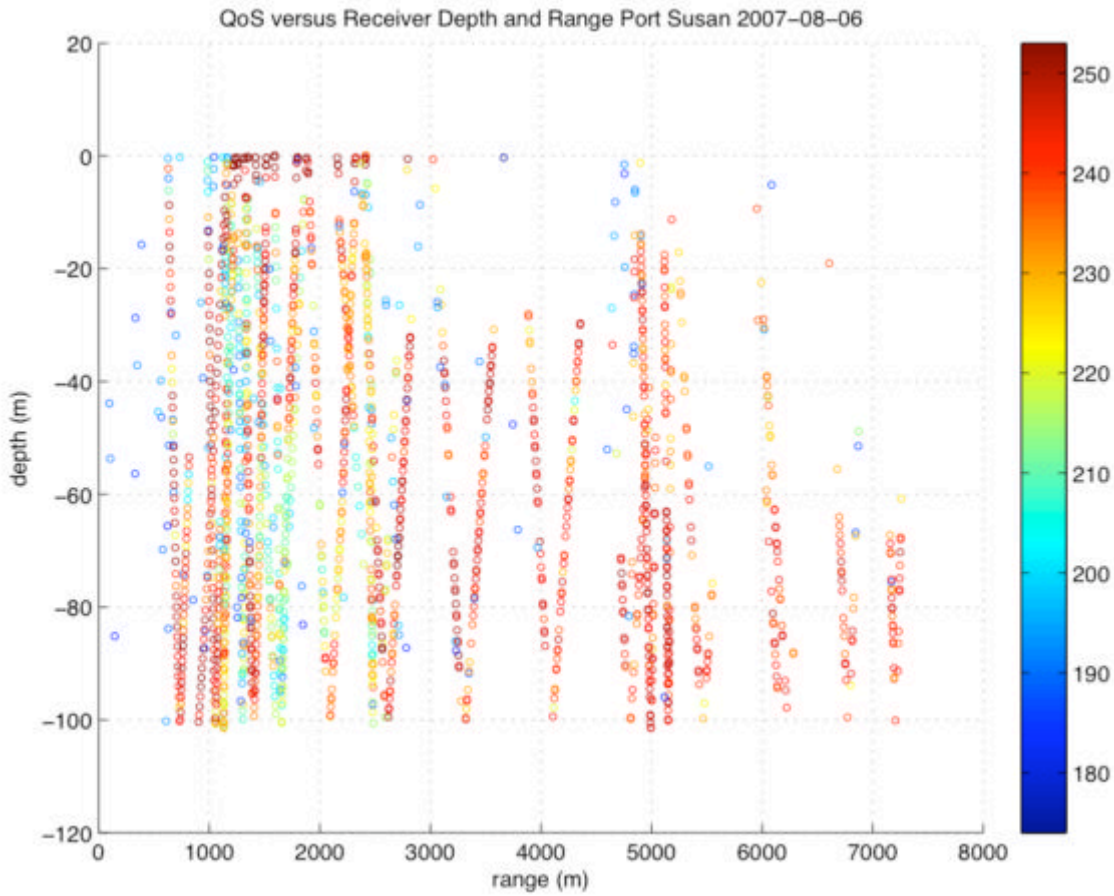
- The shallow ocean environment is a dense scattering environment and is generally highly time varying. Acoustic signals attenuate very quickly as frequency increases; hence, the underwater channel is **bandwidth limited**.

- Furthermore, underwater Seagliders are low power battery operated devices. This imposes practical constraints on the complexity of communications hardware.

Acoustic Communications and Networking

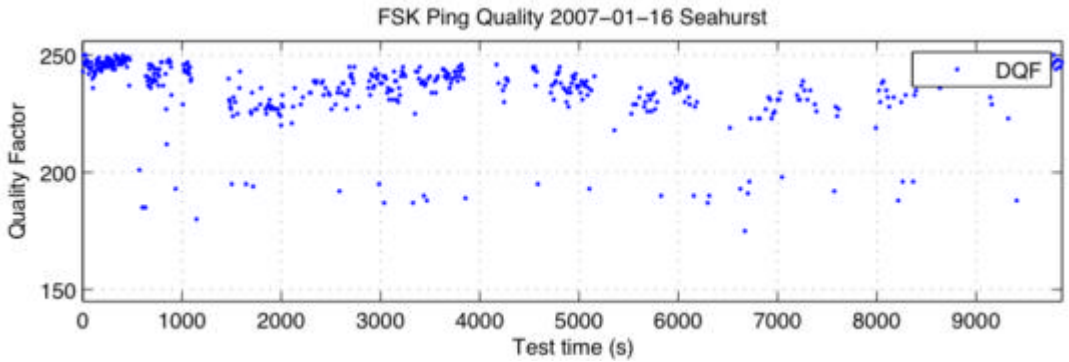
- Testing has taken place of acoustic communications between gliders and between gliders other platforms, both fixed and mobile, at the surface, in the water column, and on the bottom.

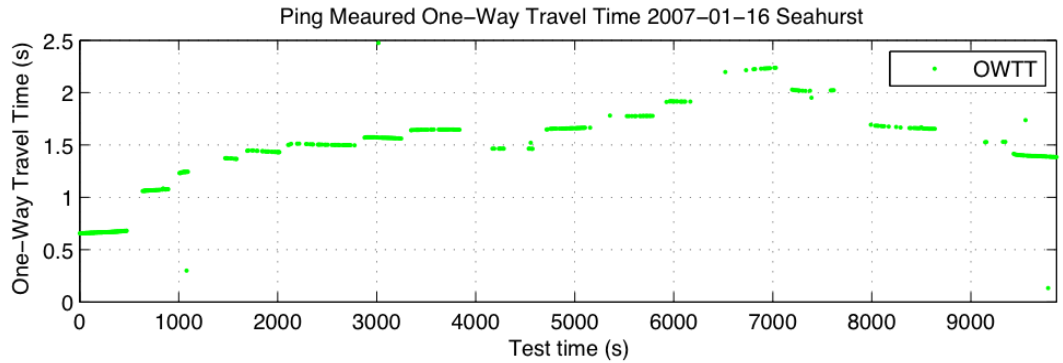
Signal quality versus range and depth. Signal quality ranges from 253 (high signal-to-noise ratio) to 100 (low SNR). One glider is sitting on the bottom communicating with another glider making multiple dives. Frequency shift-key (FSK) signal coding at 80 bits per second (b/s) used, with reliable results to 4 km and less reliable results to 7 km. Data from Puget Sound tests conducted summer 2007.

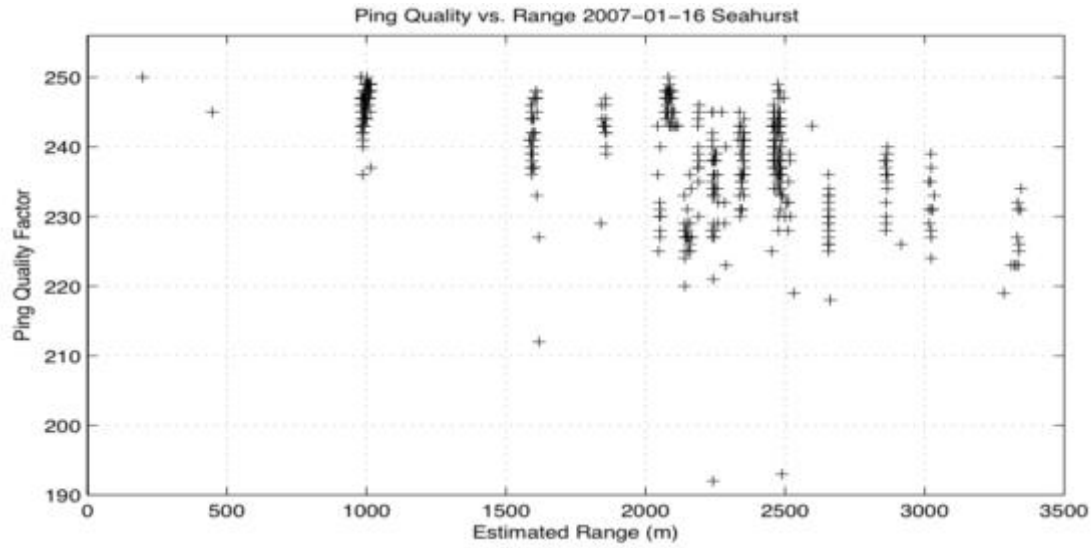


Modem Tests at Seahurst

- 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
- The lower ranges than in the first test mentioned were likely a result of the much shallower bottom.







Acoustic Communications and Networking

- In more recent testing, phase-shift-key (PSK) signal coding (coherent vs. the incoherent FSK) was used. In this case 240 b/s and 5200 b/s were obtained between a glider and a surface gateway buoy with a modem suspended beneath; this modem has a 4-element hydrophone-receiving array.

- Further, a go-to-surface command was sent to the glider to demonstrate **real-time vehicle control** via the acoustic communications channel.

- These test results confirm that the acoustic modem can perform adequately both from a communications perspective as well as for navigation.

Summary of Accomplishments

1. Modeling Performance of FH-FSK acoustic modems
2. Capacity of Underwater Channels
3. Enhanced OFDM system design and Performance evaluation
4. Experimental Results of Orthogonal Frequency Division Multiplexing (OFDM) on Lake Washington
5. New Multiple Access Protocols for Underwater Networks
6. Contributions to network simulation (ns-3) software and Micromodem API

Acoustic Communications and Networking

- The boundary conditions for a shallow body of water, i.e. the surface and bottom profiles, exert considerable impact via energy loss and scattering of acoustic waves, and thus on the **link capacity**.

- In **terrestrial communications**, typical propagation models between two fixed nodes such as the two-ray model provide a relation for signal power attenuation as a function of transmitter - receiver separation that is **independent of frequency**.

- Therefore, given a pair of nodes communicating through an additive white Gaussian noise (AWGN) channel at some fixed transmit power and bandwidth, the **capacity is only a function of distance**.

- **However, in underwater communications, both the attenuation and noise are known to be strong functions of frequency.**

Acoustic Communications and Networking

- Acoustic propagation is characterized by the sound speed profile, which can vary greatly even in shallow water.

- The sound speed profile can show great variability at different times of year and under different weather conditions. Typical non-uniform sound speeds with respect to water depth cause a 'bending' of acoustic pressure waves.

- We have shown that the c**hannel sound speed profile and boundary characteristics** play a large role in **determining the capacity between a source and receiver** pair.

- Additionally, we have shown that **two different receivers at the same distance from a transmitter have very different capacities** depending on their **vertical location** relative to the transmitter and the **sound speed profile**.

Acoustic Communications and Networking

- Our MAC analysis shows that networks using the WHOI Micromodem can increase throughput over pure ALOHA by implementing a **backoff rule assuming knowledge of the expected number of contending nodes and the maximum propagation delay**.

- Sensitivity analysis suggests that this is a robust approach.

