AUV Technology and Application Basics

Why use and AUV?

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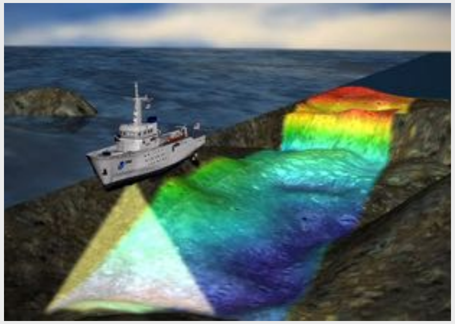
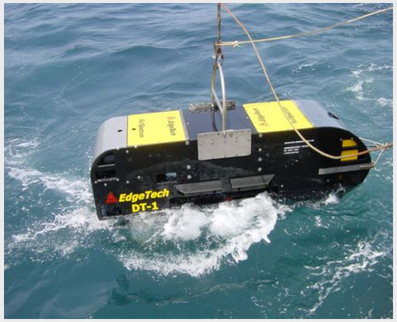
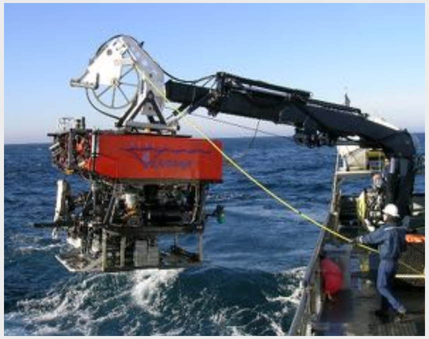
Alternatives:

- Remote sensing - Ship-hull mounted sensors
- Cabled Towfish or ROV
- Manned Submersible







AUV Advantages:

- Less Expensive.
- Higher Quality Data, especially when deep
- Safer

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Types of AUVs -1

- Propeller-driven (cruising and hovering)

Hydroid Remus 100

Bluefin 9”

ISE Explorer

WHOI Sentry

Teledyne Gavia

Bluefin HAUV

WHOI Seabed

Kongsberg Hugin 100

Ocean Server IVER2

ECA Alistar

JAMSTEC Urashima

NOCS Autosub

Types of AUVs -2

- Buoyancy driven gliders and floats,

Scripps Bluefin Spray

Teledyne Webb Thermal Glider

Teledyne Webb Argo Float

Teledyne Webb Electric Glider

UW – iRobot Seaglider

Types of AUVs -3

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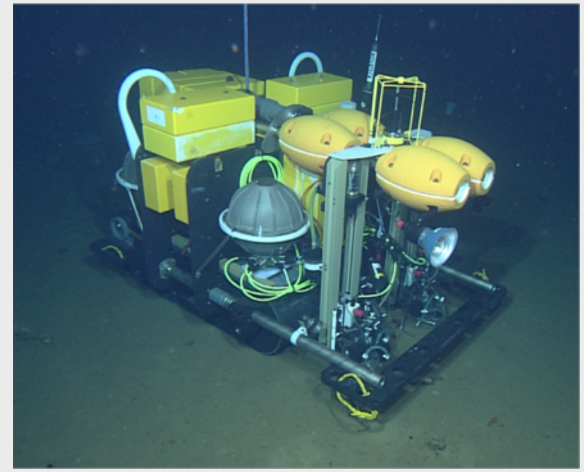
- Wave gliders
- Crawlers
- Biomimetic

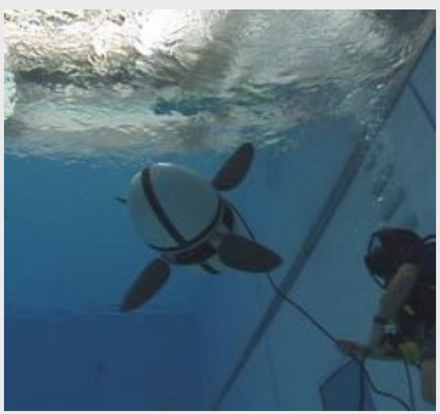
Liquid Robotics Wave Glider

NEPTUNE Canada's Wally Rover



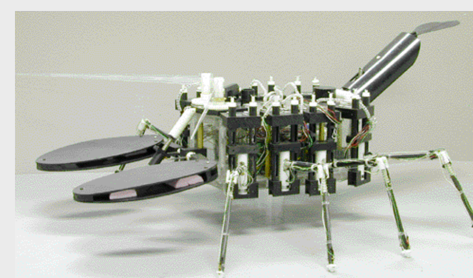
MBARI's Benthic Rover

EvoLogics Fin Ray Effect Glider



Nekton's Pilotfish

Nekton's Transphibian



RoboLobster – Joe Ayers

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Types of AUVs -4

Unmanned Surface Vehicles (USV)

Northwind Marine Sea Fox Mark II

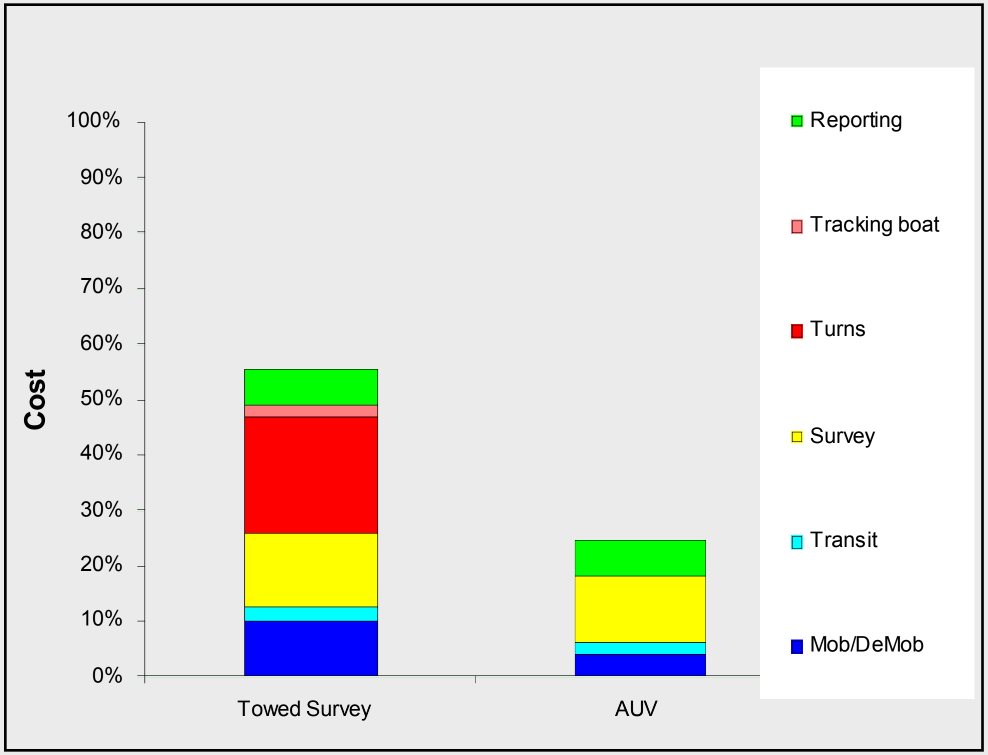
Navtec, Incorporated Owl MKII Unmanned Surface Vehicle

Naval Undersea Warfare Center Division Newport

Spatial Integrated Systems Inc.

Why use an AUV? - Less Expensive

- Faster – in deep water
  - 4-5 knots verses 2-3 knots for towfish in deep water
  - quick turns
- Expensive ship can perform other tasks
- Or, it’s possible to operate AUV without a ship



Towed sonar versus AUV Survey Cost Comparison

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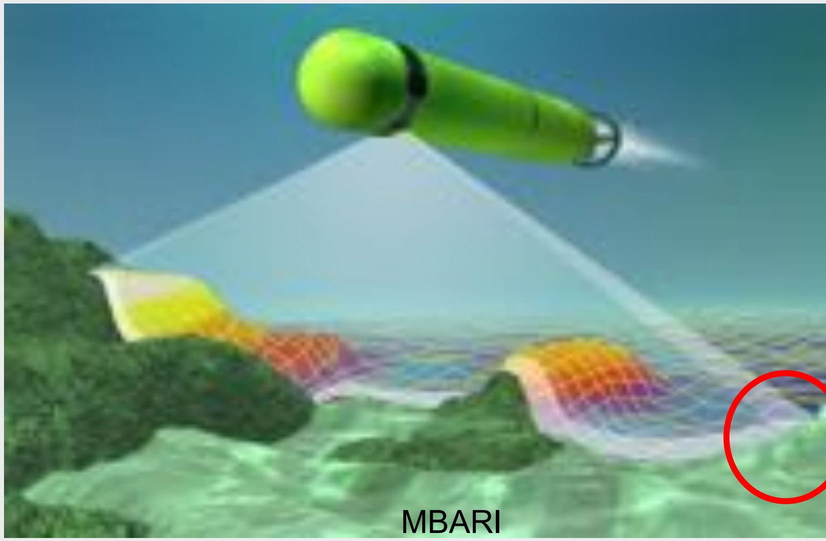
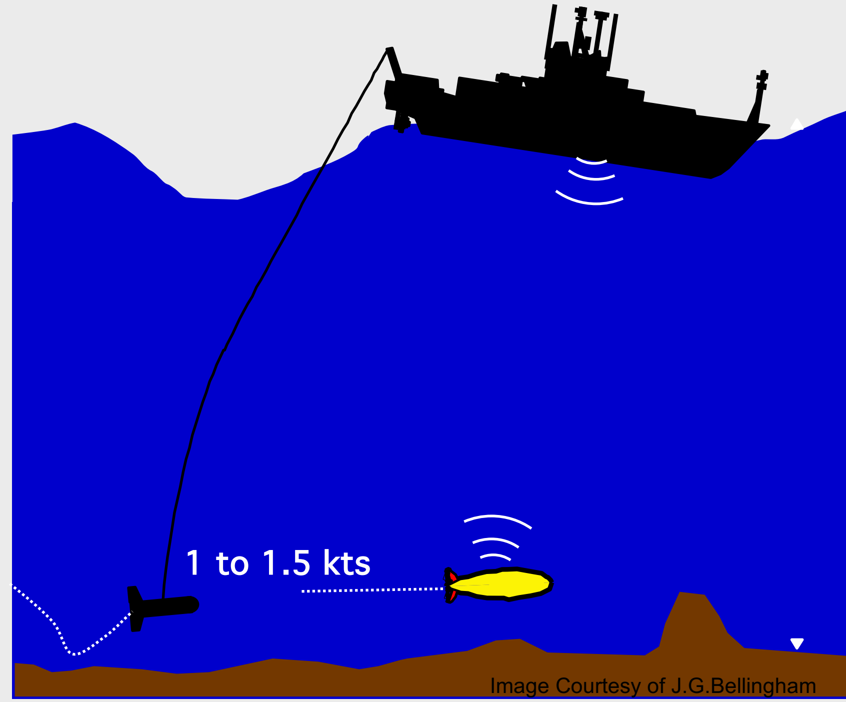
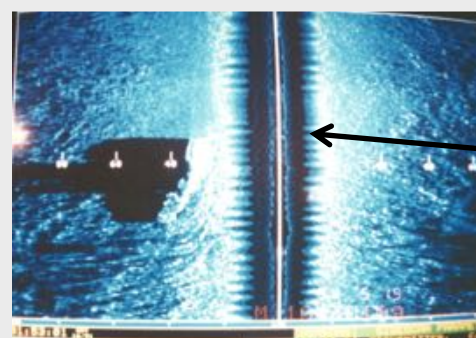
Higher Quality Data





Ship motion affects towfish

- Higher resolution than hull mounted sonar
  - Sonar beams diverge:
    - 1 degree beam footprint
    - @50m range =0.9m spot
    - @500m = 9m
    - @5000m = 90m
- Better altitude control than towfish



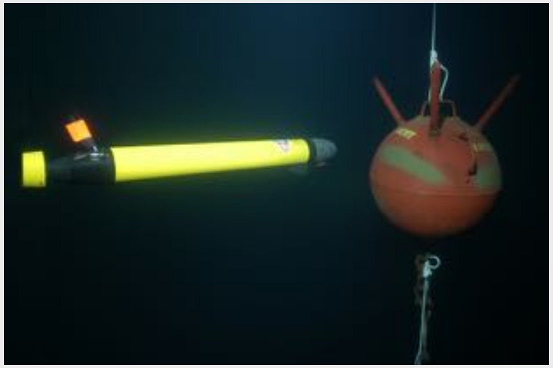
Surface wave induced noise

Deep Sea Discoveries

Safer

- Mine hunting
- Under Ice
- Tunnels
- Contested waters

Atlas-Elektronik Seafox



Nekton's Ranger mine neutralization AUV

WHOI Tunnel AUV

ISE Theseus AUV

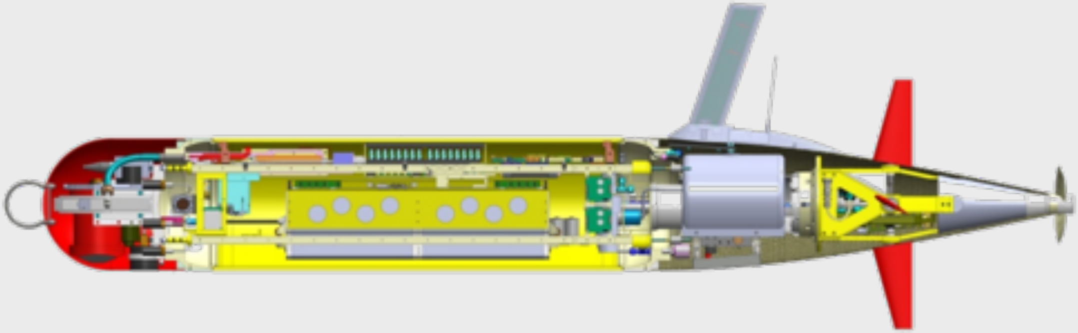
Types of AUVs: Cruising AUV

Tethys Long Range Vehicle

Specs:

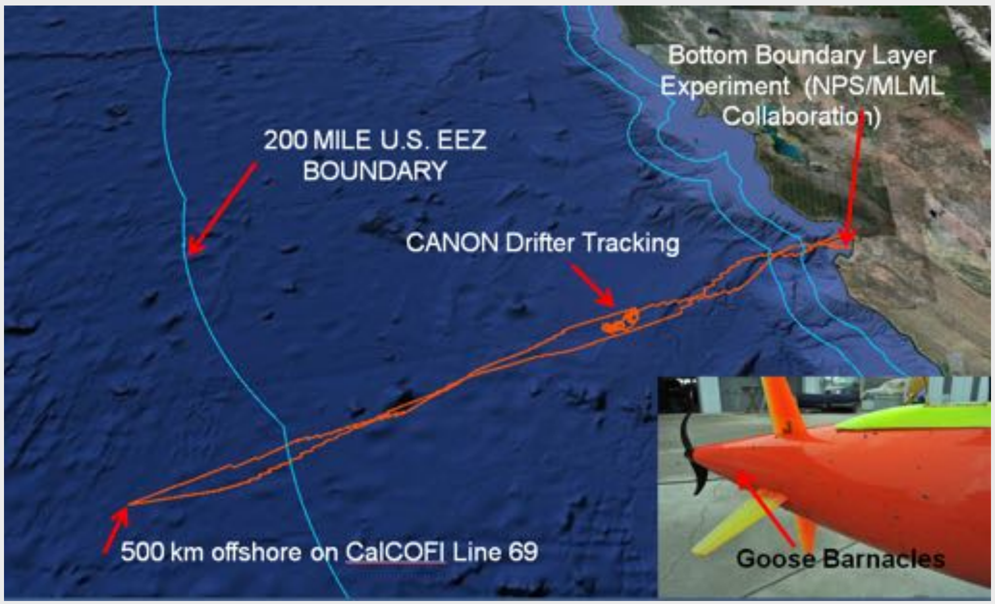
- 300m depth rated
- 105 kg, .3m dia x 2.1m long
- .05—1.2 m/s speed plus hover
- 3.8 kW-hr Secondary Battery Pack
    - ~1 week endurance or 600 km range
- 12 kW-hr Primary Battery Pack
    - ~ 3 week endurance or 1800 km
- Active variable buoyancy system
- Active mass shifter
- Paired elevator/rudder
- 16 channel load controller/monitor
- Extendable, flooded, nose section

MBARI's Tethys AUV

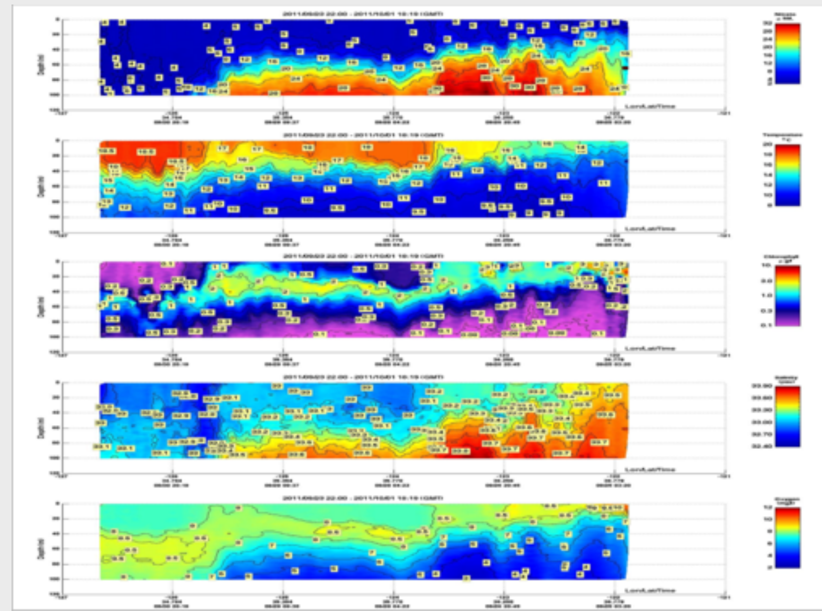


Types of AUVs: Cruising AUV

Typical Mission for Tethys



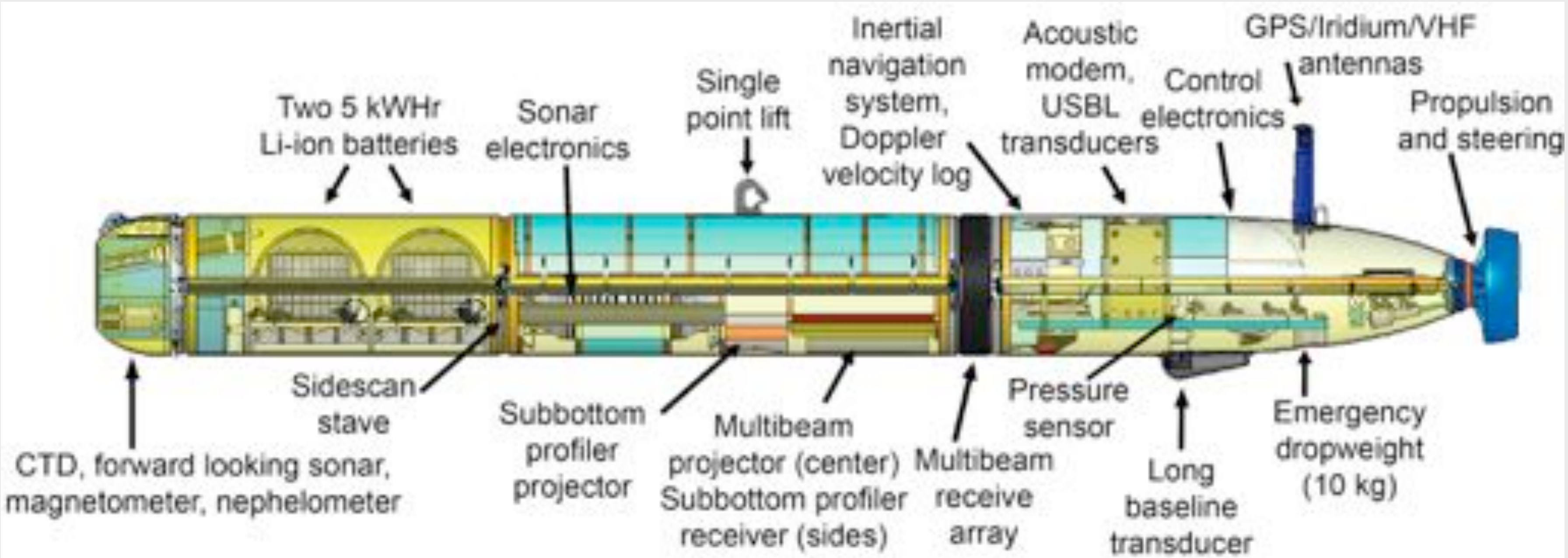
1800 km long Mission plot



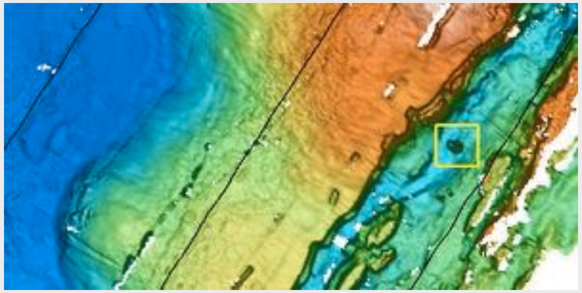
Data Products:
500 km wide, 100m deep panel
Nitrate, Temperature,
Chlorophyll Salinity, Oxygen

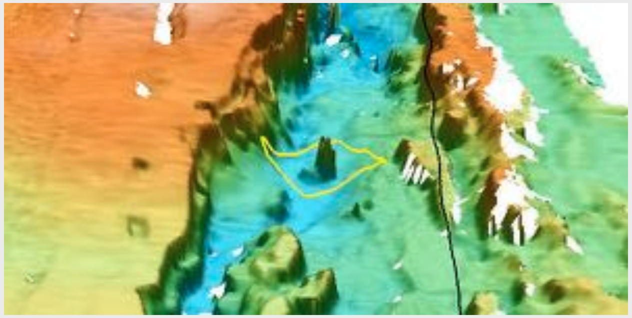
Types of AUVs: Cruising AUV

Seafloor Mapping



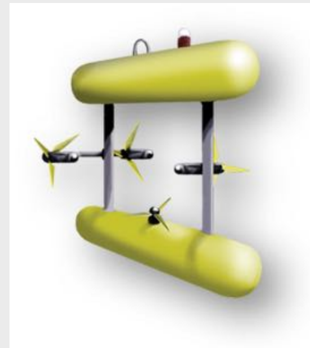
<u>MBARI Mapping AUV</u>



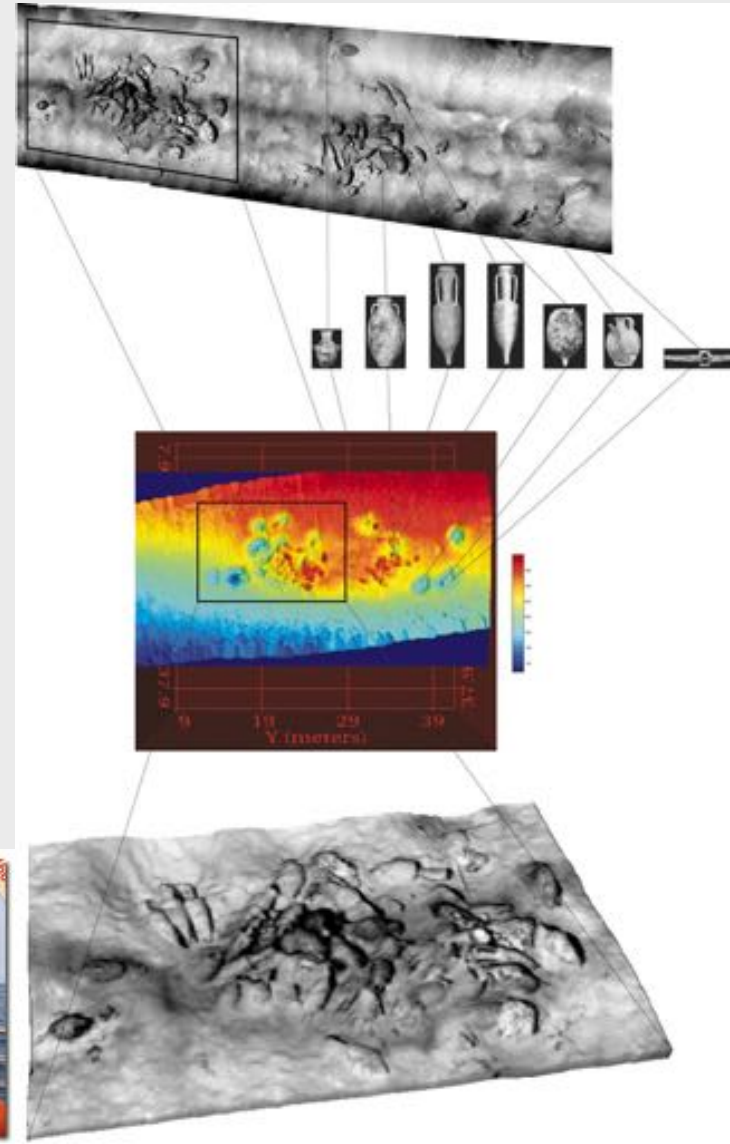


Types of AUVs: Hovering AUV

WHOI Seabed



- Deep ocean benthic survey operations
- Highly maneuverable, near bottom operations
- Sensors: High resolution imaging and bathymetry
- Navigation systems include low and high frequency LBL
- 2000 m rated.



Images Courtesy of WHOI

Types of AUVs: Glider AUV

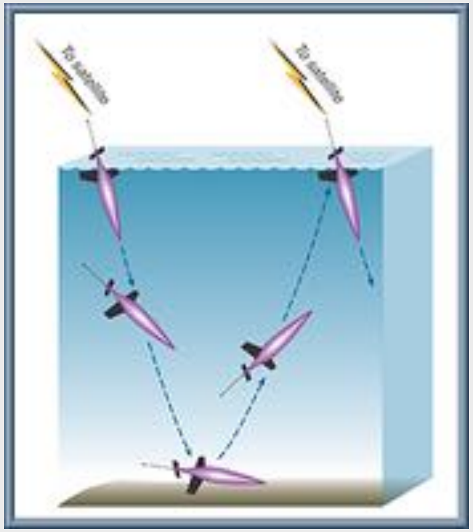
Buoyancy-Driven, Low-Speed, Long Endurance

Bluefin/Scripps Spray

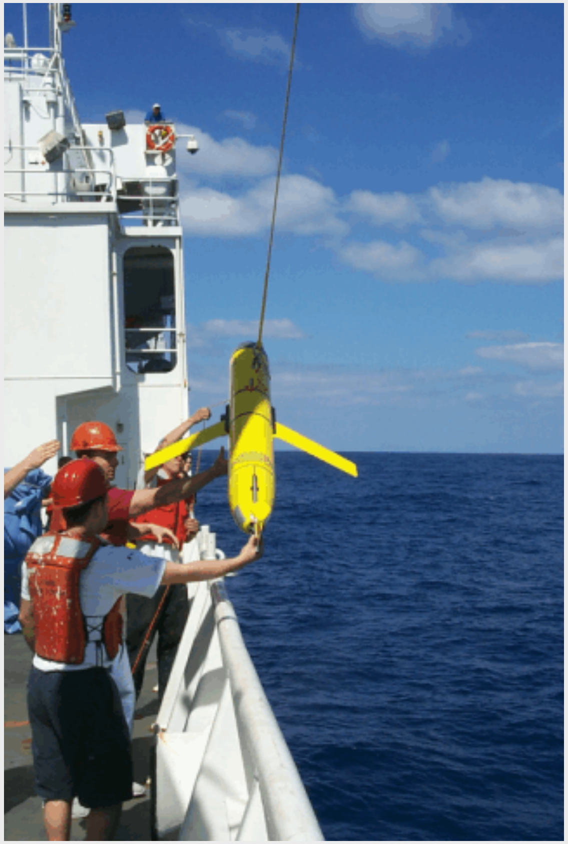
Webb Electric Glider

http://www.whoi.edu/page.do?pid=12558

iRobot/UW SeaGlider



http://www.apl.washington.edu/projects/seaglider/summary.html

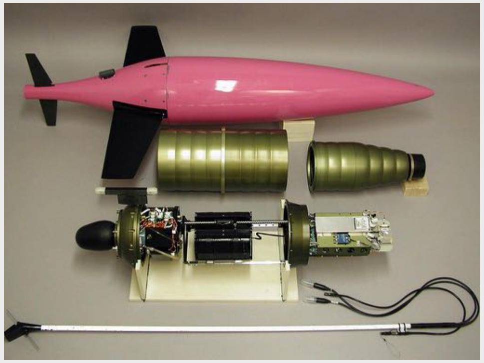


Webb Electric Glider

AUV Architectures

- Single Purpose
- Fixed Hull Multi Purpose
- Modular

Torpedo image from U.S. Navy
web page: www.chinfo.navy.mil



UW/iRobot SeaGlider

AUV Architectures

What do you gain or loose by selecting one vehicle type of another?

