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ICAPS 2006

The English Lake District, Cumbria, UK

Tutorial on Issues in Underwater Robotic Applications

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Tutorial on Challenges in Subsea Robotics

Table of contents

Preface

The Ocean Sciences have long been driven by technological advances which have enabled vast swaths of the ocean to be charted, organisms discovered and studied and physical, chemical, biological and geological dynamics of the dominant part of the earths ecosystem to be studied. Yet this observation scheme has only allowed us to charts less than 5% of the sea-floor bottom and and even smaller percentage of the actual water column where the majority of the scientific break-through are thought to exist. Further, the ocean science and engineering have historically, relied on individual scientists working in small groups, building their own, special-purpose instrumentation. These instruments have typically been built in short development cycles, for single missions to measure point data.

In the upcoming 2007 Fiscal 2007 budget, President Bush has asked Congress to authorize one of the largest investments in the sciences by allowing for the construction of Global, Coastal and Regional Cabled observatories by the National Science Foundation. With new technologies for moorings, underwater cables, power systems and nodes they will vastly help resolve measurements of ocean processes on the temporal axis by persistence presence. Such a move from the expeditionary style of science towards an observatory mode of scientific work has created a need to rethink how ocean science will be done in the large and what capabilities will be needed to support it. This has provided the opportunity for a cross-disciplinary impact on the ocean sciences.

Many oceanographic processes have an event-driven nature, such as harmful algal blooms (HABs), continental margin and submarine canyon fluxes, and terrestrial nutrient and pollutant inputs to coastal waters. This underlying event-driven nature requires intelligent observational strategies to resolve and advance understanding of complex oceanographic processes. Such processes, among others, have driven the need for a cross-disciplinary impact.

Finally Artificial Intelligence (AI) based autonomous systems have made significant strides in dealing with important real-world problems. These include dealing with closed-loop control issues for terrestrial and space robotic vehicles, decision support systems dealing with articulation and mobility of robotic vehicles, event response for earth science events, and cockpit resource management for airliners, to name a few. AI based autonomous systems have demonstrated a maturity to tackle significant robotic and automated reasoning problems in the real world.

A primary goal of this tutorial is to present a compelling problem domain with societal relevance and foster innovative ideas and projects for the future. However an equally important objective of this tutorial is to showcase the opportunities and the need in the ocean sciences to enable Computer Scientists to use the maturity of decades of research in automated reasoning to make a significant impact in this domain. The Monterey Bay Aquarium Research Institute (MBARI) is at the forefront of ocean science and engineering as an elite inter-disciplinary institution, which welcomes such cross-fertilization.

The tutorial will cover basic environmental differences between space, terrestrial and underwater robots. The topics include platform options, governing equations unique to *the ocean environment and the associated equipment for doing science in the oceans. Difficult aspects of the environment are addressed along with discussion about how they impact system solutions and instrument design for science. Key differences in optical, electromagnetic and acoustics will be highlighted.*

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Instructor

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Challenges in Sub-Sea Robotics

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Objectives of this Tutorial

- To articulate new and current needs for Automated Reasoning and Autonomy in the Ocean Sciences & Engineering
- To highlight existing approaches to Ocean Exploration and the tools/techniques/platforms being used
- To disambiguate differences with other domains
- To welcome researchers in AI to participate in Ocean Exploration collaborating with MBARI personnel and using MBARI assets

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Outline

Section A: Background
- About MBARI
- Ocean Science – Some Background on the big questions
- Environmental issues
- Navigation

Section B: Ocean Robotics
- Supporting assets - Ships, Moorings, Satellites
- Robots
  - Floats and Profilers
  - Remotely operated vehicles
  - Autonomous underwater vehicles
  - Gliders
  - Economic comparisons – engineering drivers

Section C: The Future
- Use Cases
- Observatories
- Funding and Wrap Up

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Founded by David Packard

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220 Staff
- Science
- Engineering
- Operations
- Outreach

Dedicated deep ROVs, AUVs & ships:
- R/V Western Flyer/Tiburon
- R/V Pt Lobos/Ventana
- R/V Zephyr

Annual Budget ~$37M

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The MBARI Fleet

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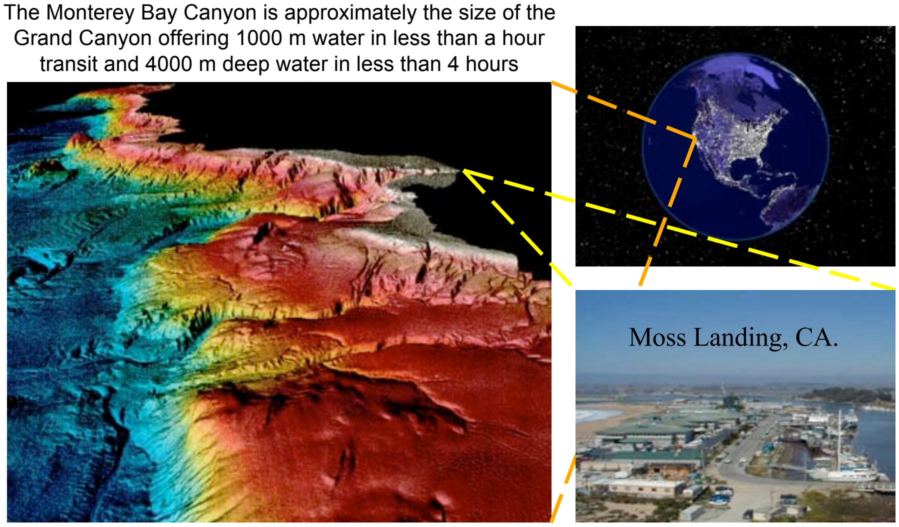
The Location

MBARI is located in Central California just at the head of a very special undersea canyon

The Monterey Bay Canyon is approximately the size of the Grand Canyon offering 1000 m water in less than a hour transit and 4000 m deep water in less than 4 hours



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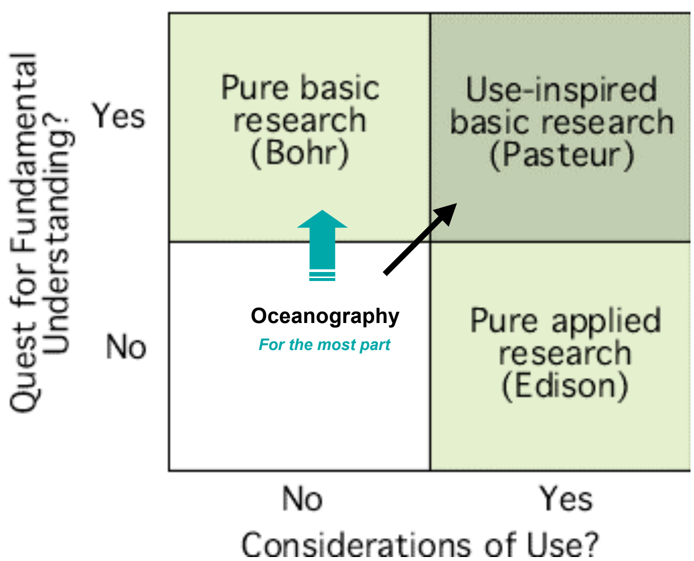
Pasteur's Quadrant or Why are we here ?



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A Sample of Oceanographic Science Topics

- Benthic Ecology
- Biogeochemistry
- Canyon Processes
- Chemical Sensors
- Coast-Ocean Processes
- Greenhouse gasses
- Microbial Oceanography
- Mid-water Ecology
- Molecular Ecology
- Physical Oceanography
- Ocean Crust geochemistry
- Seismology
- Submarine Volcanism

So, what are the types of questions that drive ocean robotics?

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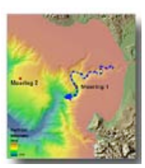
Example: Benthic Ecology

CO2 Sequestration

Carbon Flux

Pattern and Dynamics of Soft Sediment Faunal Communities

Benthic Infauna



Turbidity Events

Antarctica

Cold Seeps

The top level of each science field breaks into numerous sub groups for specific science. Within those fields the questions are asked that drive science requirements for ocean going robotics and systems

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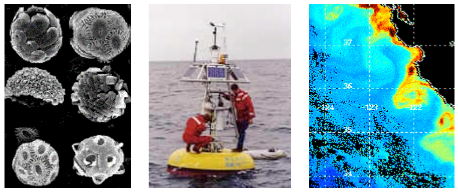
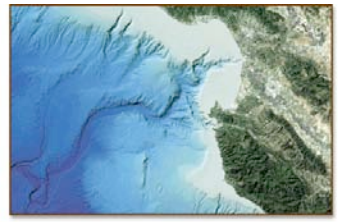
Example: Ocean Sampling

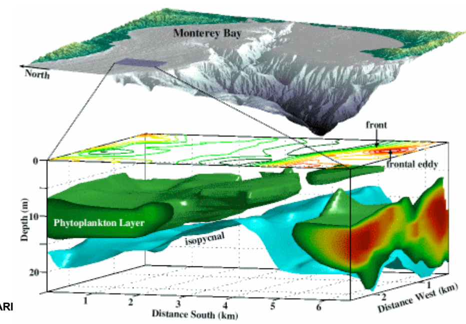
Biogeochemical



Canyon Processes



Coastal Ocean Processes



- Recent advances in Ocean Science
  - require multi-disciplinary collaboration
  - changes in measurement approaches allowing mesoscale phenomenon observation
  - go beyond the usual single PI mode of operation

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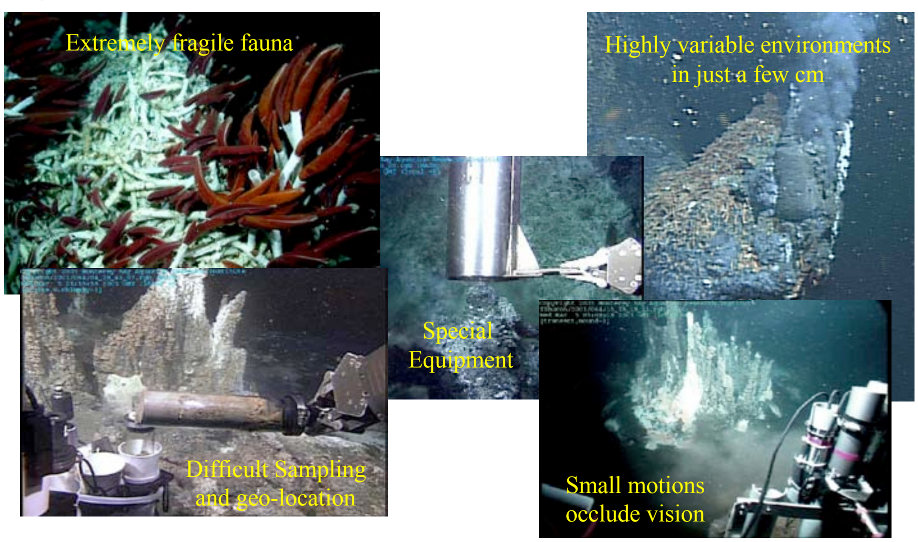
Example: Seismology & Submarine Volcanism



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Some Definitions of Terms

AUV – Autonomous Underwater Vehicle, synonymous with UUV (unmanned underwater vehicle) for our purposes.

ROV – Remotely operated vehicle, a tethered robotic system.

Autonomy – No cable (and even that is pushed sometimes), we do *not* necessarily mean the robot makes all decisions unattended.

ADCP – Acoustic Doppler Current Profiler (often a DVL too)

DVL – Doppler velocimeter log (often an ADCP too)

Decibels – Refers to in water dB which uses a different reference that in air. In water the reference pressure is 1 microPascal, air uses a higher standard of 20 microPascals

Displacement - Specific gravity calcs are based on sea water which is **1.07** times SG of fresh water (sometimes!!).

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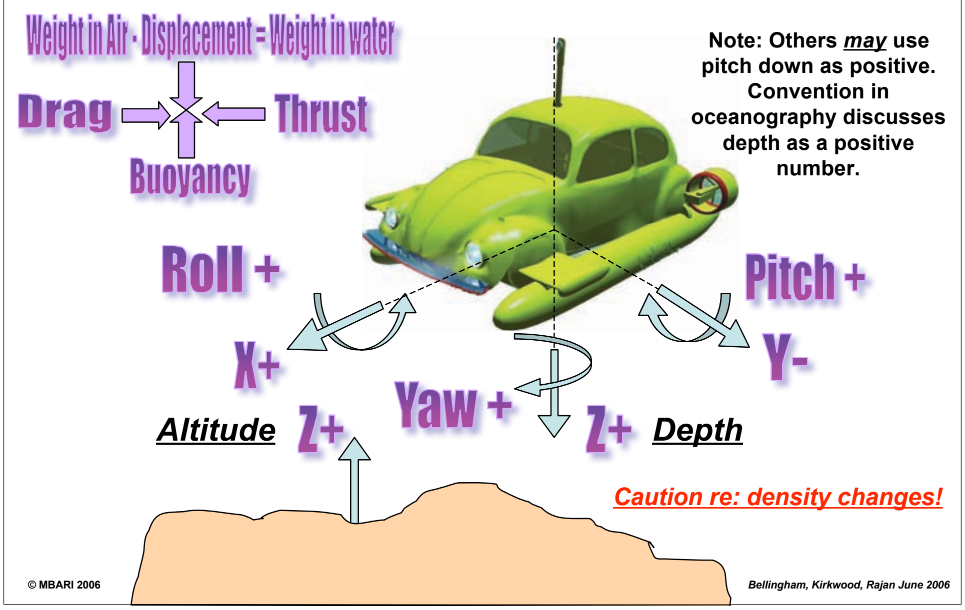
Reference Frame Differences

Note: Others *may* use pitch down as positive. Convention in oceanography discusses depth as a positive number.