- Despite MAC improvements to a WHOI Micromodem, **the achievable rate with current technology is a small fraction of the theoretical channel capacity**.

- This points to the **need for continued enhancements** to cross layer design approaches that **jointly optimize both the link and MAC** to achieve the potential of the acoustic channel.

Acoustic Communications and Networking

- Design philosophy for the MAC layer: avoid the complexities of network timing synchronization while pursuing enhanced channel utilization; → simple collision avoidance mechanisms, leading to the choice of ALOHA with a random back-off:
  - Our MAC protocol is consistent with existing underwater acoustic modem hardware, such as the WHOI Micromodem and can be readily implemented for field evaluations.
  - It can also be used with little or no modification in other modems such as the one by Teledyne Benthos.
  - In terms of MAC performance analysis (conducted with the popular freeware network simulator ns-2), a suitable abstraction is used for link losses within the protocol simulation.
  - To the best of our knowledge, this represents one of the first cross-layer attempts for underwater network evaluation within an open-source simulation environment.

Lessons

- Physical, MAC, and Network layer protocols must be designed to specifically compensate effects of the underwater channel
- No single protocol will be ideal for all underwater channels
  - Better simulation tools needed for initial characterization of performance in different underwater channels
- MAC and Routing layer designs and simulations must be complemented by real-life experiments.

Next Generation Underwater Acoustic Modem Development

- Key component of Technology Roadmap effort

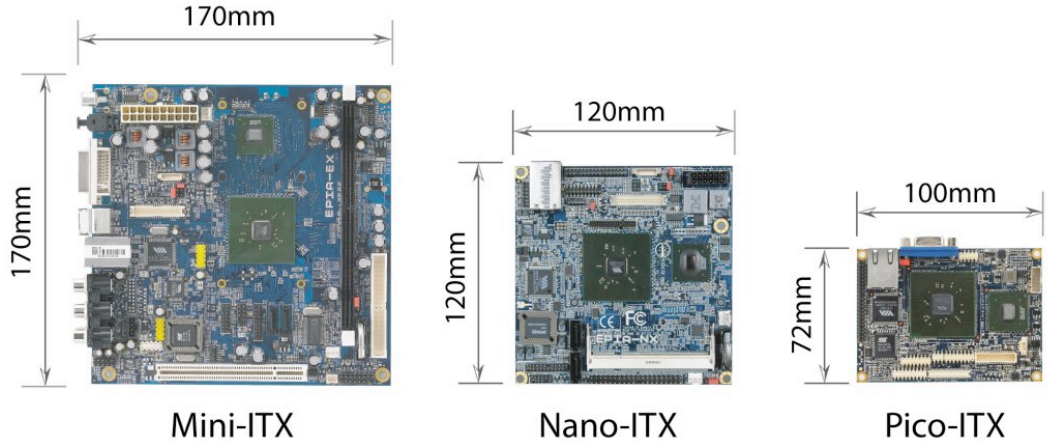
- Three hardware platforms identified to meet level-1 requirements
  - ITX-based platforms
  - GNU-based platform
  - SORA-based platform

- Established revised plan/schedule (based on review outcome) to complete:
  - Technology roadmap
  - Software acoustic modem prototypes and lab testing
    - Cost sharing with UW funds
  - Software acoustic modem design reviews

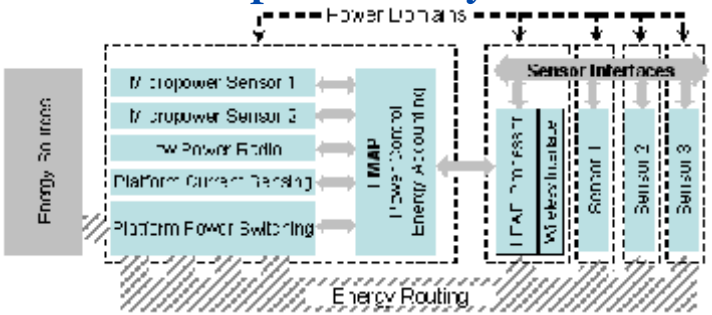
Acoustic Communications and Networking

ITX-based Architecture

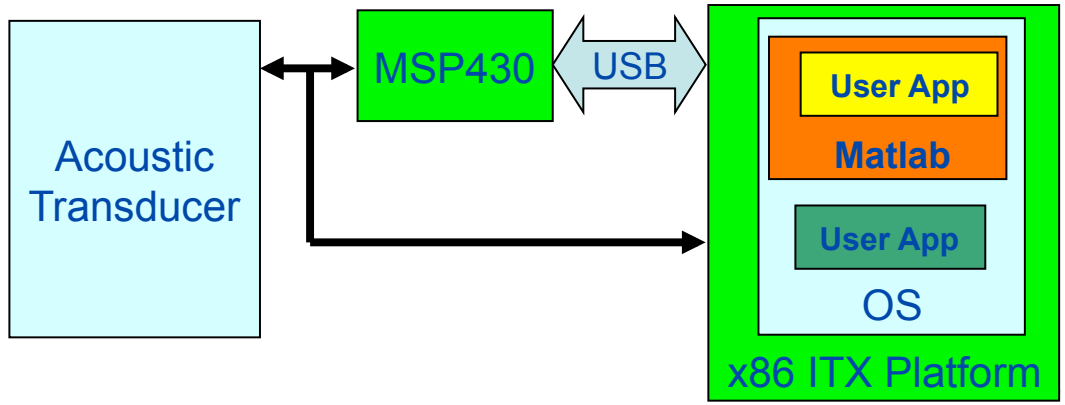
- Phase I - Mini-ITX
- Standardized I/O
- Portable
- Expandable
- Additional peripherals
- Future size reduction available
- Low-cost digital processing
- Compatible with modern COTS operating systems and software
- Compatible with low-power
- Good HW/SW migration path
- Ruggedized via low-cost approach (Pelican case housing)



Low-power subsystem



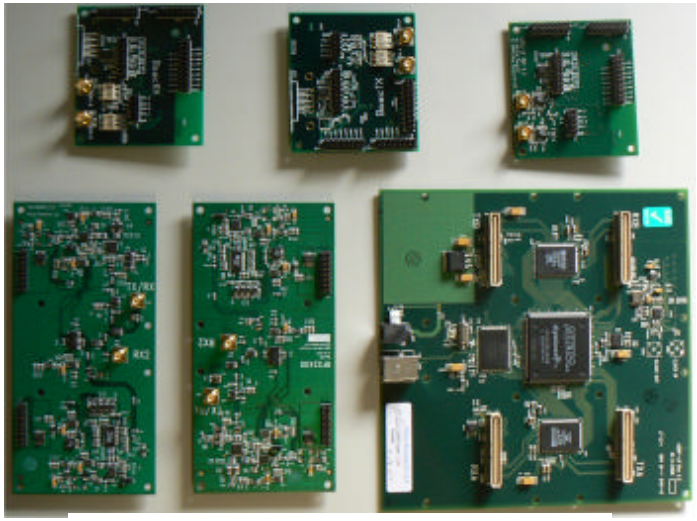
Architecture

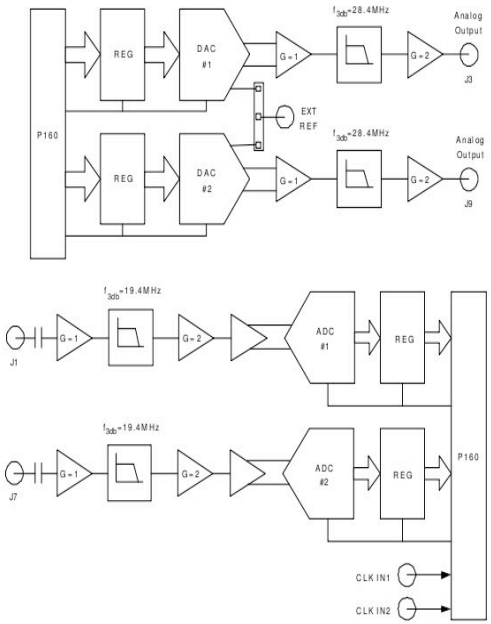


Acoustic Communications and Networking

GNU-based Architecture

- Standardized I/O and user interface
- Portable
- Expandable
- Additional peripherals
- Very low-cost digital processing
- COTS operating systems and software
- Compatible with low-power
- HW/SW migration path
- Can be ruggedized
- Mass/volume not as small as ITX-based approach

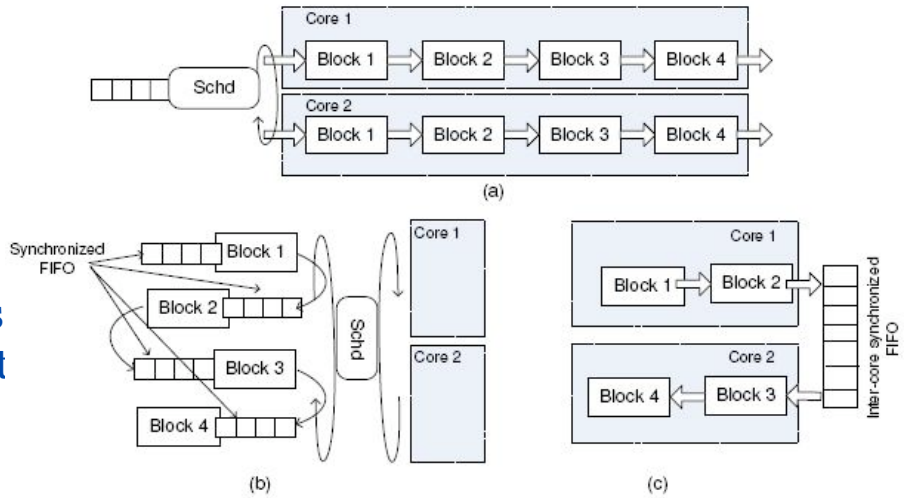




Rx and Tx side of daughterboard

SORA-based Architecture

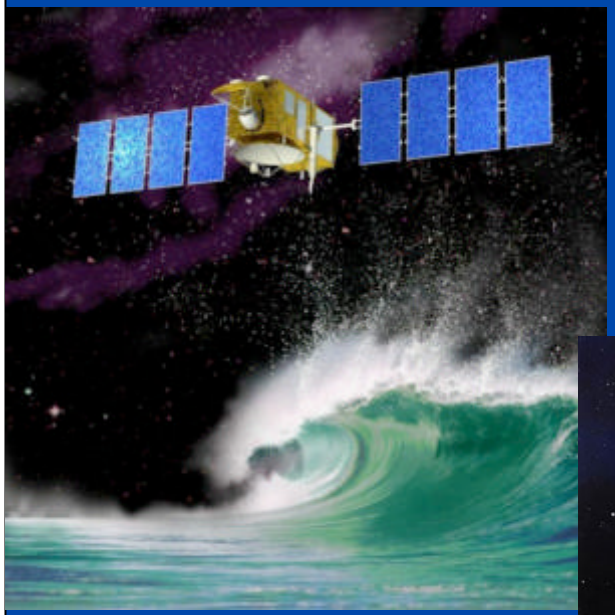
- Combines the performance and fidelity of hardware frontend with the programmability and flexibility of general-purpose processor (GPP)
- Takes full advantage of the PC architectures to achieve high-throughput, low-latency dat transfer between the analog frontend and host memories in a C programmable environment
- Makes extensive use of features of contemporary processor architectures to meet the computation and timing requirements using dedicated CPU cores, large low-latency caches, and SIMD processor extensions for highly efficient physical and MAC layer processing
- SORA Capabilities have already been tested through the realization of a full-stack commercial WiFi (802.11a/b/g, with peak rate > 54Mbps) network interface card on a commodity dual-core PC.