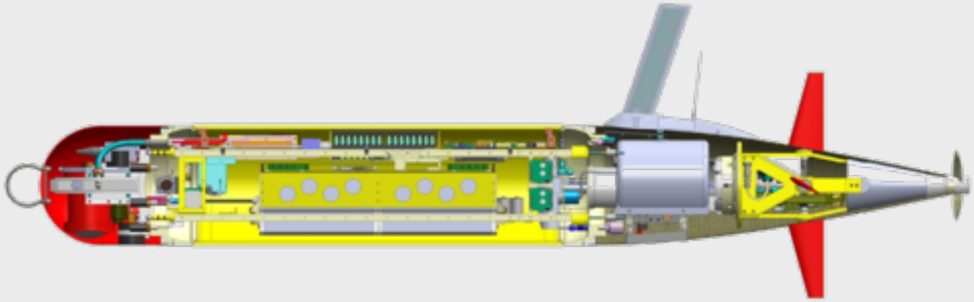
Single Purpose Architecture:

- ***Gains***
  - Reliability
  - Size and Weight (Maybe)
  - Cost
- ***Losses***
  - Flexibility
  - Opportunity
  - Capability

AUV Architectures

Fixed Hull Multi Purpose:

- ***Gains***
  - Some Flexibility
  - Size and Weight (Maybe)
  - Added Capability
  - Added Opportunity
- ***Losses***
  - Entire Vehicle Involved
  - Expert Users
  - Payload Size Sensitive



Parallel Midbody can be extended to carry new payloads

AUV Architectures

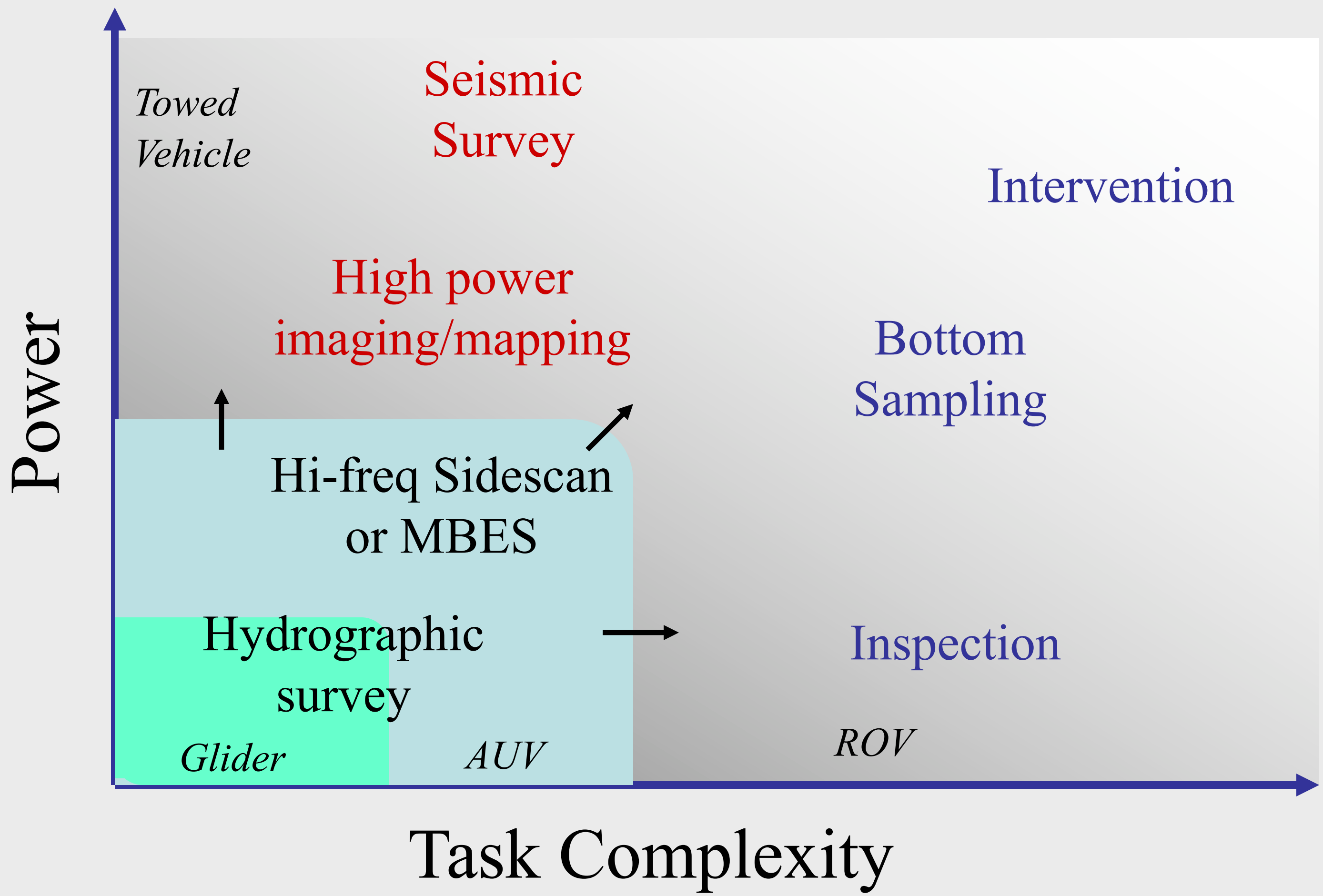
Modular Architecture:

- ***Gains***
  - Lots of Flexibility
  - Payload Options
  - Lots of Capability
  - More Opportunity
  - Easier Maintenance
  - Larger User Base
  - Reliability
- ***Losses***
  - Weight and Size
  - Additional Cost Initially

Modular AUVs - Dorado

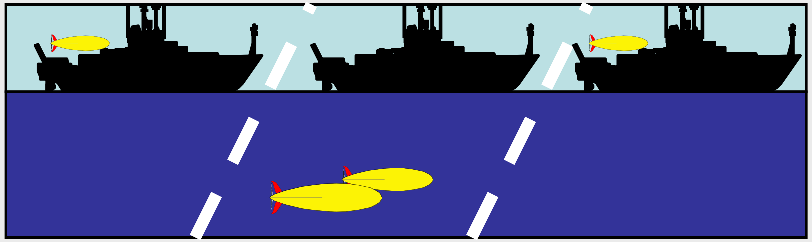
AUV Operational Overview

AUV Operational Domain

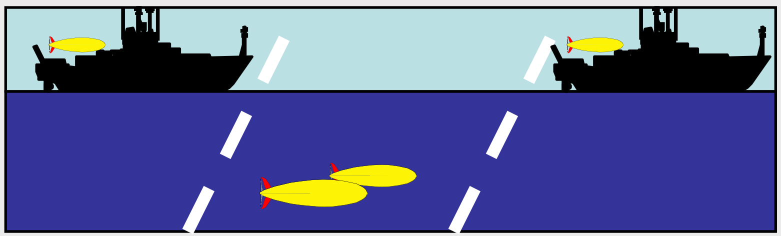


Slide Courtesy of J.G.Bellingham

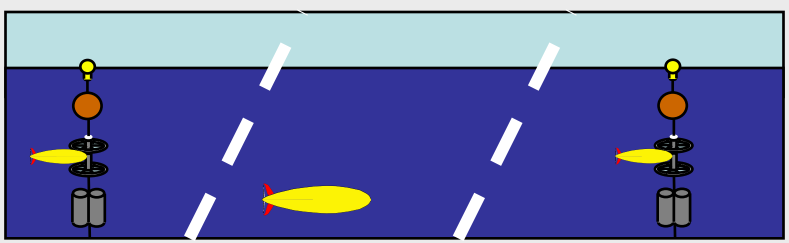
Operational Scenarios



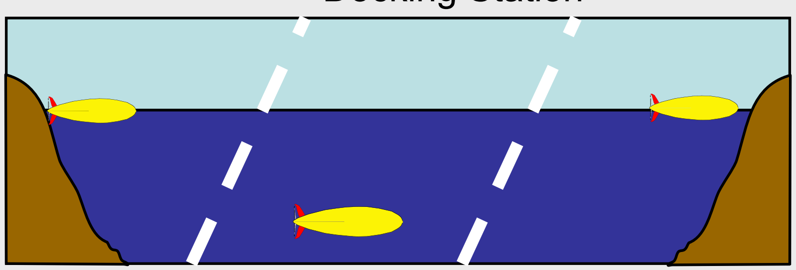
Ship Attended



Ship Supported – Unattended Operations



Docking Station



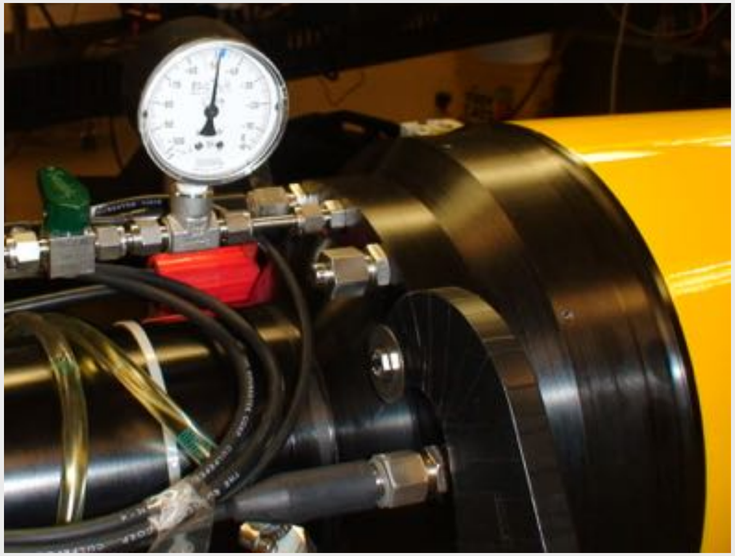
Deployed from shore

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

AUV Operations - A day in the life

Vehicle preparation

- Charge batteries
- Configure payload
- Close pressure vessels and check for leaks
- Complete close-out checklists
- Ballast and trim if necessary
- Vehicle self-test



AUV Operations - A day in the life

Mission Planning

- Determine routes (waypoints, depth, etc)
- Alter mission-level safety envelopes as needed (min altitude, max depth, etc)
- Run Simulatation

Vehicle Software

- Configure for payload
- Load necessary missions
- Alter vehicle-level safety thresholds (e.g. abort depth)
- Complete pre-deployment checklists
- Run Vehicle Self-Test

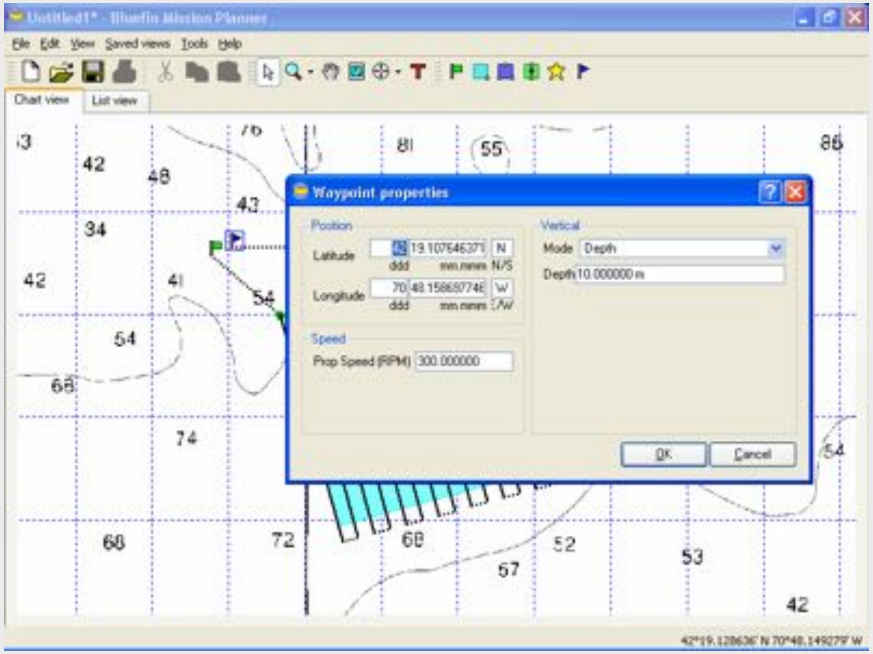


Image Credit: Bluefin Robotics

AUV Operations - A day in the life

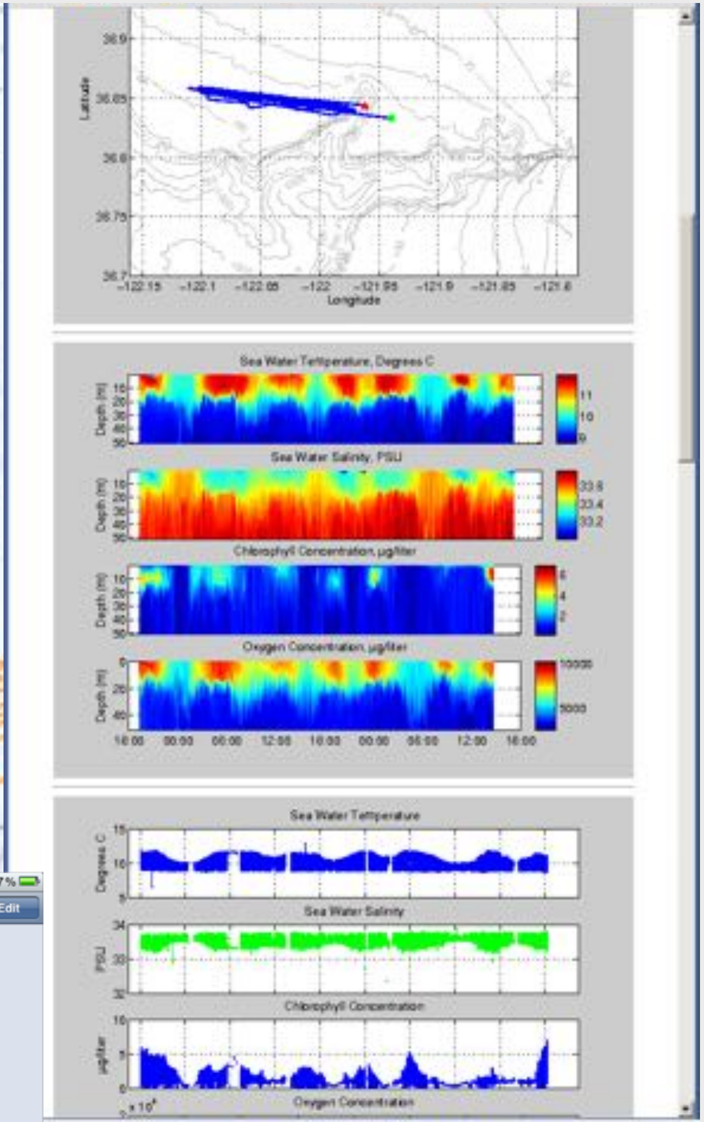
Vehicle Launch

- Verify two-way communications
- Verify backup location systems
- Launch vehicle
- Check for leaks once in water (e.g. ground fault scan, humidity, etc)
- Start mission via communication with vehicle
- User interactions with vehicle: track, monitor from shore, adjust missions…

Image courtesy of Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies.

AUV Operations - A day in the life

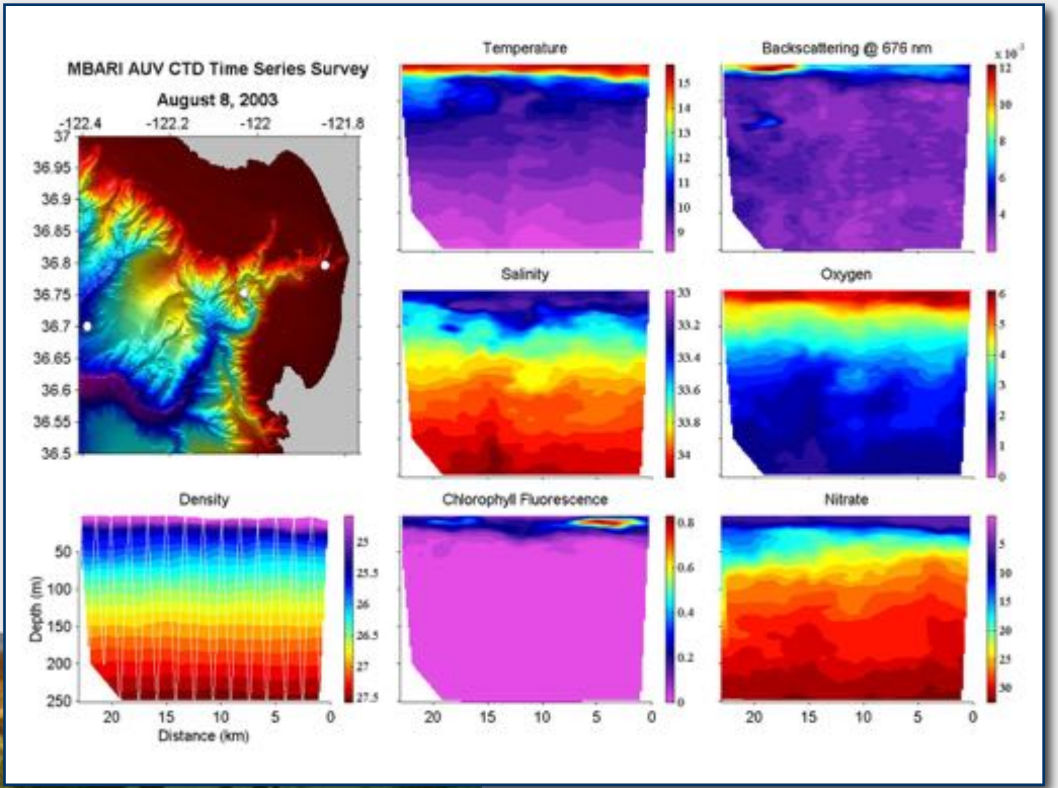
- **E-mail with SBD attachment to/from Iridium modem**
- **Web interface for “real time” data review (subset shown to right)**
- **Vehicle configuration can be changed in event of sub-system failure**
- **New Missions can be loaded or modified as deployment requirements evolve.**
- **Text message to alert operator of abnormal conditions.**

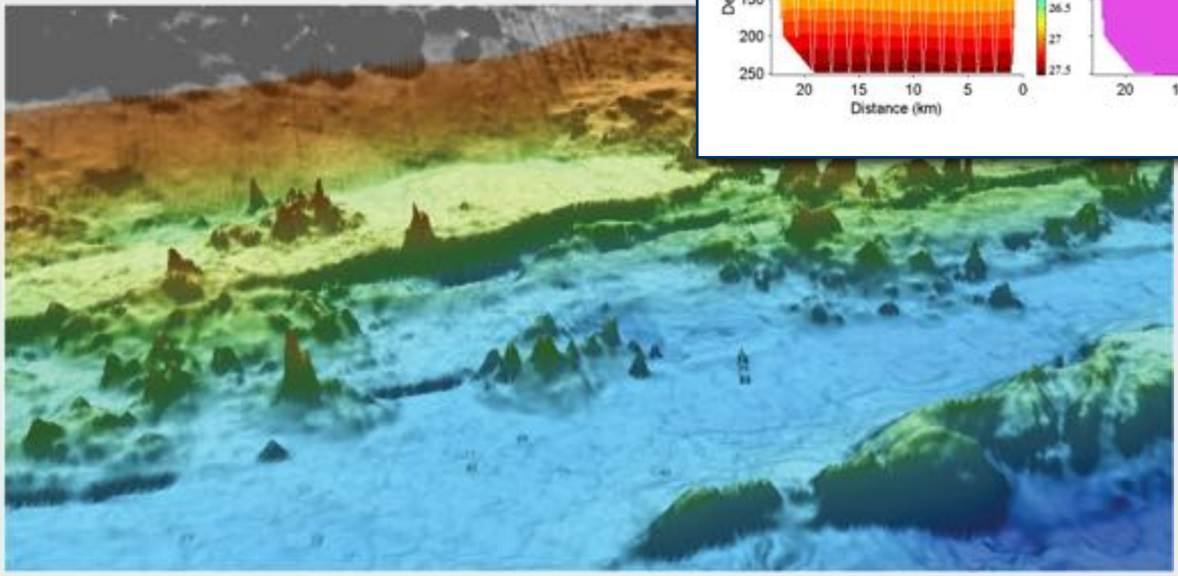


AUV Operations - A day in the life

Deployment End

- Locate vehicle if unattended
- Recover
- Download and review full resolution data (Science and Engineering)
- Note failures or large deviations from simulation and adjust
- Prepare for next mission: charge/change batteries, clean

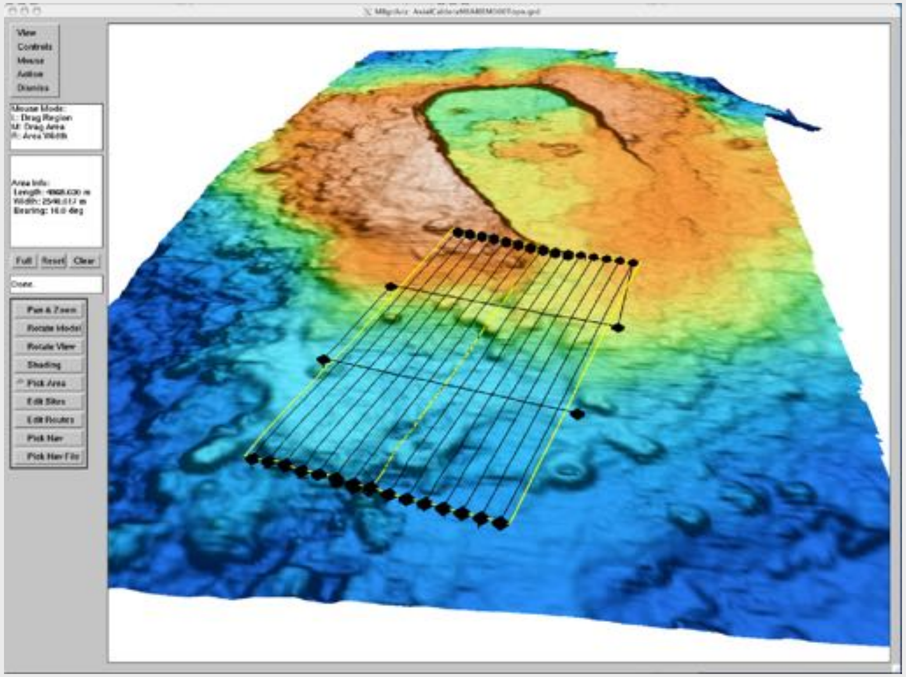




AUV Applications

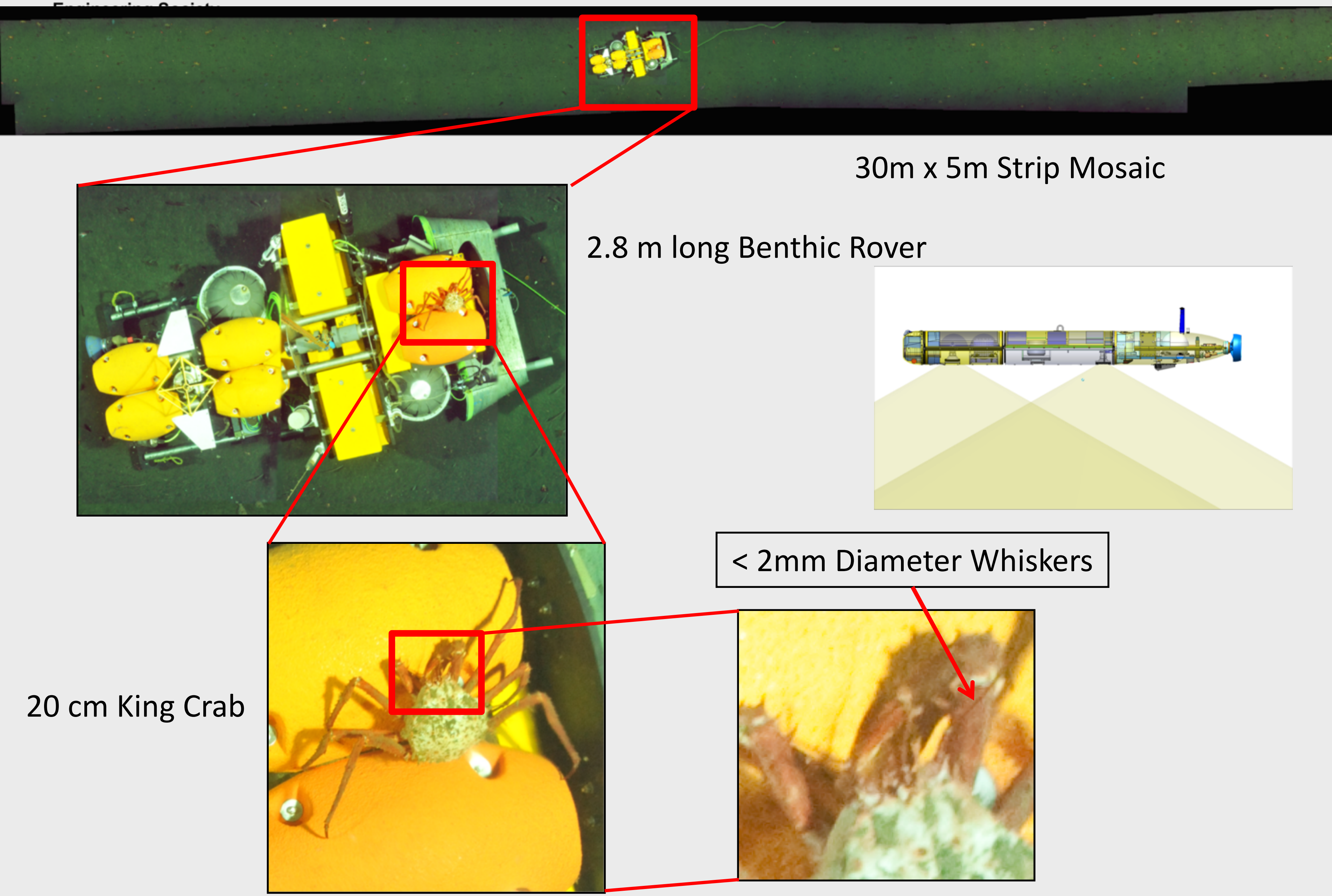
AUV Applications

- Mission planning
  - Sensor overlap
    - Navigation accuracy
    - Ping-rate verses vehicle speed
    - “no holidays”
  - Boundaries
    - Depth, hazards (shipping, etc)
    - Distance to shore
  - Endurance (battery life – reserve)
  - Environmental
    - Sea-state, currents, daylight



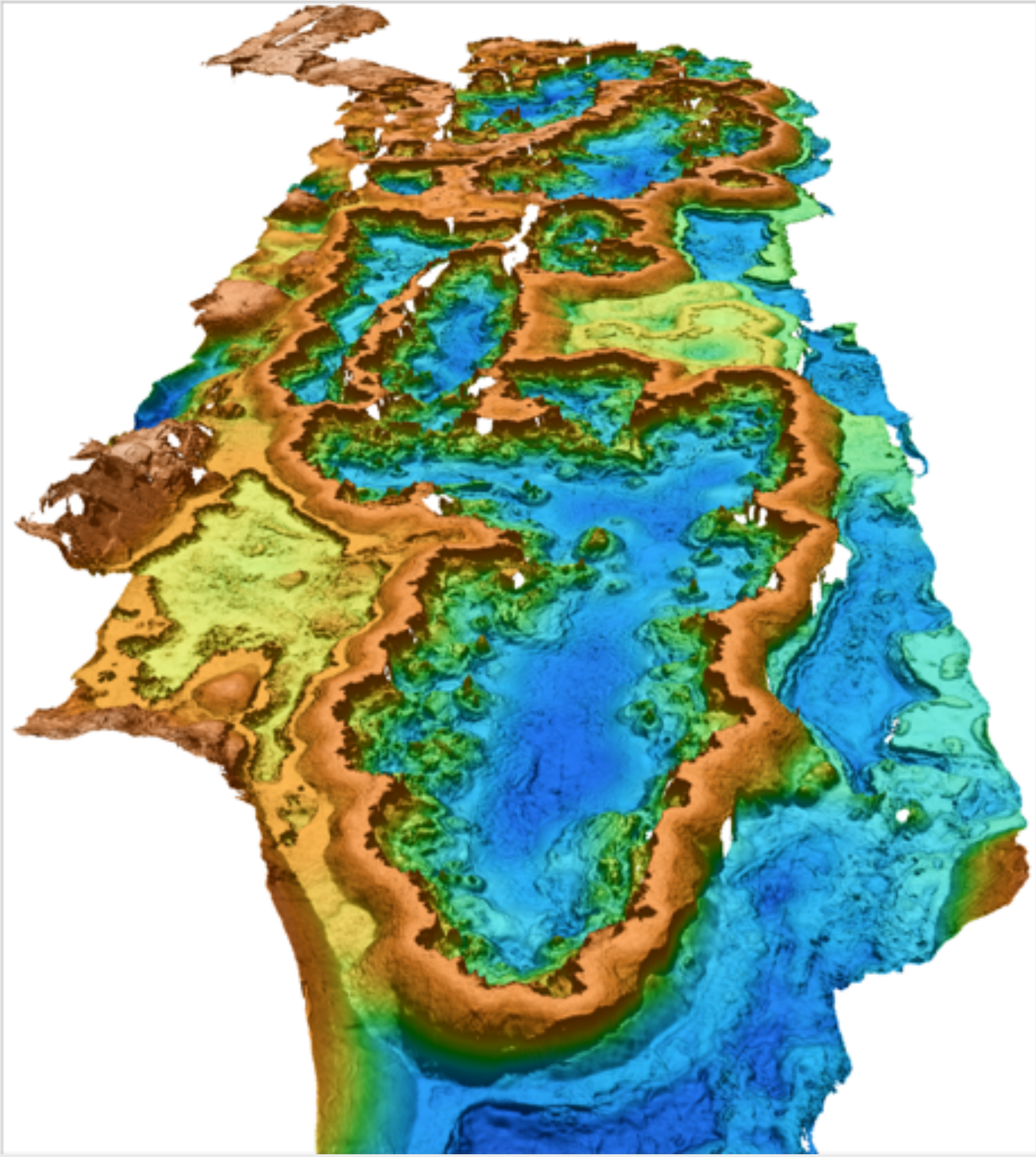
AUV Mission Planning using MB-System
http://www.ldeo.columbia.edu/res/pi/MB-System/

Benthic Imaging



Multibeam Sonar Example

Mapping AUV Survey of 80m high drained lava ponds along the south rift of Axial Seamount



Side-Scan Sonar Data Example

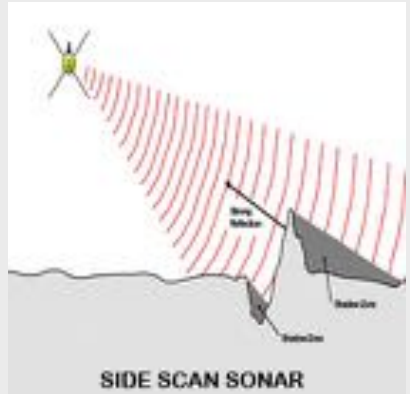
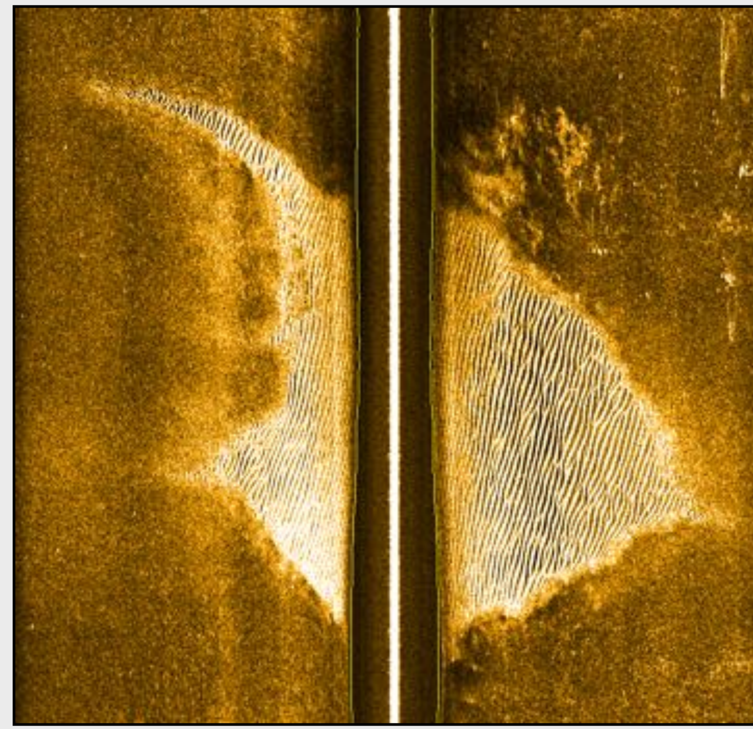


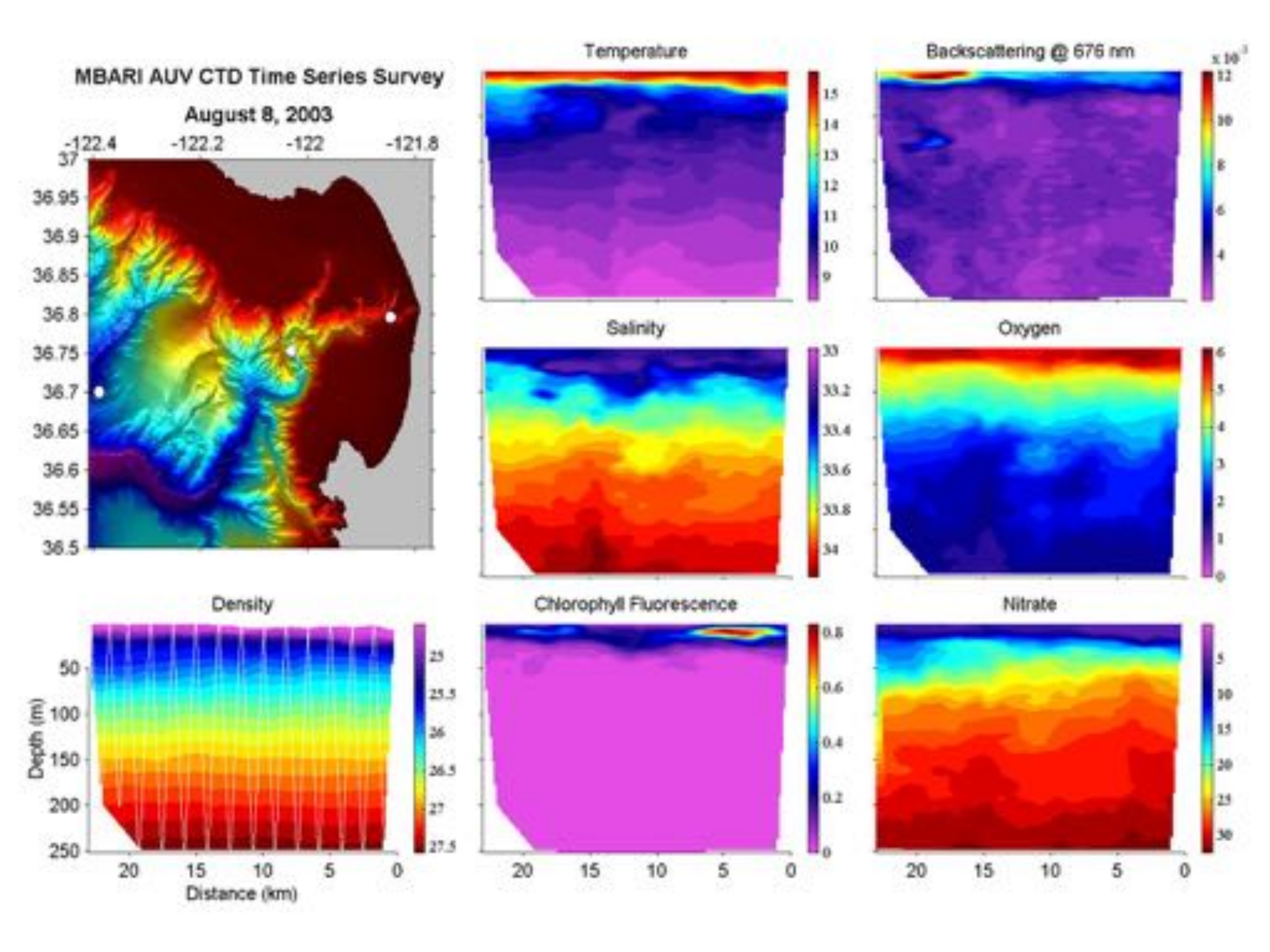
Image: NOAA Coast Survey



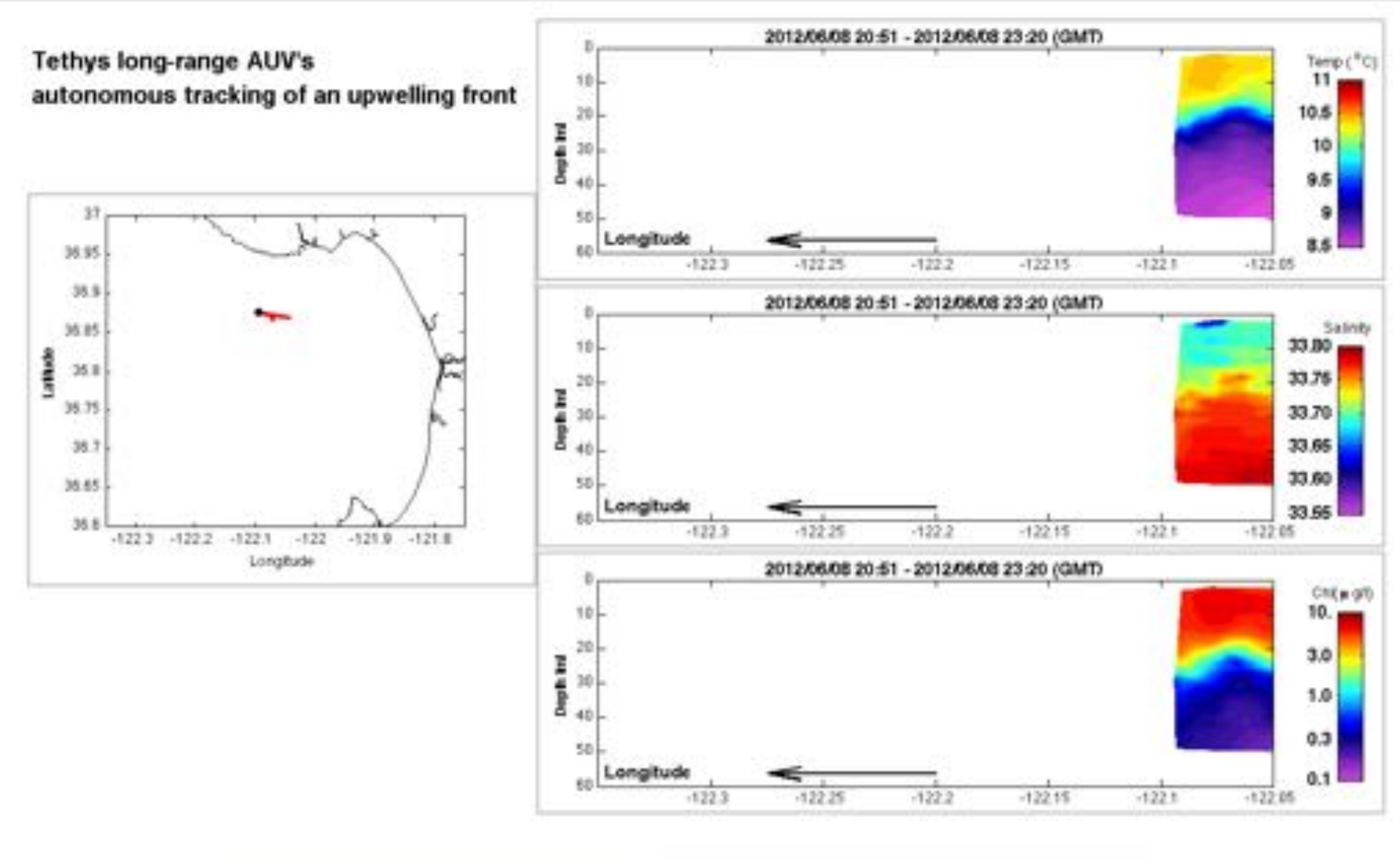
Resolution is 3 by 4 inch   Range is 50 meters per side.