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Comparison of environments

An interesting fact: More people have walked on the surface of the moon than have dove to the deepest part of Ocean

Environmental delta's compared to space (often used as a comparative philosophical thought about the ocean)

Pressure

Corrosion

Data transmission issues

The list goes on…

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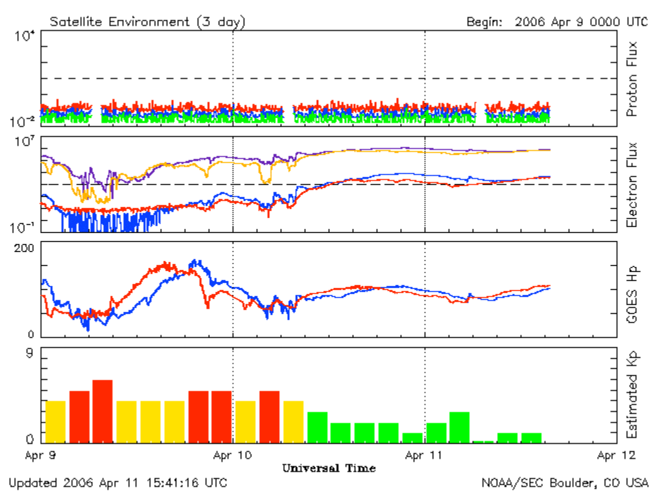
Space Environment

- **Pretty much vacuum**

Light passes through the vacuum of space. Plenty of radio waves, gamma rays, X-ray, IR, UV, visible, etc.



Satellite Environment Plot

Image:http://www.sec.noaa.gov/today.html#satenv

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The Ocean is definitely not a vacuum

The term sea state is a combined set of criteria including consistent wind speed, gusting wind speed, and significant wave height

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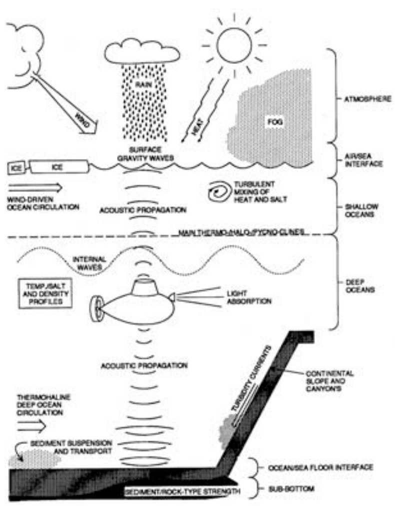
Environmental Conditions - Sea States



<u>Sea State – the Beaufort scale</u>

Sea State 0 (Under 1 Knot)
Sea State 1 (1 - 3 Knots)
Sea State 2 (4 - 6 Knots)
Sea State 3 (7 - 10 Knots)
Sea State 4 (11 - 16 Knots)
Sea State 5 (17 - 21 Knots)
Sea State 6 (22 - 27 Knots)
Sea State 7 (28 - 33 Knots)
Sea State 8 (34 - 40 Knots)
Sea State 9 (41 - 47 Knots)
Sea State 10 (48 - 55 Knots)
Sea State 11 (56 - 63 Knots)
Sea State 12 (64+ Knots)

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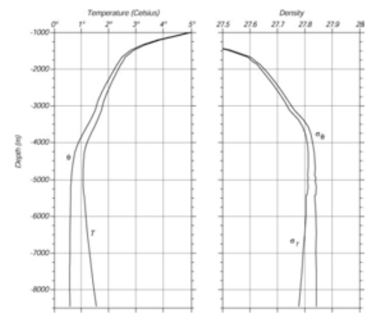
Environmental Conditions - What does the Ocean consist of?

Chloride (Cl):	55.04 wt%	Sodium (Na):	30.61 wt%
Sulphate (SO_4):	7.68 wt%	Magnesium (Mg):	3.69 wt%
Calcium (Ca):	1.16 wt.%	Potassium (K):	1.10 wt.%

Plus a host of dissolved gases with other odds and ends

Seawater make-up



Plus 1000 to the delta listed

This becomes very important later on

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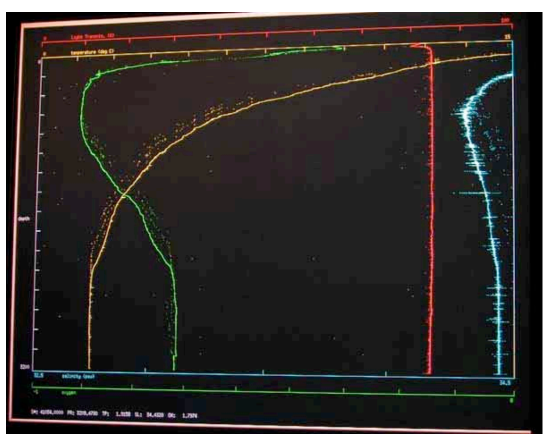
Environmental Conditions - Oxygen Minimum Zone

Oxygen minimum layer occurs at about 150 to 1500m below the surface (the green line)



This also corresponds to the most acidic water, and important area of study as atmospheric CO2 is absorbed by the Ocean

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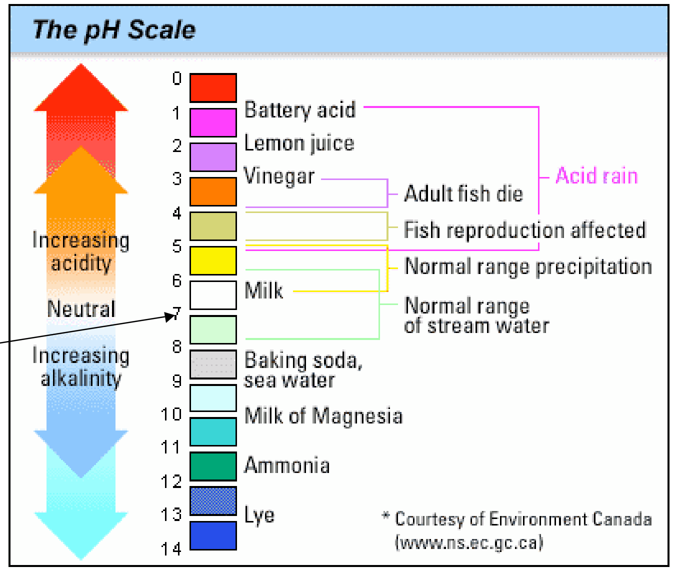
Environmental Conditions - pH

In the O2 minimum zone the pH can be in this range



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Environmental Conditions - The Photic Zone

The upper 100 -200 m of the ocean is called the photic zone

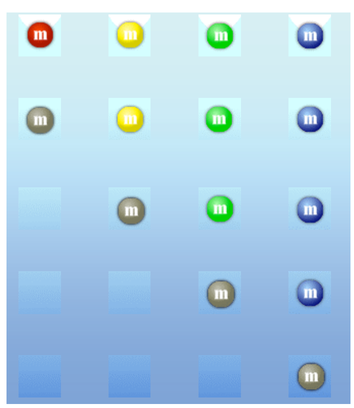
0m

1m

10m

50m

100m



by 1 m about 60% of the light is absorbed.

by 10 m about 85% of the light has been absorbed.

by 150 m about 99% of light has been absorbed.

The visible spectrum disappears quickly

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Environmental Conditions - Pressure

Demonstration of Pressure at relatively shallow depths

Image of a pipe repair – approximately
500 meters deep

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Environmental Conditions - Ocean Communications

Unlike space, light transmits very poorly. Radio waves, gamma rays, X-ray, IR, UV, visible, etc. are of little use…

Acoustics are about the best communications system.

(ULF being an exception, but this has it's drawbacks too!)

First thing to **keep in mind** with acoustics in the ocean:

dB in water is not the same as dB in air

Velocity of Sound in Water $v = (\beta\rho)^{-1/2}$

Where...
v is the speed of sound,
β is the bulk modulus of elasticity, and
ρ (rho) is the density

A number to remember

1482 m/s at 20°C freshwater or about 1531 in sea water

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Environmental Conditions - Ocean Communications

Conversion of dB from air to water (and vice versa)

In air, the sound pressure level is referenced to 20 μPa, while in water the sound pressure level is referenced to 1 μPa.

Given the above for dB's, the conversion factor for dB air è water

$dB = 20 \log (p_{water}/1\mu Pa) = 20 \log (20) = + 26$ dB

Therefore a pressure comparison between air and water differs by 26 dB.

The characteristic impedance of water is about 3600 times that of air; the conversion factor for a sound intensity in air vs water is 63 dB.

$10 \log (3600) = 36$ dB

$36 + 26 = 62$ dB

A simplified example....

If a jet engine is 140 dB re 20μPa @ 1m, then underwater this would be equivalent to
$SIL_{water} = SIL_{air} + 62 = 202$ dB re1μPa

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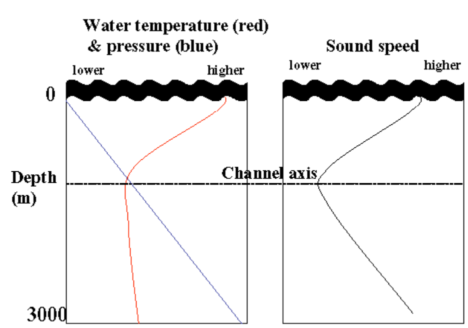
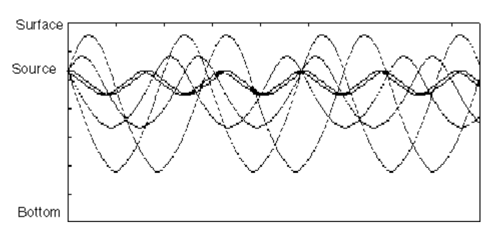
Environmental Conditions - Ocean Communications

- *Factors that affect Sound in water*
  - Temperature
  - Pressure
  - Salinity



An example of ray paths for a source in the sound channel is shown below. Note that in this idealized situation, the sound waves do not interact with either the surface or the bottom. This is a simplified example of propagation in the sound channel.



Sound will bend towards areas of slower speed.

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Environmental Conditions - Ocean Communications

- Variation of the Speed of Sound with Depth
  - This variation is termed the sound speed profile and is very important in modifying the spreading laws and determining the sound field at a distance. The speed of sound is in water is determined by temperature,salinity, and depth.The basic formula is:

$$c = 1449 + 4.59T - 0.053T^2 + 0.0163D$$

where:

c = speed of sound (m/sec)
T = temperature in degrees centigrade
D = depth in meters

Salinity is not considered here since it is negligible compared with Temperature however some applications do include it

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Environmental Conditions - Ocean Communications

Ducting

A surface duct occurs when near surface water becomes mixed due to wind turbulence causing an isothermal layer. The layer is characterized by a positive gradient effect on speed of sound. The sound travels outward in a series of upward arcs that meet the air-water interface. There is a "shadow zone" below the layer where only weak diffracted and/or surface scattered sound penetrates. The shadow area is *acoustically black* and any sound in it is weak and incoherent (i.e. this area is devoid of source sound)

When the duct is thick and the surface calm the duct provides an excellent low-loss channel for long range sonars. When the duct is thin, not developed well, and/or the surface is rough the duct can have excessive losses.

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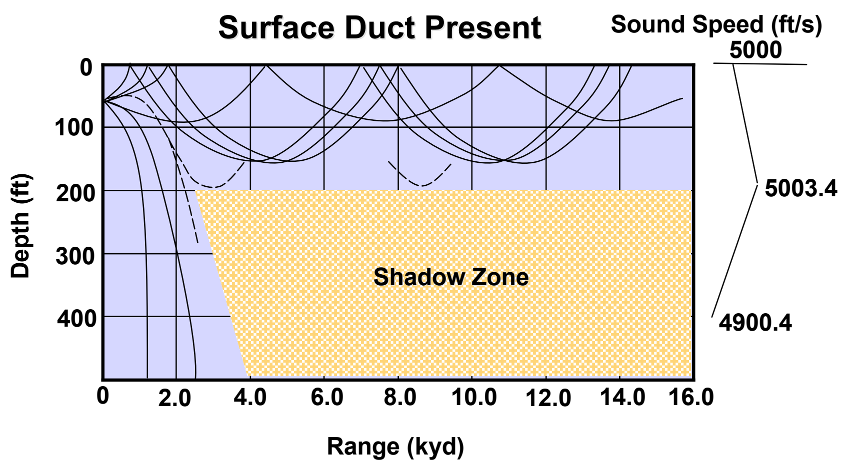
Environmental Conditions - Ocean Communications: Ducting



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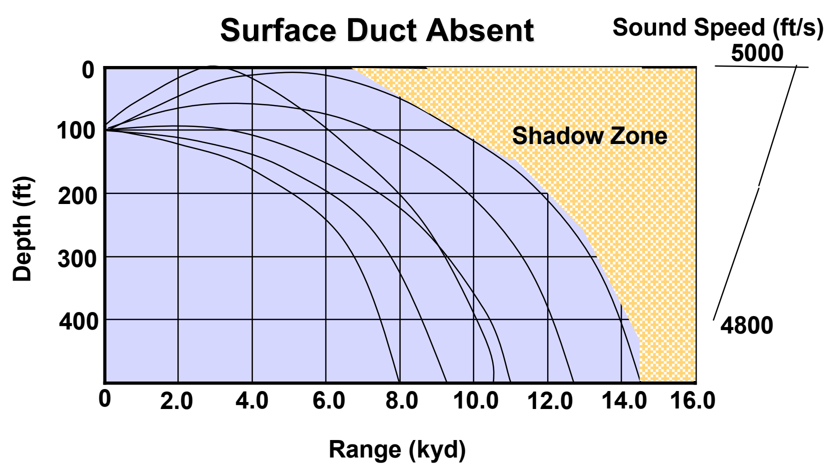
Environmental Conditions - Ocean Communications: Ducting



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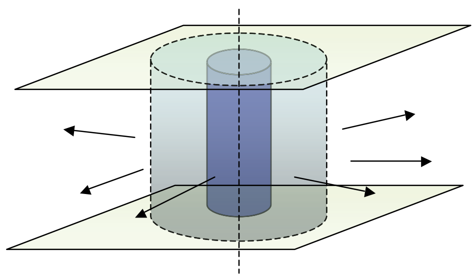
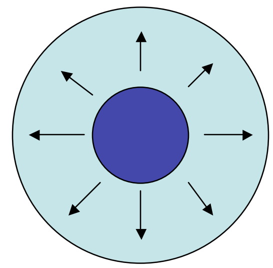
Environmental Conditions - Ocean Communications: Propagation

- Propagation of Sound in the Sea: Two types of Spreading occur,
  - Cylindrical
  - Spherical



Ducts: Cylindrical Spreading



Free Field: Spherical Spreading

Transmission loss (TL) is used to express the sum of these attenuation losses.