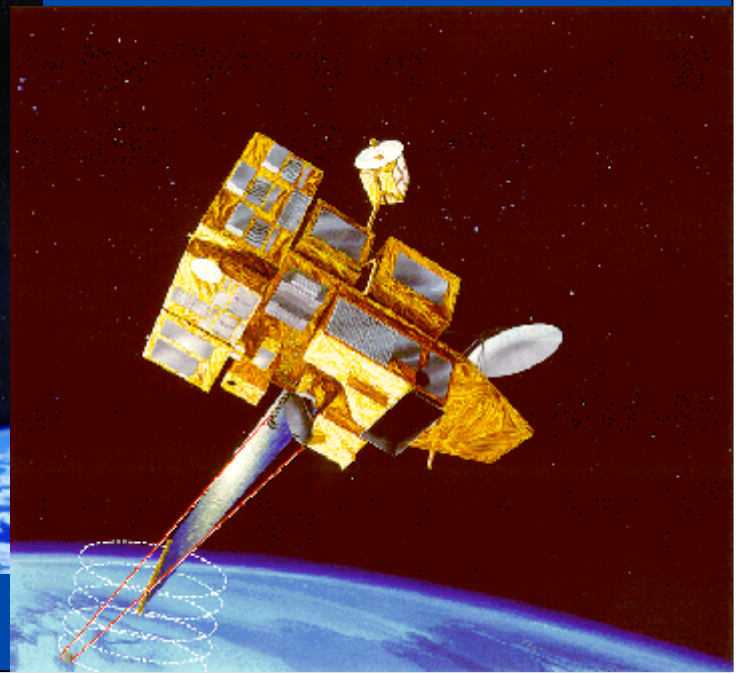


PHY pipeline scheduling: (a) parallel pipelines, (b) dynamic scheduling, (c) static scheduling

Acoustic modem front-end

4 Satellite Sensors





Satellite Sensors

- Of most direct relevance for determining the physical state of the ocean from space are sensors that determine **sea surface height and wind stress.**

- Sea surface height is measured with an altimeter, e.g., **Jason-2**, and provides a measure of depth integrated density; from this can be inferred **heat content** and **upper ocean currents** via geostrophy.

- Wind stress is estimated from wind speed as determined by a scatterometer, e.g., **SeaWinds** on the **QuikSCAT** satellite, which infers wind speed from surface roughness.

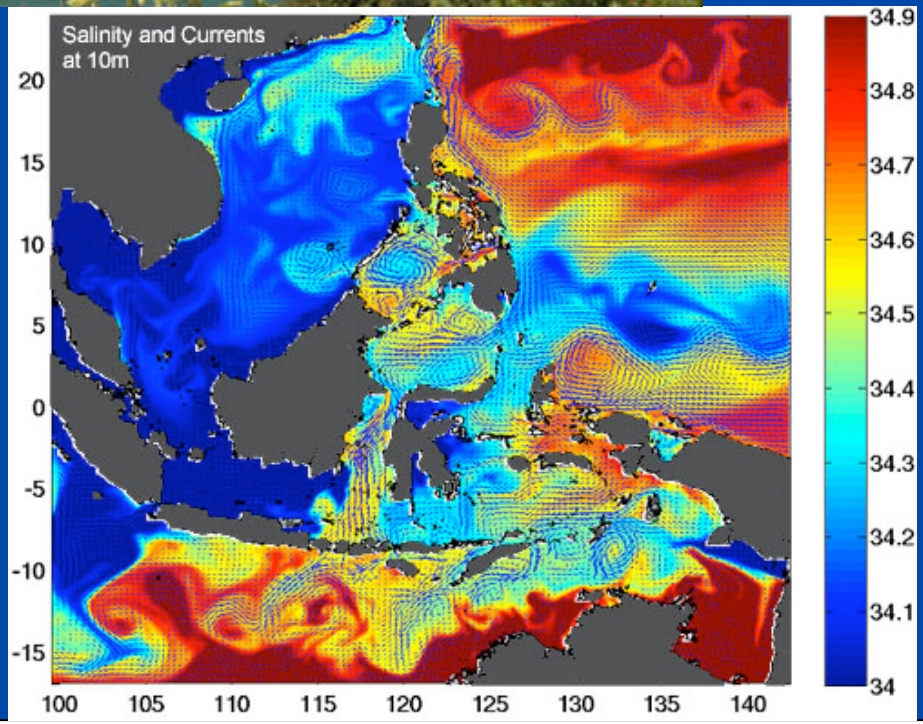
Satellite Sensors

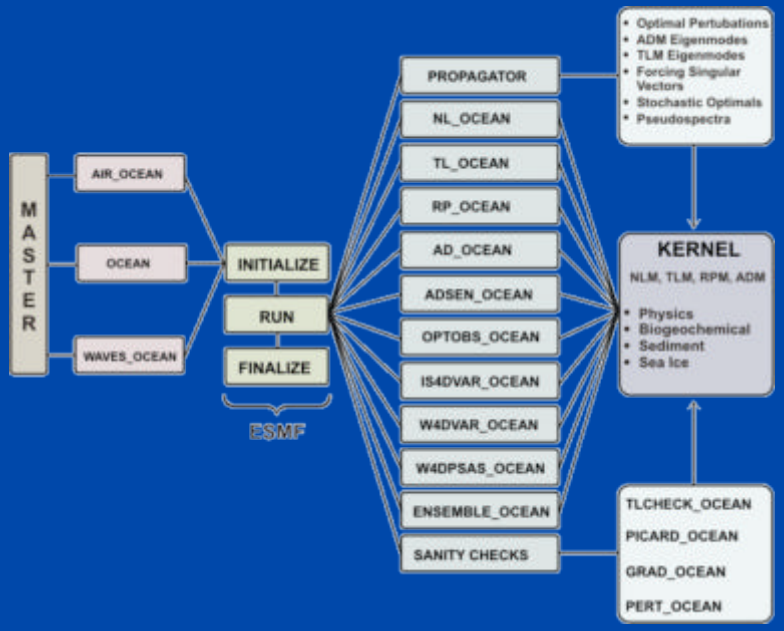
- In the future, a **wide-area swath altimeter** system (Surface Water and Ocean Topography, **SWOT**) will provide orders of magnitude more data on the ocean surface topography.

- In other missions, the estimation of **wind speed** will be improved with the Extended Ocean vector Winds Mission (**XOVWM**) and **surface salinity** (affecting ocean density among other things) will be measured by the Aquarius mission.

- These and many other space-based sensors will be used in smart sensor webs as they develop over time.

5 Ocean Modeling





Ocean Modeling

- Despite recent advances in ocean observing technology, sampling the ocean on both the global and regional scales remains a challenging task.

- While satellite sensors can only measure the surface properties of the ocean (including the surface manifestations of subsurface processes, such as with altimetry) with imperfect, though improving, time-space global sampling, there are **usually large temporal and spatial gaps between in situ sensors**.

- **Three-dimensional dynamical models** are therefore needed to **combine these in situ and satellite measurements** in a process known as data assimilation.

- The goal is to estimate the state of the ocean today and then to predict its future evolutions.

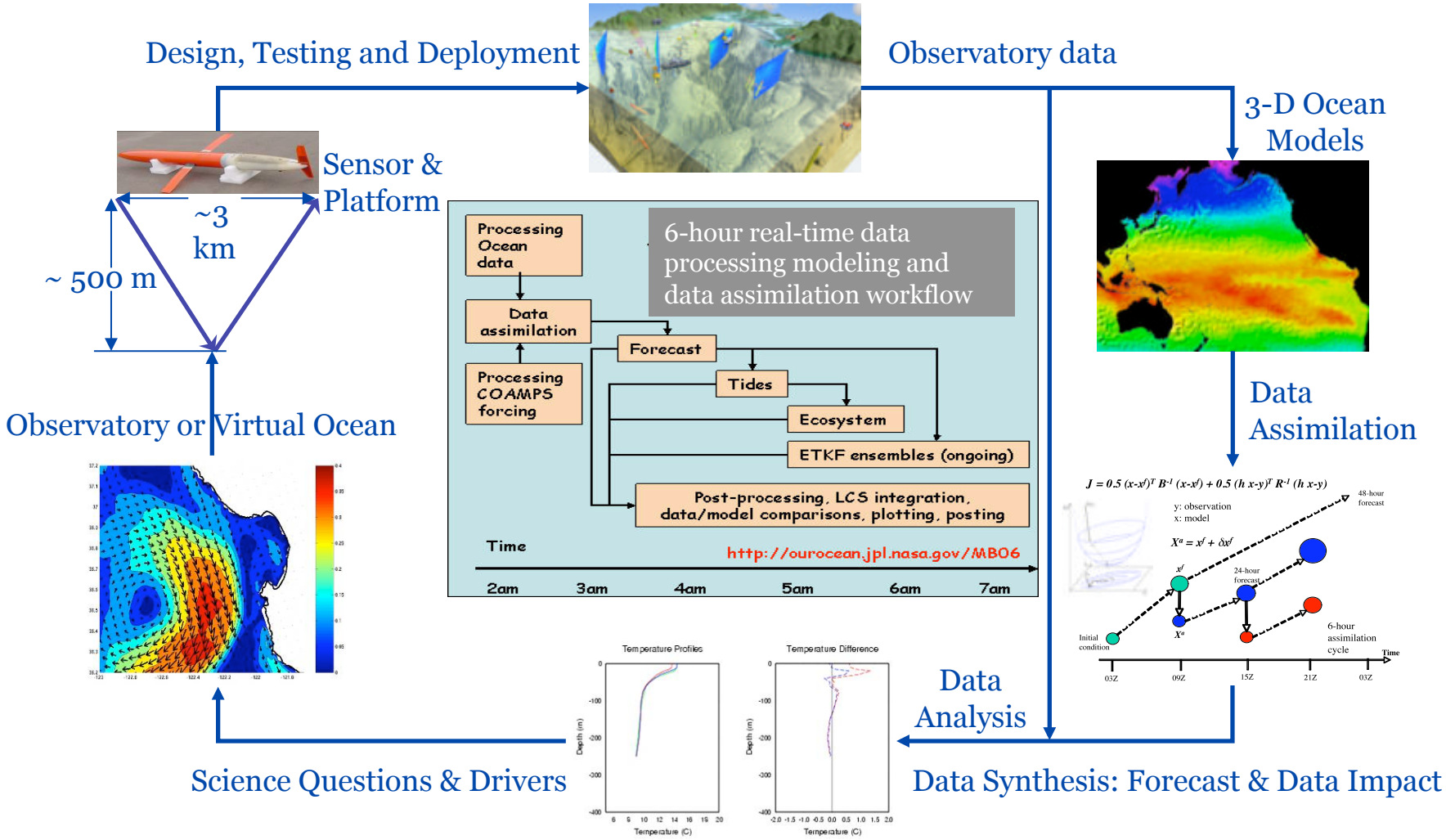
Ocean Modeling

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 field experiments in 2003, 2006, 2008, and 2009.
- ROMS is capable of assimilating glider data and providing real-time forecasts back to the glider operators for adaptive sampling and decision making.