Image courtesy of Bluefin Robotics

Post-Mission Plots



Adaptive Front Tracking



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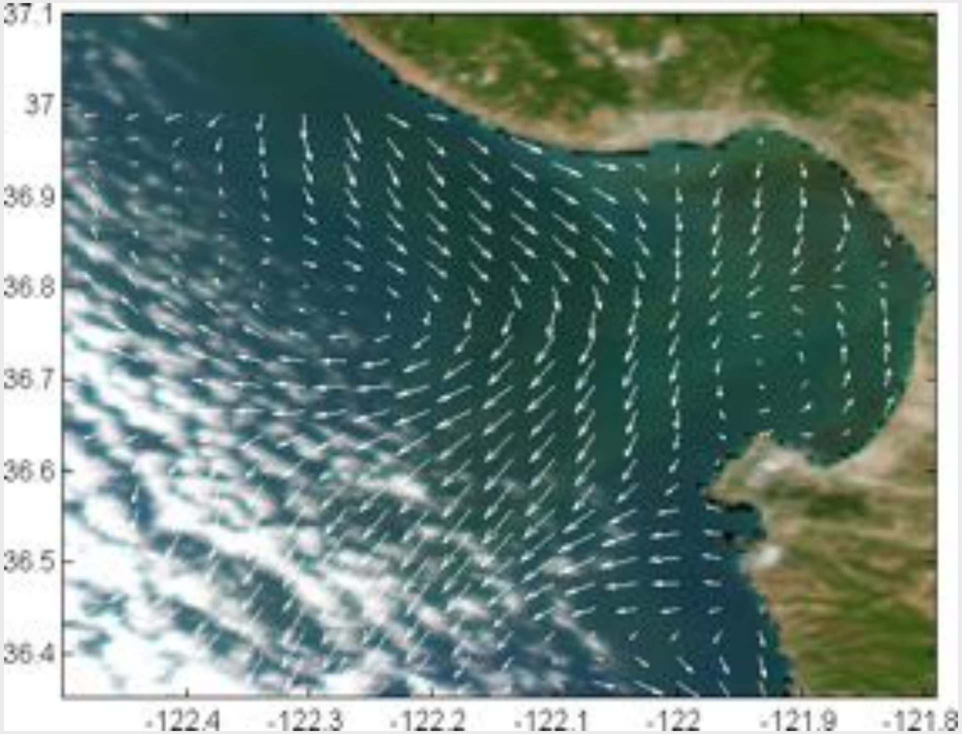
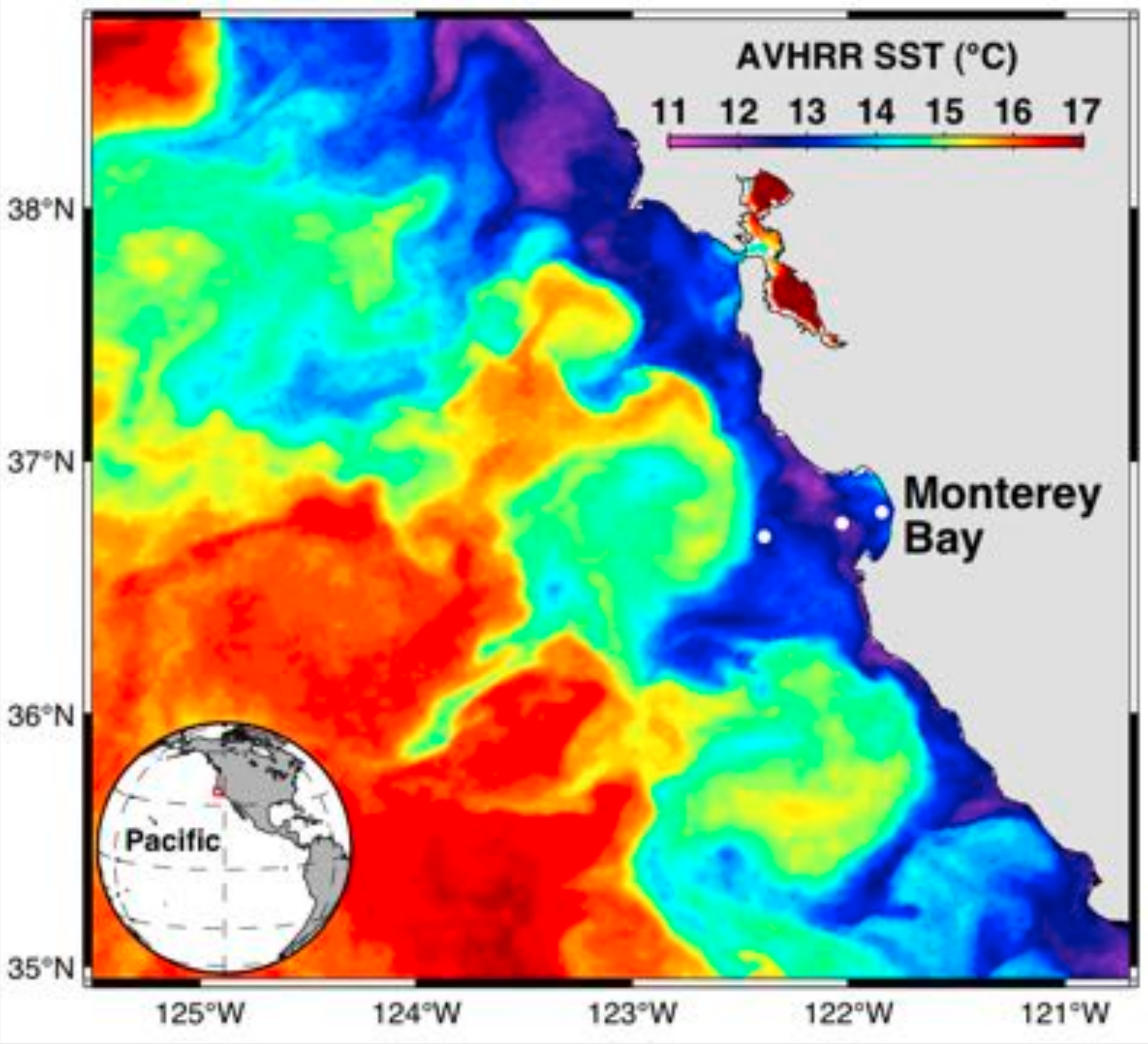
Applications Example:

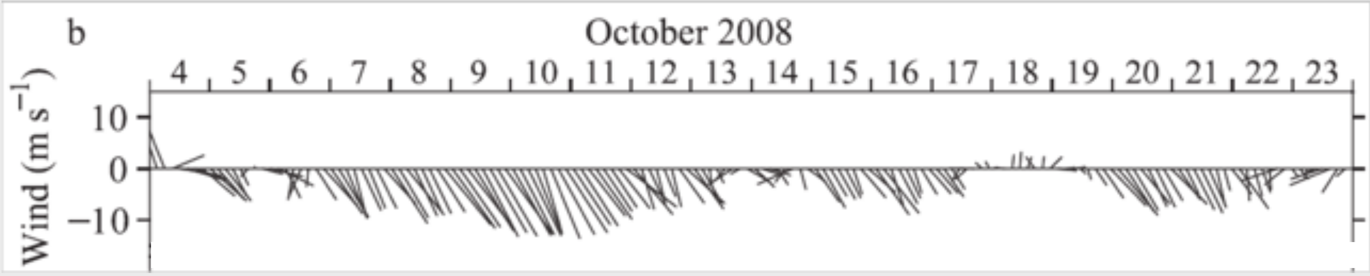
Lagrangian AUV Surveys of Dynamic Processes

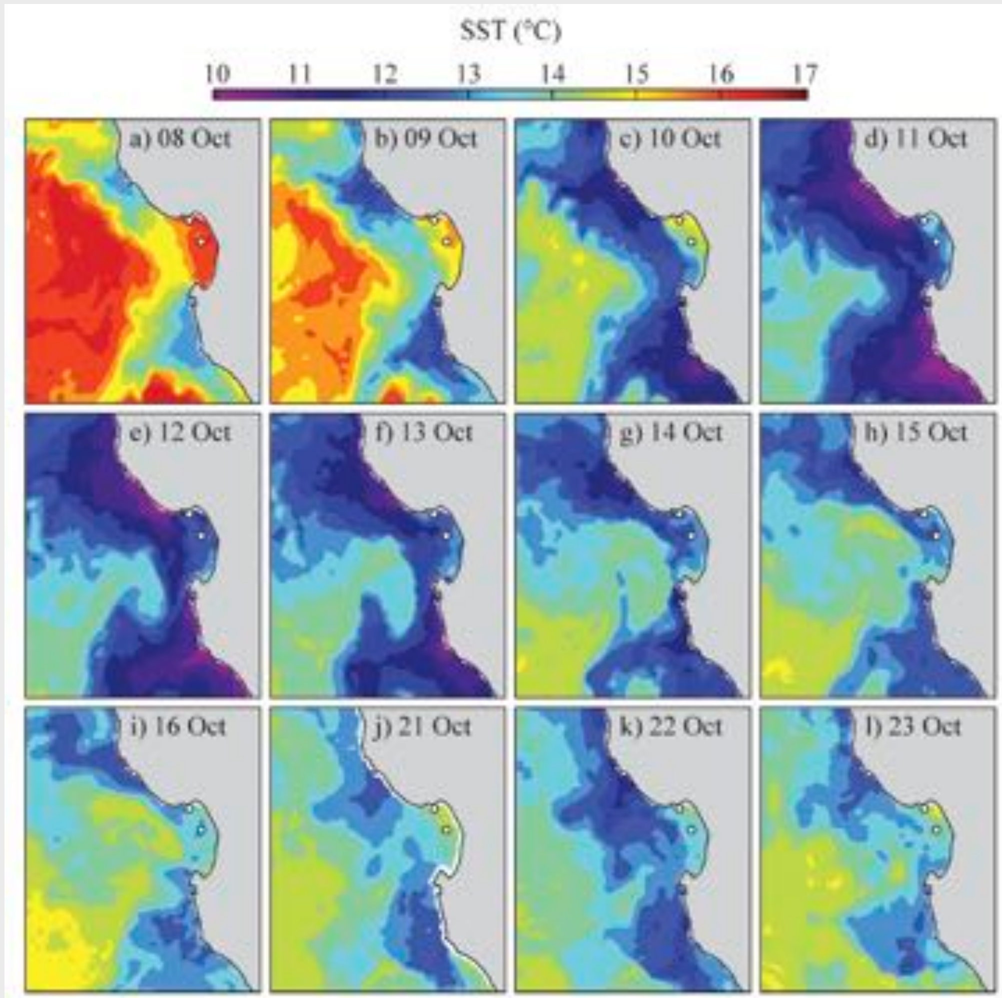


Advanced Very High Resolution Radiometer data showing coastal upwelling along California



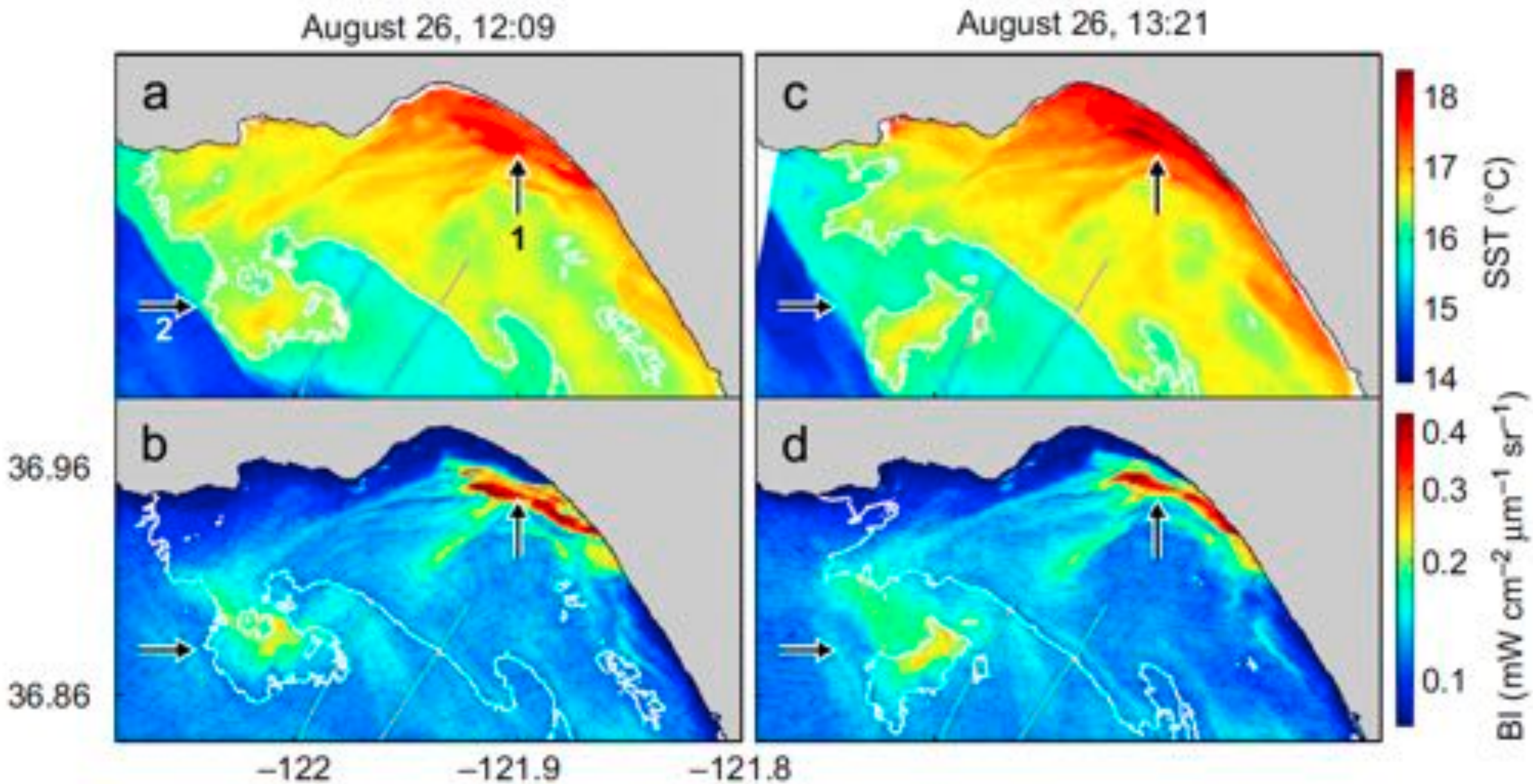
Slide courtesy of John Ryan





Ryan et al., 2011

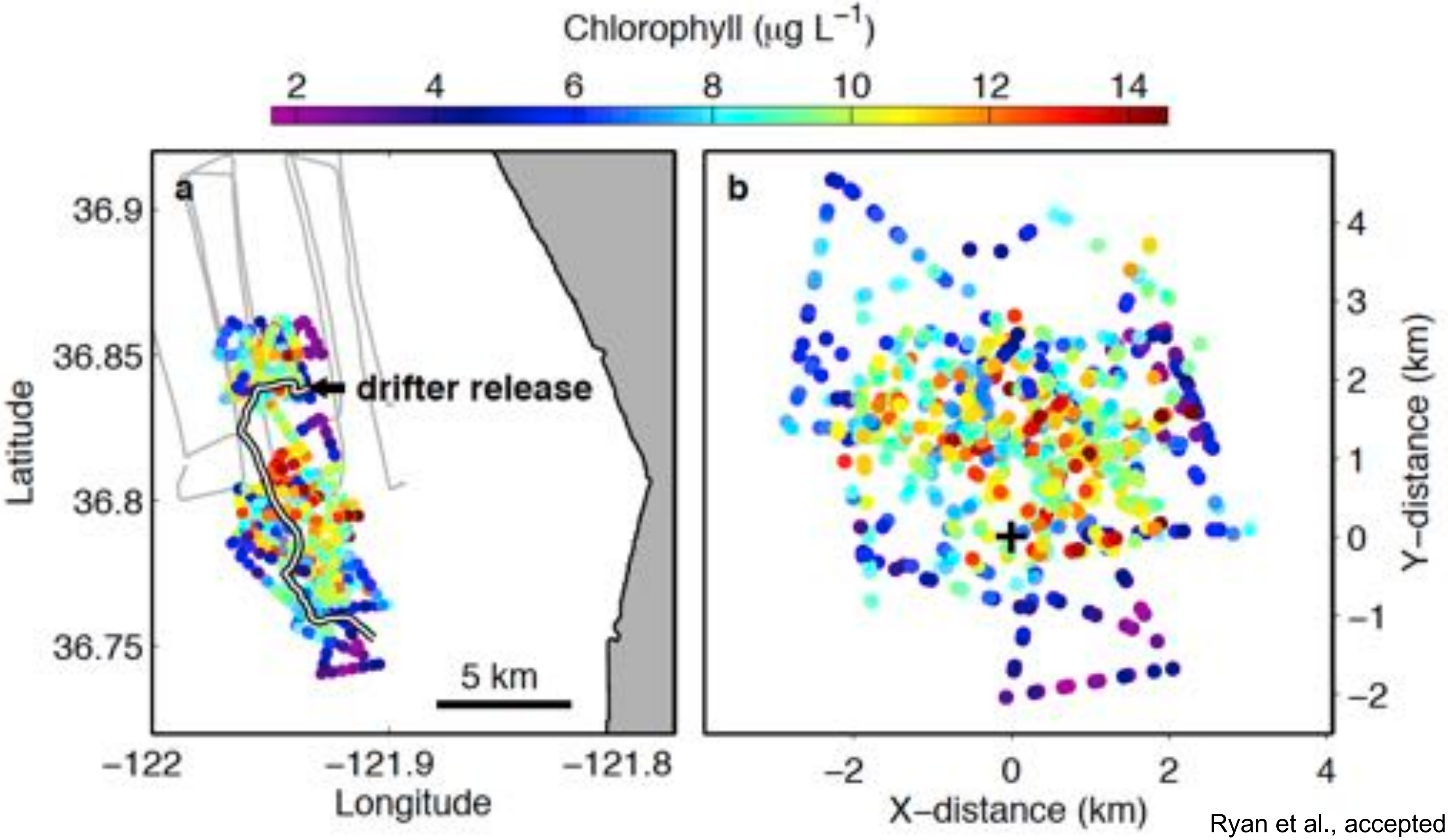
Patch Dynamics



Ryan et al., 2009

Patch Tracking

A lagrangian frame of reference clarifies the patch



Ryan et al., accepted

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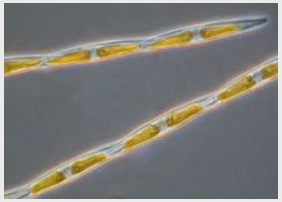
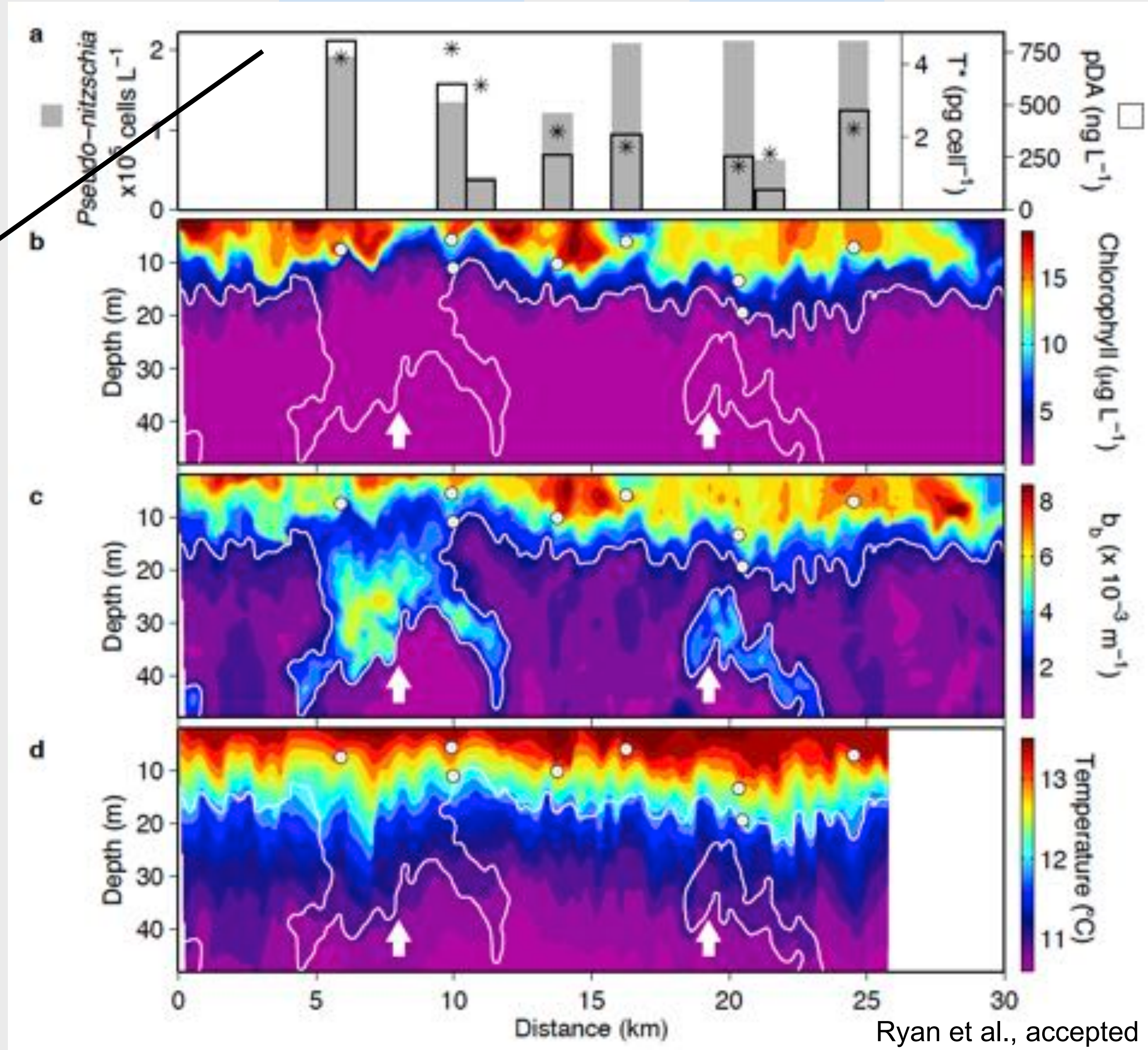
Lagrangian Observation of Toxigenic Phytoplankton

Toxic

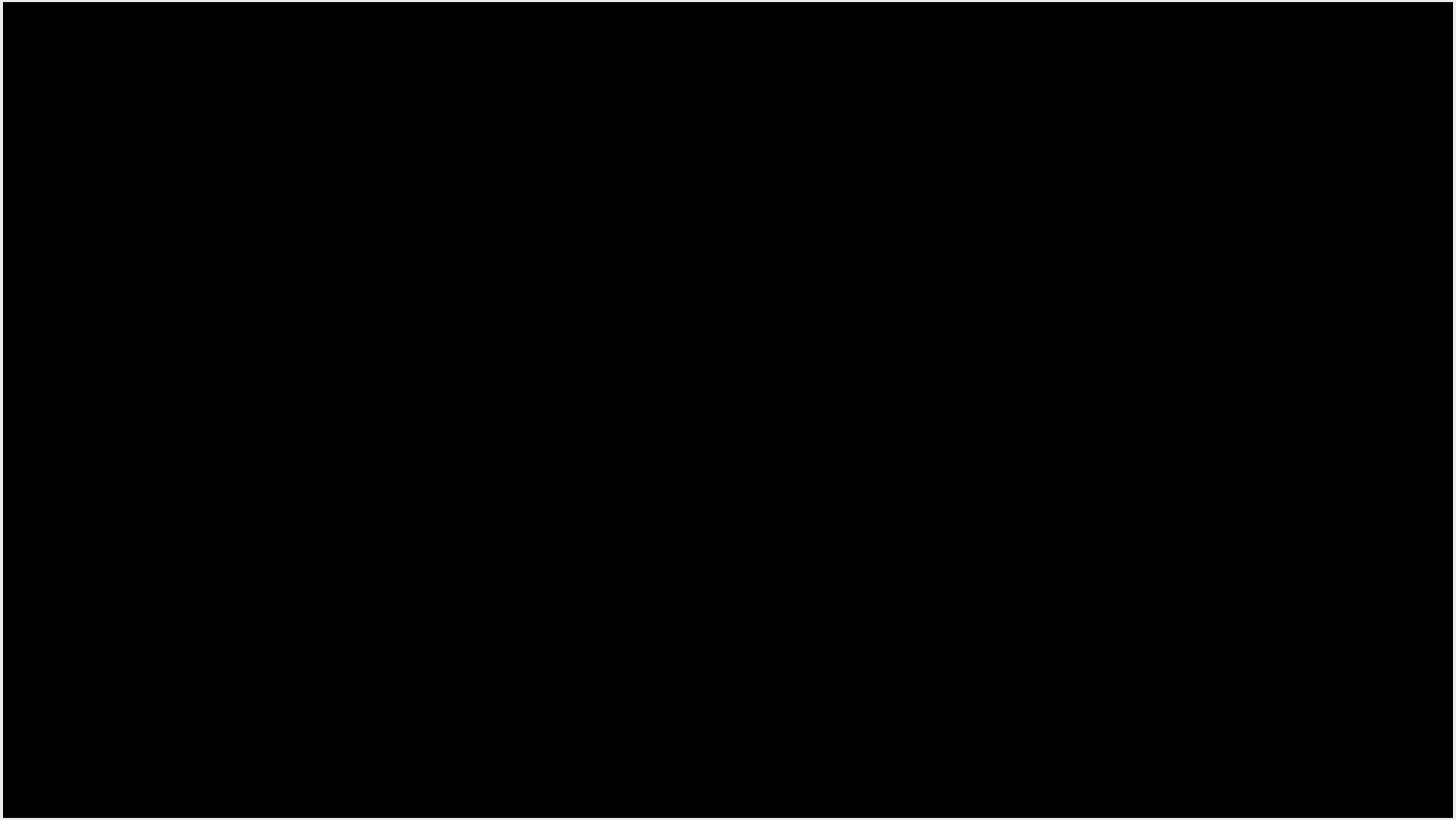
Less Toxic





Ryan et al., accepted

Lagrangian Observation of Toxigenic Phytoplankton

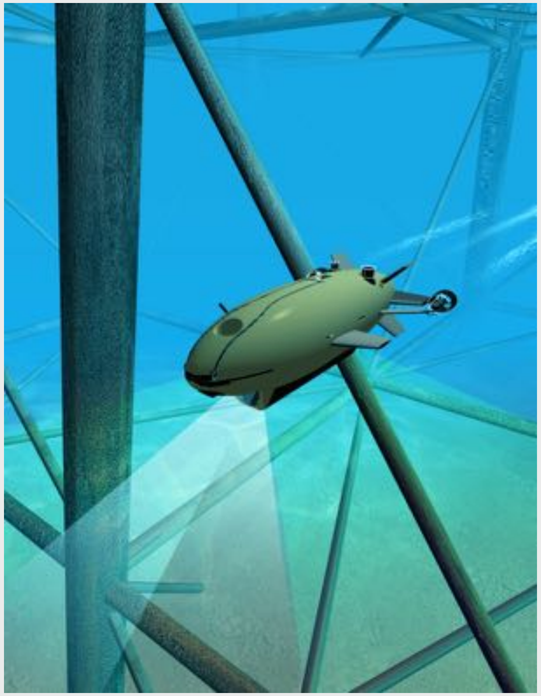


Applications

Other applications for AUV' s:

- Defense:
  - Mine hunting/classification/neutralization
  - Submarine launched countermeasures
  - Anti-submarine (detect, locate, trail)
  - Low-observable surveillance
  - Acoustic listening
  - Comms/nav aid
- Oil/gas pipeline:
  - Pipeline survey
  - Site and hazard
  - Mapping surveys
  - Intervention
  - Leak sniffers
- Mining:
  - Sulfide
  - Manganese nodules
  - Diamond
- Ship hull inspection and cleaning