$TL = 10 \text{ Log } (I_1 / I_r)$

where I_1 is the intensity at 1 yard (.9 m) of the source and I_r is the intensity at some distance r yards.

Although TL is a positive from the equation above (I_1 always being greater than I_r) common usage in sonar equations shows the number as negative because it is a loss.

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Environmental Conditions - Ocean Communications: Multi-path issues

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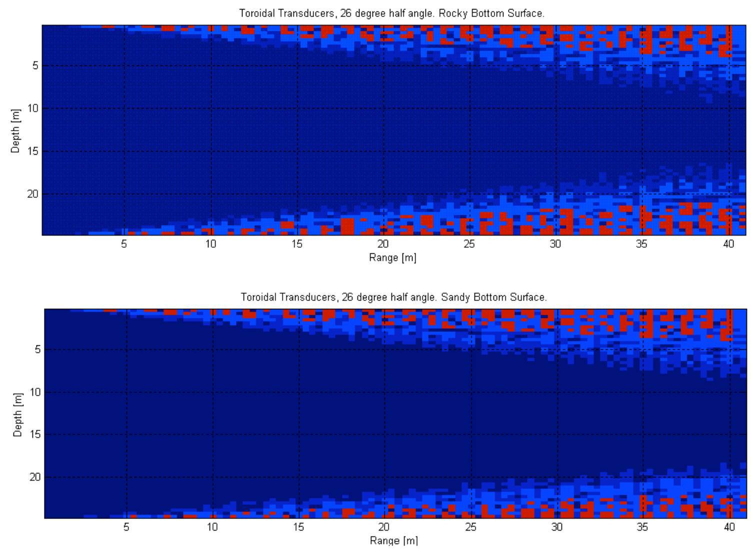
Environmental Conditions - Engineering: Toroid Transducer



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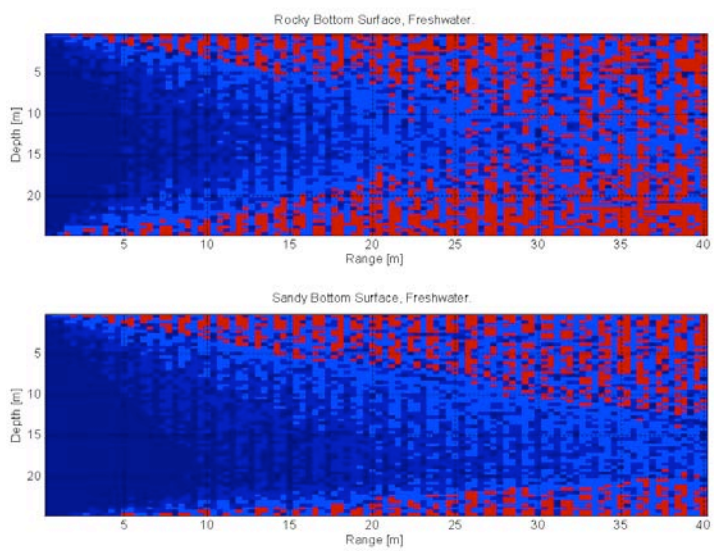
Environmental Conditions - Engineering: Spherical Transducer



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Environmental Conditions - Engineering: Sonar Classes

- Navigation / Tracking:
  - Long Baseline – 9 kHz to 15 kHz
  - Short Baseline – 15 kHz to 20 kHz
  - Ultra-short Baseline – 17 kHz – 30 kHz
- Mapping:
  - Sub-bottom Profiler – 2 kHz to 12 kHz
  - Side Scan Sonar – 50 kHz to 250 kHz
  - Multibeam Sonar – 30 kHz to 300 kHz
- Environmental:
  - Acoustic Doppler Current Profiler – 100 kHz to 1 mHz
  - Doppler Velocimeter Log - 100 kHz to 1 mHz
- Communications:
  - Acoustic Modem - 9 kHz to 17 kHz

Tomography, Biologic tracking, etc. etc.

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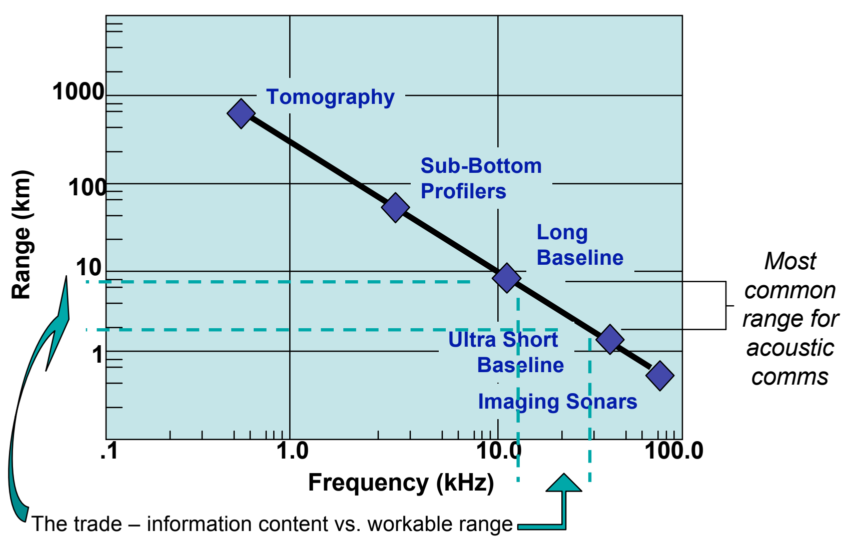
Environmental Conditions - Engineering: Range

Range at which Absorption approximates 10 dB



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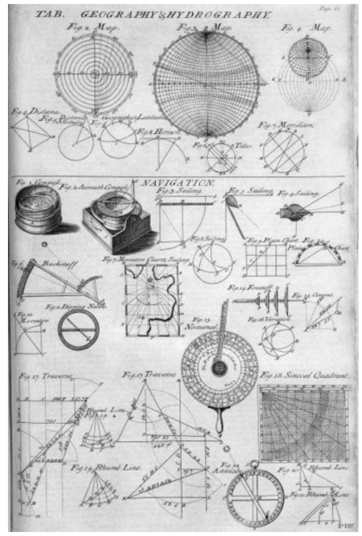
Navigation

Still in use today for many operations in science. However, no robotics of autonomous capability operate in this mode anymore.

Fluxgate compass and heading are still very common on smaller and cheaper robots as a complete nav package



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Navigation Systems

System	Accuracy	Power	Constraint
GPS	150-1m	O(1 W)	Surface only
Doppler Velocity Log w/ Magnetic AHRS	~1% Dist. Travel	25 W	1m-500m Altitude
Correlation Velocity Log w/ Magnetic AHRS	~1% Dist Travel	25W	>500m
Long Baseline Acoustic Navigation	5 cm @ 100 m 3 m @ 10 km	O(5 W)	Calibration and deployment
USBL Acoustic Navigation	.1% to 10% of Slant Range	0(30 W)	Telemetry from Surface
Inertial Navigation System	1 nm/hr (RLG & Hi Perform. IFOG)	12-20 W	Alignment
INS/DVL	.05 to .1% Dist Travel	25-40 W	Alignment

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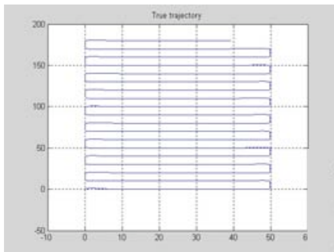
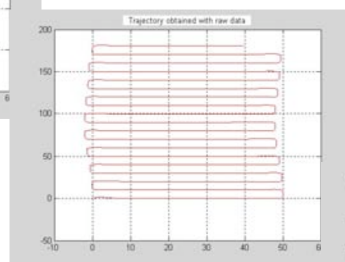
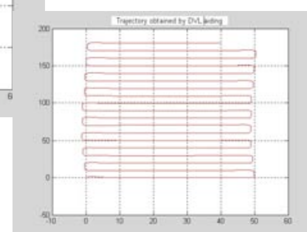
Navigation: Doppler Velocimeter Aiding



Using a low cost attitude heading and reference with an acoustic bottom tracking system, post processing of the data can do a lot to correct track





Currently, many systems are operating in this mode but using the DVL update in real time to improve autonomous operations

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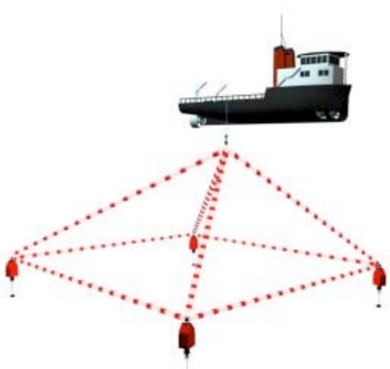
Navigation: Long Baseline Navigation – LBL



- Expensive to install / setup in terms of ship time. Each beacon must be statistically placed with GPS and least squares fitting of data
- Ship must also be instrumented and timing is critical
- Very accurate if all beacons can be observed, 10 meters or so if everything is stable
- Line of sight is required for all elements or solutions degrade quickly

Courtesy: Sonodyne

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Navigation: Short Baseline Navigation – LBL

- Easy to use once installed/setup
- Loss in accuracy due to single beacons, can approach LBL capability if everything is stable
- Ship must be instrumented and timing is critical
- Equipment is more expensive than LBL but costs are re-cooped quickly.

Courtesy: Sonodyne

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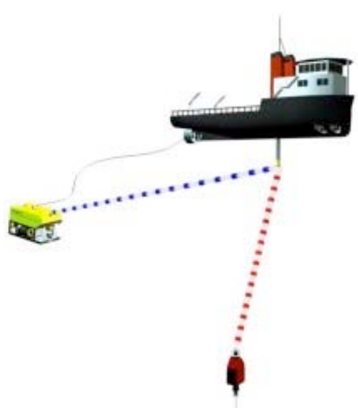
Navigation: Ultra-Short Baseline Navigation – USBL



- Once installed on systems, no setup time required other than "tuning" to conditions
- Same accuracy as SBL pretty much with less effort (advancements in electronics)
- Line of sight is required for all elements or solutions degrade quickly

Courtesy: Sonodyne

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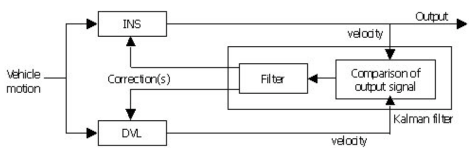
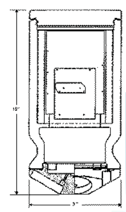
Navigation: State of the Art



GPS initialization** of a **ring laser gyro** or fiber optic gyro assisted with **integrated DVL**, limit free inertial time and for longer dives **acoustic updates using USBL

The SEA*DeViL* incorporates Kearfott's' SEAborne NAVigation (SEANAV) System, RD Instruments Doppler Velocity Log (DVL) 300 kHz and an embedded C/A code GPS receiver. Flexibility offers selection of either of two inertial rate sensors (16 or 24 cm MRLG), either of three DVL's (300, 600 or 1,200 kHz), either of three pressure housings (1,000, 3,000 or 6,000 m) and selection of an external GPS receiver in place of the embedded receiver. There is also provision for input of Differential GPS (DGPS) corrections to the embedded GPS receiver.