Ocean Modeling

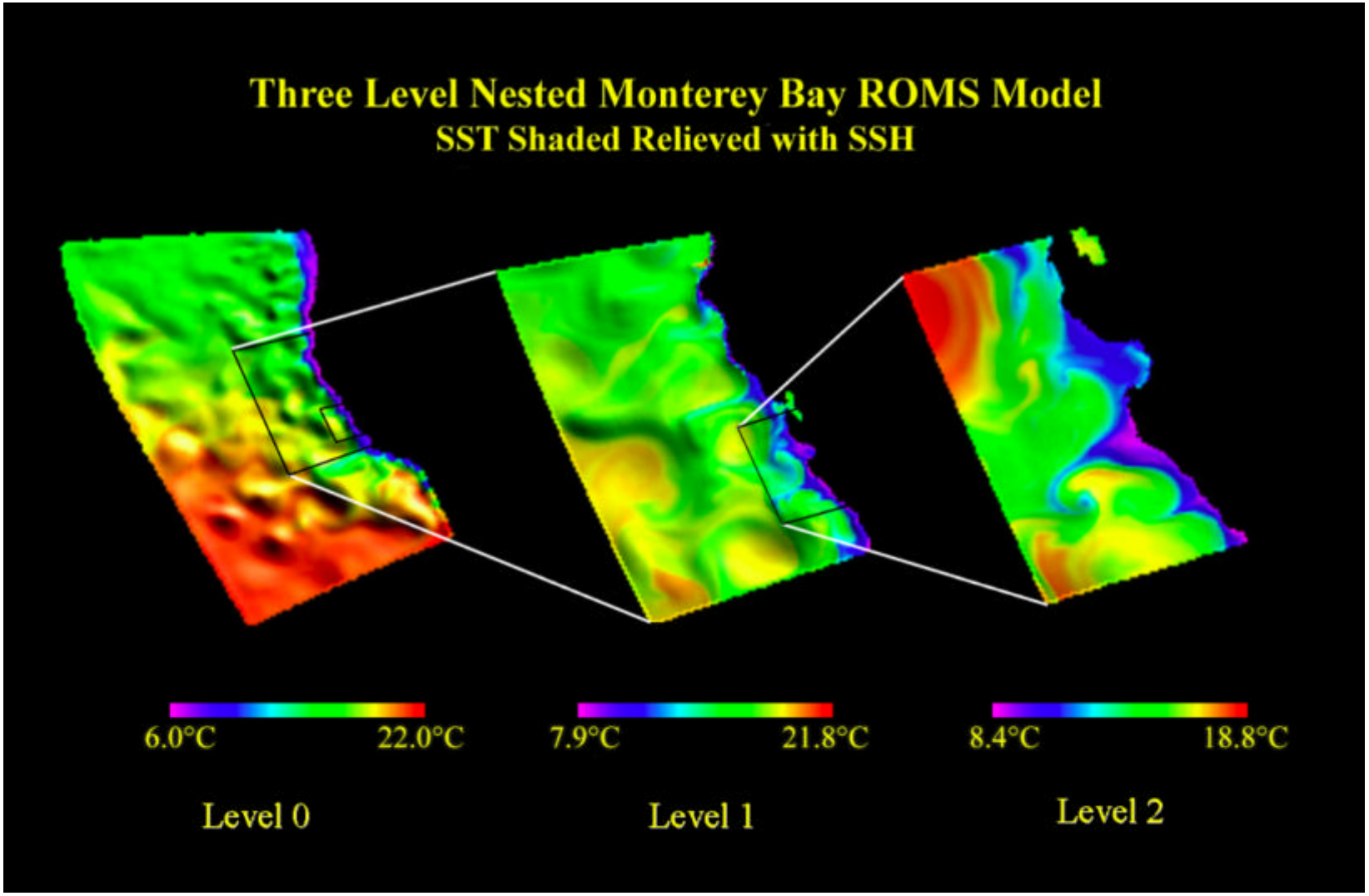
From *Virtual Ocean* Design and Test to Real-Time Experiment



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.

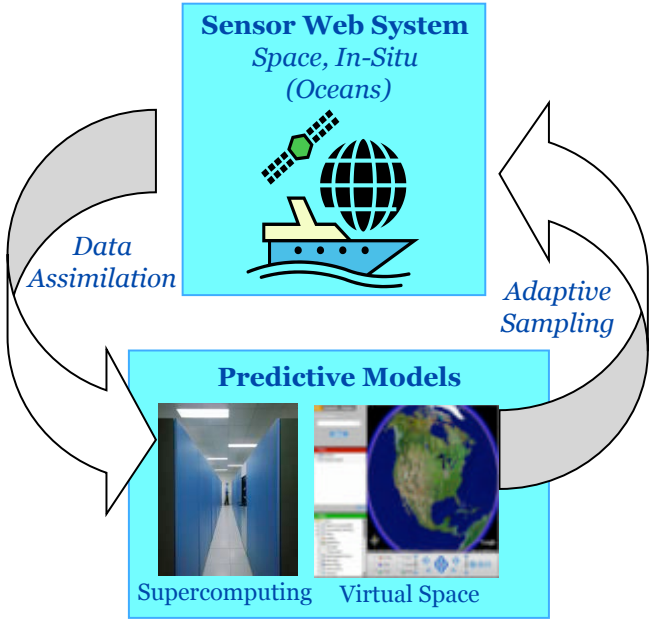
Ocean Modeling

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.



Ocean Modeling

- ***Demonstrated a Closed Loop Dynamic Smart Ocean Sensor Web Concept***
  - For the first time, we integrated in-situ sensors with space-based Earth observation system in two experiments.
  - Data gathered locally by an underwater sensor network is fed into a real-time assimilative ocean forecasting system.
  - Data are used by scientists to command the space craft to optimize the spatial coverage over the areas of interests.
  - Both data and model forecast are available in real-time to aid better decision making (e.g., warning of Harmful Algal Bloom or HABs)



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

Ocean Modeling

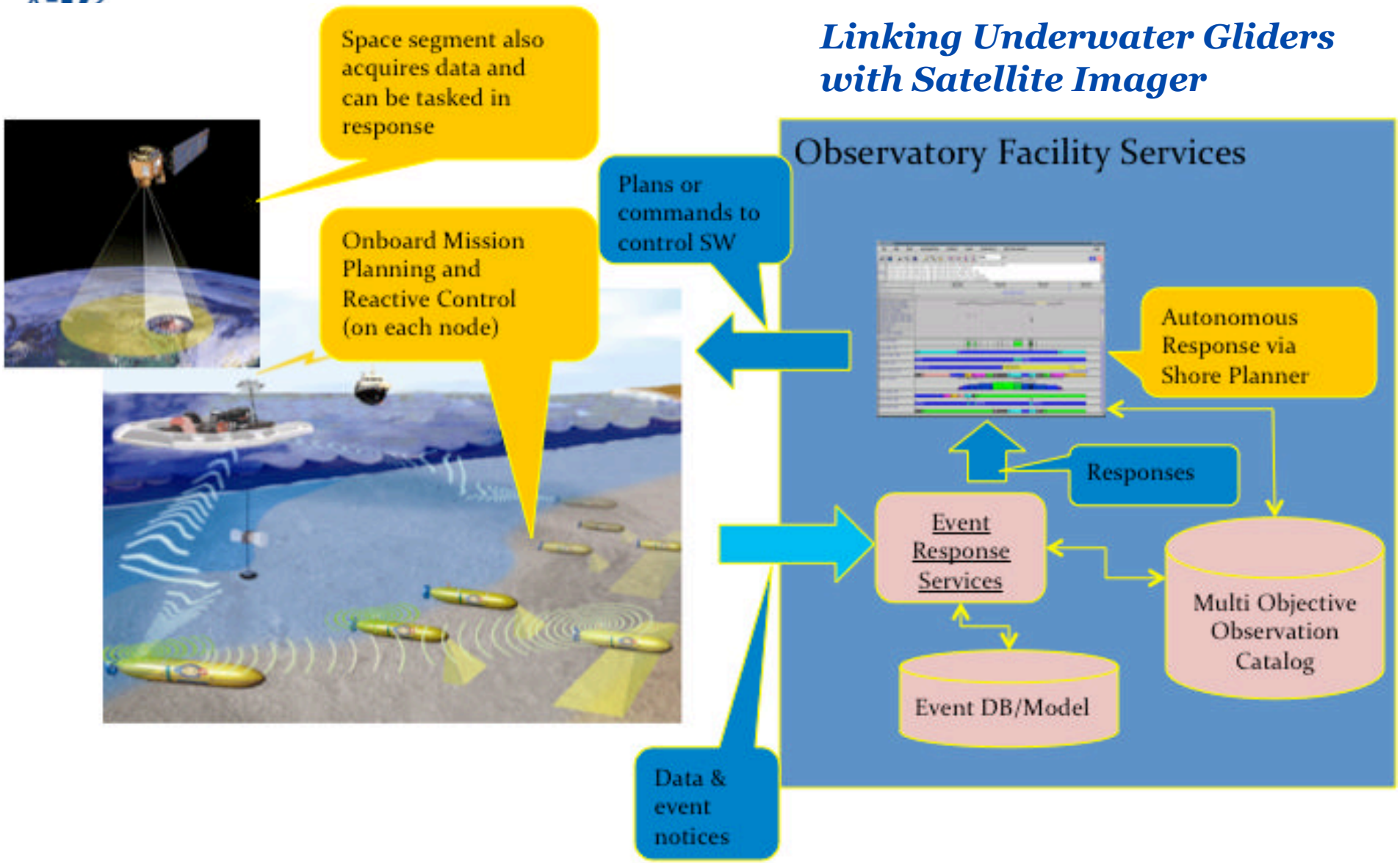
- During both field experiments, the ROMS modeling and data assimilation system was run daily in real-time, **assimilating satellite data as well as in-situ temperature and salinity vertical profile data** (e.g., derived from CTD measurements on moorings, ships, gliders, and autonomous underwater vehicles or AUVs).

- The current ROMS configuration produces nowcasts every six hours. Forced with the mesoscale atmospheric forecast, the current ROMS configuration makes a 48-hour forecast every 24 hours.