ECA Alistar

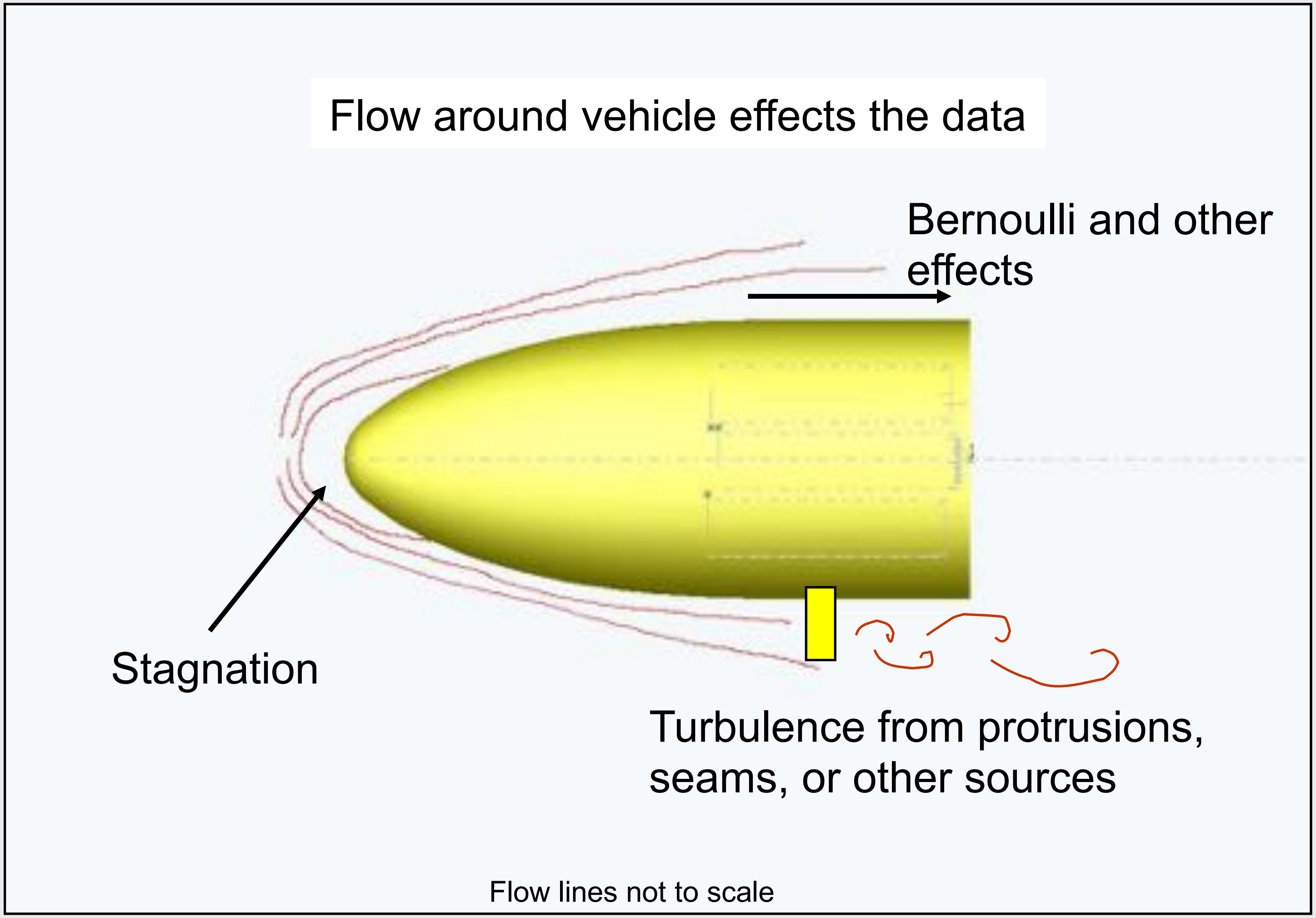


Lockheed Martin Marlin

Payload Considerations for AUV Applications

Payload Considerations for AUV Applications

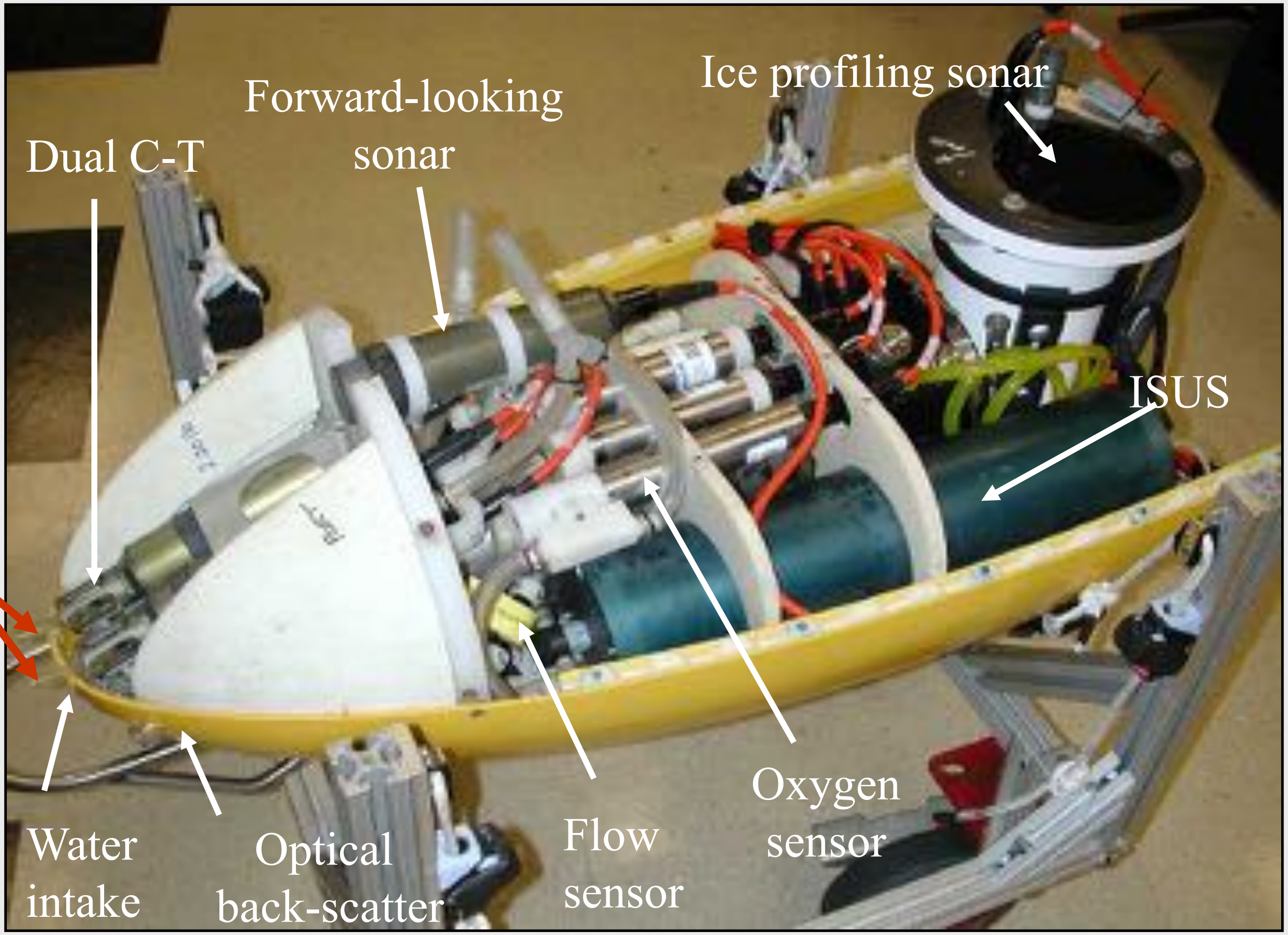
- Redundant payloads may also be necessary depending on science requirements



Payload Considerations for AUV Applications

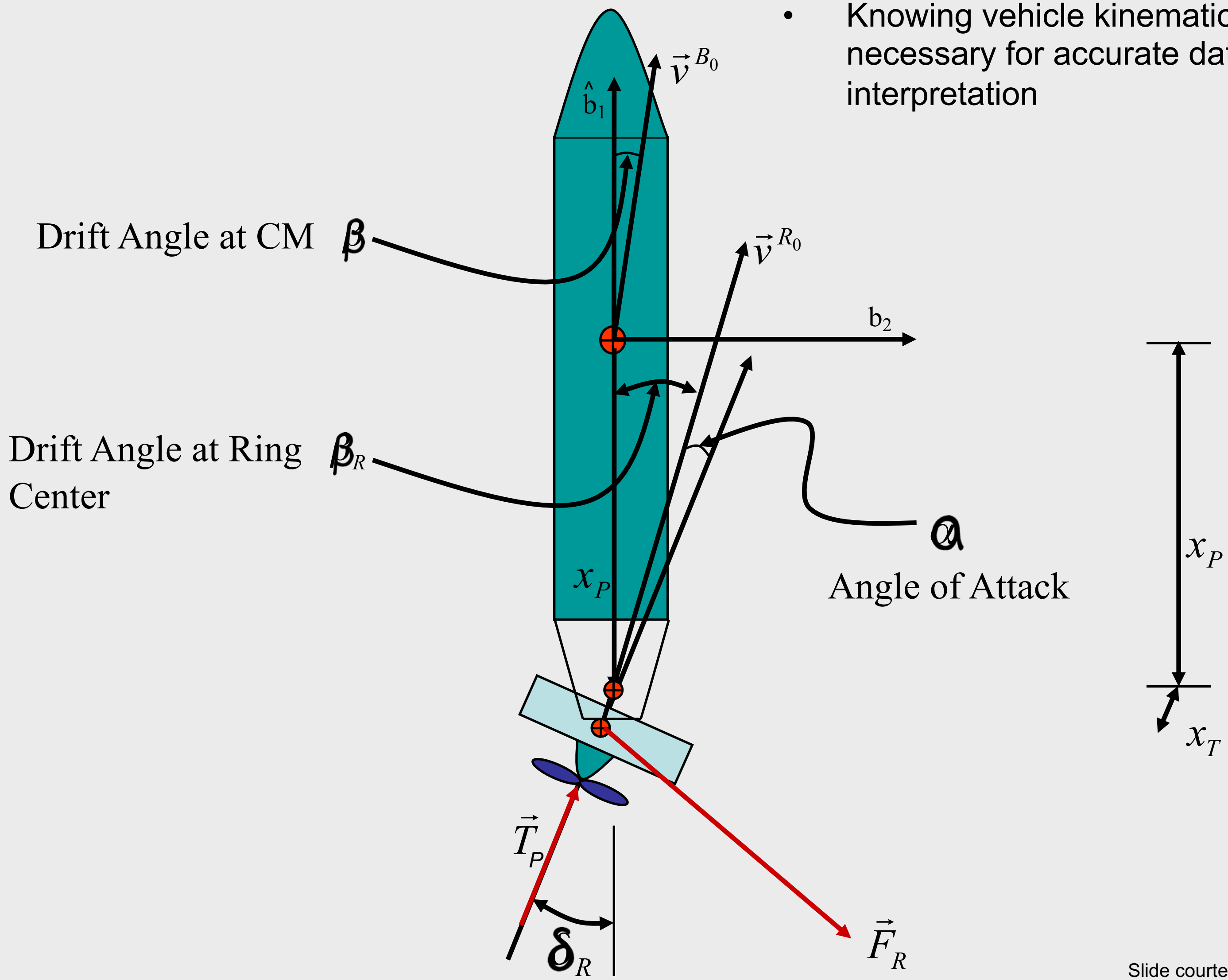
- Payload Configuration
  - Payload Interfaces (Basic) using our M2 example

Note tubes extending outside of the boundary layer



Payload Considerations for AUV Applications

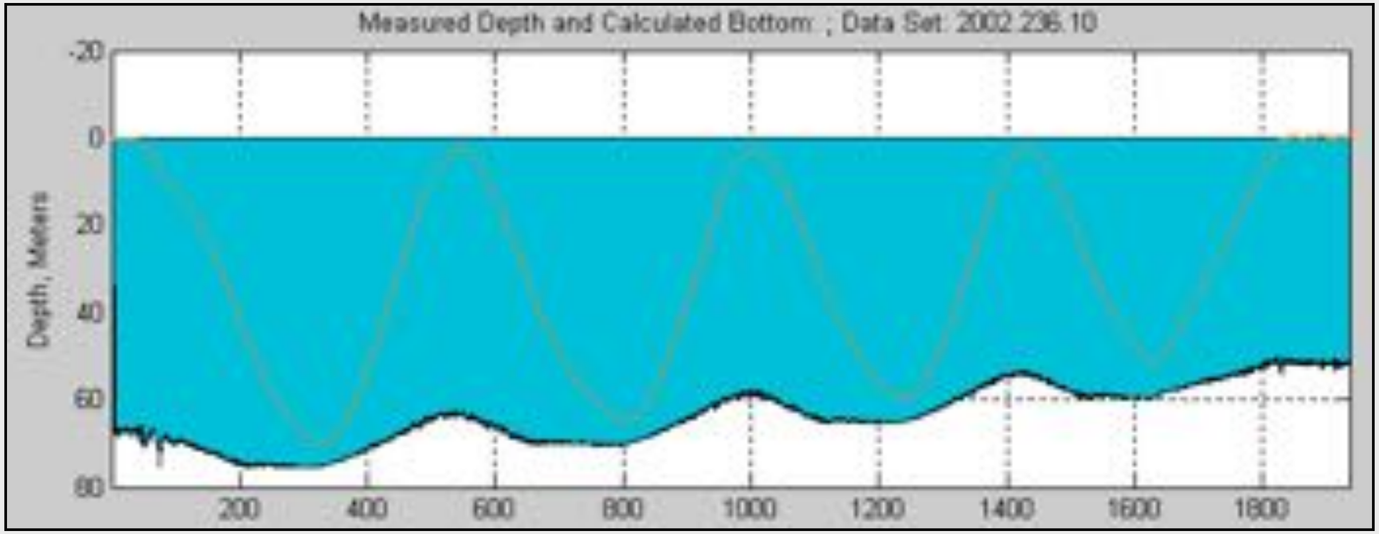
- This vehicle skids in an uncoordinated turn
- Knowing vehicle kinematics is necessary for accurate data interpretation



Slide courtesy of Rob McEwen

Payload Considerations for AUV Applications

- Payload Configuration
  - Payload Interfaces (Basic) using our M2 example



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. ***Important point here is to collect all raw vehicle and raw science data for post processing and analysis.***

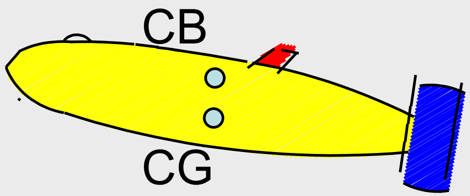
Payload Considerations for AUV Applications

- When and where were the measurements taken?
  - Compensating for delays of time-stamping
    - Vertical speed = 1.0 m/sec
    - CTD data packet of 40 bytes at 4800 bps (83ms of data transmission)
    - Vehicle travels 8.3cm vertically during data packet transfer from instrument to RS-232 serial input device

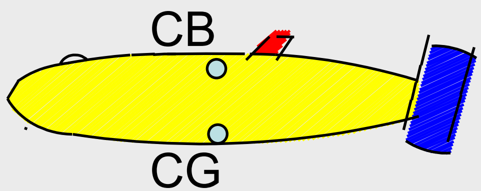
Things that Affect Control

AUV Technology and Application Basics

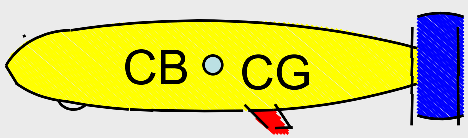
- Things that affect control
  - **CB-CG**



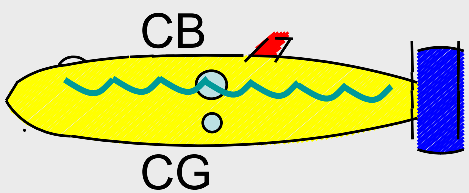
CB-CG horizontal offset causes vehicle to fight, increasing drag and making straight and level flight troublesome



CB-CG vertical offset makes diving and altitude control difficult, control inputs have diminished effectiveness



CB-CG coincident makes vehicle unstable causing control loop problems with gains and cross coupling of controls if vehicle rolls to side



CB too large makes diving and altitude control difficult, causes pitch control oscillations

AUV Technology and Application Basics

- Things that affect control
  - Weight and Balance

SI units x is from the nose						
Item	Weight	Displacement	Buoyancy	Displacement total	W x-mom	B x-mom
	(N)	(m^3)	(N)	(m^3)	(N-m)	(N-m)
2Kw/Hr Battery	254.1771	0.01547	155.5547175	0.04641	727.1117211	444.9876026
Spacer, Center Battery	0.4299723	0.000044	0.442431	0.000044	0	0.51576792
Bulkhead, Forward	4.8895983	0.00052	5.22873	0.00052	3.187529132	3.408609087
Spacer, Forward Bulkhead	0.4371336	0.00005	0.5027625	0.0002	0.52456032	0.603315
Bulkhead, Aft,Aft	5.4603441	0.00058	5.832045	0.00058	6.242265375	6.667193844
Bulkhead, Aft	5.4603441	0.00058	5.832045	0.00058	4.95731536	5.294773686
SBE-49 CTD	26.487	0.00114	11.462985	0.00114	11.38941	4.92908355
CTD Acrylic Shroud	2.9674269	0.0003	3.016575	0.0003	0.59348538	0.603315
Washers	0.04905	0.0000004	0.0040221	0.000012	1.015335	0.08325747
Compression Ring	3.50217	0.00013	1.3071825	0.00013	5.4633852	2.0392047
Shell Splice Joint	7.047504	0.00069	6.9381225	0.00138	16.86298567	16.60126199
Cables w/ connectors	7.3575	0.00021	2.1116025	0.00042	14.582565	4.185196155
TOTALS				**0.18965682**	**1483.2321**	**1544.6917**
Balance Point from Nose (m)	**0.8099915**				**0.8573902**	**0.8099915**
Total Dry Mass of Nose (kg)						
Dsplcmt of Nose (m^3)						
Net Buoyancy (N)						
Cb - Cg (m)						

Note: this sheet has hidden columns – see handout or appendices for the complete sheet

Depth Control

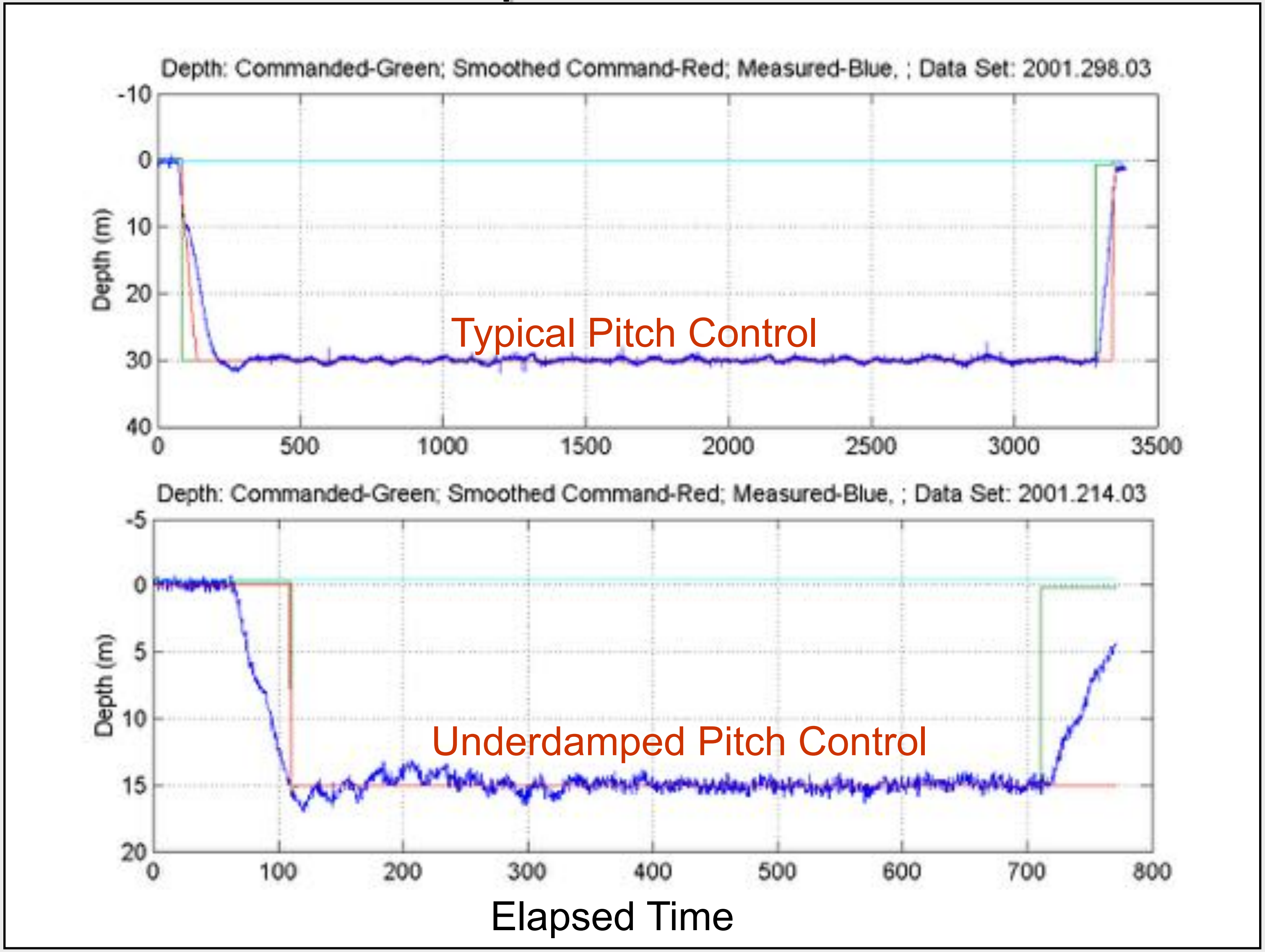


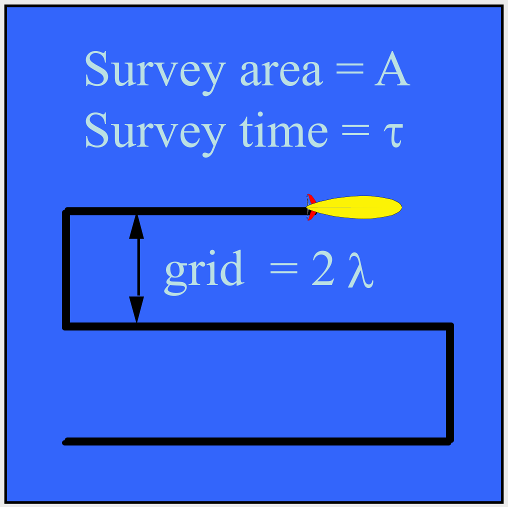
Image courtesy of Rob McEwen- MBARI

Optimizing AUV Surveys of Dynamic Processes

Based on efforts from Dr. Al Bradley WHOI, modified and published by J.G. Bellingham and Scott Wilcox of MIT
Reference in Appendices

The Grid Survey

Speed and Resolution



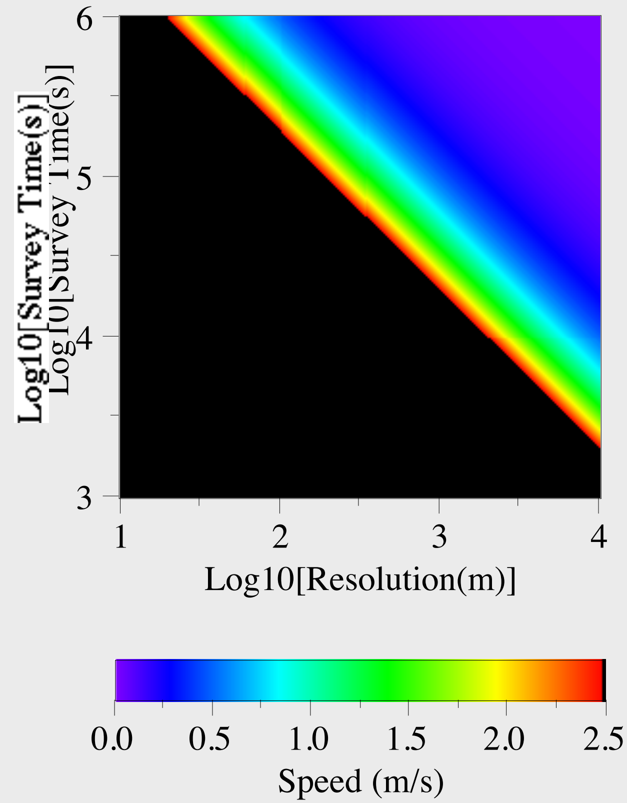
Total Survey Distance

$d = A/2\lambda$

Required Speed

$v = A/2\lambda\tau$

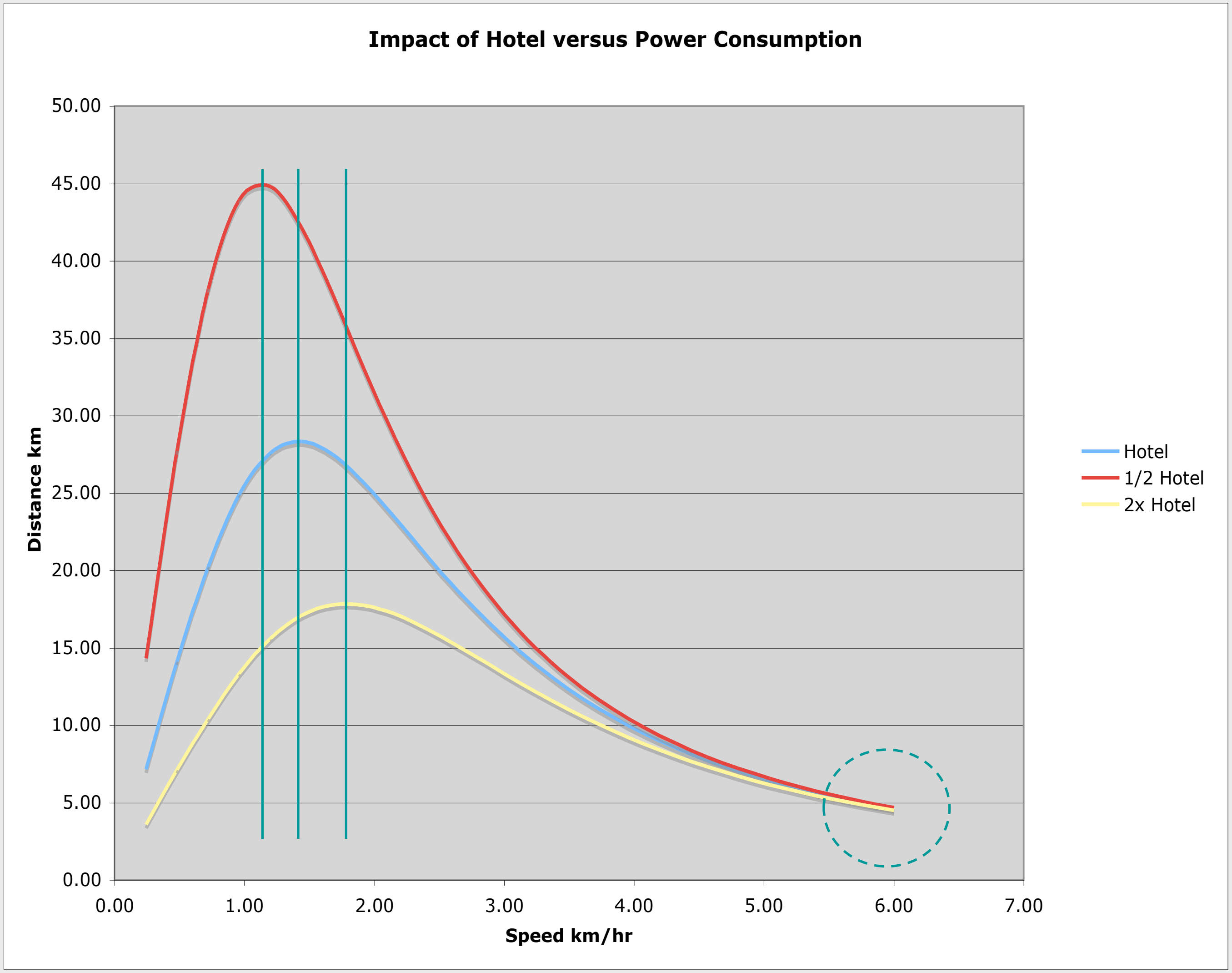
Example - 100 sq km Area



$$\lambda\tau = A/2v$$

Range/Speed Relationships

Optimizing For Distance



This is in the Excel Worksheet Power vs Distance

Survey Envelope

Determining the accessible survey space

Minimum vehicle velocity (1kts)

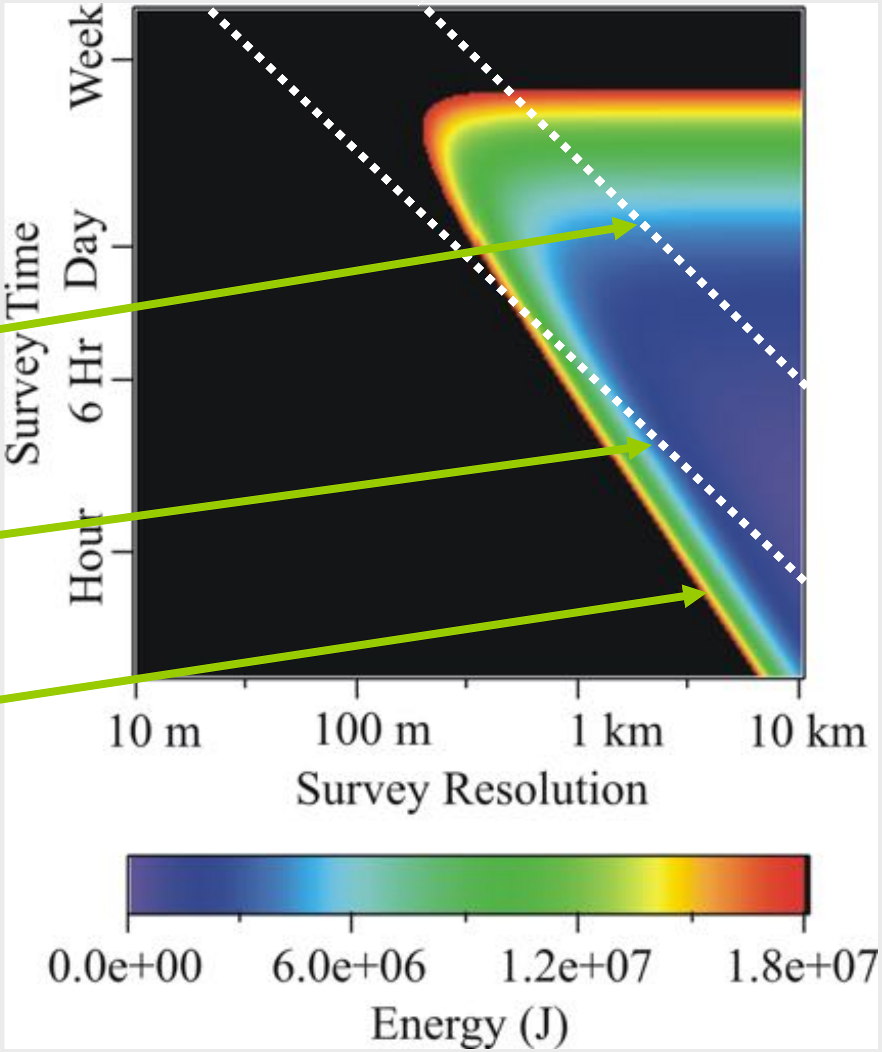
Maximum vehicle velocity (5kts)

Energy limit of vehicle (5 kWh)

E_{total} = total energy available.