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Navigation: SLAM

- Simultaneous Localization and Mapping
  - Currently, SLAM algorithms are used for mosaic reassembly of missions
  - High navigation error over time limits effect range to date
  - Lighting and imagery physics create a different condition than terrestrial robotics, depth of field vision very limited
  - Acoustic augmentation is possible but resolution is low compared to vision and radar systems
  - Efforts in bio-mimetics looking at alternatives for iamge assmebly
  - Limited power for autonomous operations to take on heavy in situ computing at present

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Outline

Section A: Background
- About MBARI
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Section B: Ocean Robotics
- Supporting assets - Ships, Moorings, Satellites
- Robots
  - Floats and Profilers
  - Remotely operated vehicles
  - Autonomous underwater vehicles
  - Gliders
  - Economic comparisons – engineering drivers

Section C: The Future
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- Observatories
- Funding and Wrap Up

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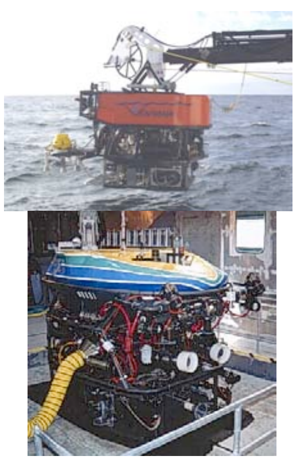
Platforms: Ocean going Robots

ROVs



AUVs

Gliders

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Primary Sensing Platforms in Oceanography

- Lagrangian
  - Drifters
  - Profilers
  - Mooring
- Mobile platforms
  - AUV's
  - Gliders
- Tow Sleds
- ROV's

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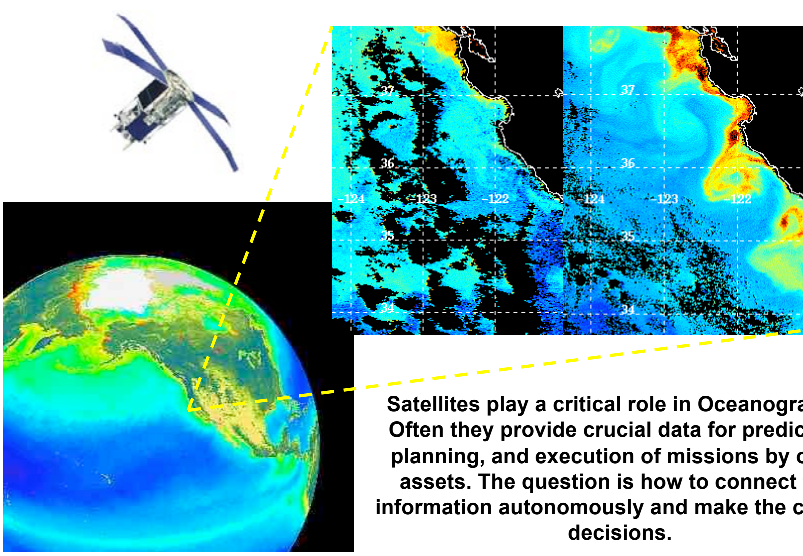
Supporting Assets:Spacecraft in the Ocean Sciences



Satellites play a critical role in Oceanography. Often they provide crucial data for prediction, planning, and execution of missions by other assets. The question is how to connect this information autonomously and make the correct decisions.

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Supporting Assets:Ships

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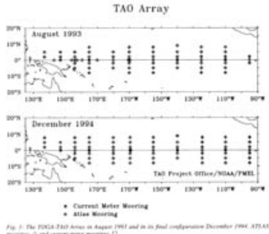
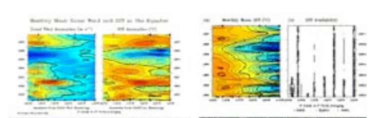
Platforms:Moorings

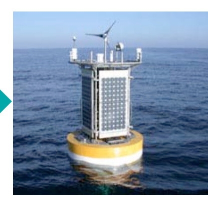
TOGA-TAO

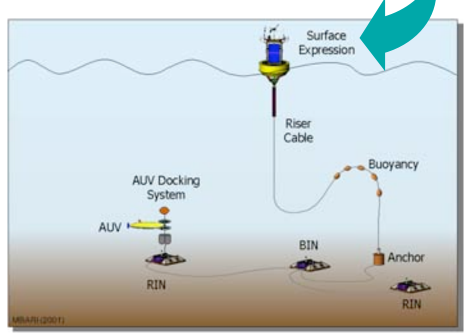
MOOS

TAO Array









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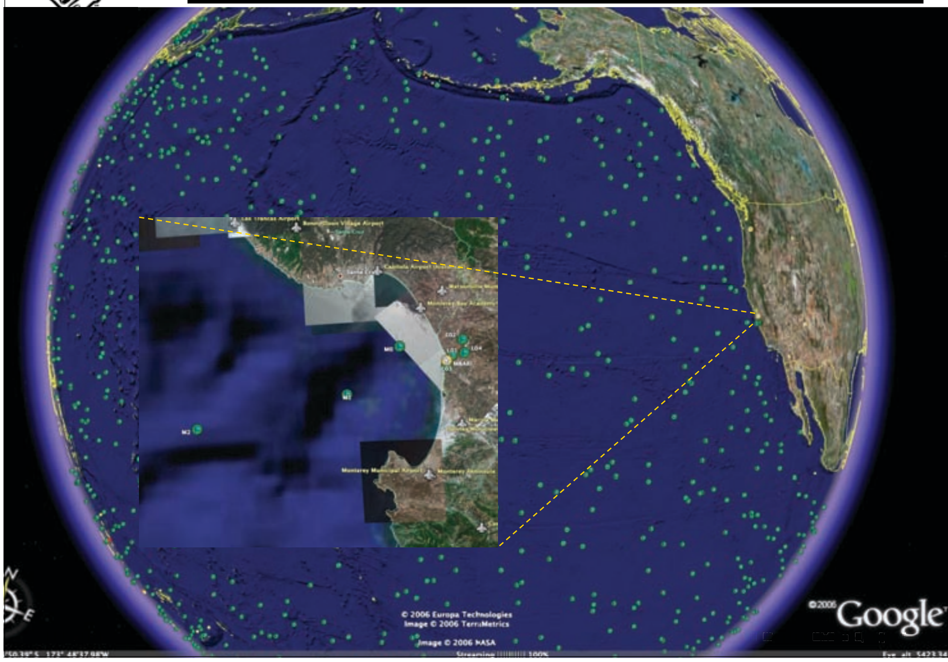
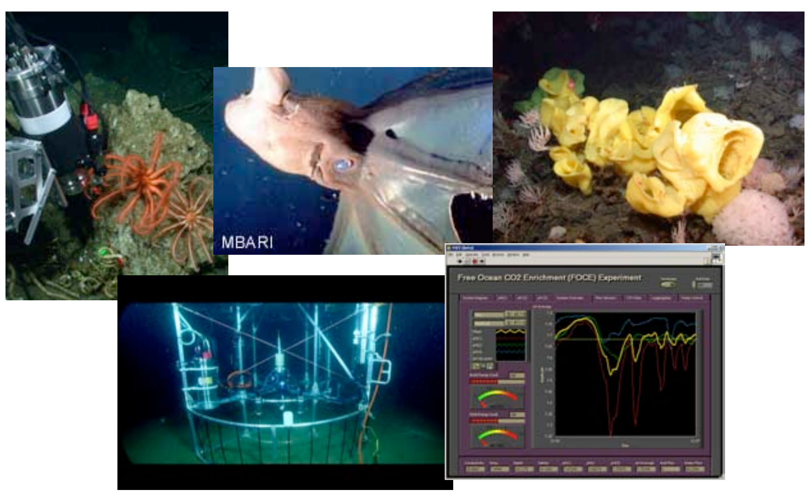
Platforms:Moorings & Floats: Where are they?



ROV Data and Sample Collection



ROVs yield very rich and robust data and in situ manipulation because they have power, but they have limited temporal and spatial capability

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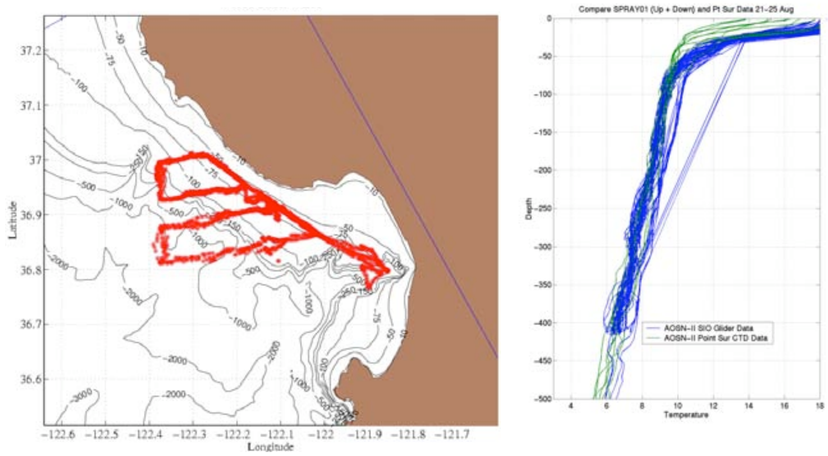
Platforms: Gliders



Gliders give position and data that can be collected with relatively low power

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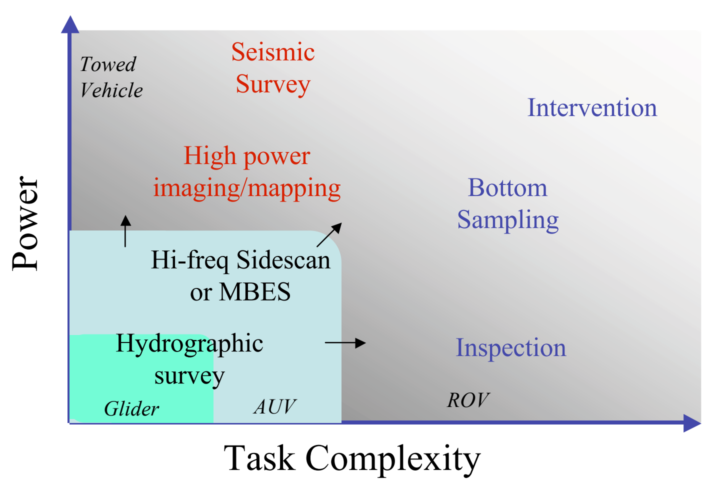
Platforms: Comparisons and Operational Domains



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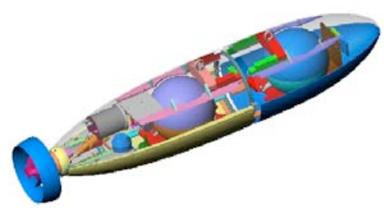
So what is the best available platform (for Autonomy research)?

- Need for
  - Event response in the large
  - Closed-loop control with shore-based data system
- To characterize these phenomenon need:
  - In-situ presence
  - Ability to find and understand the boundary conditions
  - To track their movement



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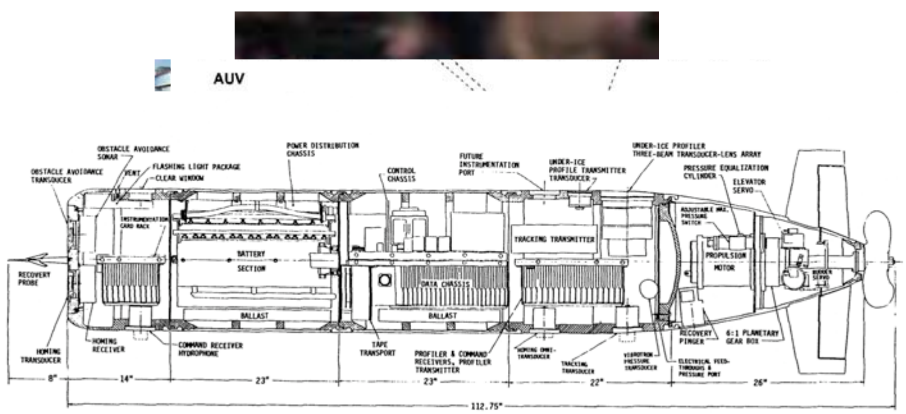
AUV's:The Choices



UARS

AUSS

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MBARI's Bluefin AUV

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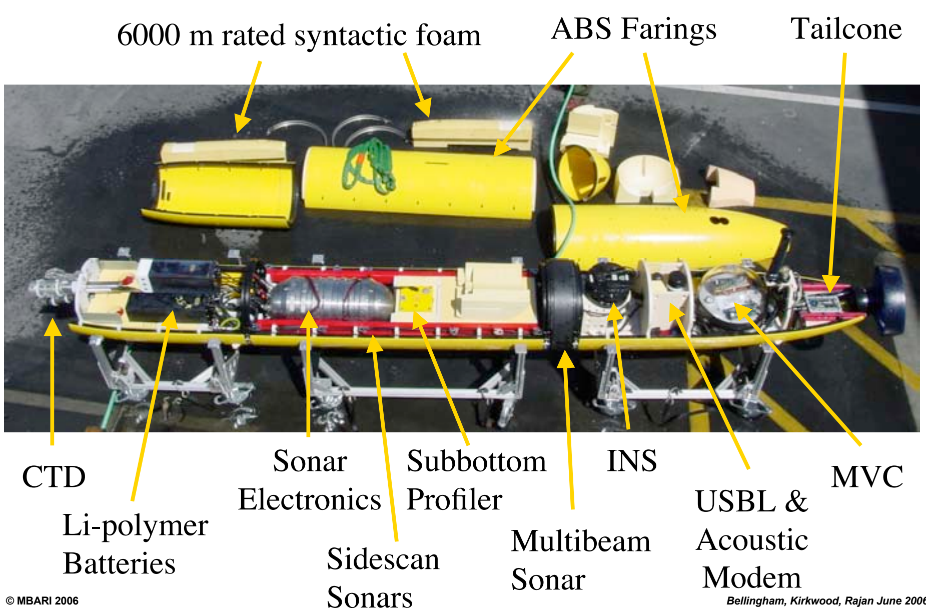
AUV internals: MBARI's Mapping AUV



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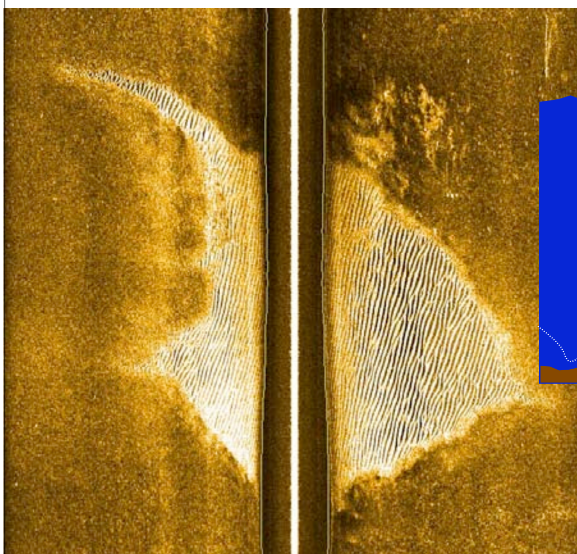
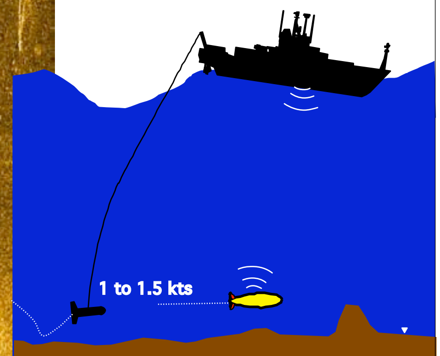
AUV Data Quality