- Initial results show **significant skill in the ROMS model in describing and predicting the coastal circulation and variability**.

Ocean Modeling

Linking Underwater Gliders with Satellite Imager

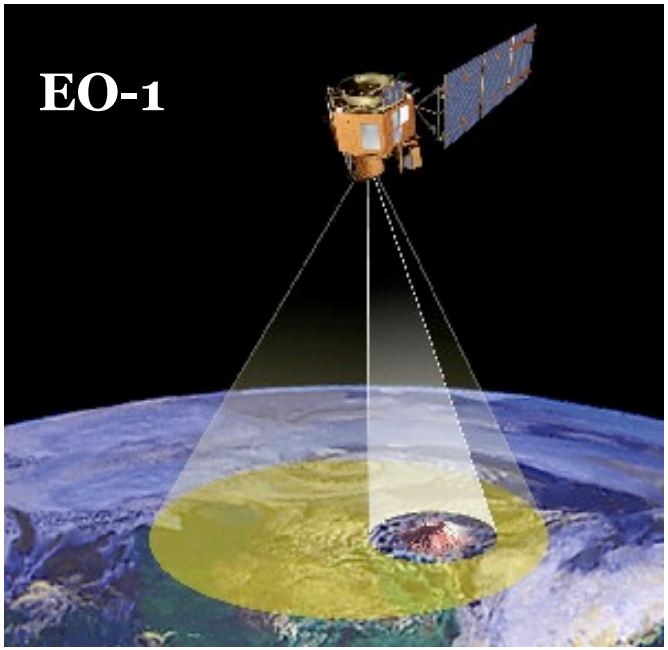


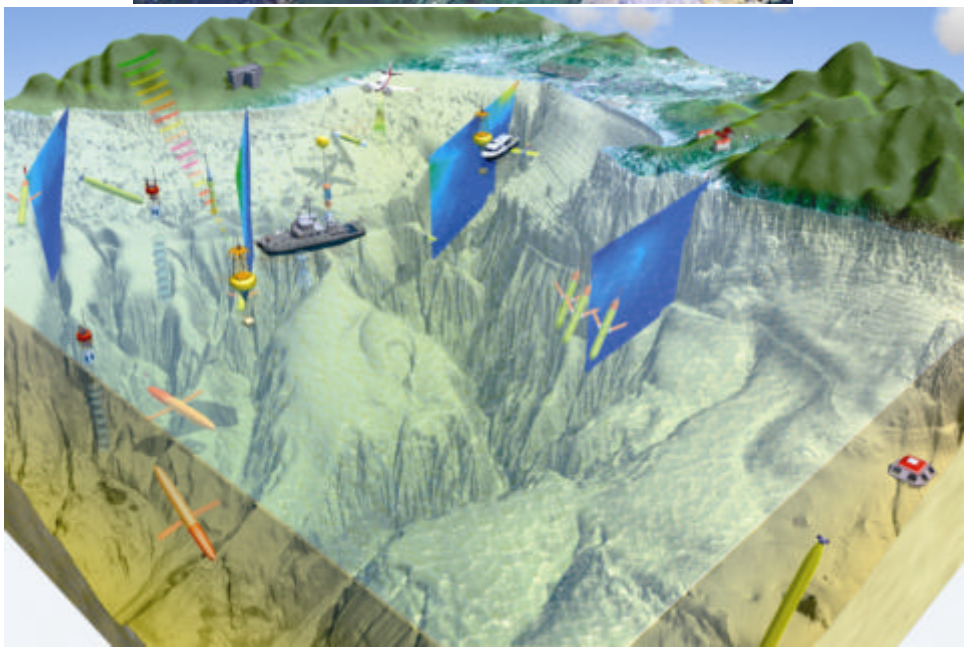
(in collaboration with Steve Chien, David Thompson, and Dan Mandl)

Monterey Bay 2008 (MB08) Field Experiment

- A first demonstration experiment for our task was carried out during 13-23 October 2008 in Monterey Bay (MB08).
- The major science goal was to **detect and predict extreme blooms in Monterey Bay using a smart sensor web -** integrating in situ and remote sensing observations with predictive models.
- A unique innovation of MB08 was to bring the **adaptive sampling** concept to the satellite platform, for the first time.

Ocean Modeling





- Unique Features
  - End-to-end integration with hardware in the loop
  - Autonomous adaptive sampling using EO-1 based on model-based predictions
- Observations
  - In situ platforms
    - Slocum gliders (Rutgers)
    - AUVs (MBARI)
    - Moorings (MBARI)
    - Ships (MBARI)
  - Remote sensing platforms
    - EO-1 (on-demand, 30-m reso.)
    - Satellite observations
    - High-frequency (HF) radar
- Prediction models
  - ROMS real-time data assimilation and prediction to enable decision making

Monterey Bay 2008 (MB08) Field Experiment

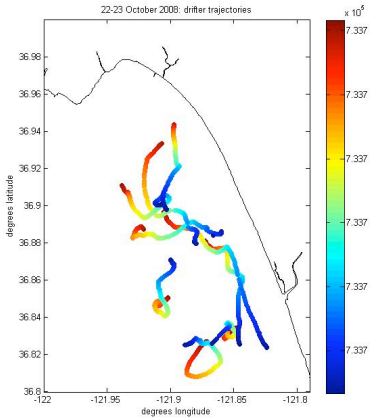
- During MB08, the EO-1 satellite was tasked to automatically deliver oceanographic science data products for scientist evaluation.
- Specifically, EO-1 Hyperion high-resolution hyperspectral imager acquisitions were made in coordination with the EO-1 Sensorweb team on 10 days during the MB08 deployment.
- EO-1 used automated workflows to process and deliver the data to the MB08 science and operations team along with two derivative science products, Fluorescence Line Height (FLH) and Maximum Chlorophyll Index (MCI) linear baseline data products.
- Resultant science products were automatically delivered to the scientists through a collaboration web portal. from EO-1 servers.
- Ultimate goal is to develop automated processing flows that deliver alerts and science classification products to interested parties.

Ocean Modeling

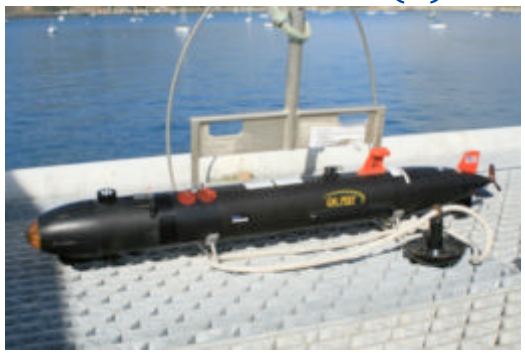
Slocum Glider (2)

Spray Glider (1)

Surface Drifters (6)



REMUS AUV (1)



DORADO AUV (1)

HF Radar network

R/V Pt. Lobos

Synergistic In Situ & Remote Sensing Observations

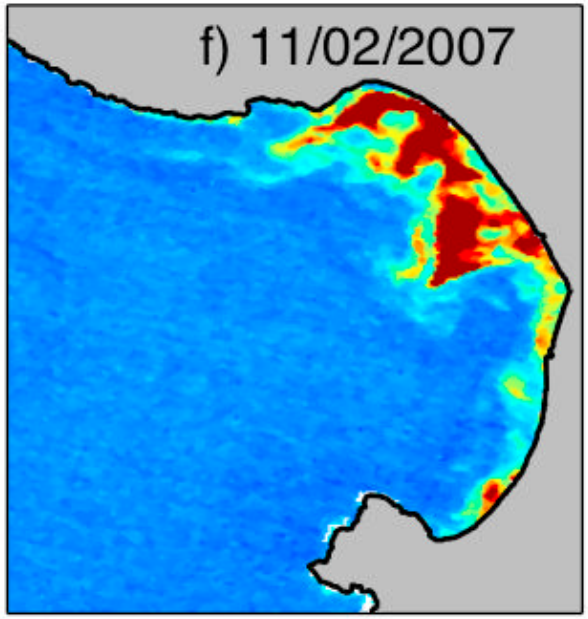
Suite of Satellite Images

SST from 10+ satellites (e.g., MERIS, MODIS, AVHRR)