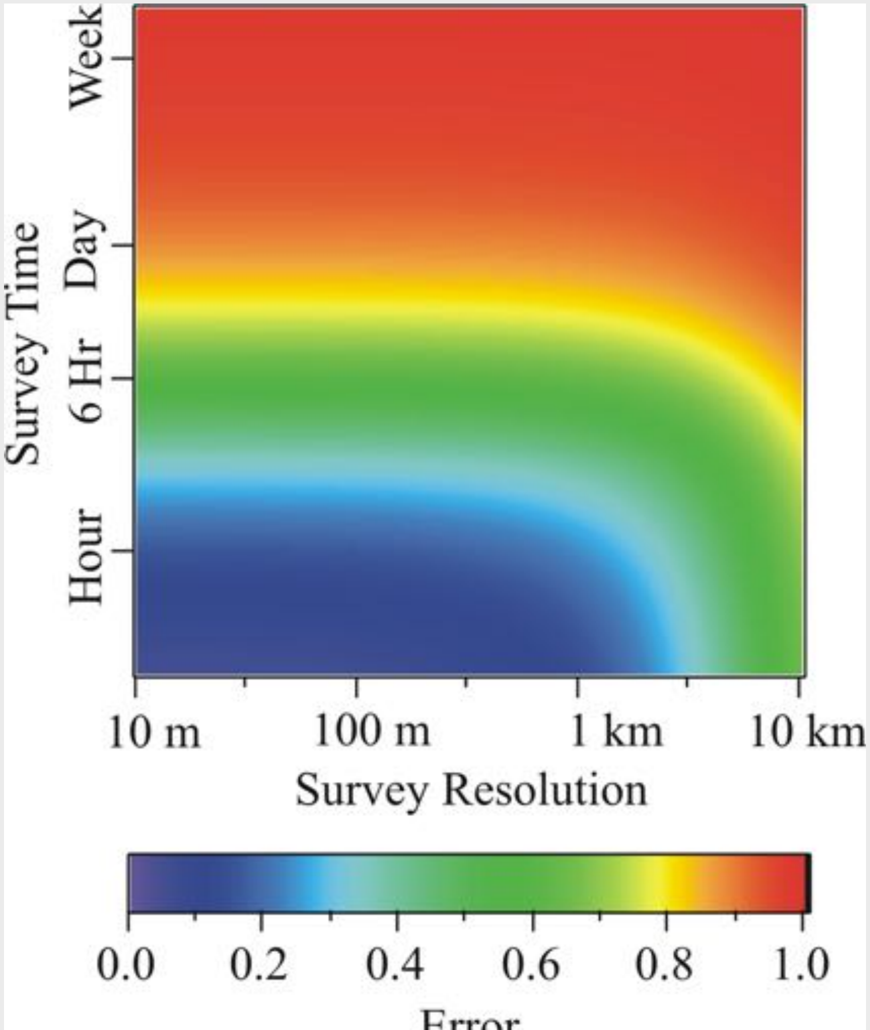
$$=$$

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



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:

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

Cumulative Error:

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

R(*t*) = how fast field changes over time

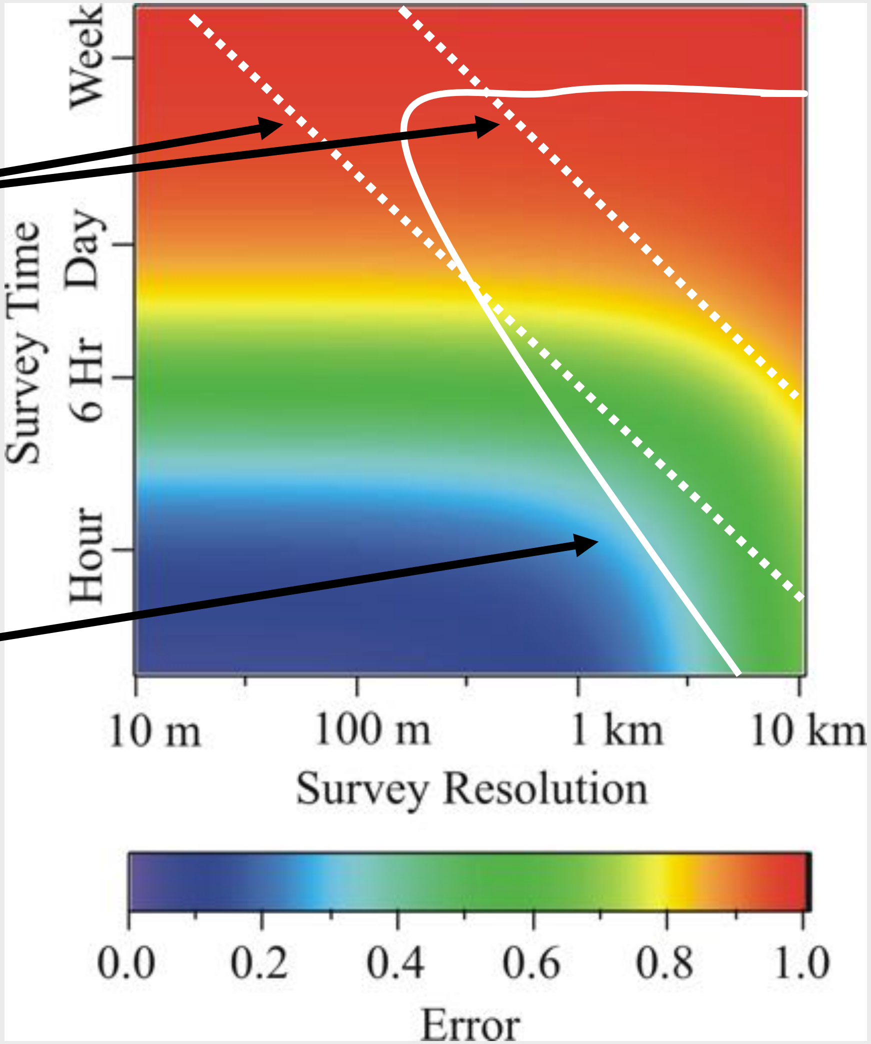
P(k) = how fast field changes over space

Slide Courtesy of J.G.Bellingham

Picking the Optimum Survey

Adding velocity constraints

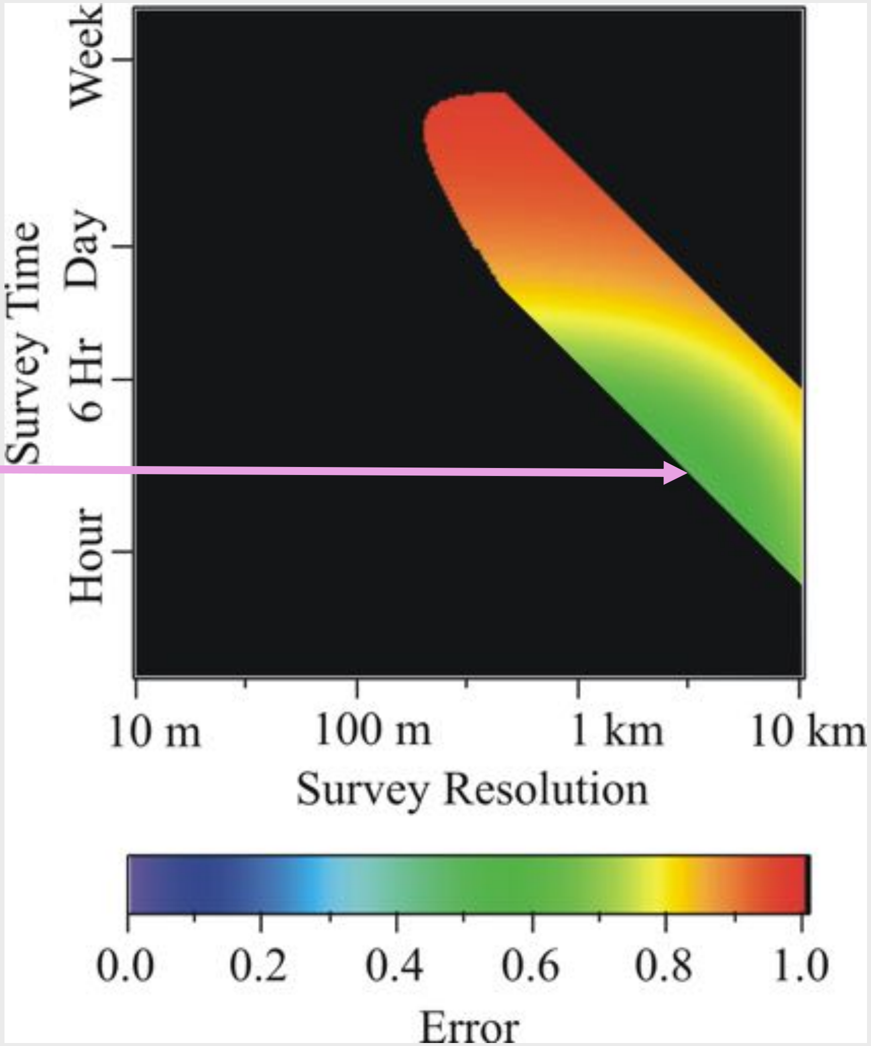
And energy constraints



Slide Courtesy of J.G.Bellingham

Picking the Optimum Survey

Optimum survey to minimize error



AUV Operations:
Launch and Recovery

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AUV Operations – Launch and Recovery

Ramp

- Generally good for low freeboard
- Low Cost
- Requires instruments to be protected from rollers

Images from MBARI

AUV Operations – Launch and Recovery

Overboard Crane

- Simple and effective for ships of opportunity with minimum freeboard
- Quick release to launch
- Reattach with pole from low-freeboard ship
- Small boat usually required for high freeboard ship
- Difficult to attach tag-lines

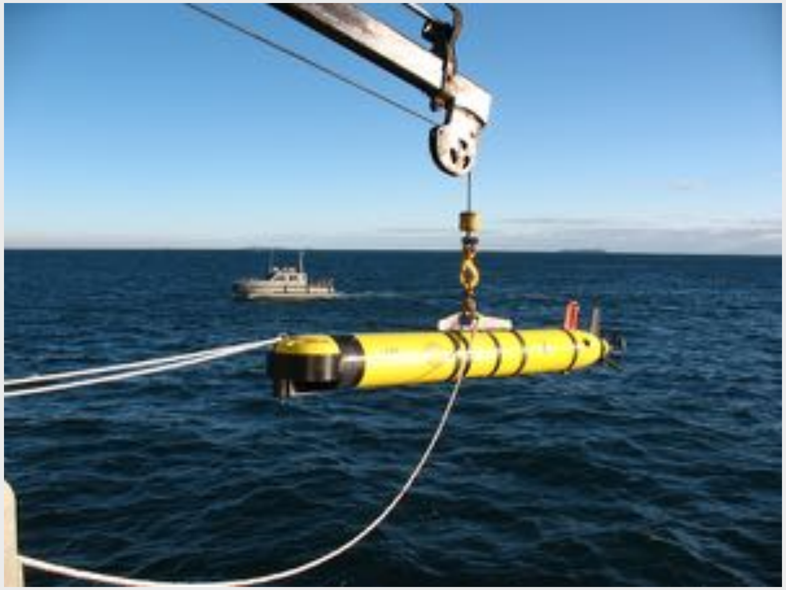


Image: ARL/UT ATLAS AUV – Hydroid Remus 600

MBARI AUV

AUV Operations – Launch and Recovery

A – Frame

- Standard on many vessels of opportunity
- Usually mounted on stern, where pitch motions are high
- Large distance between sheave and AUV: must constrain swing
    - Need two tag-lines

Images from MBARI

US Navy BPAUV recovery during AUVFest 2008

AUV Operations – Launch and Recovery

Specialized L & R systems (LARS)

- Dedicated ship, or Fly-Away
- Most control and safest for AUV
- Most expensive

NOCS Autosub LARS

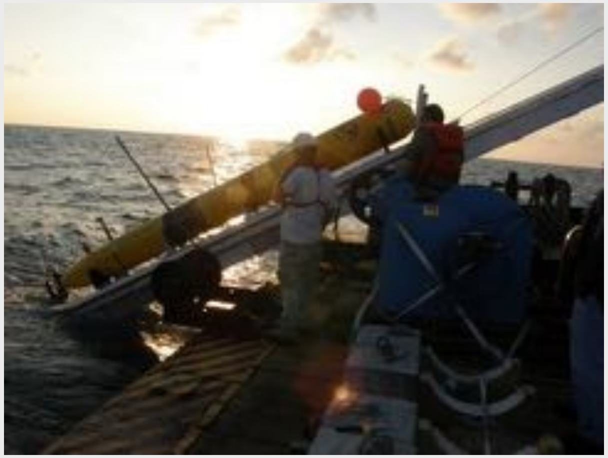
Image from Bluefin Robotics, Inc.

Image from MBARI

AUV Operations – Launch and Recovery

Ramps and Nose-lift

- Usually built as Fly-Away
- Good control during transition
- Long extensions must be very strong



Kongsberg Hugin LRS

WHOI SAMS LRS

Image courtesy of Naval Surface Warfare Center Panama City Division

AUV Operations – Launch and Recovery

Detachable Nose Tagline - Pre-rigged tow-line

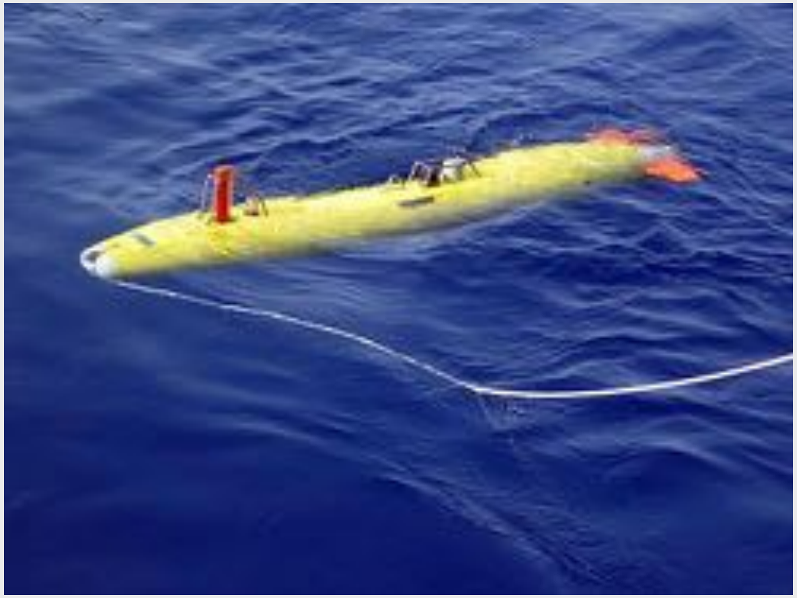


Image courtesy of WHOI/Hydroid

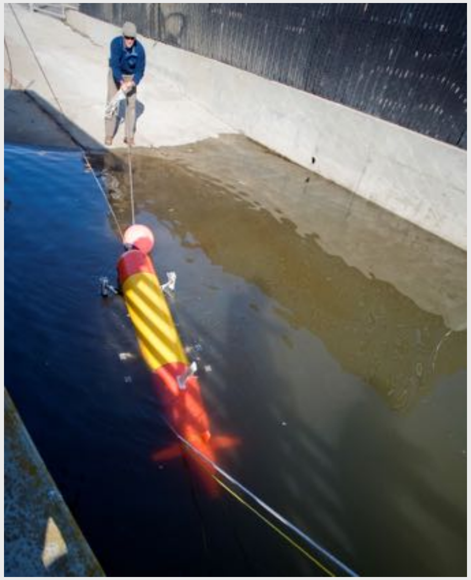
Image courtesy of Norwegian Defense research Establishment

Pre-rigged lift lines – can be grappled from ship: SOC AutoSub

AUV Operations – Launch and Recovery

Ship-less AUV Deployment

- Trailer lowered down boat ramp
- Tow out behind small boat
- Large float attached to nose help tow-ability
- Vehicle must reliably make it back to rendezvous point
  - No provision for at-sea recovery!



MBARI Tethys

MBARI Tethys

AUV Operations – Launch and Recovery

Operational Location Devices

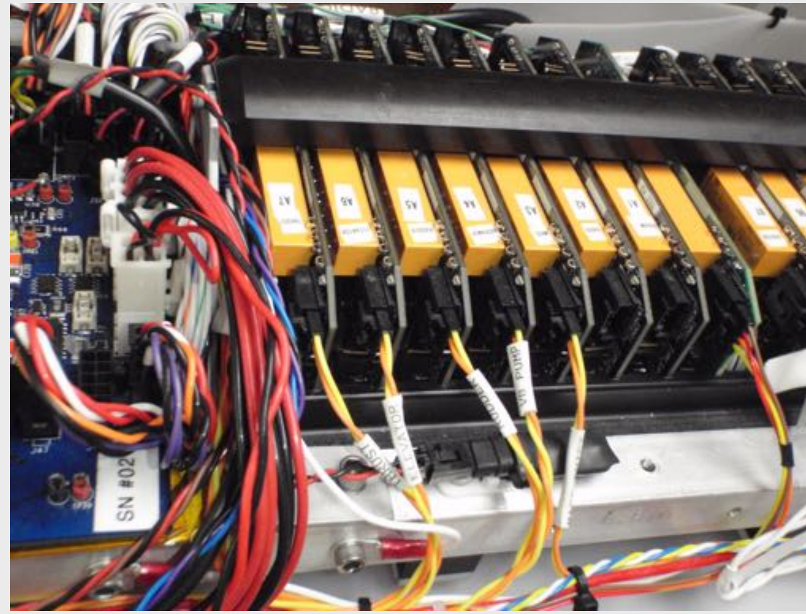
Teledyne Benthos Acoustic Modem

- GPS and Radio/Satellite
  - Transmit GPS position over VHF or Iridium satellite modem
- VHF beacon
  - Radio direction finder (RDF) on recovery ship
- Strobe light
  - Very effective at night
- Ultra-short baseline (USBL) tracking AUV from ship
- Acoustic Modem
  - AUV can tell ship where it is
  - Ship can tell AUV what to do

Applied Acoustics Easy Trac

WHOI Sentry

Electrical Systems and Instrumentation



- Energy sources
- Electrical connectors
- Scientific instrumentation
  - Upper water column
  - Mid water column
  - Benthic
  - Special topic: hysterisis
- Common vehicle instrumentation
- Timing and synchronization of instrument data

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Energy Systems

- Primary batteries – One use
  - Alkaline Manganese - Autosub
  - Lithium Sulfuryl Chloride – Gliders
- Secondary - Rechargeable
  - Lead-Acid, Ni-Cd, NiMH
  - Ag-Zn
    - Odyssey
  - Alkaline
    - Autosub
  - Lithium Thionyl Chloride
  - Lithium Sulfuryl Chloride
  - Lithium Ion, Lithium Polymer
    - Most AUVs
  - Semi-fuel cell
    - Hugin
    - ALTEX AUV


Ocean Server Battery


MBARI 5 KW=hr Battery


MBARI Fuel Cell

Energy Systems - Lifetime

Lifetime

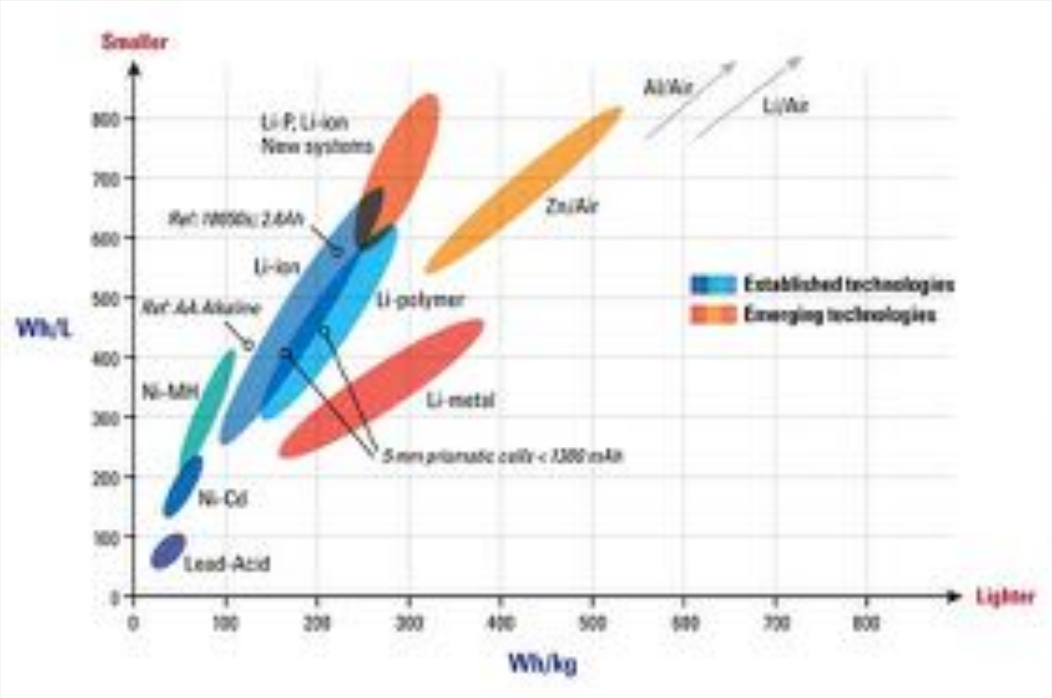
- Primary batteries – no recharge
  - Alkaline Manganese
  - Lithium Sulfuryl Chloride

- Secondary batteries – multiple recharges
  - Silver-Zinc (~50 recharges)
  - Lead-acid (~200 recharges)
  - Lithium Ion (~1000 recharges)

- Fuel-cells – multiple cycles
  - Semi-fuel cells
    - Recharge with chemical liquids
    - Need to replace stack often

Energy Systems - Energy Capacity

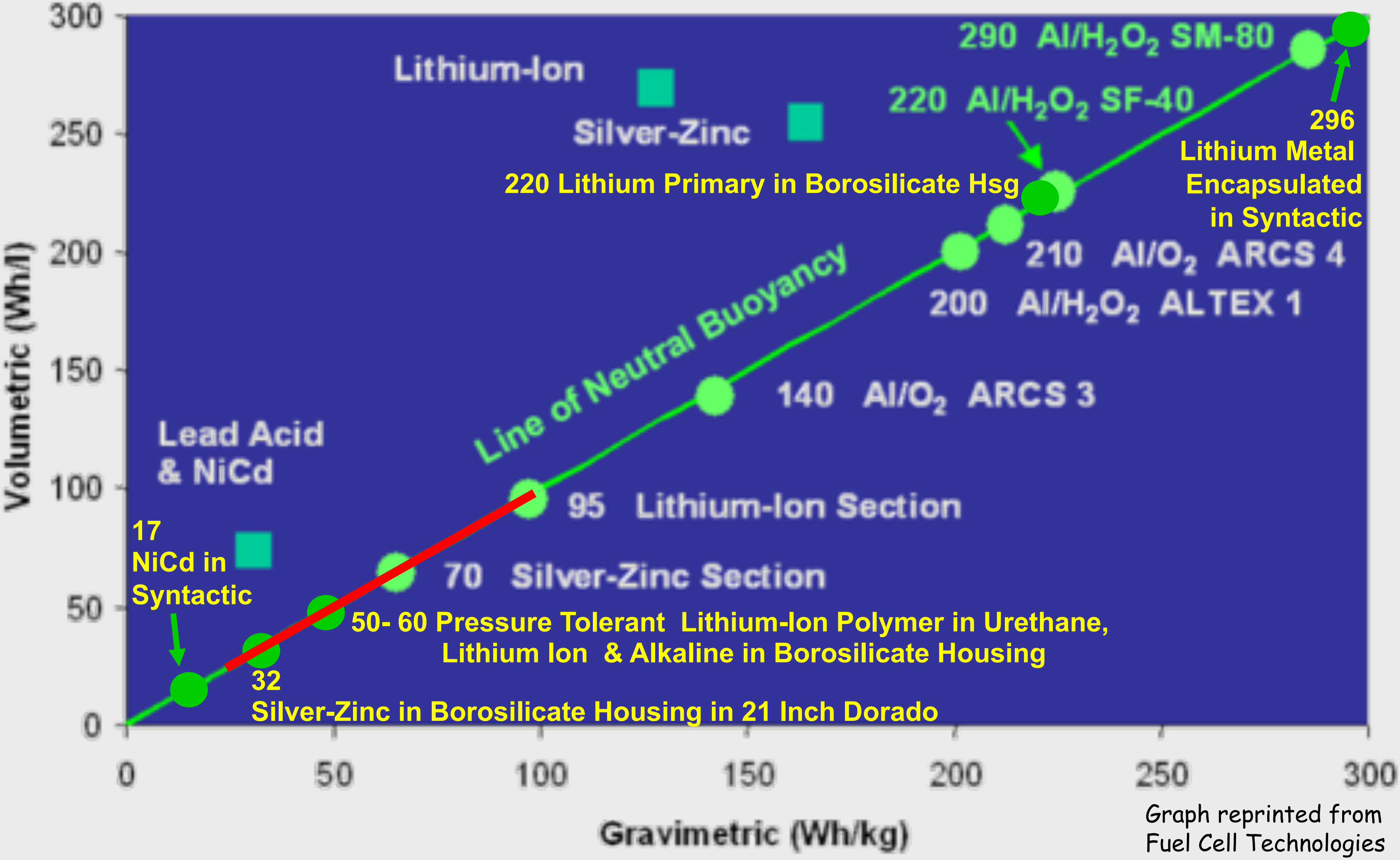
- Gravimetric energy density is battery capacity in weight: Whr/kg
  - Determine weight of battery for a given consumption and range
  - Range from Lead-acid (70 Whr/kg) to Lithium primary (530 Whr/kg)
- Volumetric energy density is battery capacity in volume: Whr/l
  - Determines how large a battery is needed for a given consumption and range



Ragone chart (source Nexergy)

- Neutrally buoyant energy
  - How much energy after it is packaged in a pressure vessel and trimmed to neutral buoyancy

Energy Systems - Specific Energy



Graph reprinted from Fuel Cell Technologies

Pressure Tolerant Battery

- Lead-acid and Lithium Polymer Batteries
- Must be bathed in a Non-conductive fluid to fill air voids – oil
- Volume changes with pressure and temperature
- Flexible pressure boundary is needed
- Syntactic Foam is usally used to offset weight

Energy Systems - Safety & Failure Modes

<u>Failure Modes</u>

- Open or short circuit
- Charge mode and discharge mode failure
  - Permanent cell damage
  - Plasma jet – high power flare

<u>Safety</u>

- Shipboard hazards
  - Fire during charge
  - Fire caused by a short circuit
  - No good way to put out a Lithium fire – Address heat
  - Sensors should monitor the temperature of each battery

- AUV hazards
  - Fire on vehicle under deployment could mean 100% loss
  - Electronic circuits on each cell provide protection
  - Sensors monitor batteries when discharging
  - Fuses are used to protect batteries from anomalies found on DC bus

Energy Systems - Cost

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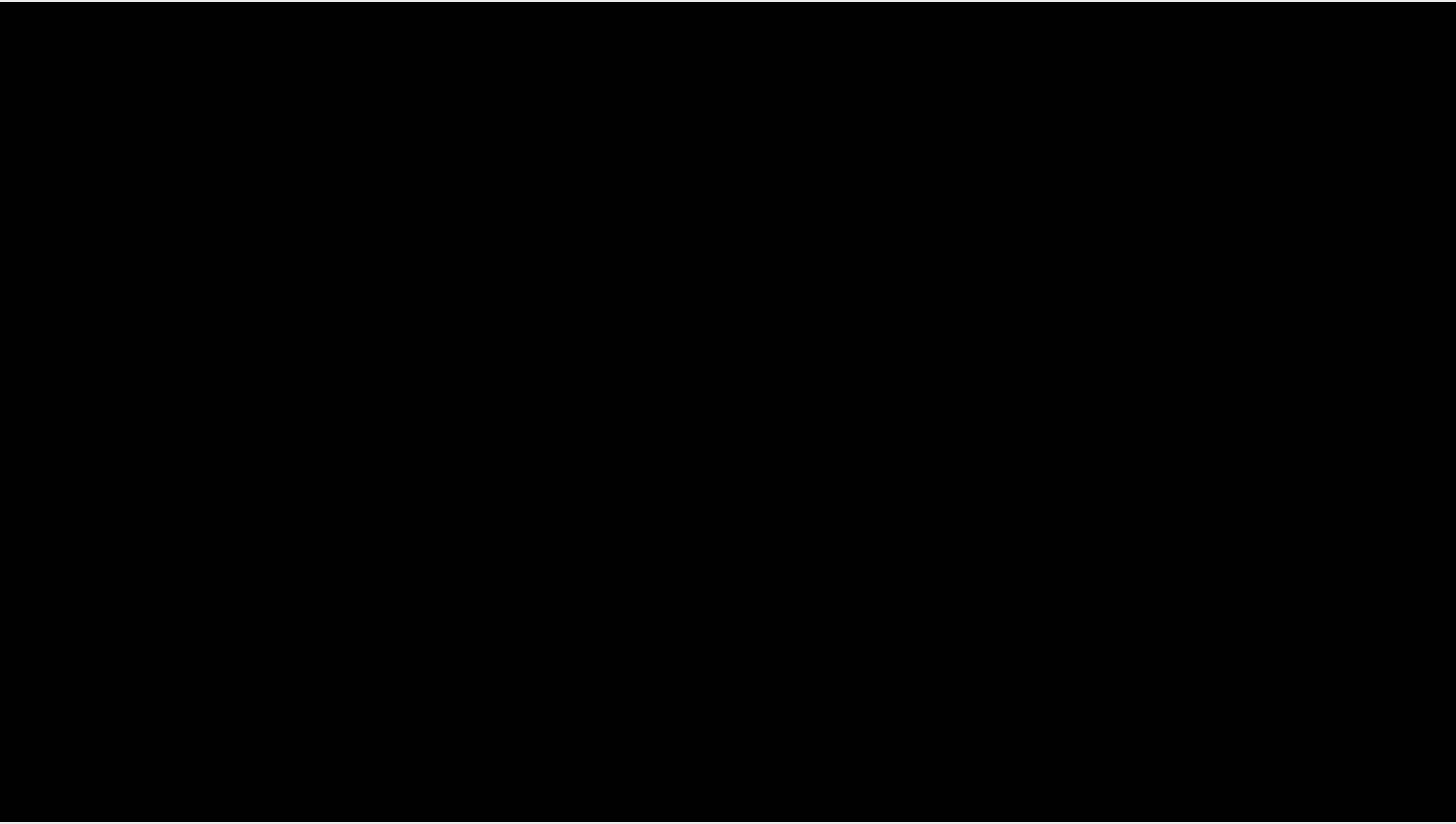
Total Cost of energy source

- Need to consider operational scenario first
  - How easy to replace energy: change cells/pack, charge pack, change reagents
- Need to add in cost of support technicians, storage, transportation, etc.
- Need to add in costs during recharge time, e.g. downtime
  - If ship/customer is waiting: Quickly change pack, quick charge
- Number of cycles

Chemistry	Capacity (kWhr)	Average Cost/kWhr	Cycles	Cost/kWhr cycle	Initial Cost 3kWhr	Cost of 10x5yr cycles 3kWhr	Cost of 180x5yr cycles 3kWhr	
Lithium Primary	1	$ 1,000	1	$ 1,000	$ 3,000	$ 150,000	$ 2,700,000	
Alkaline Primary	0.018	$ 56	1	$ 56	$ 167	$ 8,333	$ 150,000	
Lithium Ion	1	$ 3,000	1000	$ 3	$ 9,000	$ 30,000	$ 30,000	
Silver Zinc	0.054	$ 3,704	50	$ 74	$ 11,111	$ 11,111	$ 200,000	

Energy Systems - Safety & Failure Modes

Battery Fire



Components: Electrical Connectors

PBOF – Pressure Balanced Oil Filled
- Allows access to wires to lengthen or re-terminate
- Easy to fix cabling in the field
- Able to accommodate custom wiring quickly
- Conduit for compensation oil
- Extremely messy

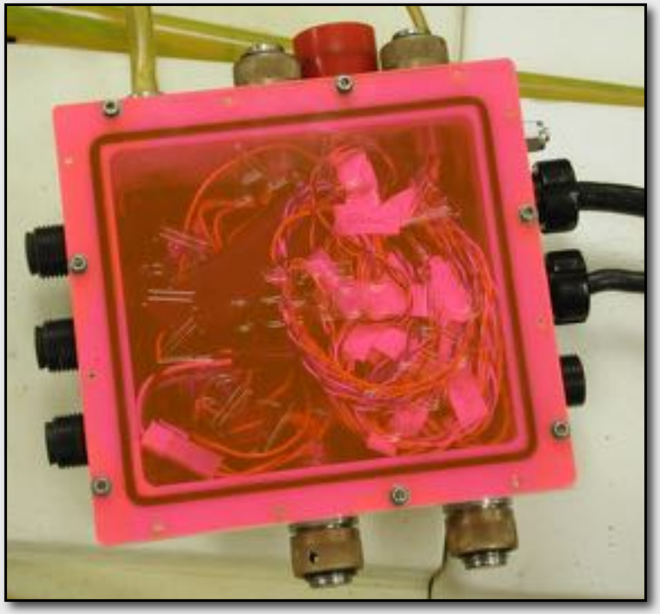
Seacon MINcon

Epoxy potted
- Very reliable
- Many configuration options

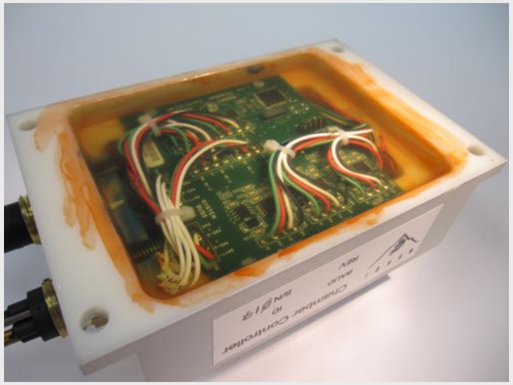
Rubber Molded
- Less expensive
- Reliable
- Limited number of mate/de-mate cycles