150 m





Courtesy: Bluefin

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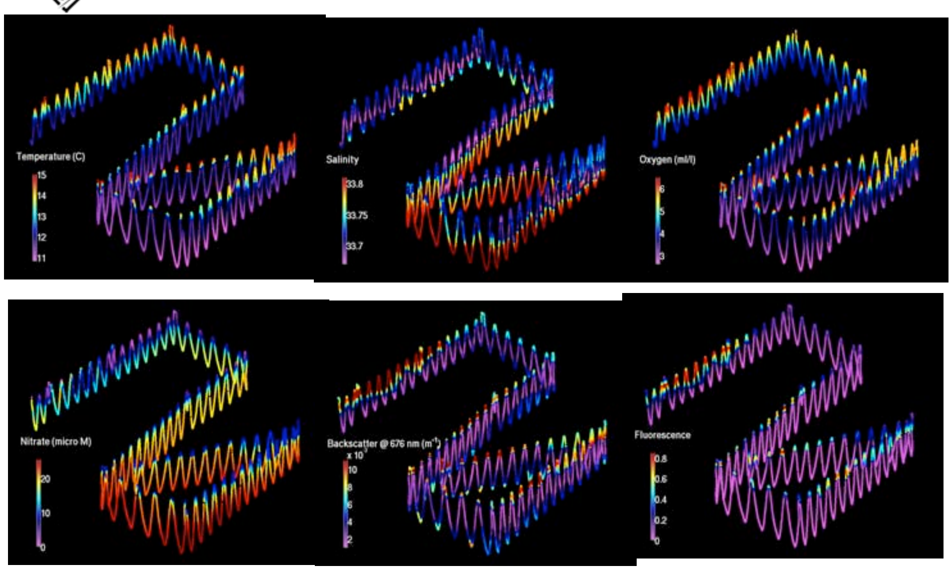
What can we map in a typical AUV survey?



(upper 30 m)

August 23, 2002

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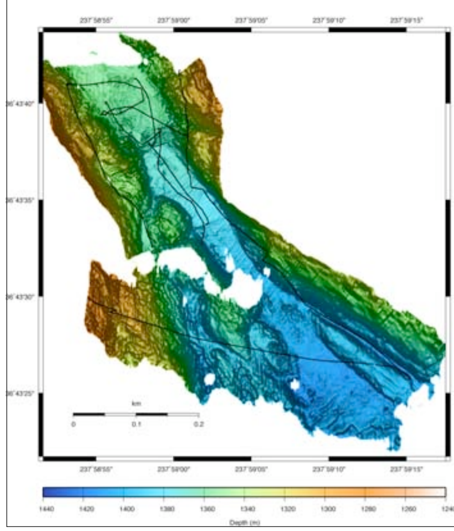
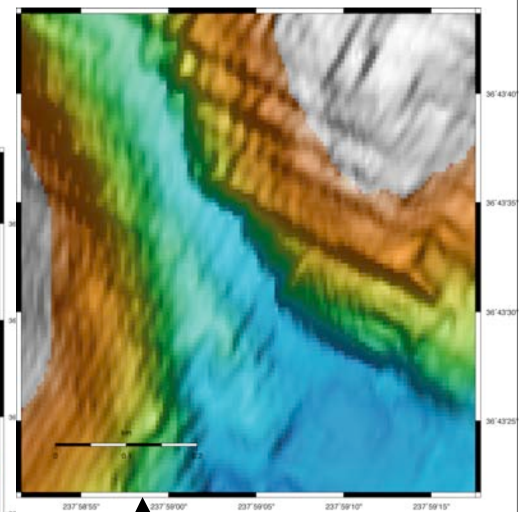
Why AUV's?: Data Quality

Monterey Canyon Narrows

Canyon Axis: 1400 m depth





Hull Mounted 30 kHz Multibeam

MBARI Mapping System
200 kHz Multibeam

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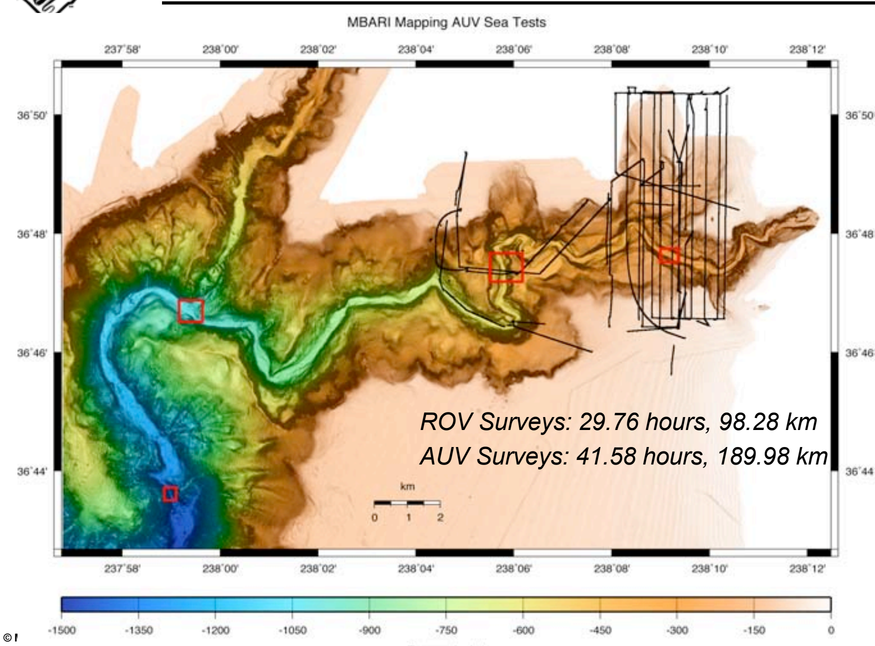
Why AUV's?: Sampling Area



June 2006

Platforms: AUV Launch and Recovery

Some images courtesy: Bluefin

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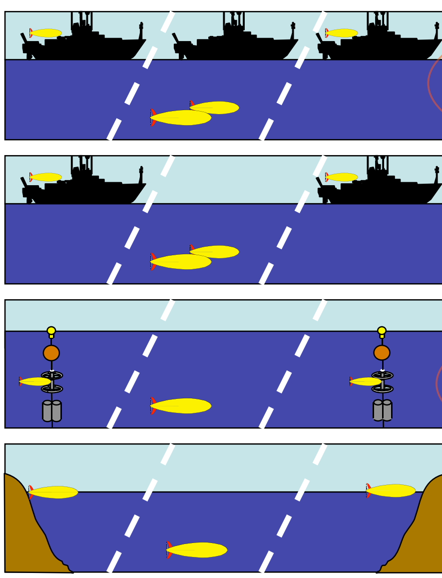
Platforms: AUV Operational Scenarios

we want to be here



Pro	Con
* Navigation by tracking * Faster deep survey * Multiple platforms	* Ship costs dominate
* Ship free for additional activity	* Navigation an issue
* Episodic response * Rough weather ops * Multiple platforms * Space-time cov.	* Complex * Dock expensive * Deployment and recovery
* No ship!	* Energy required for transit * Navigation an issue

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Platforms: A day in the life of an AUV

1. Vehicle preparation
   a. Check batteries
   b. Close pressure vessels
   c. Check vehicle trim
   d. Vehicle self-test
2. Mission configuration
3. Pre-launch
   a. Check tracking
   b. Check navigation
   c. Check location devices
   d. Run vehicle self-test
4. Position ship/boat for launch
5. Launch vehicle
6. Command mission start via RF communications
7. Track vehicle or commence other operations
8. Mission end
   a. Locate vehicle if unattended
   b. Recover data subset if operations to continue or
9. Recover vehicle
10. Download and review data

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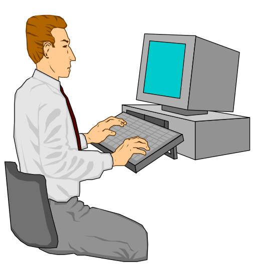
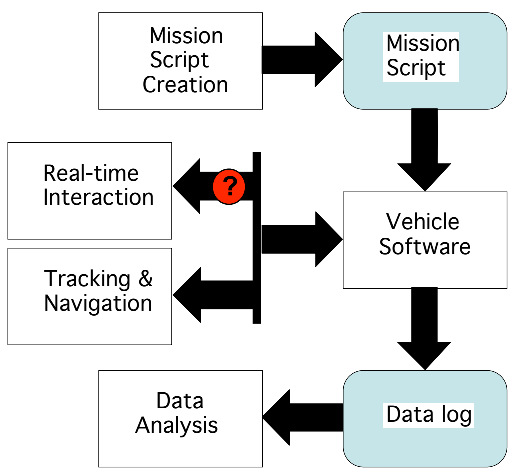
Platforms: AUV Software - User Interactions





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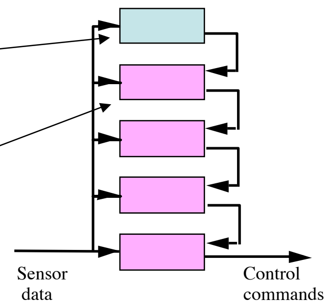
Platforms: Mission configuration

Behavior-based arbitrated control architecture:

- missions are configured from a library of 'behaviors'
- multiple behaviors can run at once
- combinations of behaviors can give
- behaviors are prioritized

Goal oriented behavior examples:
- descend to a set depth
- run in a particular direction and speed
- go to a particular location
- home on a transponder

Safety behavior examples:
- avoid hitting the bottom
- don't let the batteries get too low
- time out after a certain period



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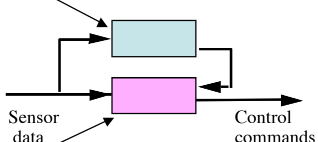
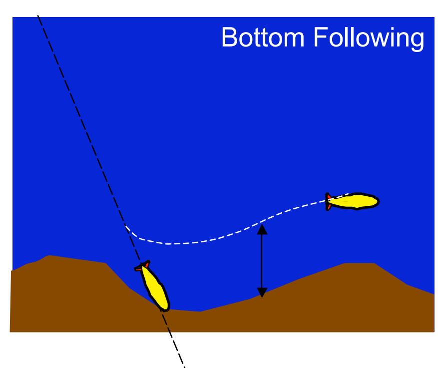
Platforms: Combining Behaviors

More complex performance can be obtained by combining behaviors…

Setpoint – run at a particular direction, depth and speed.
INTENTIONALLY SET TO RUN THROUGH BOTTOM



Depth Envelope – keep vehicle from approaching to close to bottom



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Platforms: Energy Calculation for Self-Propelled Vehicle

$$P = \frac{1}{2\eta} C_D \rho_{SW} S V^3$$

- ***P*** **= power *(w)***
- ***n*** **= propulsion efficiency (dimensionless, typically .5)**
- **CD = Coefficient of Drag (dimensionless)**
- ***p_{sw}*** **= density of seawater (1000 kg/m^3)**
- ***S = effective area of drag (in this case πR^2) with R =*** **max radius (m)**
- **V = velocity (m/s)**

NOTE: There is a load we refer to as hotel (P_h) that includes all those items burning power when you start up the vehicle excluding propulsion

$$P_{total} = P_{propulsion} + P_{hotel}$$

Key: Hotel Load = Mass including all payload *without* propulsion

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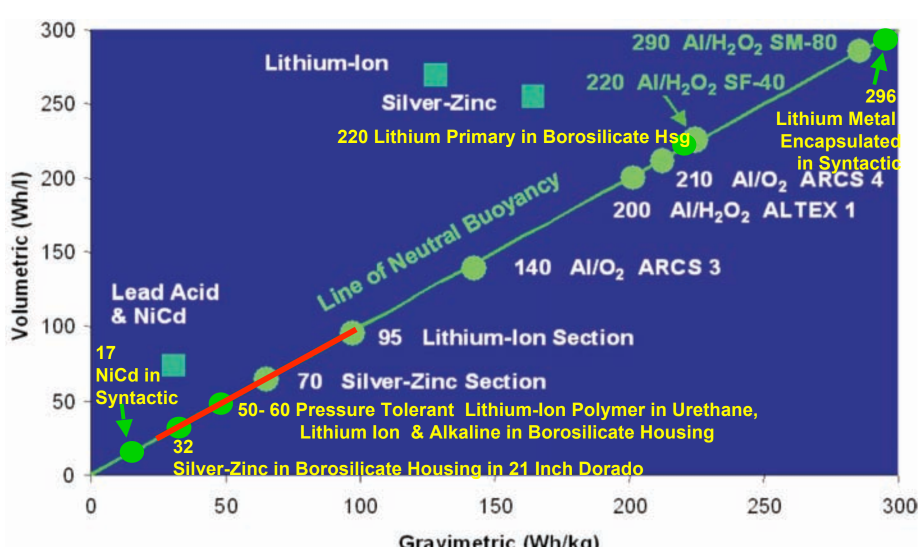
Platforms: Power Technology



Courtesy: Fuel Cell Technologies

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Platforms: Range/Speed Relationships