SAR Images

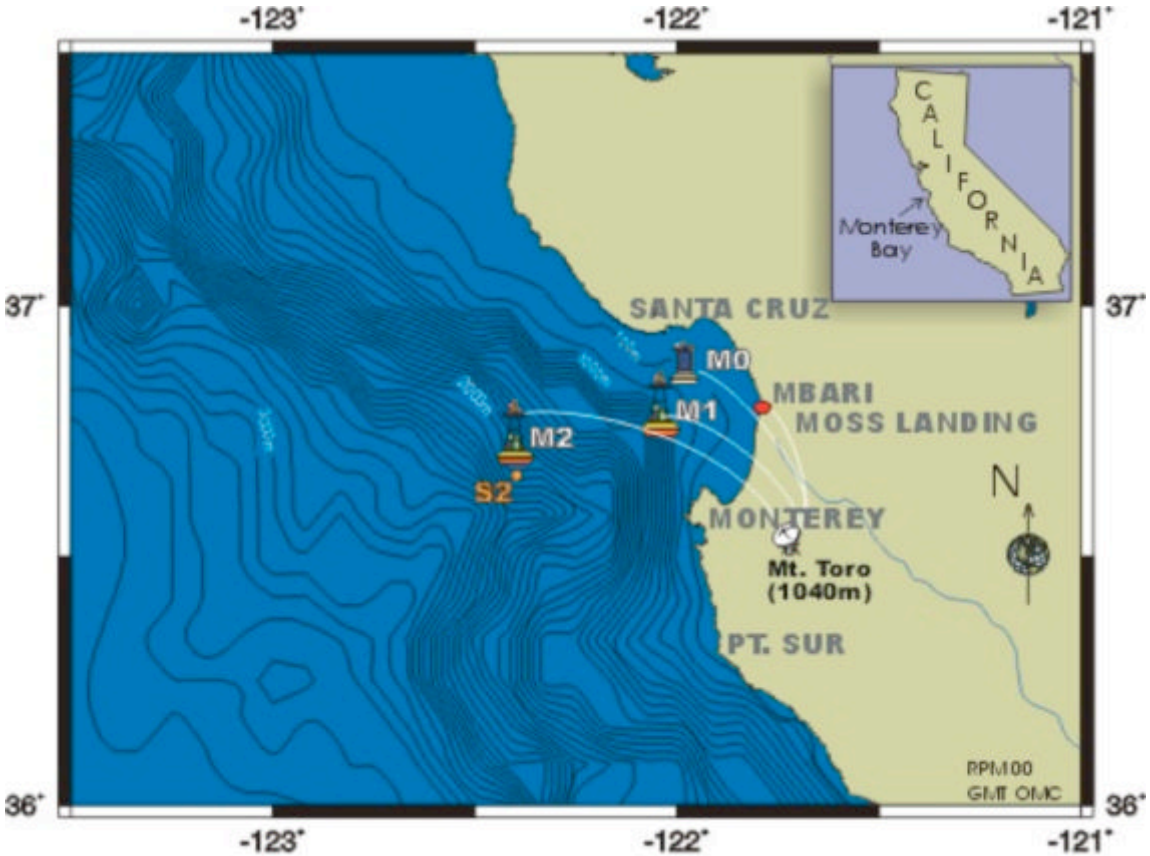
ASTER

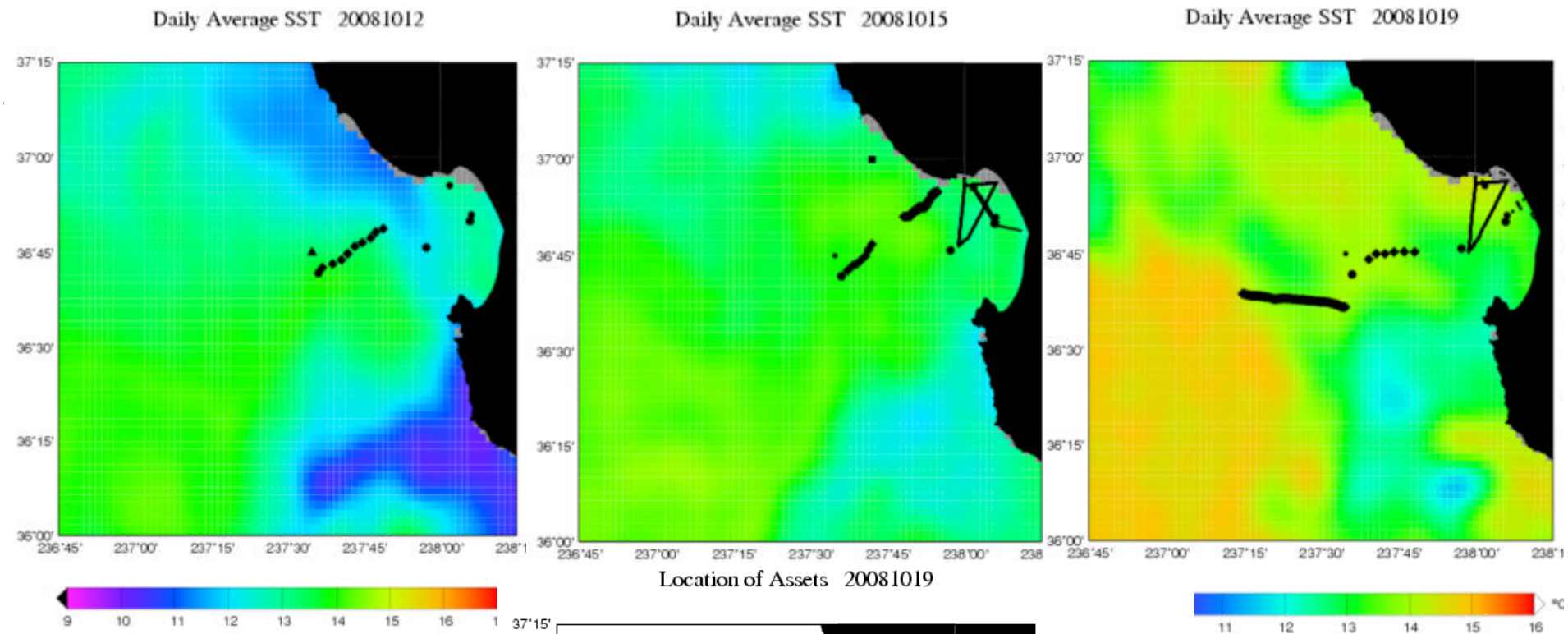
Monterey Bay: Ideal site for Smart Ocean Sensor Web



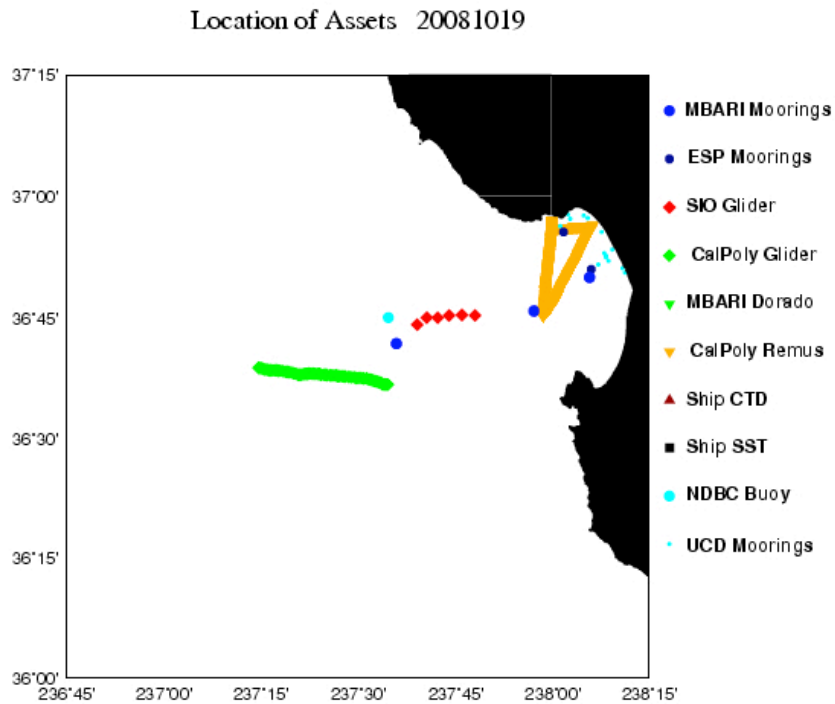
Monterey Bay is selected because it is the home of intense dinoflagellate blooms (or red tides), with surface chlorophyll two orders of magnitude above background. They occur primarily during August through November and can persist for > 1 month.

Monterey Bay is selected also because it has a comprehensive observing system and been the home of several recent field experiments funded by ONR (e.g., MOOS 2000, AOSN 2003, ASAP 2006).