Subconn

Components: Junction Boxes



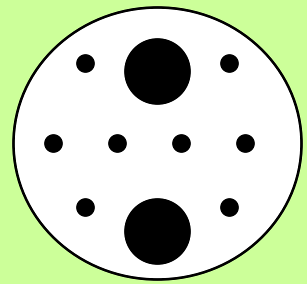
- Oil filled
  - Allows changes in the future
  - Changes can be made quickly in the field
  - Sealing surfaces are prone to problems
  - Messy because of oil seepage and draining
- Potted
  - Non re-enterable: epoxy
  - Re-enterable: soft urethane
  - High reliability
  - Sealed against water intrusion



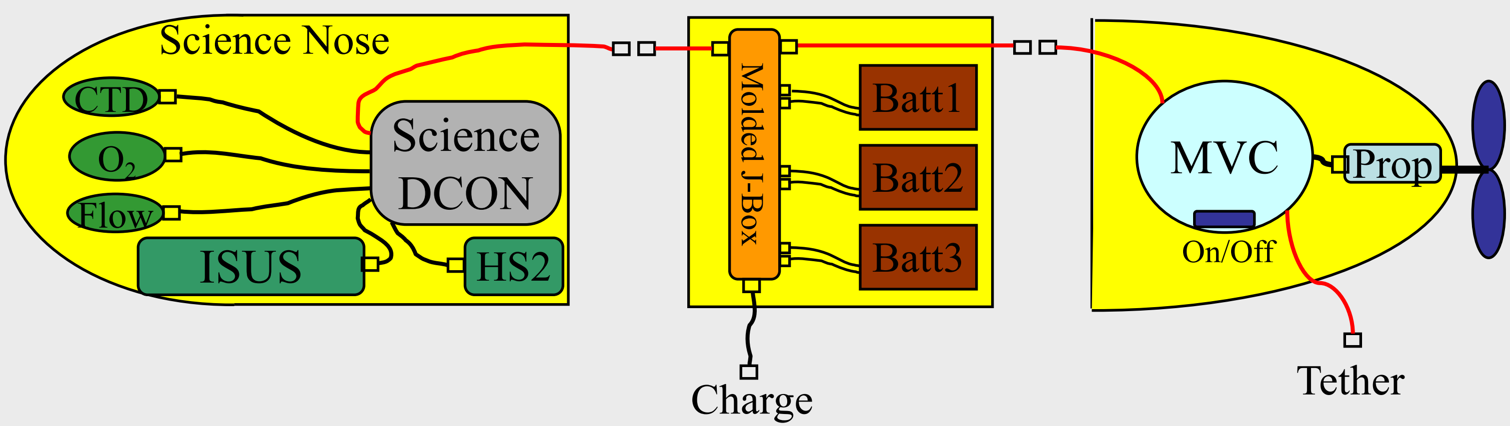
Components: Cable Modularity and Isolation

Modularity and isolation

- One cable provides power and comms
- Standard circular connector for bus
- Comms are CANbus and Ethernet
- Galvanic isolation



- 2 pins power
- 4 pins ethernet
- 2 pins CANbus
- 1 pin shield
- 1 pin enable



Components: Instrumentation

- Navigation instrumentation
  - GPS
  - Inertial Navigation System (INS)
  - Doppler Velocity Logger (DVL)
  - Attitude Heading Reference System (AHRS)
  - Altimeter / obstacle avoidance sonar
  - Ultra short baseline (USBL)

INS

ORE

USBL Transponder

DVL

Obstacle Avoidance Sonar

Crossbow

AHRS

Components: Upper and Mid Water Instruments

Upper and mid water columns

- CTD (Conductivity, Temperature, Depth)
- ADCP (Acoustic Doppler Current Profiler)
- LISST - particle size analyzer
- Fluorometer
- Nitrate ISUS (In-Situ Ultraviolet Spectrometer)
- Optical backscatter
- Bathyphotometer
- pH and O_2

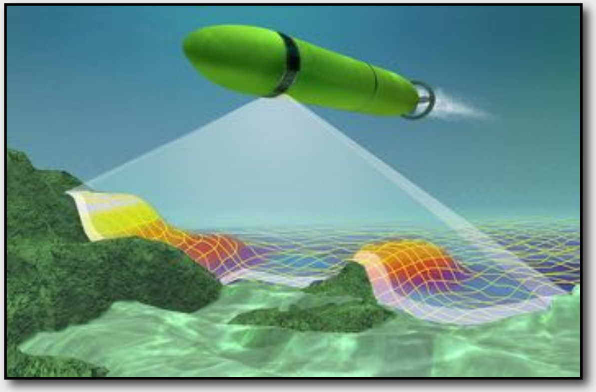
Bathyphotometer

DVL/ADCP

SeaBird

CTD

Instrumentation Types - Benthic



Benthic and mapping

- Multibeam sonar
- Chirp sub-bottom profiler
- Side-scan sonar
- Digital camera
- Chemical sensors: pH, O_2, CO_2, methane, sulfide, nitrate, etc.

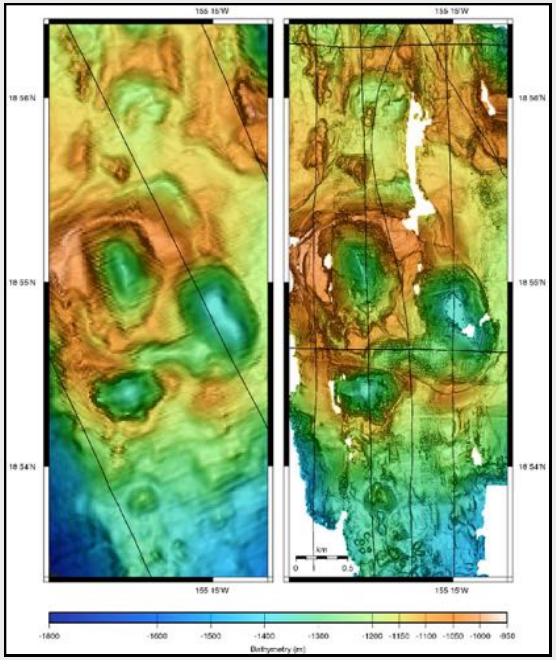
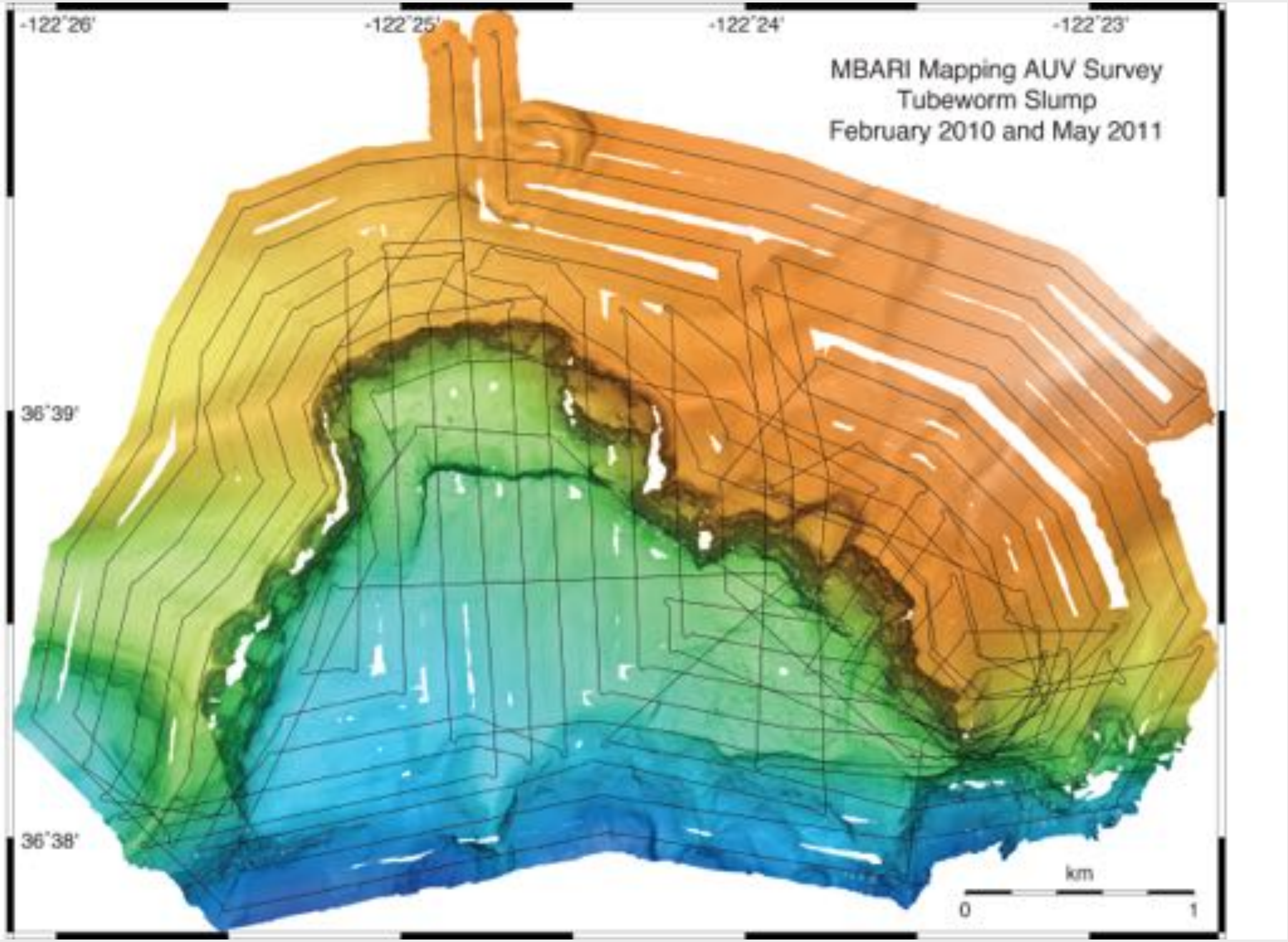


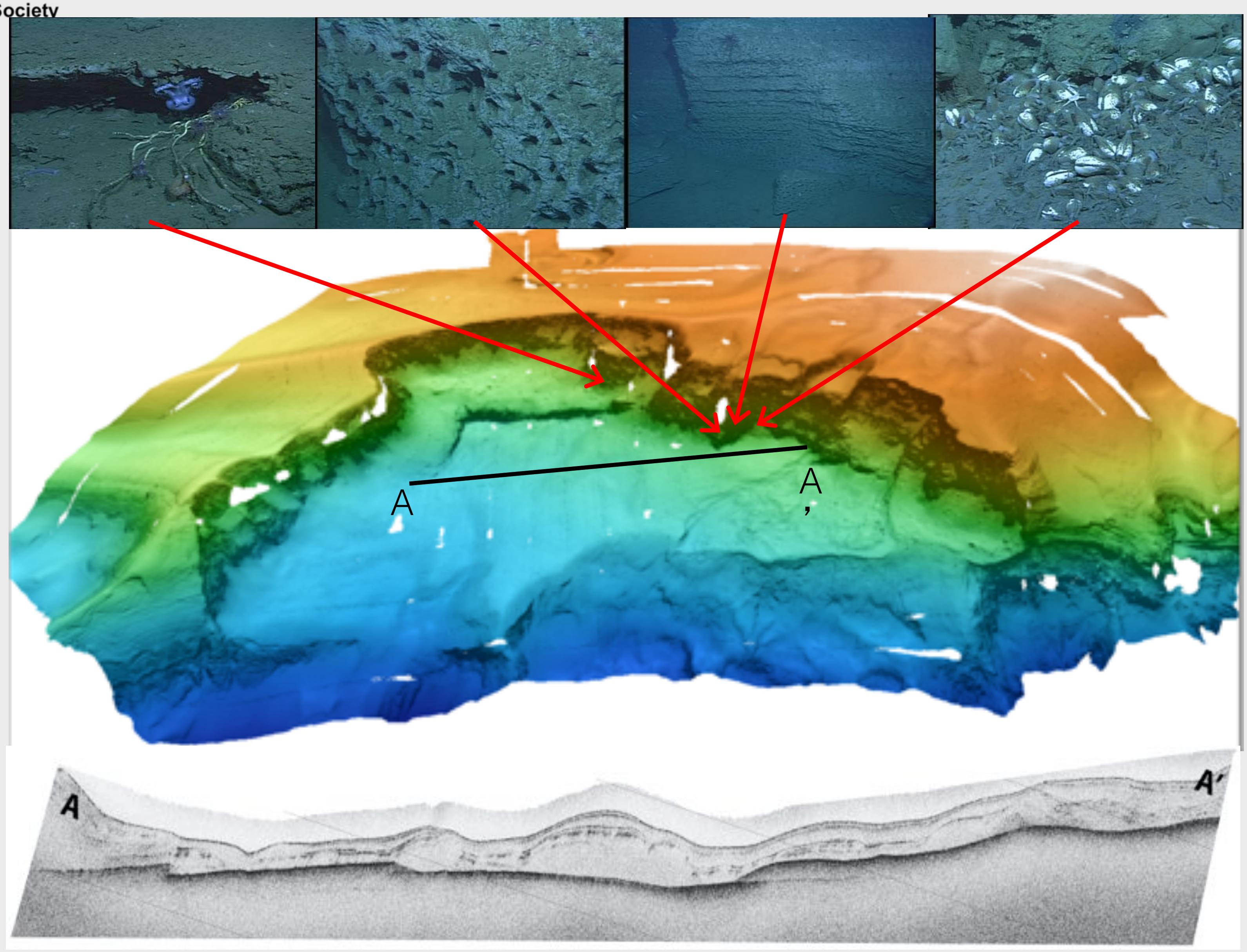
Image courtesy David Caress

- Left – hull mounted sonar
- Right – towfish with corrected navigation
- Location – Loihi Seamount near Hawaii
- AUVs can collect much higher resolution data

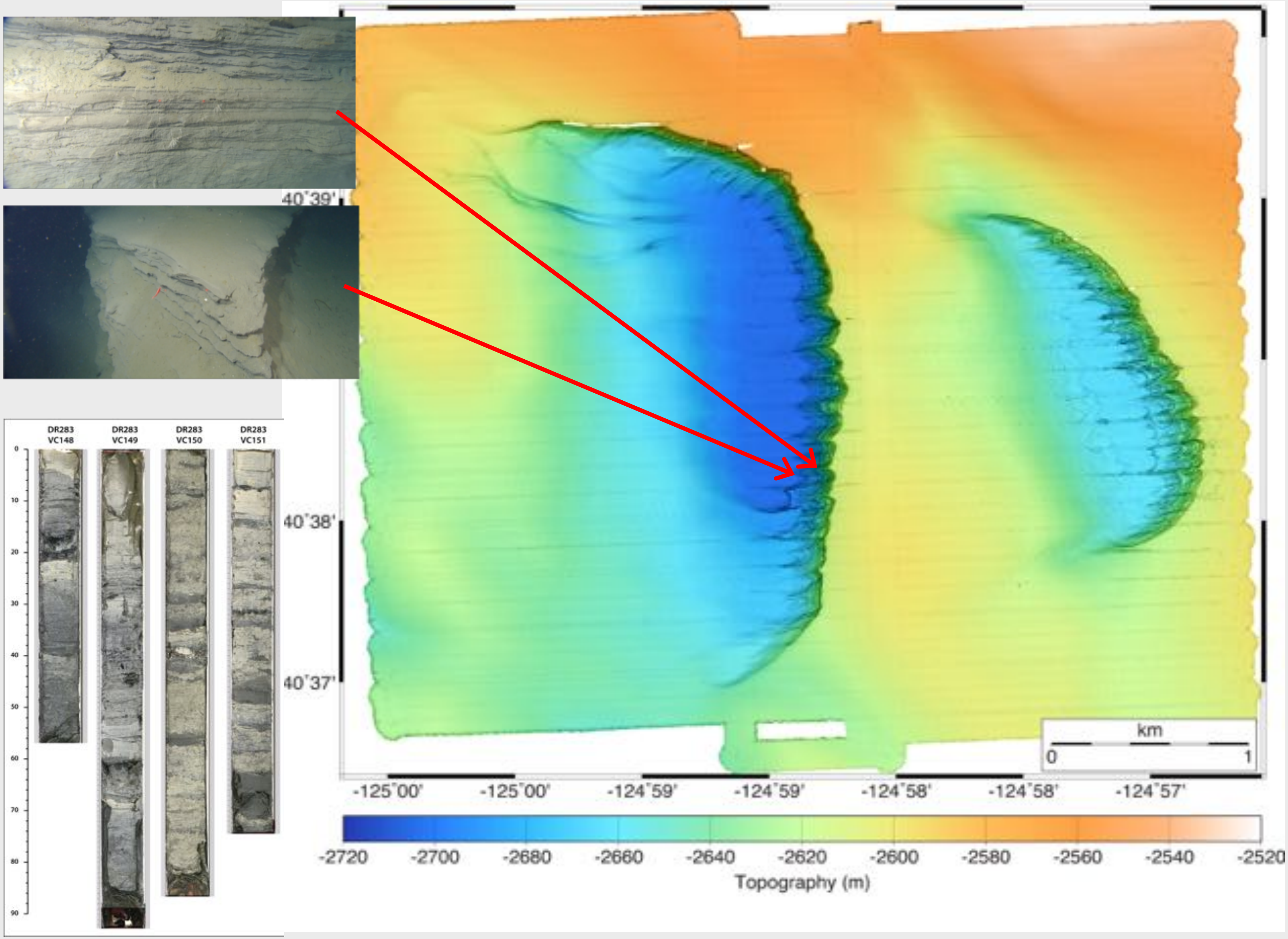
Seafloor Mapping - Planning



Seafloor Mapping – Ground Truth



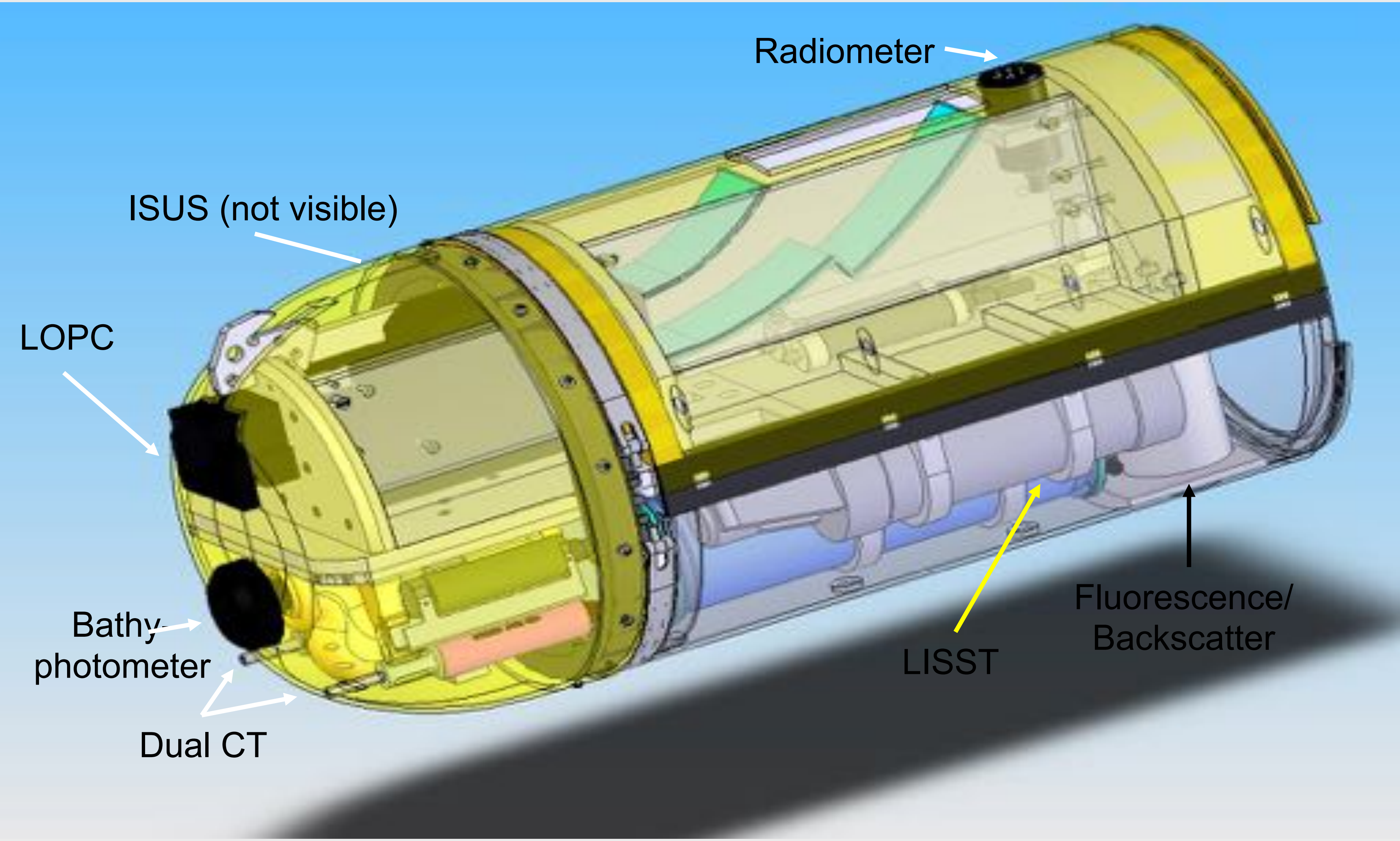
Seafloor Mapping



Payload Instruments

- Sensors: PAR, Nitrate, CDOM, methane, transmissometer, turbidity, particle counter (LISST)
- Samplers
  - Water for chemistry and trace metals
  - Water for biology
- Passive acoustic array
- Magnetometer
- Turbulence
- Imaging
  - holographic, video
  - midwater, plankton, fish
- Mass spectrometer
- Genomic: ESP
- Custom integration – watch out for issues with OS

Midwater AUV Nose Section



Buoyancy and Housings 1/2

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Benthos

Issues:
- Specific Strength: What does it weigh?
- Cost: What will the complete housing cost?
- Corrosion: Will it corrode in saltwater?
- Bulk Modulus: Will it loose or gain buoyancy at depth?

Common Pressure Housing Materials
- Aluminum (6061-T6, 7075-T6)
- Titanium (6AL4V)
- Glass
- Alumina Ceramic
- Stainless Steel
- Steel
- Carbon and Glass Fiber


WHOI Nereus

http://www.benthos.com

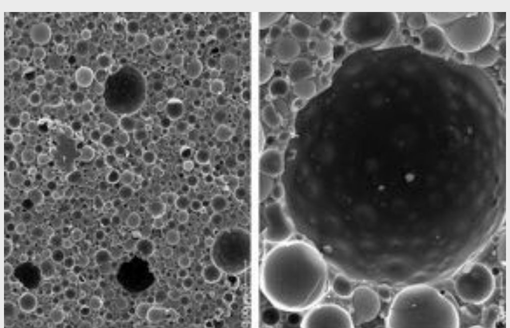
Buoyancy and Housings 2/2

<u>Syntactic foam</u>

- Made of hollow glass spheres bound together by a urethane or epoxy matrix
- ~ \$1000 US/ft^3
- 24 lbs/ft^3 to 45 lbs/ft^3
- Compresses more than water
- Absorbs water- up to 3% weight gain
- Can be machined to any shape
    - no macro-spheres
- Can be cast into any shape

Tom Kleindinst, WHOI

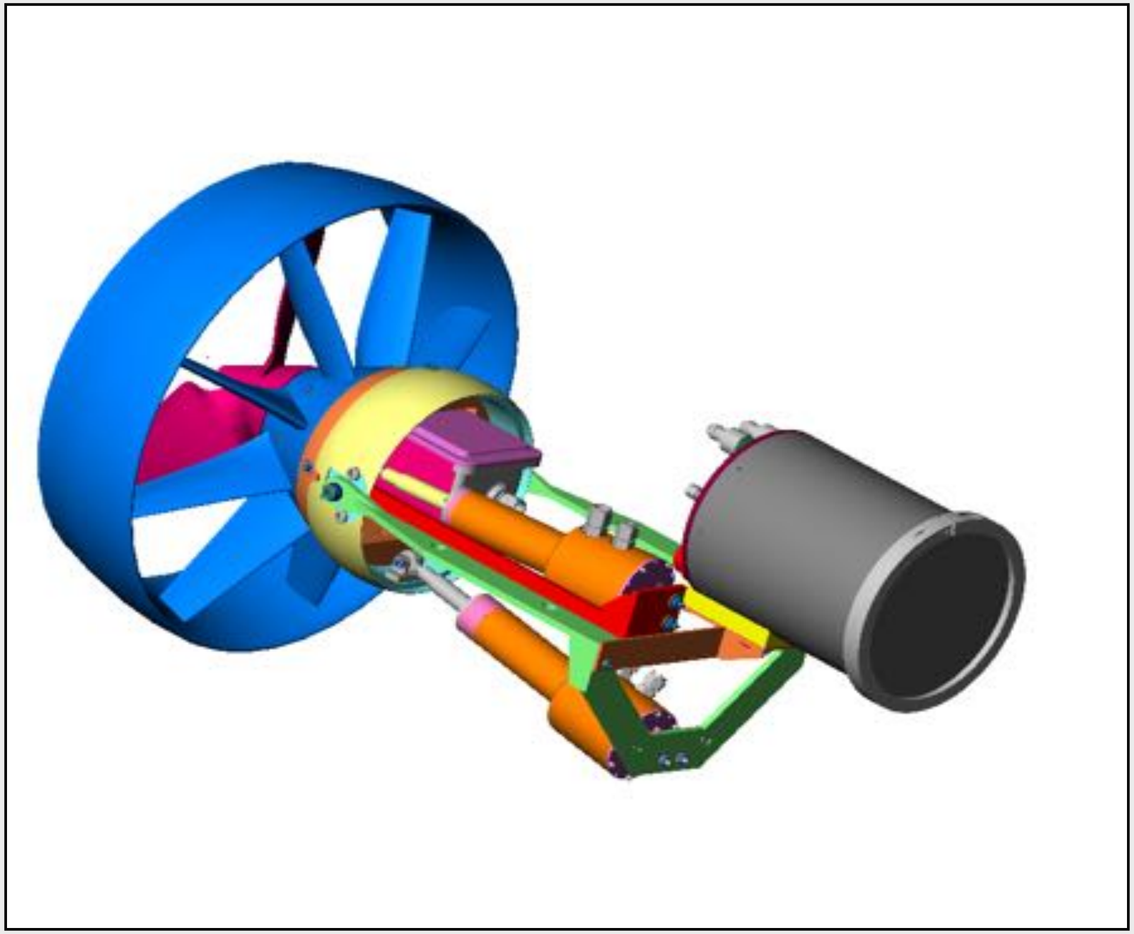
Trelleborg SMD



G. Tagliavia,
M. Porfiri,
N. Gupta 2009

Propulsion

Propulsion

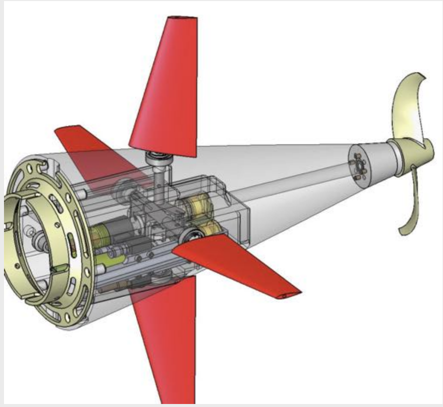


A Dorado class AUV tail section

Although there are options the most common and widely used system is a propeller and some configuration of control surface to set AUV direction

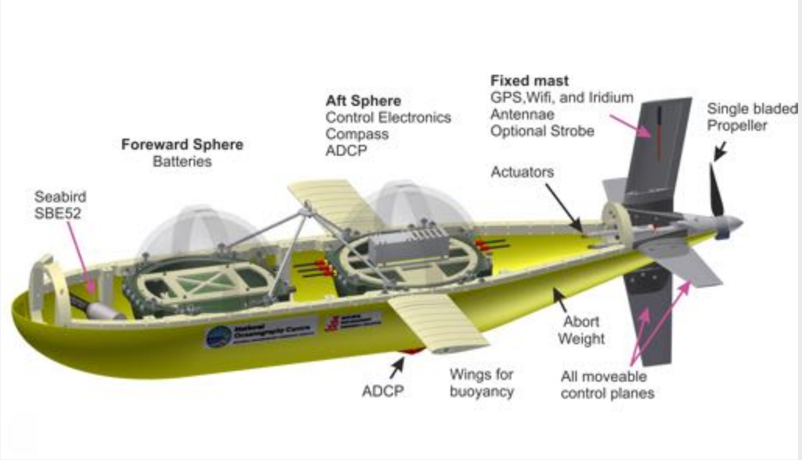
Propulsion

A Remus 600-S tail section



A Tethys Long Range AUV tail section

Teledyne Gavia



AutoSub Long Range. NOC, Southampton

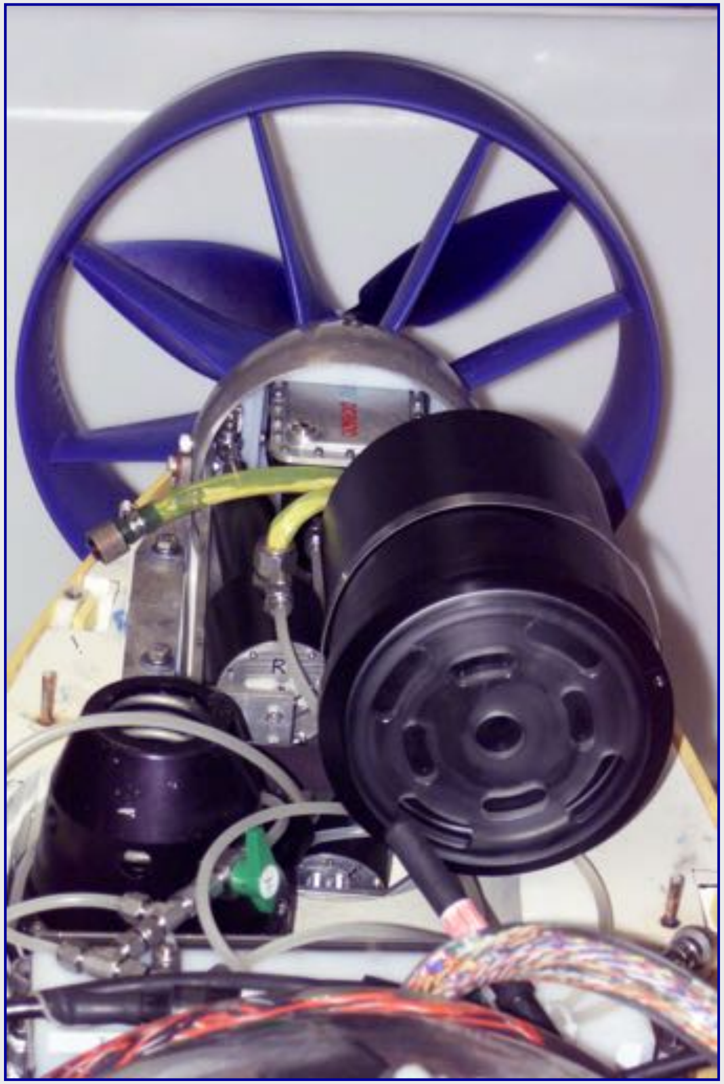
Propulsion

Some Rules of Thumb:

• Large diameter propellers turning relatively slow are more efficient

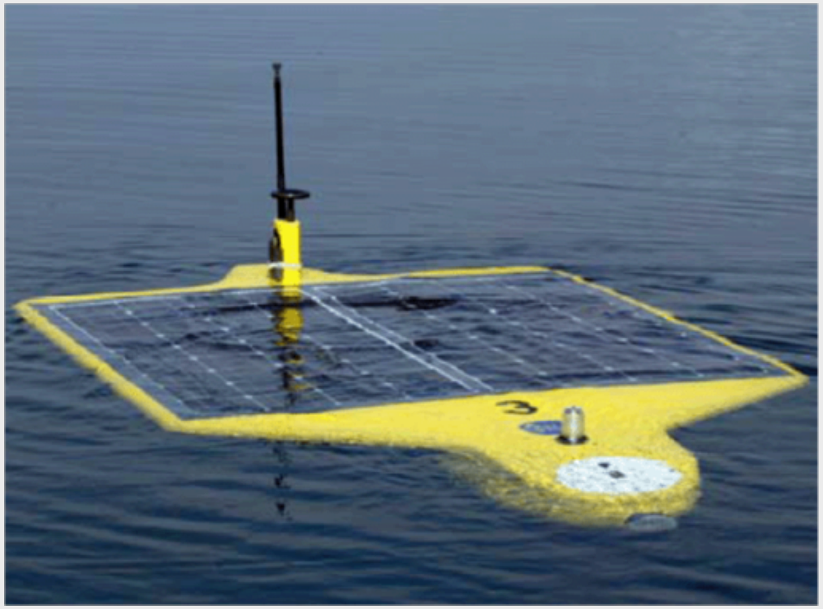
• Ducted propellers offer better efficiency at low speed by minimizing tip losses

• Propellers will induce a vehicle torque roll that should be correct by ballasting or trim tabs



Propulsion

<u>Environmental:</u>
- Solar
- Wave
- Wind,



Harbor Wing Technologies Inc. X1 prototype (Elkaim and Boyce, 2008)

Propulsion

How much power does it take to drive an AUV through the water?