Power consumption:

$$P_T = \frac{1}{2}\frac{\rho\, C_d\, S}{\eta} v^3 + P_h$$

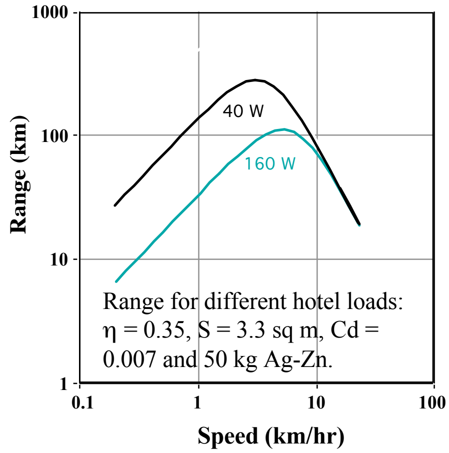
Energy per distance traveled:

$$e = \frac{1}{2}\frac{\rho\, C_d\, S}{\eta} v^2 + \frac{P_h}{v}$$

Best speed:

$$v_{opt} = \left(\frac{P_h\, \eta}{\rho\, C_d\, S}\right)^{1/3}$$

$$\textbf{when} \quad P_p = \frac{P_h}{2}$$



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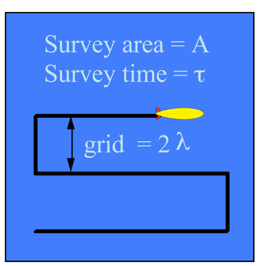
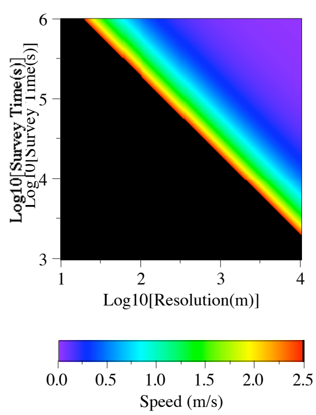
Platforms: Grid Survey



Total Survey Distance
d = A/2λ

Required Speed
v = A/2λτ

Example - 100 sq km Area



Slide Courtesy of J.G.Bellingham

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Platforms: Survey Envelope

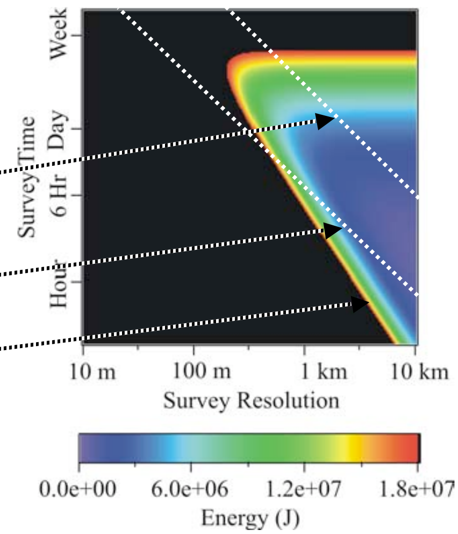
Determining the accessible survey space

Minimum vehicle velocity

Maximum vehicle velocity

Energy limit of vehicle
E_{total} = total energy available.

$$(P_{total})\tau = \left(\frac{\rho \, C_d S V^3}{2\eta} + P_h \right) \tau$$



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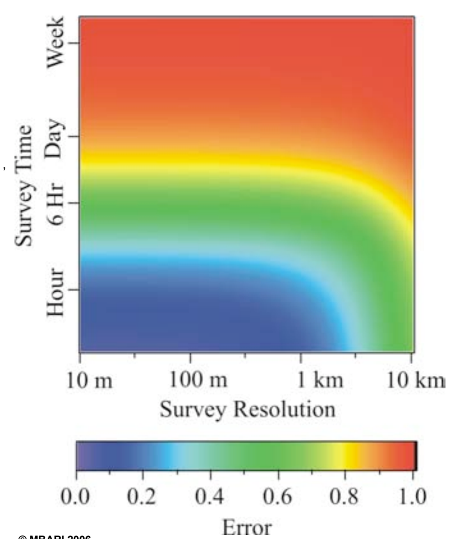
Platforms: Survey Error

Computation for a Time-Varying Oceanographic Field



Temporal Error Contribution:

$$\varepsilon_\tau = \int_{-\tau/2}^{\tau/2} R(t)\,dt$$

Spatial Aliasing Contribution:

$$\varepsilon_\lambda = \frac{\int_{\Omega} P(\mathbf{k})\,d\mathbf{k}}{\int_{\Omega+\Psi} P(\mathbf{k})\,d\mathbf{k}}$$

Cumulative Error:

$$\varepsilon_{total} = 1 - (1-\varepsilon_\lambda)(1-\varepsilon_\tau)$$

$R(t)$ = temporal correlation function.
$P(\mathrm{k})$ = spatial energy density spectrum

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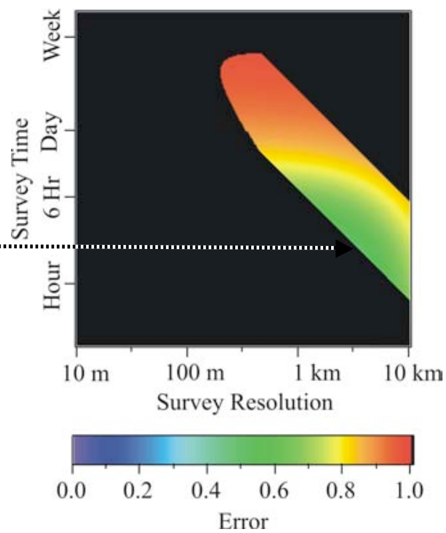
Platforms: Picking the Optimum Survey

Optimum survey
to minimize error



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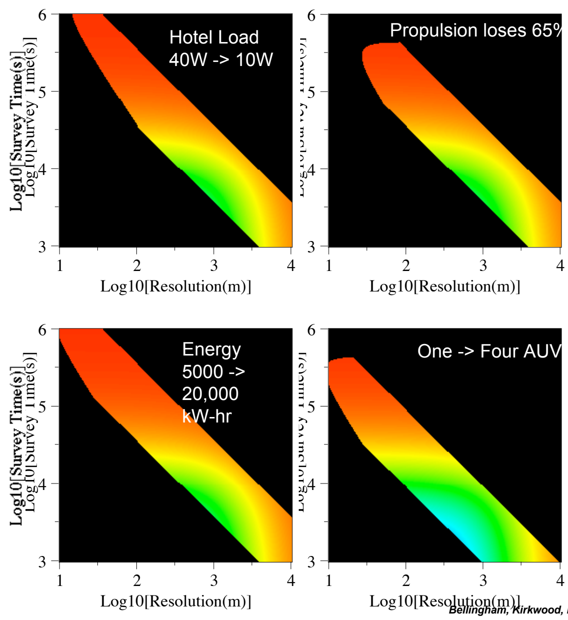
Platforms: Picking the Optimum Survey

Exploring
Design Space
with Survey
Envelope
Analysis



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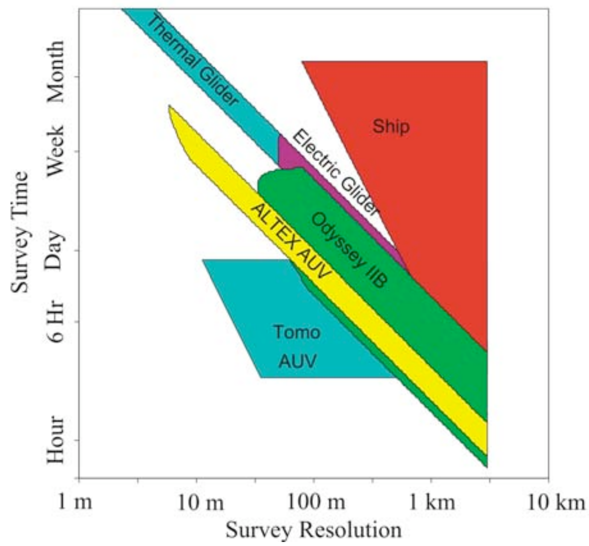
Platforms: Picking the Optimum Survey



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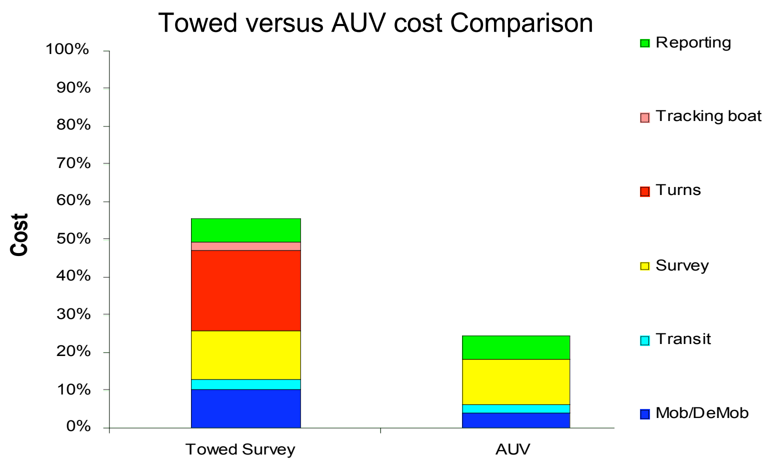
Platforms: Economics of Surveying



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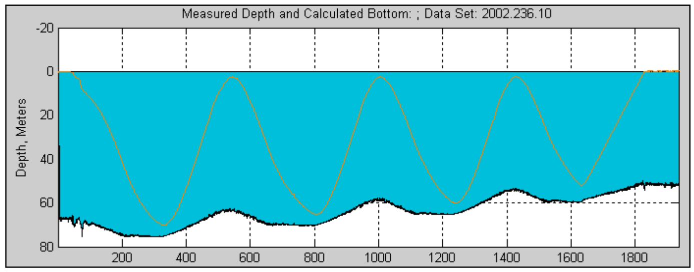
Platforms: Payload Configuration



Example: Altimeter data, if not calibrated, shows the bottom as having ripples when in fact it is very smooth. Altimeter geometry combined with vehicle pitch introduced anomalies in this example that must to be corrected afterwards.

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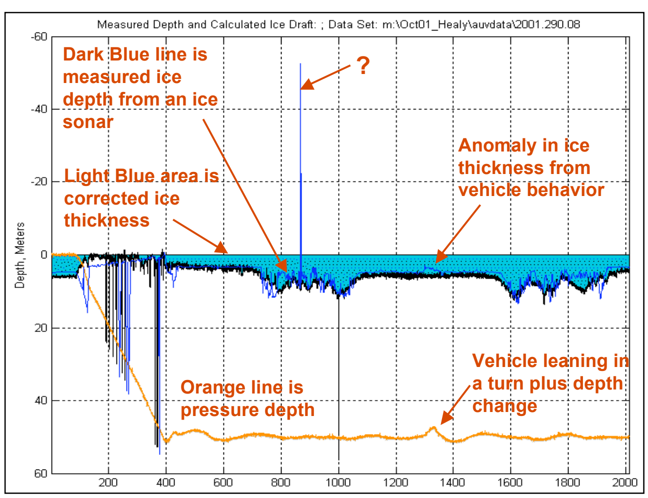
Platforms: Payload Configuration



Another simple example of vehicle data laid over ice thickness data and how vehicle motions have introduced errors.

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Use Case 1: ROV End Point Control

- Goal:
  - enable complex manipulation operations by the pilot while reducing the end-effector control effort
  - coordinate all vehicle motions through an intuitive and simple interface
  - allow the user to focus on achieving a single high-level goal, abstracting all other aspects of decision making and safety
- Why is it challenging?:
  - Servo off visual input with uncertain lighting
  - Control of coupled vehicle-manipulator in the presence of large disturbances (e.g. tether-coupled surface motion) with complex dynamics.
  - Planning and execution in an uncertain environment

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Use Case 1: ROV End Point Control: Current State

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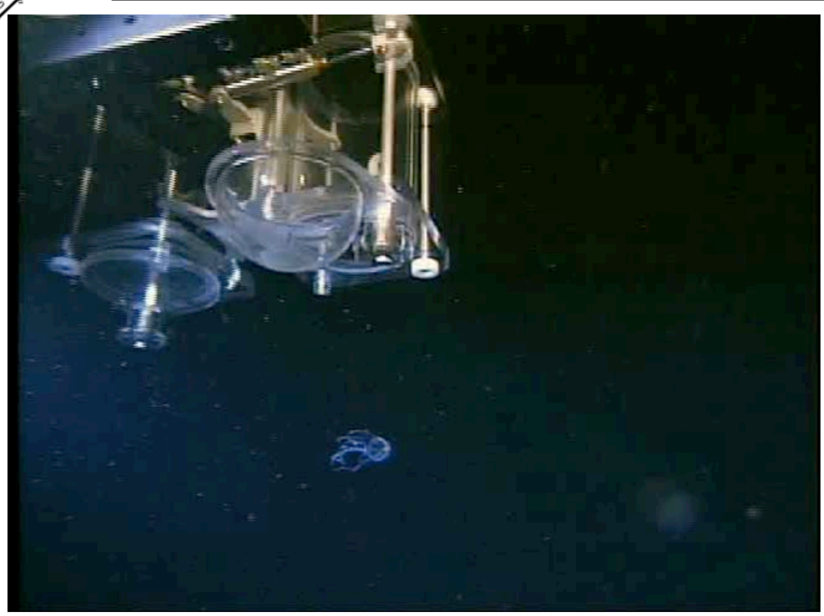
Use Case 1: ROV End Point Control: Current State



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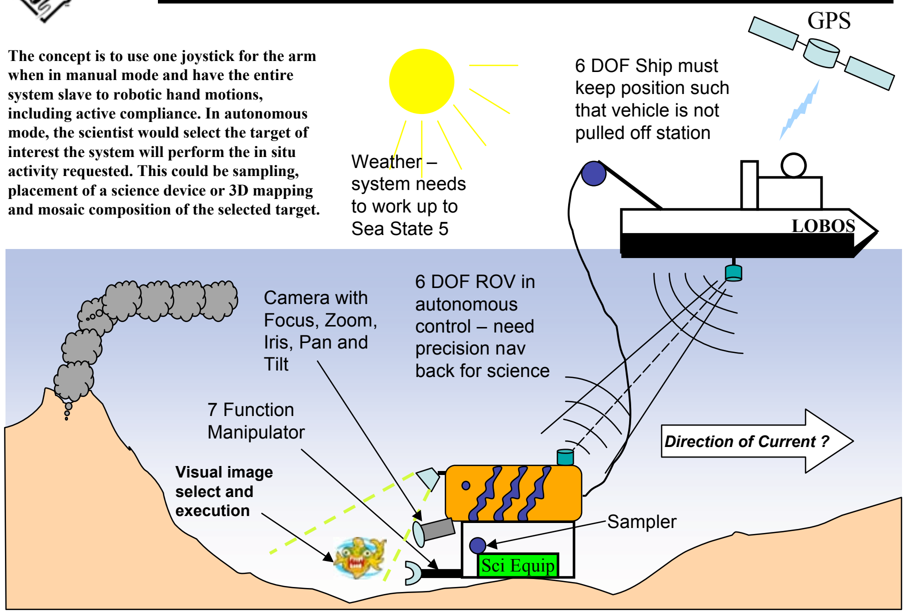
Use Case 1: ROV End Point Control Concept of Operation

The concept is to use one joystick for the arm when in manual mode and have the entire system slave to robotic hand motions, including active compliance. In autonomous mode, the scientist would select the target of interest the system will perform the in situ activity requested. This could be sampling, placement of a science device or 3D mapping and mosaic composition of the selected target.