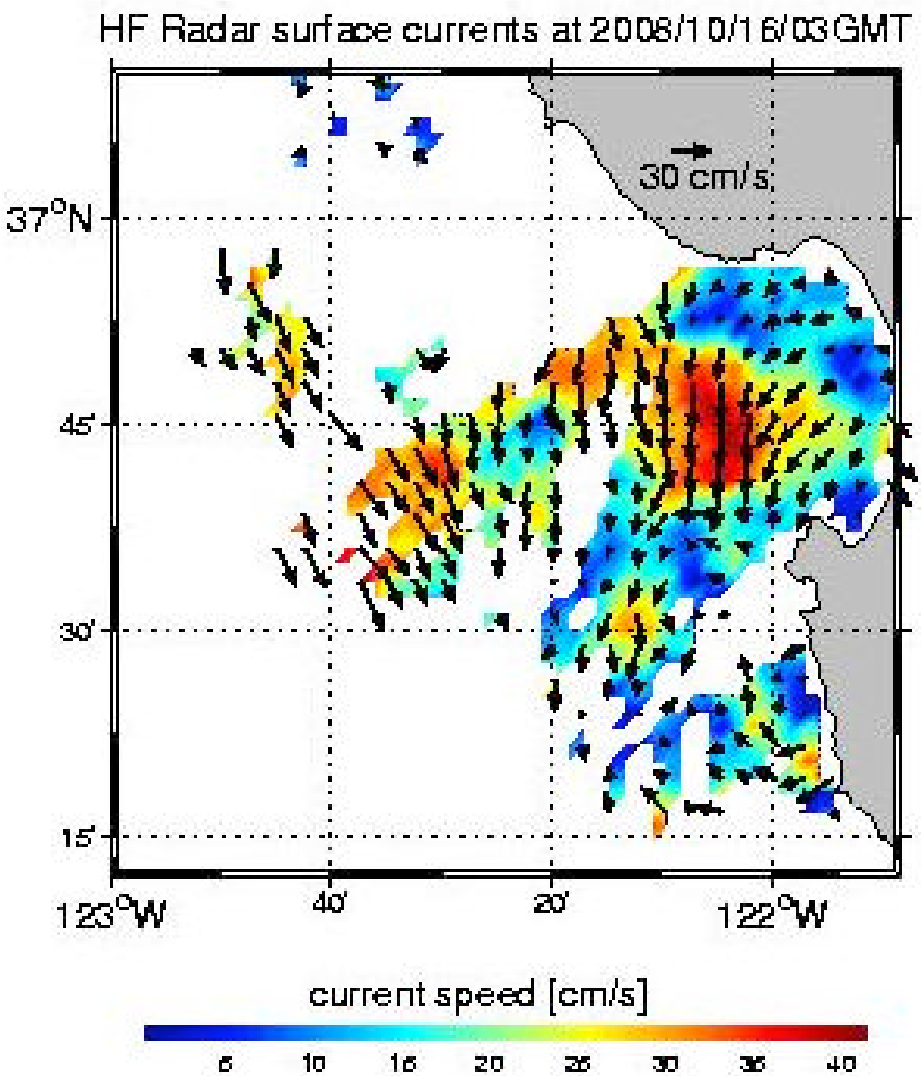


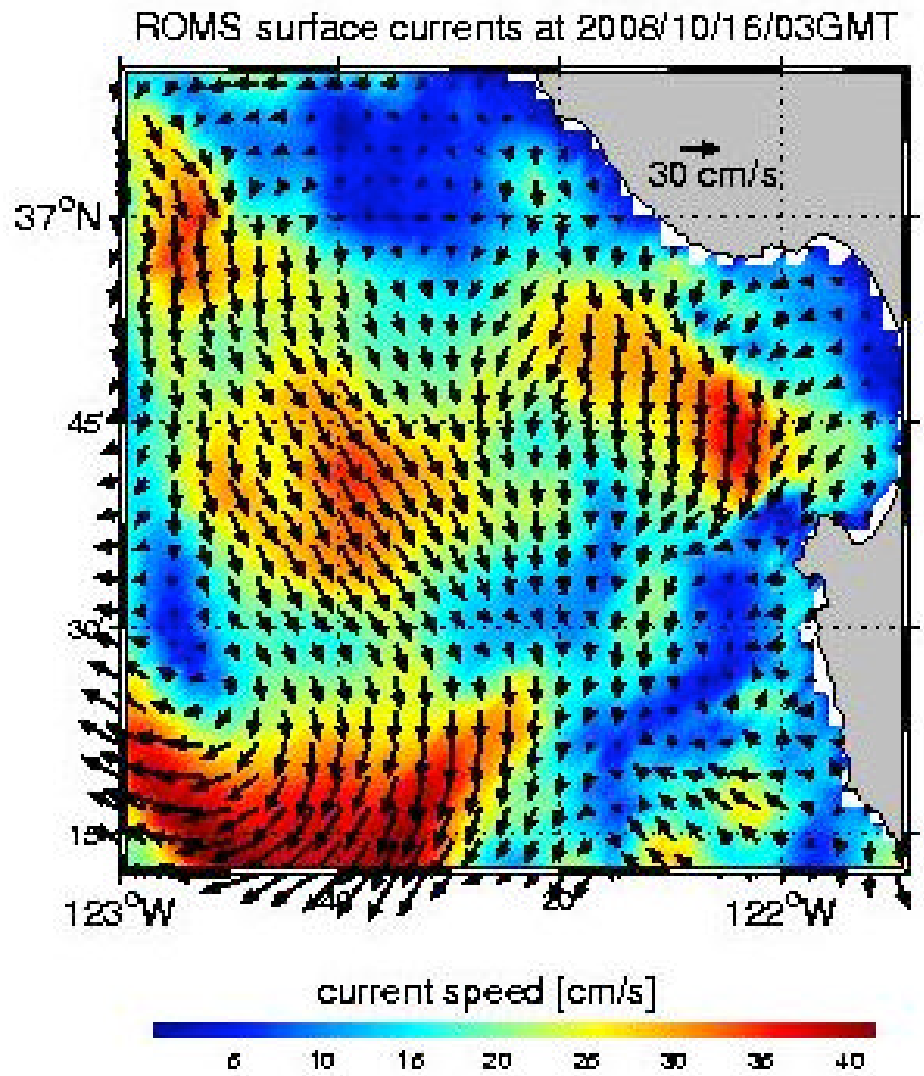


MB08: Assets Distributions & Satellite SST Images



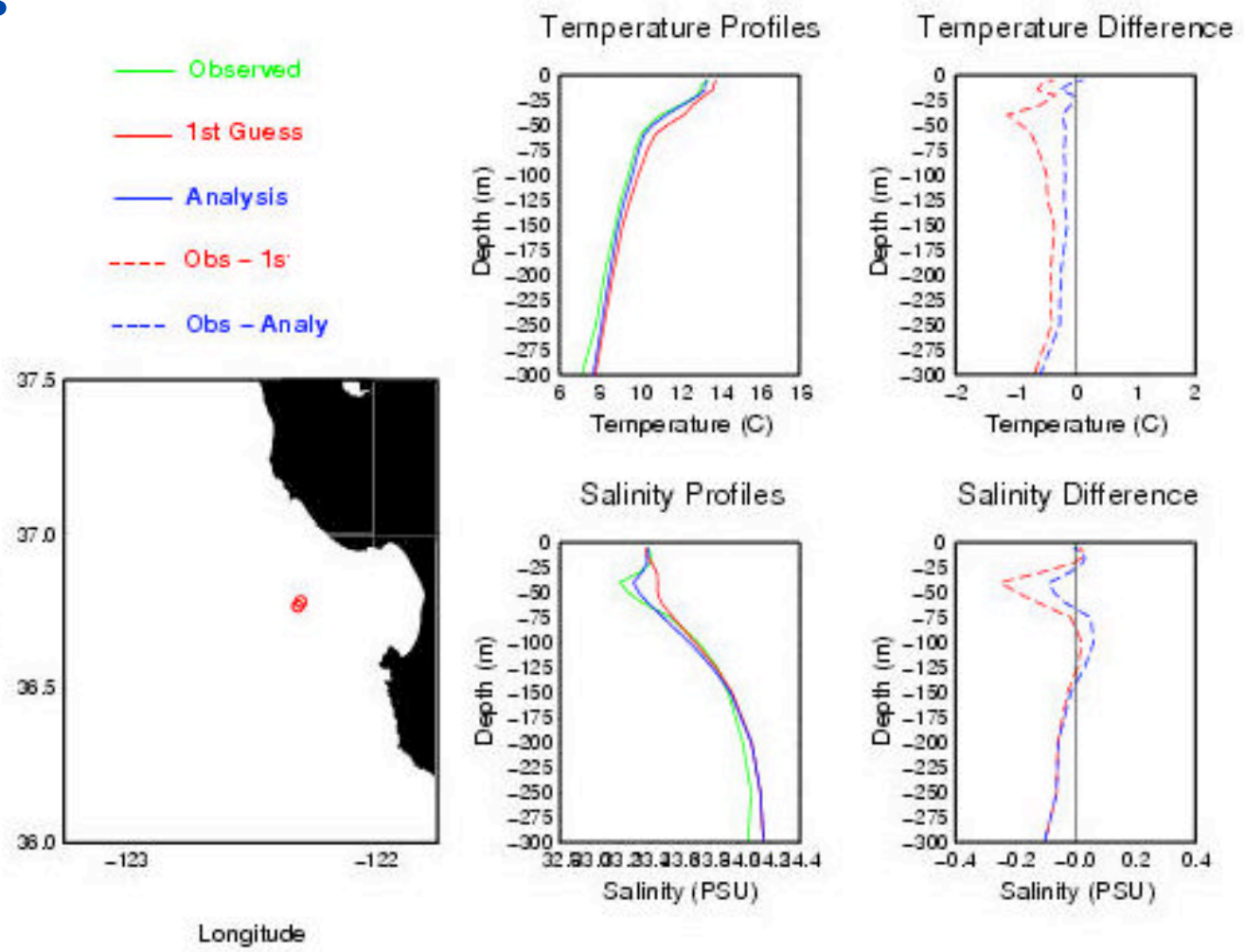
MB08: HF Radar Data (left) vs. ROMS Nowcast (right)





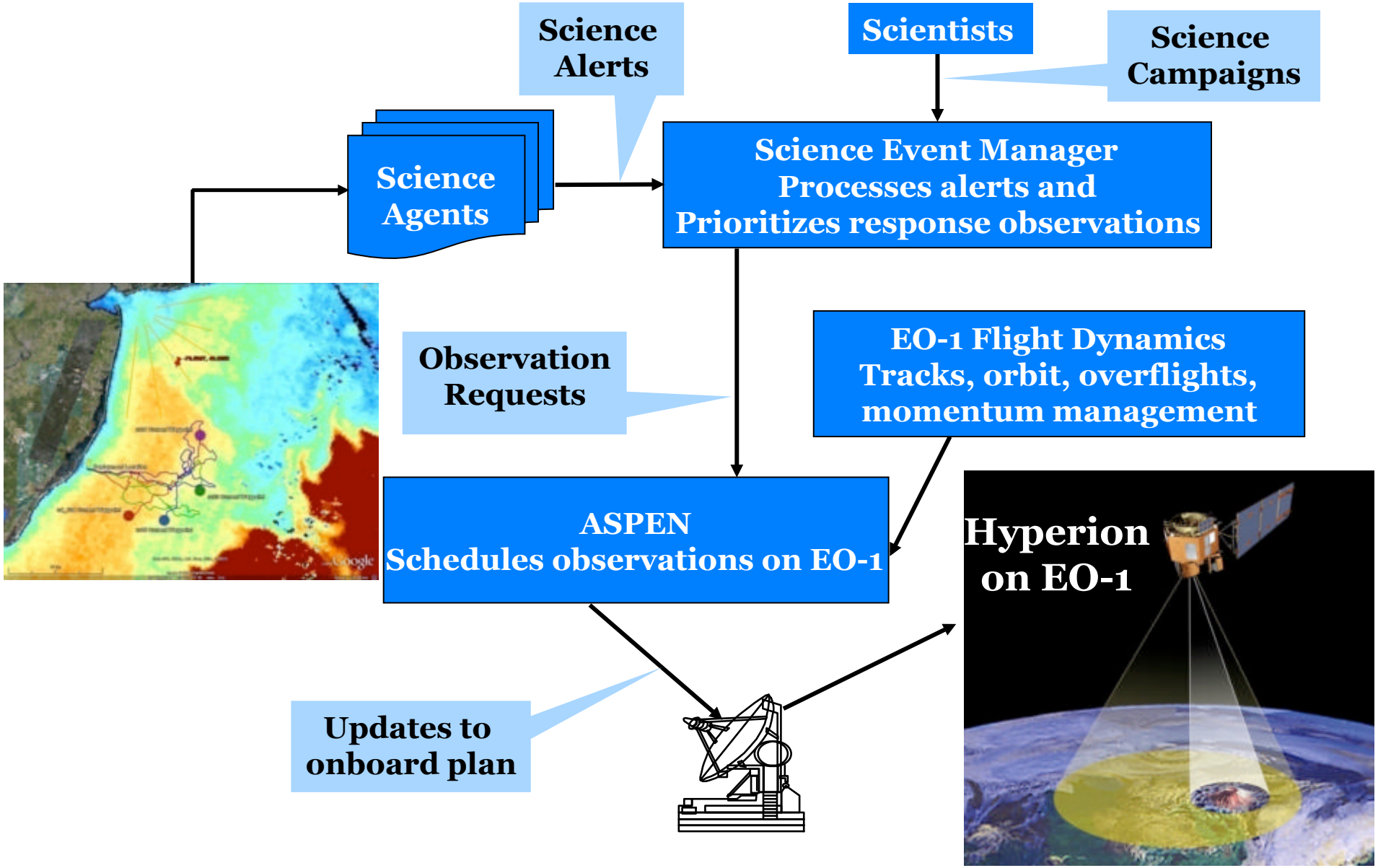
MB08: Data Analysis

Glider Data (green) vs ROMS with (blue) & without data assimilation (red)



Ocean Modeling

Nov 2009 Field Experiment off the New Jersey Coast



Ocean Modeling

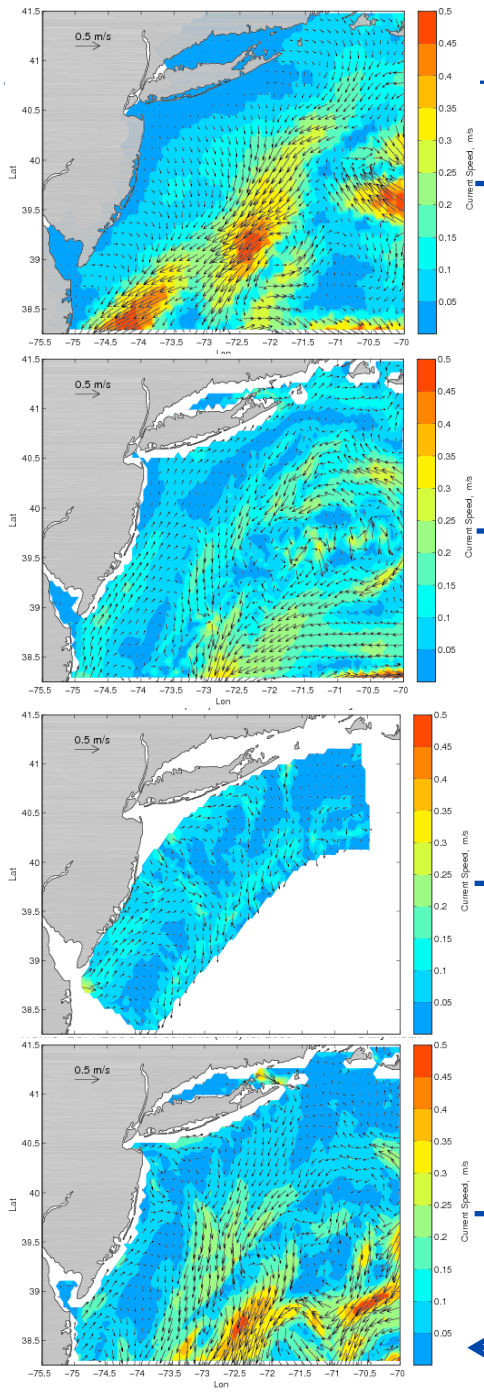
- The routine measurements included moored ocean buoys, land-based high-frequency (HF) radars, and ship survey.