Power Calculation for Self-Propelled Vehicle

$$D = \frac{1}{2}\rho_{SW} U^2 \mathbf{C}_D S$$

$$P = \frac{1}{2\eta}\rho_{SW} U^3 \mathbf{C}_D S$$

- ***P*** **= power *(W)***
- ***n*** **= *(Eta)* propulsion efficiency (dimensionless, typically .5)**
- **p_{sw} = density of seawater (1025 kg/m^3)**
- **C_D = Coefficient of Drag (dimensionless); but matched with S**
- ***S = effective area of drag; It can be:***
  - **Frontal area**
  - **Planform area**
  - **Surface area**
  - **Volume raised to 2/3.**
- **U = forward speed (m/s)**

Sample Calculation of Reynolds Number

Example: Vehicle is moving at **1.5 m/sec** ~ 3 knots

In sea water : ρ (rho) = 1025 kg / m^3

For this example, the vehicle length is **2 meters**

Dynamic viscosity of seawater: μ= 1.08 x 10^{-3} Pa sec (20 C)

Kinematic viscosity of seawater: υ= **1.05 x 10^{-6}** m^2/sec = μ/ρ

$$R_e = \frac{UL}{\upsilon}$$

Plugging in we get:

Re = 1.5 x 2 / 1.05e-6

Re = **2.2 x 10^6**

For a particular shape, drag depends on Reynolds number

Beware: Meaning of L for Reynolds Number may Vary!

- For bluff 3D bodies it is typically the diameter and perpendicular to the flow.
- For **streamlined bodies** it is typically the length parallel to the flow.
- On the next slide, the left-hand chart employs both.

This example vehicle is streamlined and has the Reynolds number based on vehicle length, even though the C_D is based on cross-sectional area.

Drag Component of Equation

Three-D drag based on Frontal Area
For $10^4 < R_e < 10^6$.

R_e based on Dia.

R_e based on Length

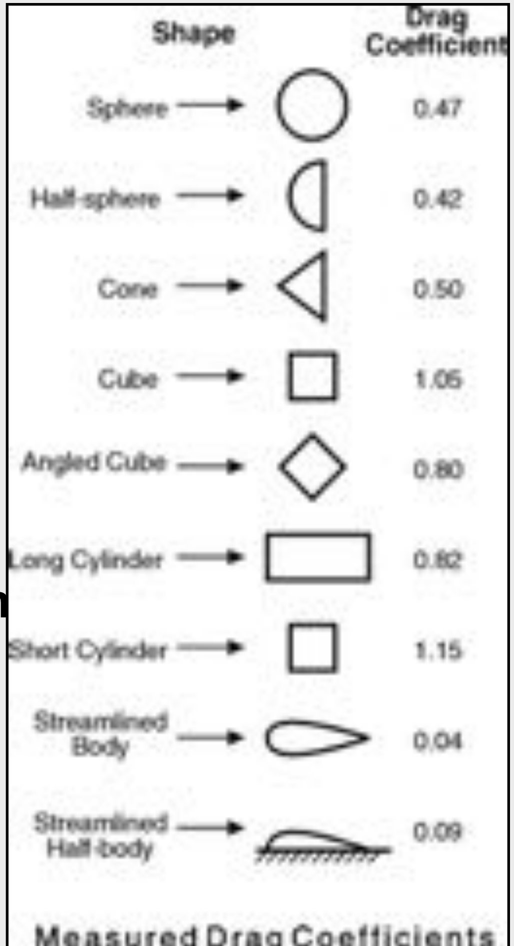


Image from web page: http://www.insideracingtechnology.com/tech102drag.htm
Also see See Hoerner, Drag, 1965, p.3-17 and 6-16.

Two-D sectional drag. Note area definition.

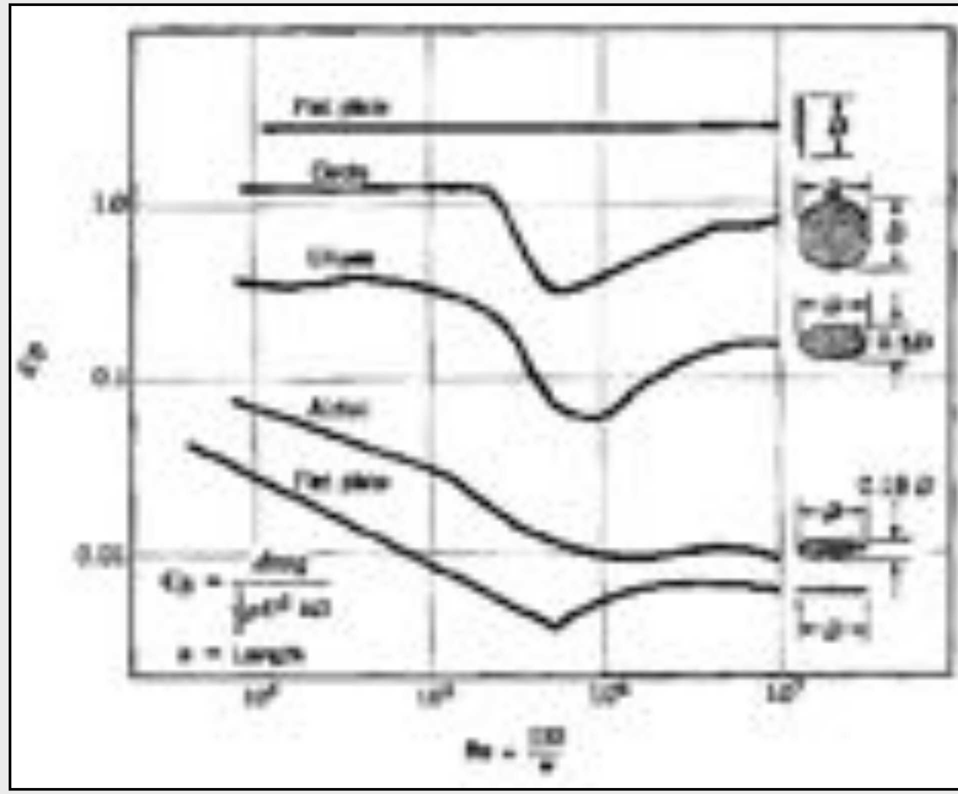


Image from **Fundamentals of Fluid Mechanics,** [Bruce R. Munson](#) et al.

Sample Power Calculation

$$P = \frac{1}{2\eta}\rho_{SW}U^3\mathbf{C}_D S$$

- $S = \pi R^2$
- R = .5332/2 m (maximum dia = 21" for Dorado)
- η = .5
- C_D = .04
- p_{sw} = 1025 kg/m^3
- U = 1.5 m/s

Substituting:

P = 1/(2 * .5)) * 1025 *(1.5^3) *.04 * 3.14 * (.27^2)

P = 31 watts ***< But this is only a smooth hull with nothing else! Hull roughness and control surfaces will increase this number.***

Power Required for a Sample Science Appendage

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

R_e = .0254*1.5/1.05e-6
= 3.6e4

Using the same process – let's add a 6 in. tall x 1 in. dia cylindrical probe.

- p_{sw} = 1025 kg/m^3
- U = 1.5 m/s
- η = .5
- *S = 6 x 1 = 6 in² ~ .0039 m²*
- C_D = 1.2 at Re=3.6e4 based on Frontal Area.
  - See previous sectional drag chart, or Hoerner, Drag, 1965, p.3-9

Substituting:

P = 1/(2 * .5)) *1025 * (1.5^3) * .0039 * 1.2

P = 16 watts *< this is for one small appendage*

Power Required for a Streamlined Antenna Mast

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

R_e = 3*.0254*1.5/1.05e-6
= 1.1e5

What does the antenna from our example cost in drag and power?

- *Span x Chord= 10 x 3= 30 in^2 ~ .019 m^2*
- η = .5
- C_D = .02 (airfoil section previously)
- p_{sw} = 1025 kg/m^3
- U = 1.5 m/s

Substituting

P = 1/(2 * .5)) *1025 * 1.5^3 * .02 * .019

P = 1.3 watts *< much better than a tube*

Energy Calculations Continued

31 watts	**Vehicle**
16 watts	**Probe**
1.3 watts	**Antenna**
48.3 watts	*Power for just these three items*

The take home message from here:

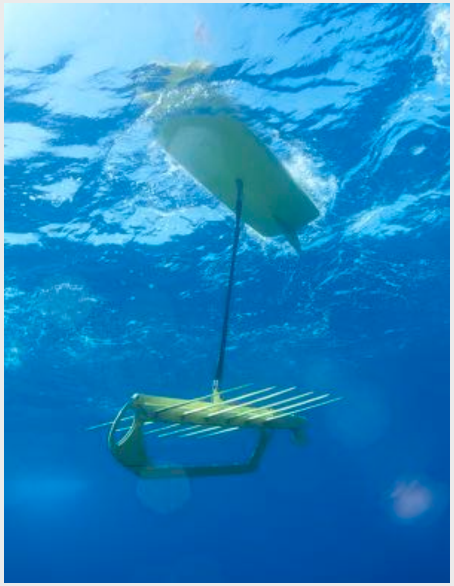
33% of the power is used just to push the un-streamlined probe through the water

NOTE: Hotel load (P_h) is everything except propulsion

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

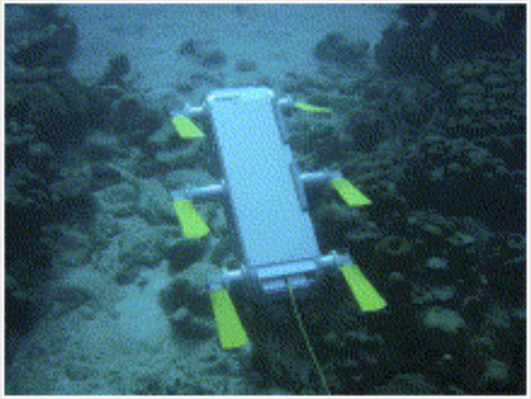
Other propulsion

- Oscillating foils or undulating body
- Buoyancy
- Wave



Liquid Robotics Wave Glider

Nekton's Pilotfish



McGill Aqua

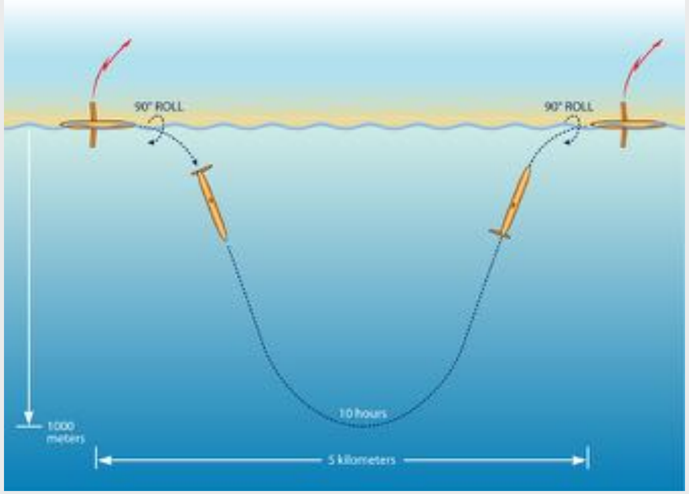


Image Courtesy of Scripps

AUV Navigation

Note: GPS does not work underwater

AUV Navigation Architectures

- Autonomous
  - Deduced (dead) reckoning
  - Inertial navigation

  both can be aided by doppler velocity log (DVL) to reduce error. Subject to altitude restrictions

  Position error increases over time without position fix

- Surface Aided
  - Short & Ultra-Short Baseline (SBL & USBL)
  - Inverted Long Baseline
    - Places transponders on surface instead of bottom (underwater GPS)
  - Inverted USBL
    - Places transponder on ship, phased array receiver on AUV

  Depending on solution, may require additional telemetry channel

  - GPS: nearly worldwide differential accuracy
- Bottom Aided
  - Long baseline
    - Typically requires water depths > 4 x baseline length
  - Ultra Short Baseline
    - Transponder mounted on seafloor in known location

AUV Navigation Architectures

- Terrain Aided
  - Terrain Relative Navigation
  - Simultaneous Location And Mapping (SLAM)

Position error does NOT increase with time or distance.

Requires "view" of the bottom. Only acoustic solutions and IMU will work in mid-water zone.

AUV Navigation Architectures

System	Accuracy	Approx Power	Constraint
GPS	.1-5m	1W	Surface only
Doppler Velocity Log w/ Magnetic AHRS	~1% DT	25W	1m – 500m altitude
Long Baseline Acoustic Navigation	5 cm @ 100m 3m @ 10 km	5W	Calibration and deployment/recovery
USBL Acoustic Navigation	.1% - 10% of slant range	30W	Telemetry from surface if on a moving platform
Inertial Navigation System	1 nm/hr	12-20W	Alignment
INS/DVL	.05 - .1% DT	25-45W	Alignment

AUV Navigation Architectures

Recommended Reading

J.C. Kinsey, R.M. Eustice and L.L. Whitcomb , *A Survey of Underwater Vehicle Navigation: Recent Advances and New Challenges* , In Proceedings of the IFAC Conference of Manoeuvering and Control of Marine Craft, September 2006, Lisbon, Portugal. Invited paper.

Nav Instruments – Magnetic Heading Reference

- Magnetoresistive Magnetometer
  - Based on principle of anositropic magnetoresistance, where resistance of ferrous metals changes based on incident magnetic field
  - Wheatstone bridge of four sensing elements creates self-compensating single axis magnetometer
  - Three-axis configuration w/ orientation sensing creates full up compass
  - Surface mount IC's w/ multi-axis magnetometers, conditioning electronics, on-chip temperature compensation available from many commercial vendors
  - Integrated packages w/ accelerometers offer **1^o to 2^o magnetic heading accuracy**

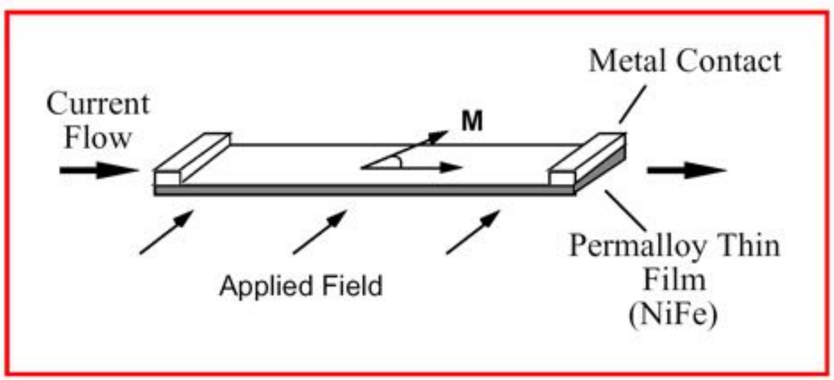


Figure 1. Principle of operation for MR sensors.

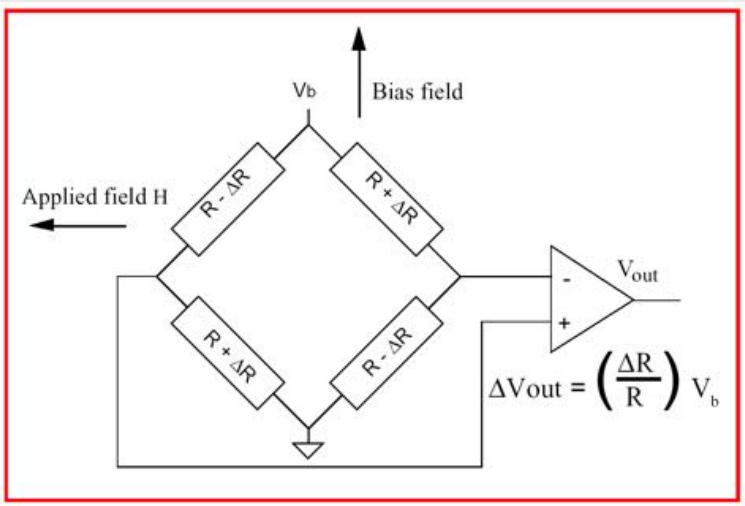


Figure 2. Magnetoresistive transducers.

Figures from http://www.ssec.honeywell.com/magnetic/datasheets/magsen.pdf

Nav Instruments – Magnetic Heading Reference

Proper calibration is key

- Calibration
  - Automatically calibrate by rotating magnetometer through 360^{o} in yaw, practical range of pitch & roll (similar to spinning the compass in aircraft or ship)
  - Also calibrate by referencing optically to local landmarks, GPS, etc.

- Hard Iron Distortions
  - Caused by local, static magnetic field(s) (nearby magnets, etc)
  - Must ensure these do not saturate detector
  - Modeled as vector (direction & magnitude) offset and subtracted from measured field

- Soft Iron Distortions
  - Caused by changes in magnetic field of nearby ferrous metals due to change in orientation with Earth's magnetic field
  - Harder to compensate

- Distortions generated by current flows
  - Spurious load switching or change in current demand can cause distortions

Nav Instruments – Magnetic Heading Reference

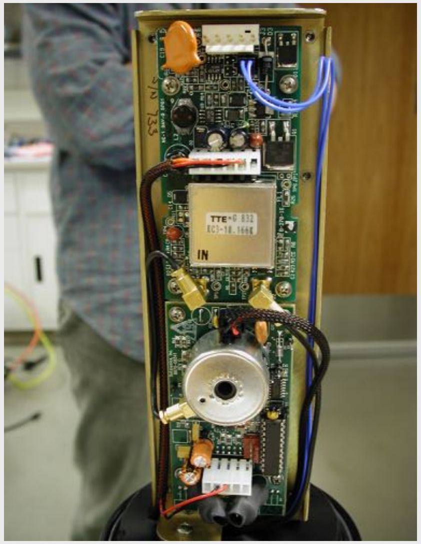
- Integration w/ Tilt Sensors
  - Provide vertical reference to convert field measurements to heading
  - Electrolytic Tilt Sensors
    - Higher static accuracy, poor dynamic accuracy, limited range
  - Solid State Accelerometers
    - Higher dynamic accuracy, (typically) lower static accuracy, wide range

- Integration w/ Rate Sensors
  - Provides mechanism to
    - filter noise
    - detect dynamic field disturbances
  - Some vendors (Crossbow for example) integrate full-blown Kalman filters
    - provide higher output rates than possible with standalone magnetometer
  - Typical rate sensors are lower-end vibratory gyros
    - Drift rates typically .01º/s to 1º/s
    - Piezo-electric
    - Piezo-ceramic
    - MEMS

Nav Instruments - Acoustics

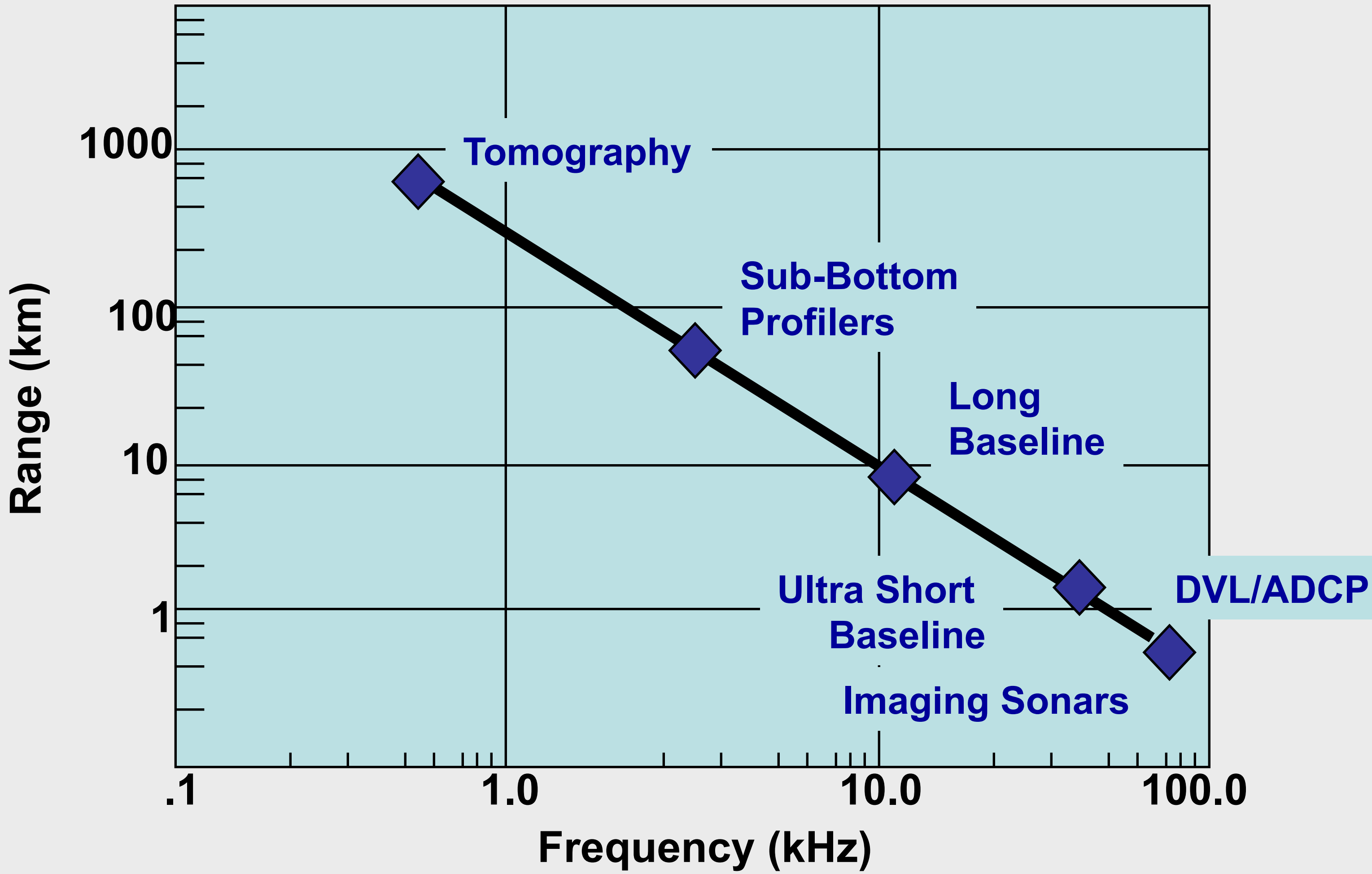
- Collision avoidance
- Comms: acoustic modem

- Limitations
  - Absorption & Scattering losses
  - Upwardly-refracting paths
  - Ship & Vehicle radiated noise
  - Bottom/surface reflection



Nav Instruments – Acoustics

- **Range at which Absorption approximates 10 dB**



Navigation– Long Baseline Navigation

- Operate at LF(7-14 kHz), MF(14-29kHz), and HF(30-60kHz) frequencies ,EHF, etc..
- Two-way travel times used to calculate horizontal position of ship or vehicle
- Typical System Architectures
  - Single beacon (requires precise dead reckoning of vehicle between fixes)
  - Two beacon (results in “which side of the baseline am I on” ambiguity)
  - > Two beacons (unique solution)
- System considerations
  - Transponder height over bottom
  - Upwardly refracting sound channels
  - Ship/vehicle noise

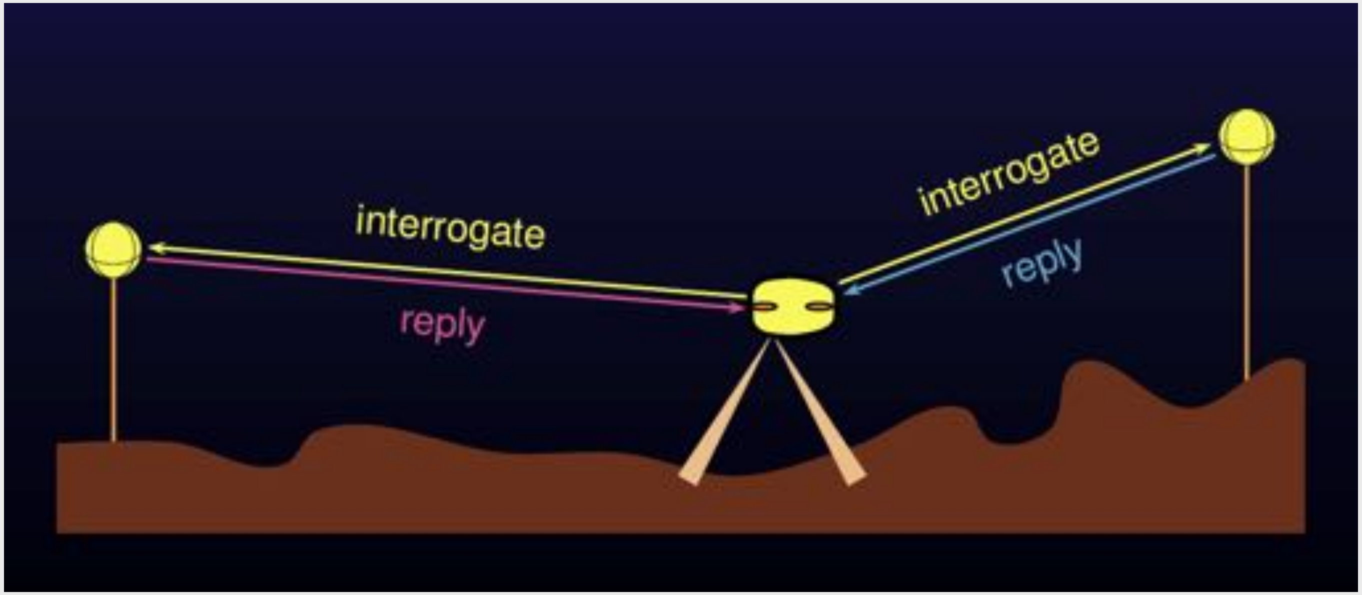
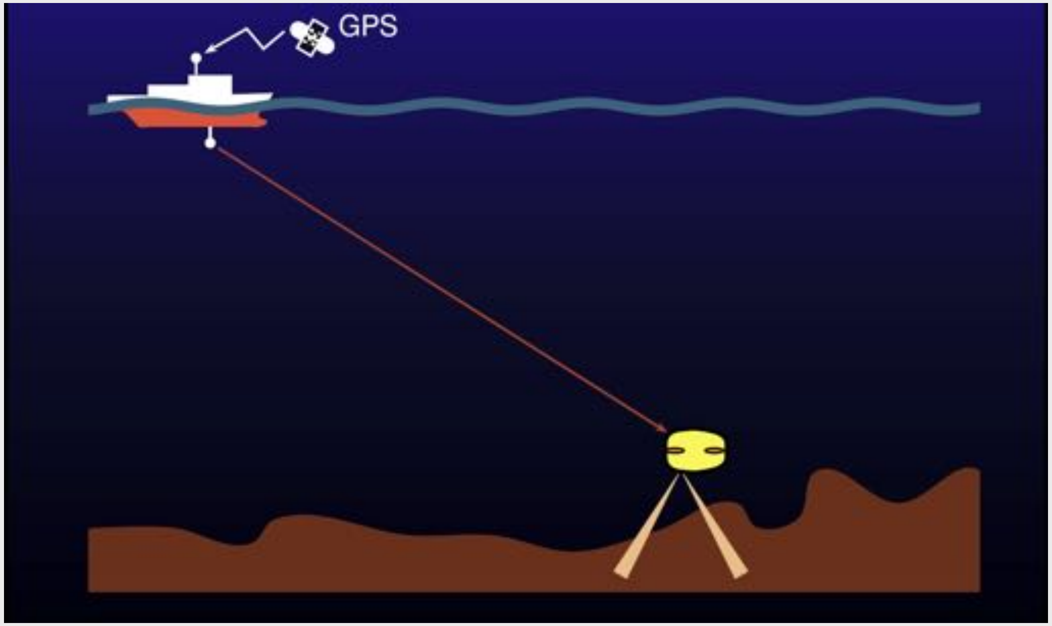
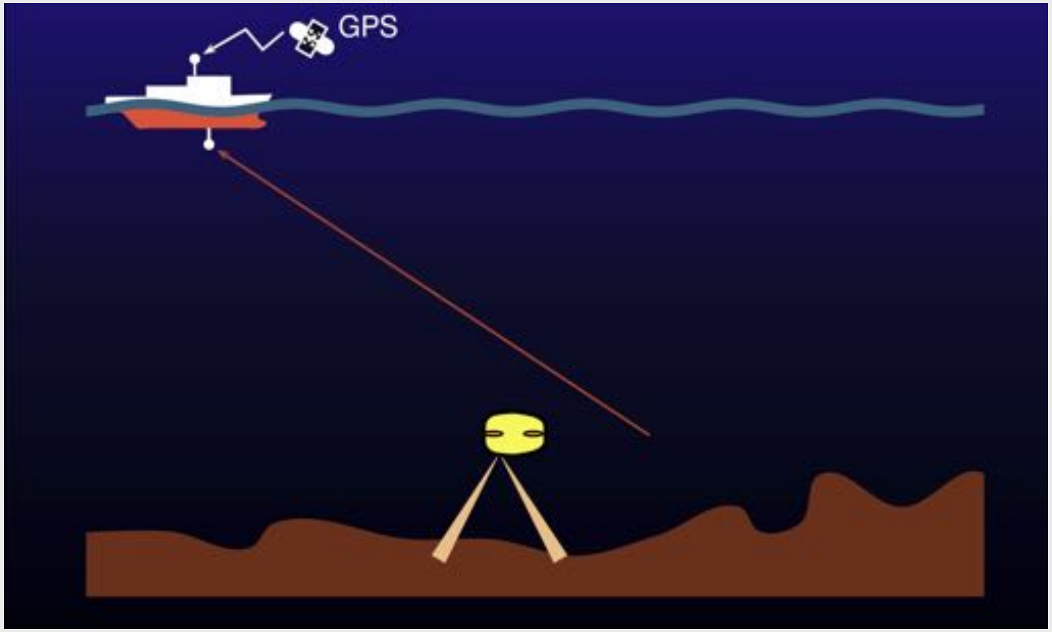


Image courtesy of M Jordan Stanway, PhD

Navigation– Ultra Short Baseline Navigation





Images courtesy of M Jordan Stanway, PhD

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Navigation– Ultra Short Baseline Navigation