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Use Case 2: Multi-AUV Observation Systems

- Goal:
  - to develop multi-vehicle operations with increased spatio-temporal variability
  - coordinate all vehicle motions through an intelligent synergy of science inputs, predictive models and sensor knowledge obtained in real time
  - manage a multiple set of non-homogenous autonomous ocean robots
  - maximize return while allowing for dynamically targeting and serendipitous science
- Why is it challenging?:
  - mapping a changing ocean with vehicles that move very slowly
  - need to minimize error of reconstructed ocean field
  - need to send the platforms to the right place with adaptive sampling
  - need for situational awareness both onboard and onshore
  - defining quantitatively the trade between communications (power, complexity) and onboard autonomy

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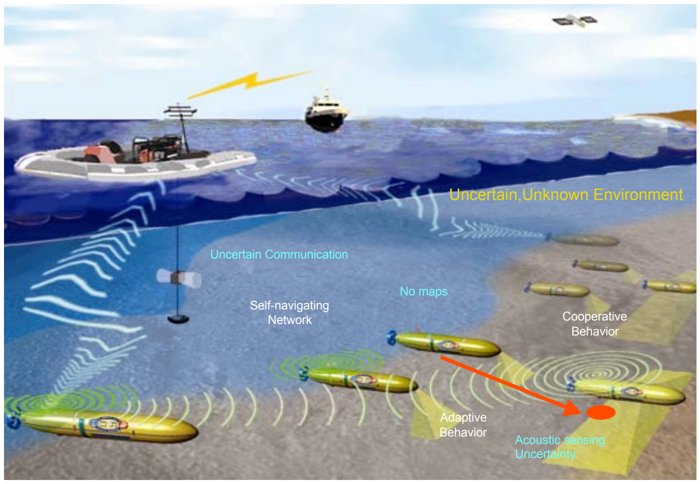
Use Case 2 : Multi-AUV Observation Systems



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Use Case 3: Event Response

- Goal:
  - respond to a episodic event trigger
  - ensure the event is of legitimate scientific interest
  - ensure a gradated response using less “expensive” assets to validate event signal followed by deployment of more valuable assets
  - ensure adequate resources (energy, data buffers) available to track event for viable coverage
- Why is it Challenging?:
  - event signal may be difficult to characterize
  - managing large number of heterogeneous assets in a sensor-web
  - need to deal with time and resources with TBD optimality criteria
  - energy is limited, so the “right” signal should trigger various assets
  - observability of the phenomenon and assets is limited (far from shore)
  - need for situational awareness both onboard and onshore
  - in-situ decision making *simply does not exist*

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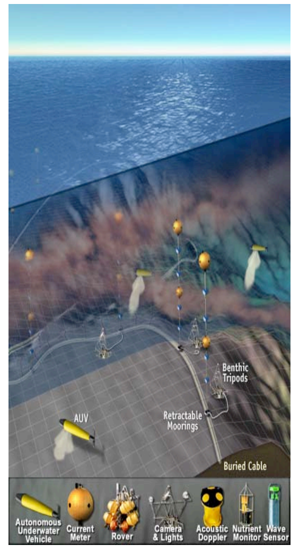
Use Case 3: Event Response

- Sensor data indicate events of interest, e.g.
  - Fluorometer indicates plankton bloom
  - Optical backscatter indicates volcanic plume
  - Meteorology sensors indicate wind speed and direction
- Response to event may be resource-intensive
  - Wakeup vehicles/sensors from sleep mode
  - Collect data at high rate, high power (e.g. video, lights)
  - Launch AUV



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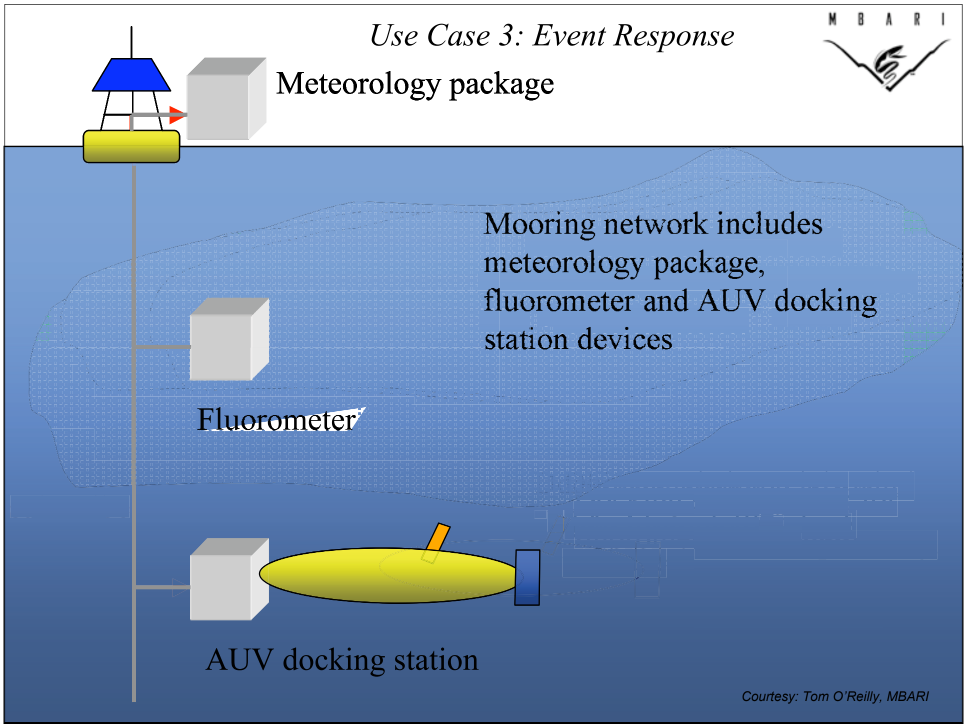
Use Case 3: Event Response



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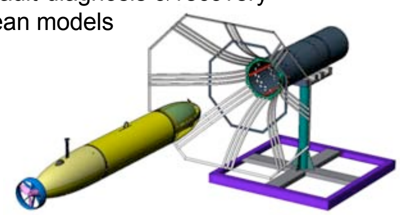
What is the (near-term) Future in Ocean Science?

- Paradigm shift from Expeditionary to Observatory science
  - ➢ Extended presence will require more autonomy and automation
  - ➢ Event response to episodic events of scientific interest
  - ➢ Resource Optimization
  - ➢ Goal-oriented desktop based command/control
- Distributed and Coordinated Observations
  - ➢ Multi-asset planning and execution
- Other impacts on Intelligent systems
  - ➢ Robust mission operations including Fault-diagnosis & recovery
  - ➢ Coupled Observation systems and ocean models
  - ➢ Optimization for asset management



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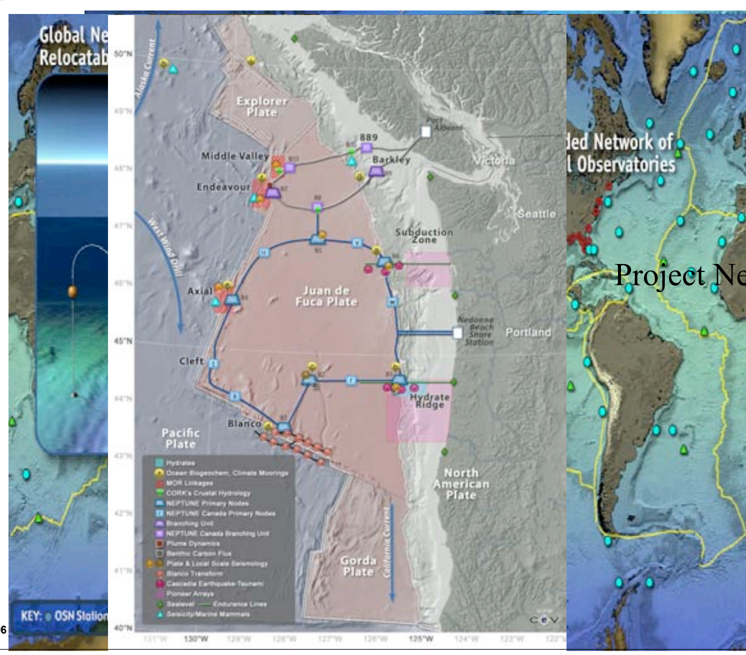
Near Term Challenges/Drivers for Autonomy: Ocean Observatories



Project Neptune

AUV Docking

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Near Term Challenges/Drivers for Autonomy: Adaptive Sampling

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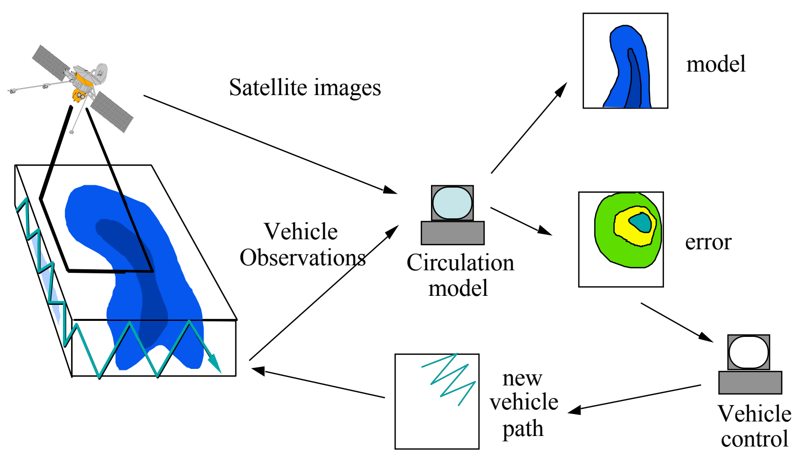
Near Term Challenges/Drivers for Autonomy: Coupled Observations+Modeling



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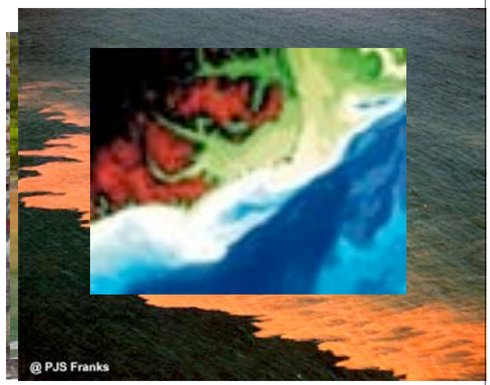
Near Term Challenges/Drivers for Autonomy: Relevant interesting Science

- Understanding large scale physical, chemical, biological phenomenon
  - HAB (Harmful Algal Bloom)'s
  - Chemical transport
    - Nitrates
    - Hydrates
  - Impact of CO_2 absorption
    - Rise in acidity over the last 200yrs Nutrient transport in the water column
  - Upwelling and its consequences
  - Canyon Dynamics
- Autonomous Mapping
- Managing event-response scenarios for Sensor-Webs
- Need for persistence presence to see biology evolve
  - Eyes on the Sea/HD TV in the ocean



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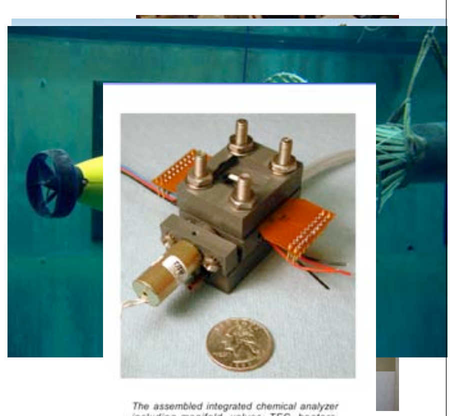
Near Term Challenges/Drivers for Autonomy: Key Technology Drivers

- AUV Docking will enable
  - power and data connection to the sea floor
  - deployment time will be cut short
  - allow a capable asset to be clos(er) to the action
  - game-changing equation in persistent, mobile and capable asset
  - need for goal-oriented commanding for AUV's
- In-situ robotic instrumentation will enable
  - sense-deliberate-act cycle for critical science questions
  - E.g: AUV Gulper and ESP
- MEMs will enable
  - tight packaging of sensors within smaller platforms
  - consume less power



The assembled integrated chemical analyzer including manifold, valves, TEC, heaters, optical detector and pump.