- Four autonomous underwater gliders were used to perform additional measurements and adaptive sampling.

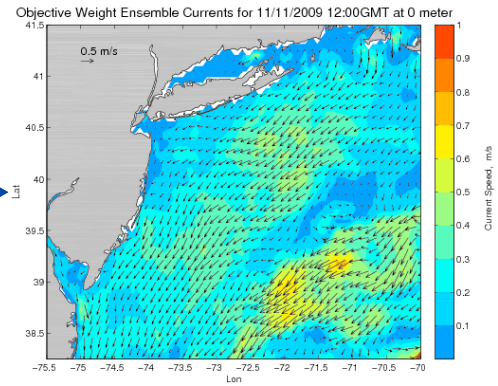
- During the field experiment, four numerical ocean models were used to provide nowcasts and 48-hour forecasts that will be used to guide gliders and improve decision making.

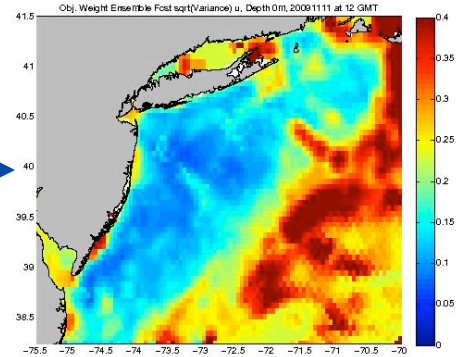
- A major feature of this field experiment is the web portal (http://ourocean.jpl.nasa.hgov/CI) developed to provide a single access point for the observational and model predictions.

Ocean Modeling



Multi-Model Ensemble

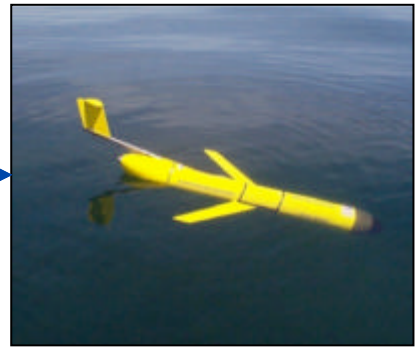




Error Estimation

Linking Gliders with Prediction Models

Glider Planning



- Known constraints (slow 0.5 knot, Battery, shipping lanes)
- Uncertain constraints (time-varying 3D currents)
- Operate autonomously & re-plan daily

Real-time glider data are used to improve the model forecast

Ocean Modeling

- The highlight of the field experiment was **the formation flight between underwater gliders and the Hyperion imager** flying on the Earth Observing One spacecraft.

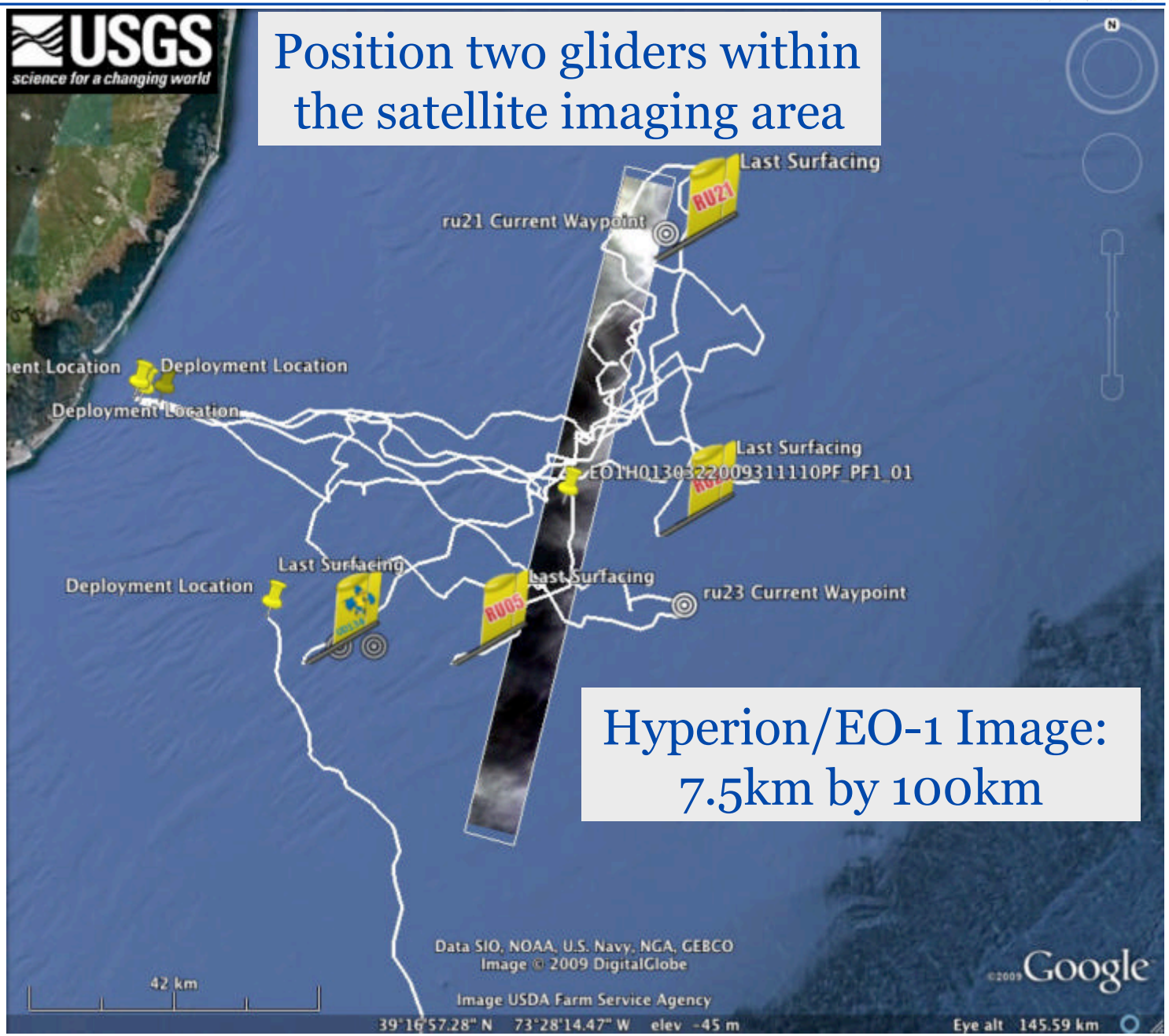
- The Hyperion images are typically 7.5 km (across track) by over 100km (along track) and resolve 220 spectral bands from 0.4 to 2.5 microns with a spatial resolution of 30m.

- During the field experiment, both observational data and multi-model forecasts are analyzed to determine a tasking location. These coordinates are then used by the EO-1 sensor web capability that enables autonomous operations and tasking of the EO-1 spacecraft.

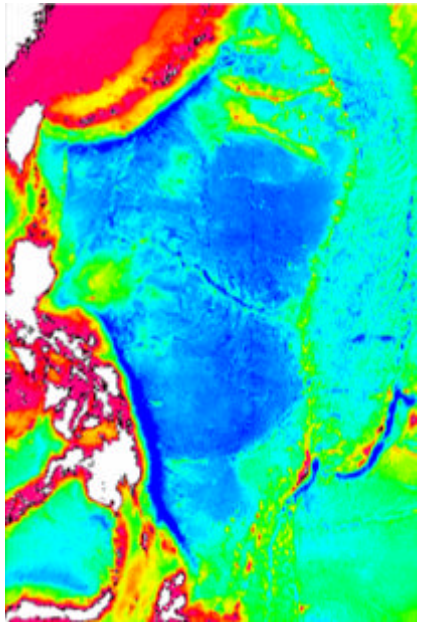
- With several days' planning, we were able to co-locate two gliders within the EO-1 Hyperion swath, a **major technology breakthrough in simultaneously coordinating satellite and underwater assets guided by multi-model forecasts.**

Ocean Modeling

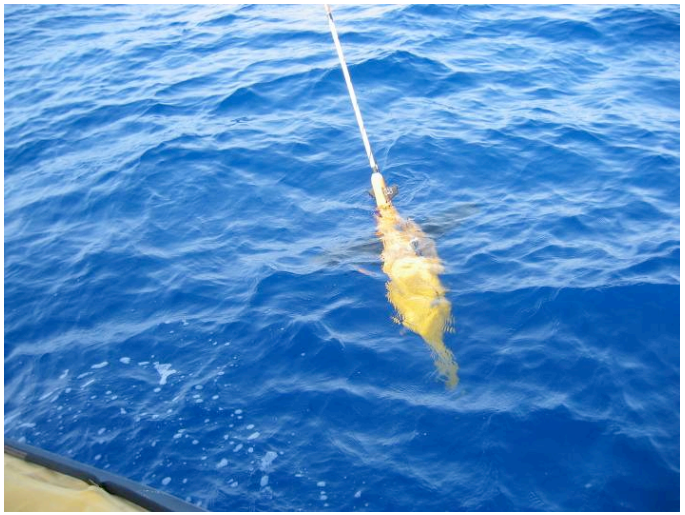
Gliders and EO-1 Satellite Formation Flight!

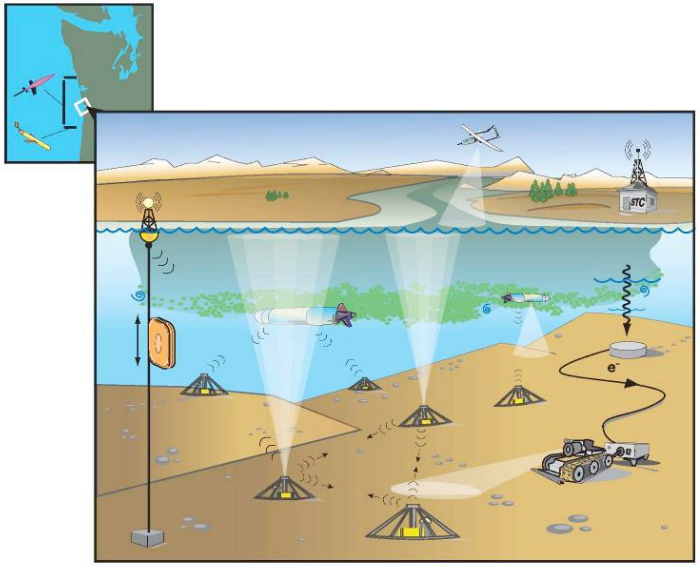


Related Projects



- 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!