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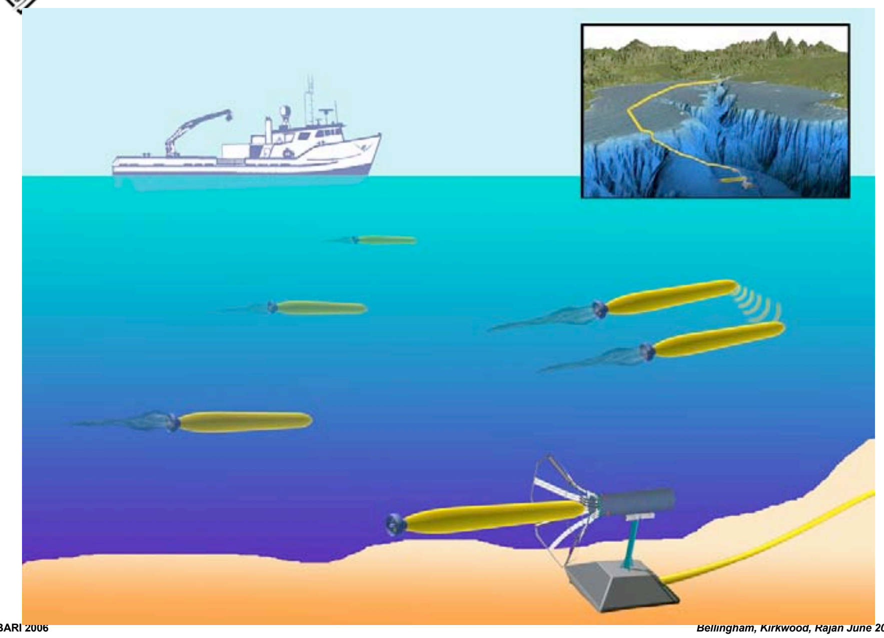
The Brave New World of Oceanography?



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But…What are the Tall Poles?

- Power
  - Platform life is dependant on battery life
  - Battery technology is rapidly changing
    - Fuel cells are very promising
    - But explode ever so often
- Perception
  - Visual methods are poor
  - Sonar is most effective with lots of false positives but saps power
- Communication
  - Acoustic methods are the currently the best methods
    - Low bandwidth and high-power requirements
- Navigation
  - Localization is hard
    - Lack of visual perception
      - To “see” need power
- Critters!

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Tall Poles: Bio-fouling

Tall Poles: Dynamic Undersea Phenomenon

RIN: Remote Interface Node

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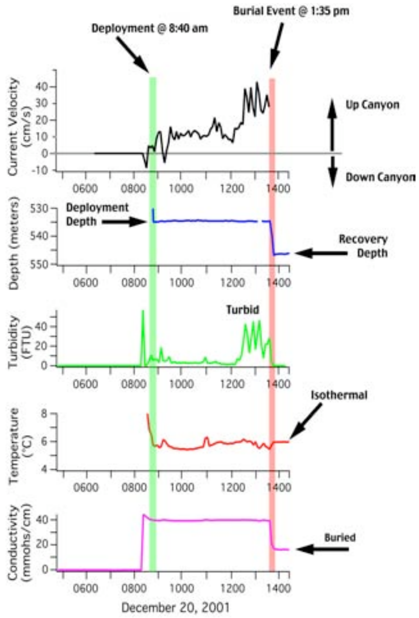
Tall Poles: Dynamic Undersea Phenomenon



Data logger intact.
A sediment transport event occurred in Monterey Canyon
on December 20, 2001 between
13:30 and 13:40 PST.

Instrumented frame moved 11.9 m downcanyon
in less than 10 minutes (>1.1 m/sec.) and found buried in >70 cm thick gravity flow deposit.

Funding and Wrap Up

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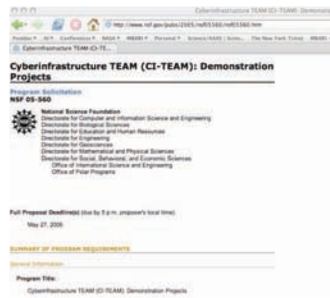
This is interesting but where do I get the $'s…?

- Primary sources of funding in the Ocean sciences in the US are:
- NSF's new division of CyberInfrastructure (CI):
  - Ocean Sciences Division funds pure science
  - Engineering Division is where Computer Science researchers can focus on
- ONR is more geared towards engineering support for existing platforms rather than new starts
- NOAA is a poor source; mostly for providing ships and vessels
- Overall NSF and NASA (Earth Science) provide viable technology funding



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Some criteria for success in working with MBARI

- Crucial areas of interest in AI/Autonomy
  - Fault Diagnosis and recovery
  - In-situ goal-oriented commanding
  - Resource management of deployed sensor networks
  - Decision-support Mixed-Initiative systems for asset deployment and management
- Some salient points on *how* to collaborate:
  - MBARI internal funds cannot be used for external collaborators
  - MBARI external projects are capped at 25% of budget (~ $10M)
  - MBARI assets *can be* used for collaborations and can be funded from external sources
  - Working with MBARI scientists is essential; technologists can help
  - Measure of success is using open-source systems which can be used at other oceanographic institutions
  - Non-US collaboration is doable, albeit not the norm
  - Visitors are welcome (including for Sabbaticals)
- Look for synergistic programs at NSF, NASA, ONR, DARPA etc.
  - Use to test algorithms in a situated setting in the ocean
  - Impact an existing MBARI asset
  - Factor in costs of using the assets

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Potential Collaborators (besides MBARI)

- Major US and non-US Oceanographic research institutions:
  - Woods Hole (WHOI)
  - Scripps (SIO)/UCSD
  - Oregon State Univ.
  - Univ. of Washington
  - Florida Atlantic Univ.
  - IFREMER, France
  - Univ. of Southhampton, UK

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How can Autonomy make an impact in the Oceans?

- Key areas of impact:
  - Chemical and Biological observations
  - Command and Control
  - Resource Management
- Why? Because systematicity of Vehicle Control System development:
  - Model-based approaches _scale_ in complexity of the domain model
    - Control knowledge is separate from domain knowledge
    - Reuse of command/control avionics including existing dynamic control techniques
  - _Abstraction_ of commanding results in
    - Increased science return
    - Risk reduction
    - Better use of workforce
    - Potential ROI in cost reduction
  - _Robustness_ of commanding
    - Dealing with unpredictability (predictable control algorithms in an dynamic environment don't cut it)
    - Recovery in Off nominal scenarios must be done
      - Expediently (millisecond control loop)
      - Contextually
      - Safely (i.e verifiable behaviors)

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Take Home Message

- Ocean Science and Engineering has a very robust robotics legacy
  - Allows for tracking point phenomenon
  - Does not allow for observing large scale spatio-temporal phenomenon
  - Goal-oriented AI based control system are next to non-existent
    - So lots of opportunity!
- Oceanographic science is at a cusp;
  - Large scale phenomenon key to understanding climate-change
  - Maturity of tools, processes and techniques to allow integration into work-processes
  - Robots have become our proxy in the ocean for many activities
  - New methods to deliver power and communications into the deep ocean
  - AI based robotic platforms the backbone of next generation ocean observing systems
- Current Autonomy architectures have made a substantial impact in Space Science
  - They could make an equally (if not more) substantial impact on Ocean Sciences
- MBARI is open to using its internal resources as test-beds to leverage external funding sources

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[redacted]

Reference Material

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Key Sources of Information on Ocean Sciences and Engineering

- MBARI's web site: www.mbari.org
- NSF's Orion Program on Ocean Observatories. www.orionprogram.org
- Current set of Ocean Observatories: www.orionprogram.org/links/default.html

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Discussion on Pressure

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Pressure

The pressure at the base of a column of liquid of height **h** and density ρ is given by the expression:

$$p(h, L, A) = g(L, A) \cdot \rho \cdot h$$

atmosphere-ocean interface at $z = \eta(\lambda, \phi, t)$ to some ocean depth z

η is the free surface displacement with respect to a resting ocean

p_a is the atmospheric pressure at the surface of the ocean

ρ is the *in situ* ocean density

(λ, ϕ) horizontal position

$$p(\lambda, \phi, z, t) = p_a(\lambda, \phi, t) + g \int_z^{\eta(\lambda,\phi,t)} \rho(\lambda, \phi, z', t)\, dz'$$

In general, we use the simple state unless the application instrumentation requires otherwise – i.e. we set η to zero (note the sign of Z)

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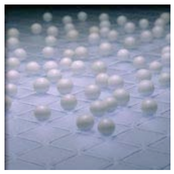
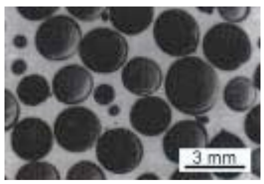
Pressure: Technology used for flotation

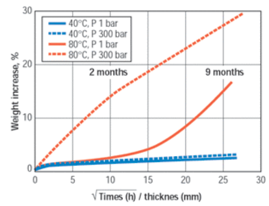


Micro-spheres

Easily formed or machined

Macro-spheres





The pressure effects and aging issues are pretty much solved except for pressure cycling

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Pressure

We handle it like space (but in reverse)

A graceful failure

Vendor forgot about annealing by heat

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Pressure: Environmental advantage and disadvantage

Materials that perform well in compression can be applied to solve cost or other problems

Common samples or other experiments can store energy that is a potential hazard at the surface

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Governing Equations For Communications

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Ocean Communications

Nyquist Intersymbol Interference Theorem

B = bandwidth
D = Max data rate
K = number of possible voltage values

$D = 2\,B \log_2 K$

C = max effective data rate
B = bandwidth
S/N = signal to noise

$C = B \log_2 (1+s/n)$

S = avg power signal
N = avg power noise

S/N is measured in dB

S/N dB = $10 \log_{10} (S/N)$

Ocean Communications: Information Density

Claude Shannon – Bell Labs 1948

bps = BW $\log_2$ (1+ P/N)

Where:

bps = bits per second

BW = channel bandwidth

P/N= signal to noise power ratio
This is a real power ratio and not a dB ratio.

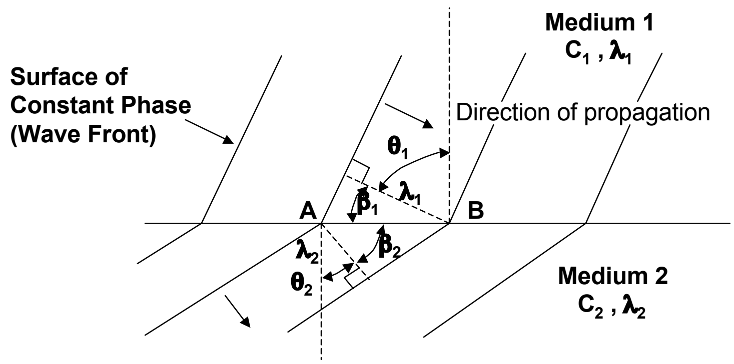
dB = 10 $\log_{10}$ P/N

dB/10 = $\log_{10}$ P/N

$10^{dB/10}$ = P/N

The take home message is the frequencies we work with limit the amount of information that can be exchanged… but wait, it gets worse

Ocean Communications: Snell's Law



AB = λ_1 /cos β_1 = λ_2 /cos β_2

Since $\lambda = c/f$, c_1 /cos β_1 = c_2 / cos β_2 or

c_1 /sin θ_1 = c_2 / sin θ_2

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Other environmental issues

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Corrosion

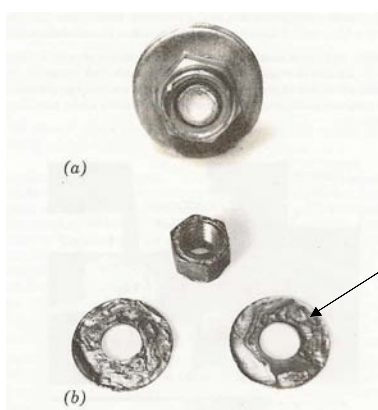
Aluminum
6061-T6

Figure 2.2 Scanning electron micrograph of a corrosion pit on aluminum alloy 6061-T6 after one week in seawater. The diameter of the central pit is about one-thousandth of an inch. Note the extensive branching which amplifies the damage.

Pit corrosion

Corrosion

Stainless Steel – CRES 304



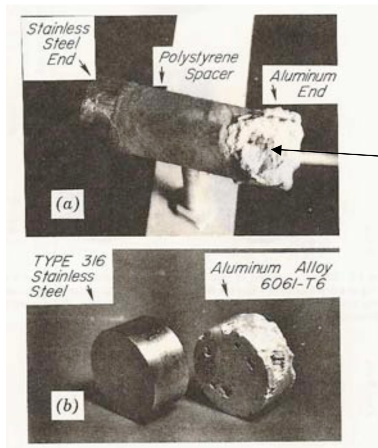
Lack of Oxygen in seawater (anaerobic)

Crevice corrosion

a) as seen assembled in sea water
b) hidden surfaces exposed showing corrosion

Corrosion

Stainless Steel to Aluminum



Aluminum acting as sacrificial anode

What's odd about this situation ?

Galvanic corrosion
a) assembled after exposure to sea water
b) hidden surfaces exposed showing corrosion

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