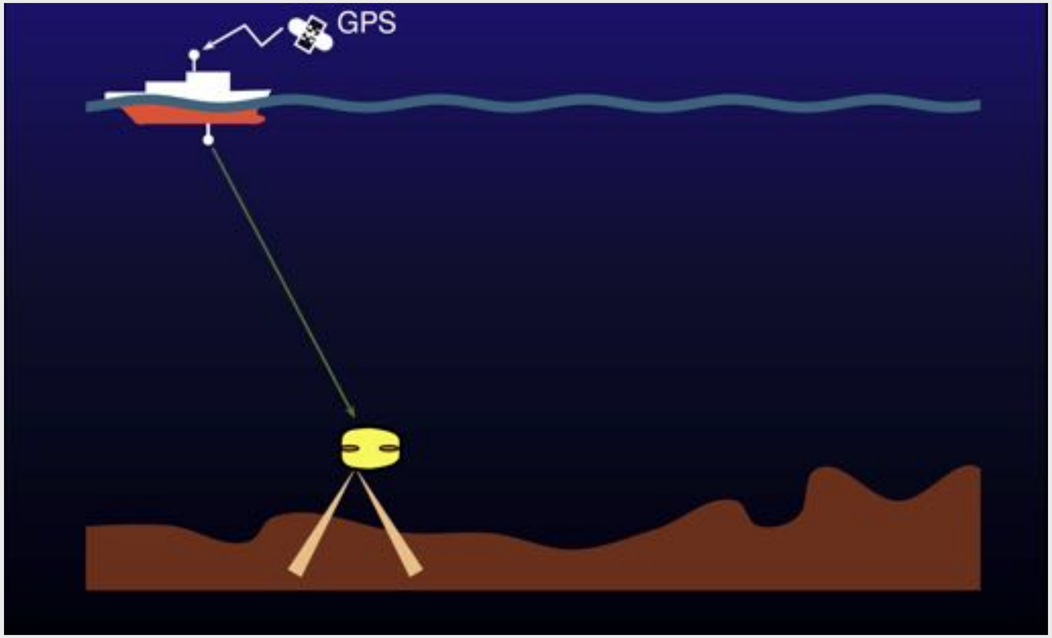


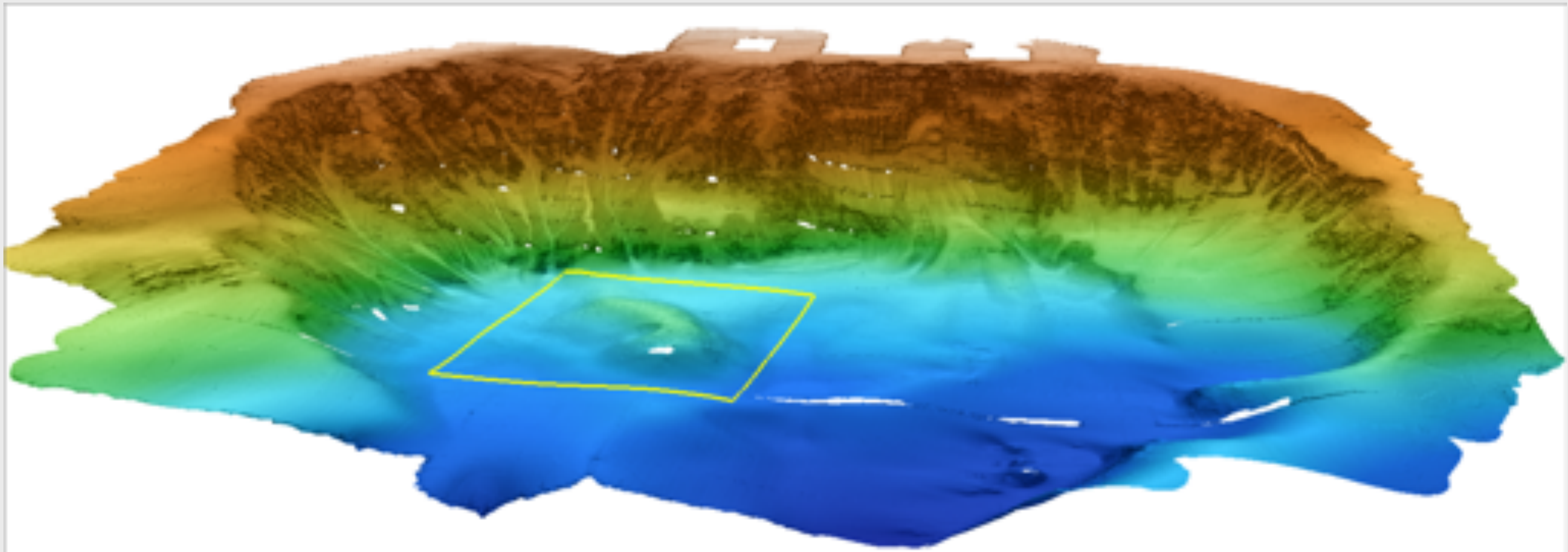
Image courtesy of M Jordan Stanway, PhD

Navigation – Integrated INS/DVL

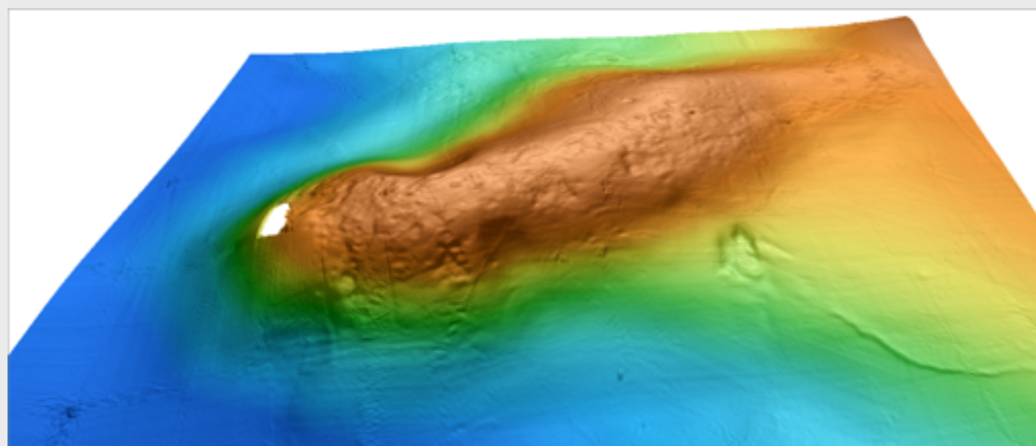
- INS provides short period/high precision measurement of velocity
- DVL provides long period/bounded measurement of velocity
- Utilize Kalman estimator to aid inertial solution with DVL-measured velocities
  - Think of it as averaging velocity data over a multi-second window
  - Allows navigation .5%-.1% Distance Traveled when bottom-locked
- INS Alignment
  - Process of determining the orientation & velocity of the INS
  - Complicated if we have to do it on a moving platform (called moving base alignment)
  - Basic Sequence (moving base)
    - Leveling – determine INS pitch and roll
    - Coarse gyro-compassing – determine INS yaw using earth-rate measurement
    - Fine velocity/orientation alignment – integrate GPS position/velocity measurement and propagated INS position/velocity until error goes below threshold

Kearfott
INS/DVL/GPS
SeaDevil

Terrain-Relative Navigation (TRN)

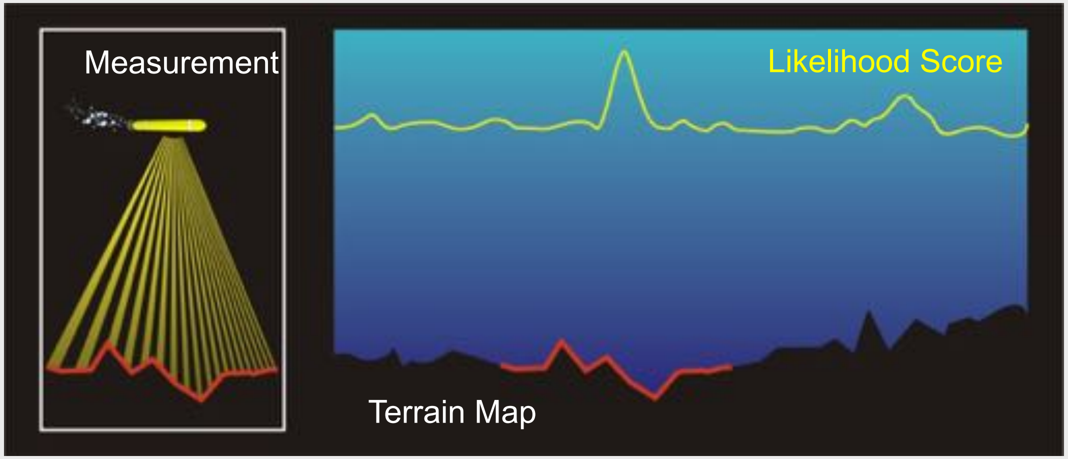


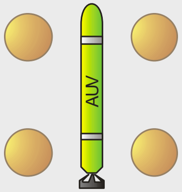
AUV-based mapping provides meter-level accuracy



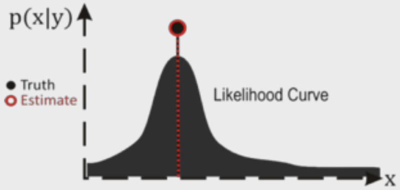
Images courtesy of Dr. Dave Caress

Terrain-Relative Navigation





Doppler Velocity Log (DVL) sonar used for correlation



Benthic Imaging/CTD AUVs

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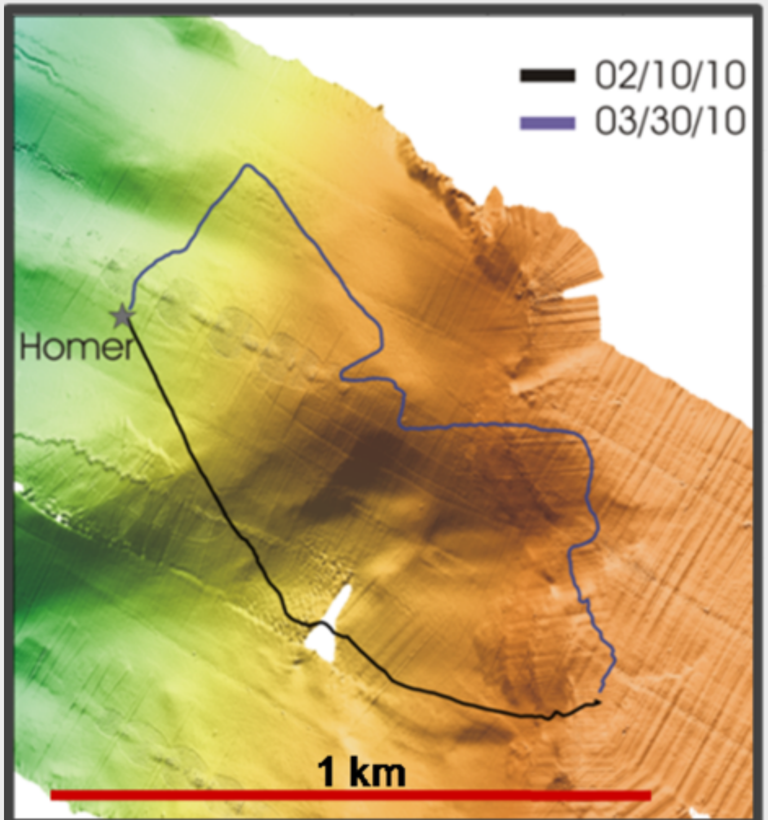
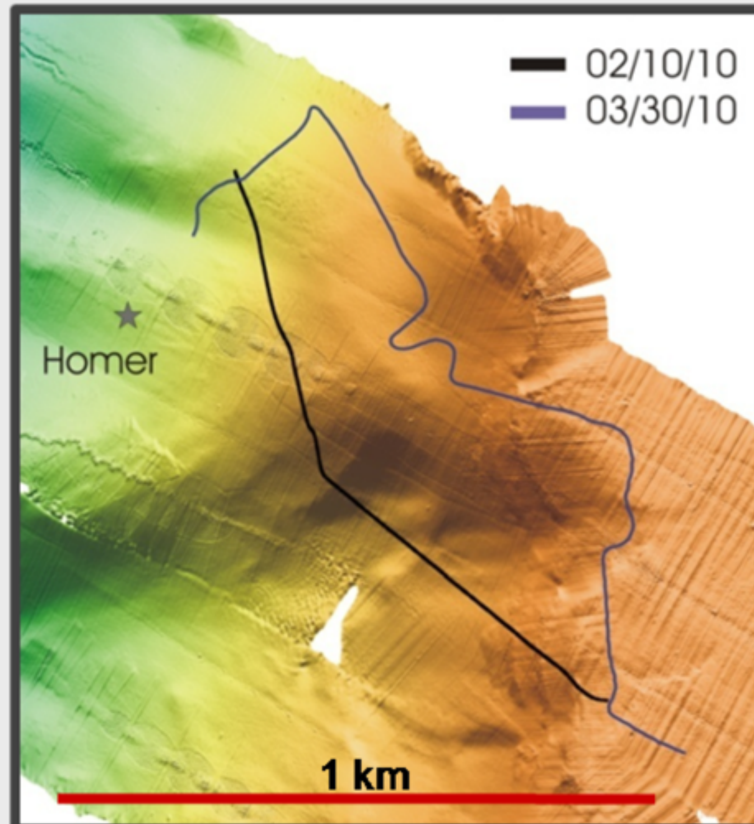
Actual track



Navigation data

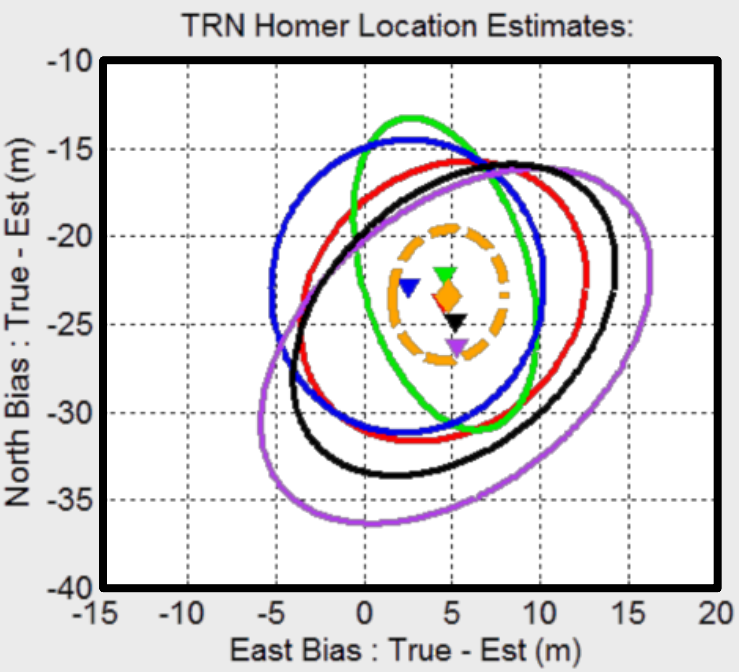


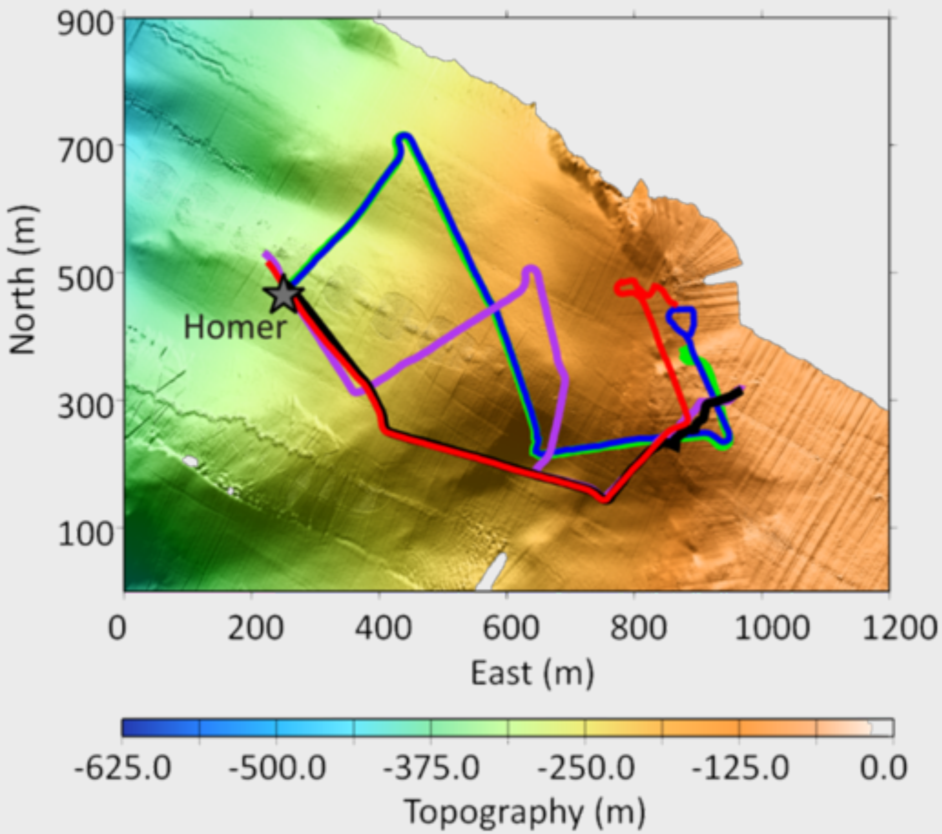
DVL/Compass errors yield poor results for an unaided dead-reckoning system
Georeferencing errors can be significant (>100m observed)

Slide courtesy of Dr. Steve Rock

Georeferencing Errors

Repeat runs at Soquel Canyon





Slide courtesy of Dr. Steve Rock

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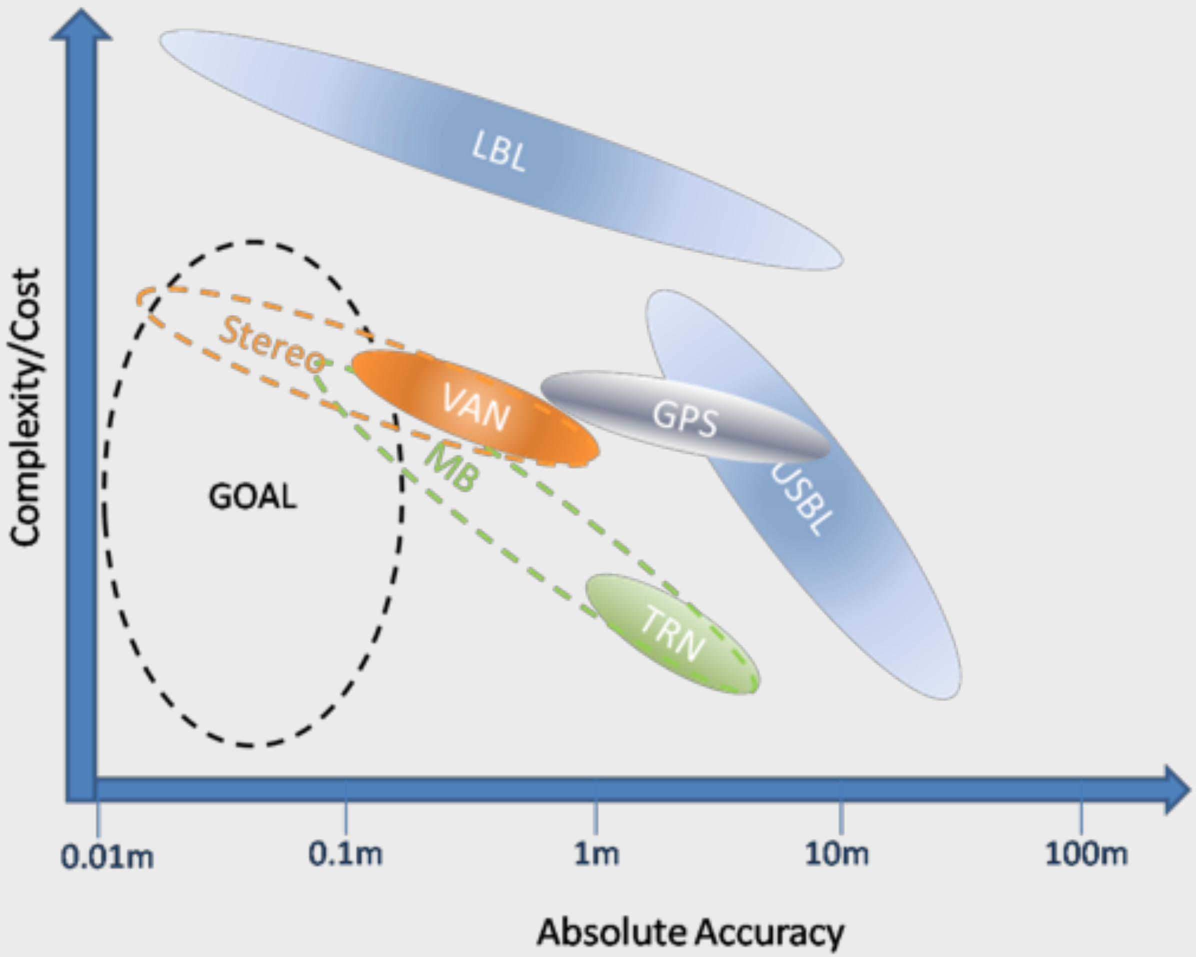
Navigation Technologies



Slide courtesy of Dr. Steve Rock

AUV Hazards

AUV Hazards 1/6

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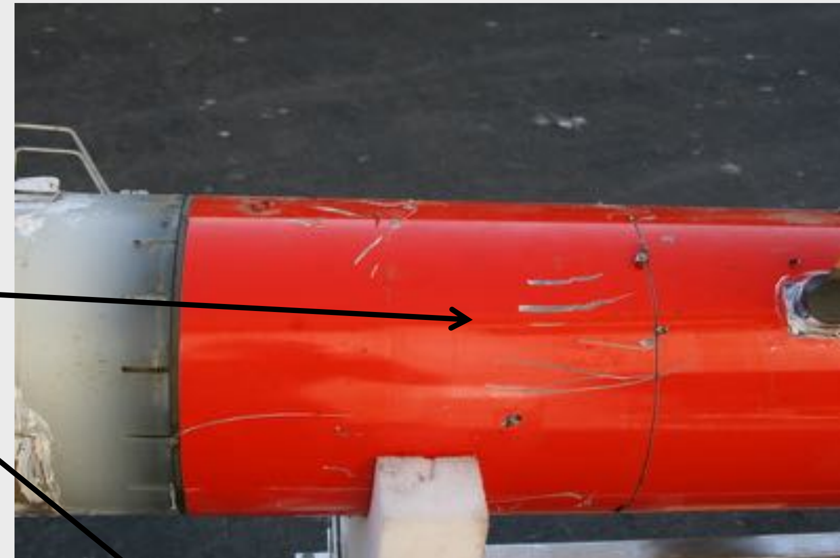
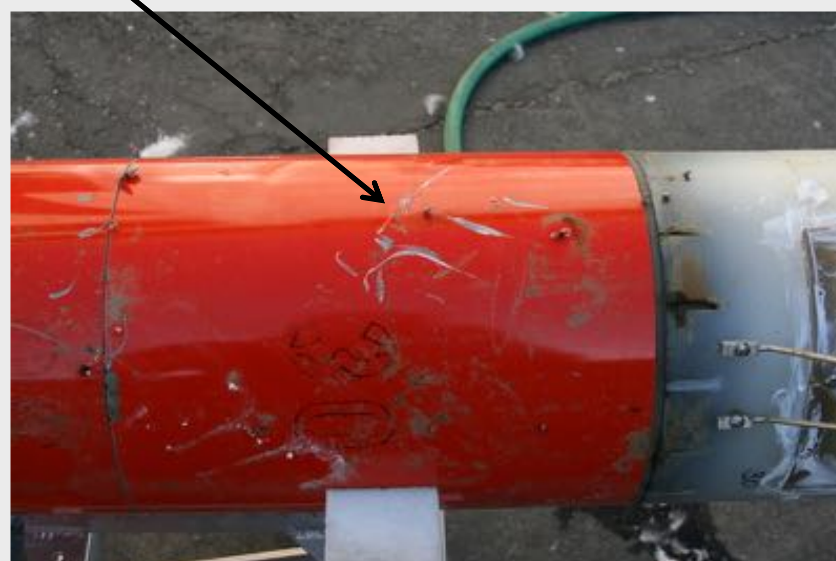
- Entrapment
  - Fishing nets
  - Under rocks or ledges
- Entanglement
  - Kelp
- Flooding
  - Seals
  - Implosion
- Vulnerable on the Surface
  - GPS position updates and radio communications
  - Rendezvous for recovery
  - Antenna damage, or worse
  - Liability – was the boat or people injured?
  - Stolen
- Communications Failure

AUV Hazards 2/6

Shark Bites!

- Spray glider shark bite. Monterey Bay, fall 2008





Images courtesy of Scripps Instrument Development Group

AUV Hazards 3/6

Dead Vehicle

- Following a deep dive:
  - Primary comms failed
  - Backup location beacon failed

- Vehicle drifted on surface for 16 days
- Picked up < 10km from where it started

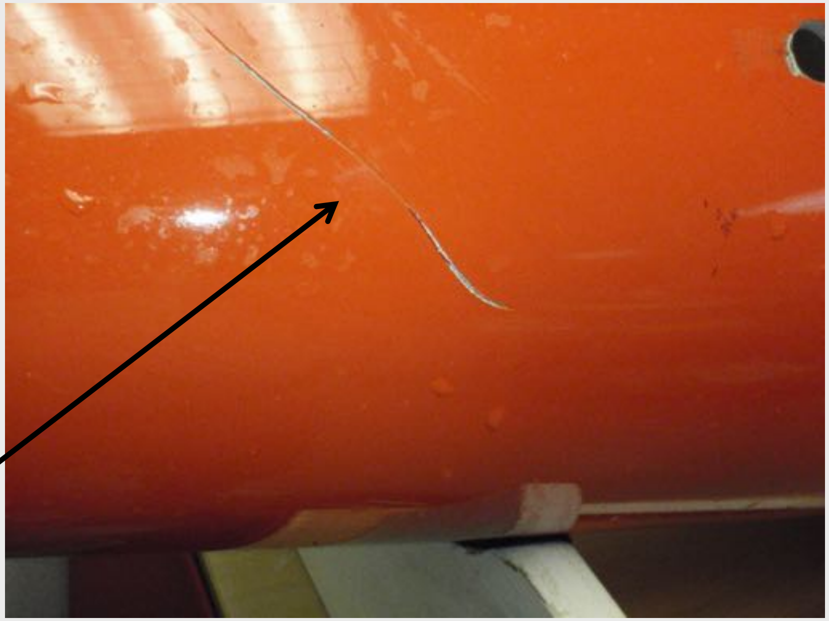
- Worst circumstance is a dead vehicle drifting in the mid-water column

MBARI

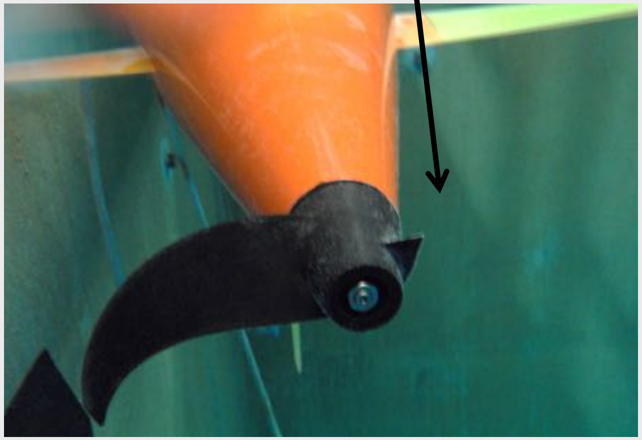
AUV Hazards 4/6

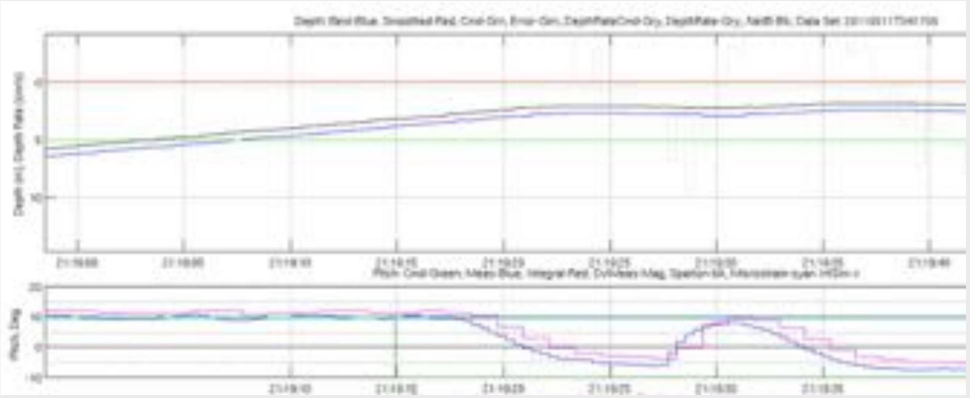
Surface or Near Surface

- Boat strikes, fishing gear near surface, and waves pose a threat.
- Look at your data



Damage from fishing gear at 3m depth





MBARI Images

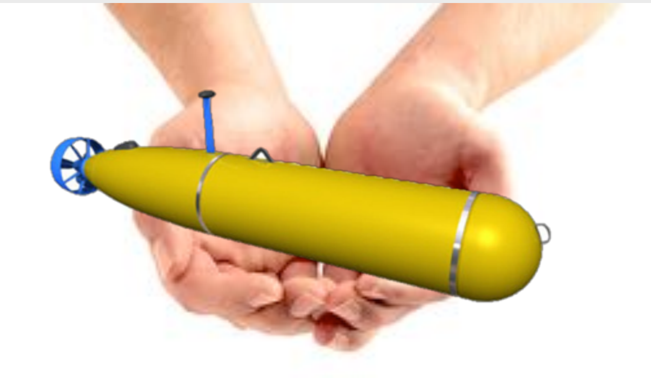
AUV Hazards 6/6

Insurance

- Premiums dependent on history
  - No history? Rate reflects history of all AUVs and is very expensive!
  - Good option to “piggyback” on group who knows what they’re doing to establish history

- Having an ROV available reduces insurance cost considerably

- AUVs have liability coverage but not much
  - Most of the cost is for vehicle replacement versus human injury or environmental damage



Bluefin

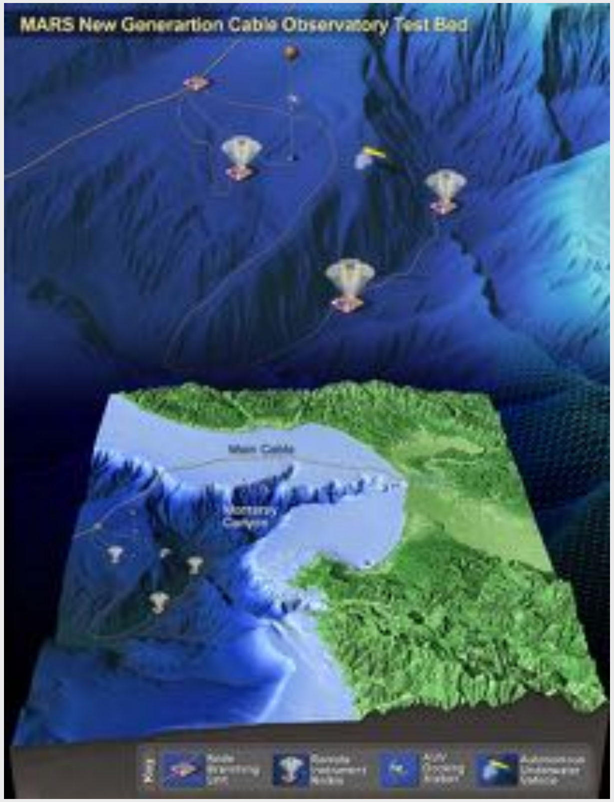
AUV Frontiers:

Next Generation Ocean Observing Systems

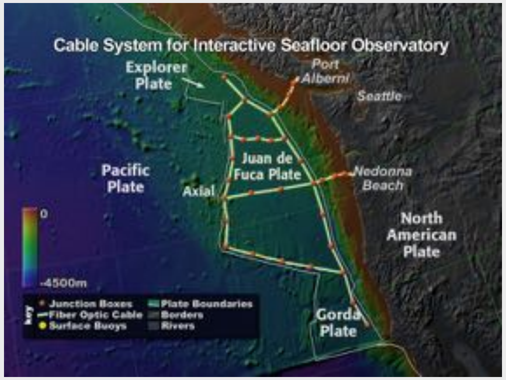
Cabled Observatories

MARS

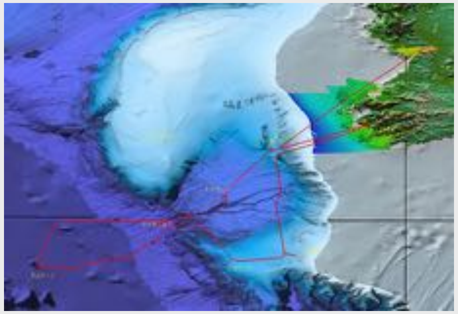
- 62 km of fiber optic cable
- Single undersea node at 1.2 km depth
- 100 Mbits per second data rate
- 10 kW of power to 4 instrument ports
- Capability of siting instruments on “extension cords”
- Serviced using *Ventana* ROV



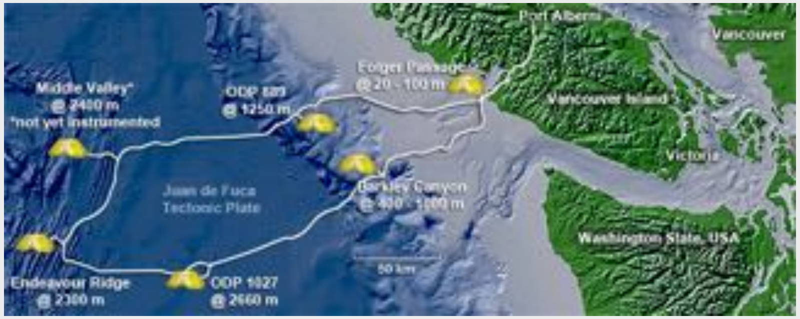
MBARI



NEPTUNE

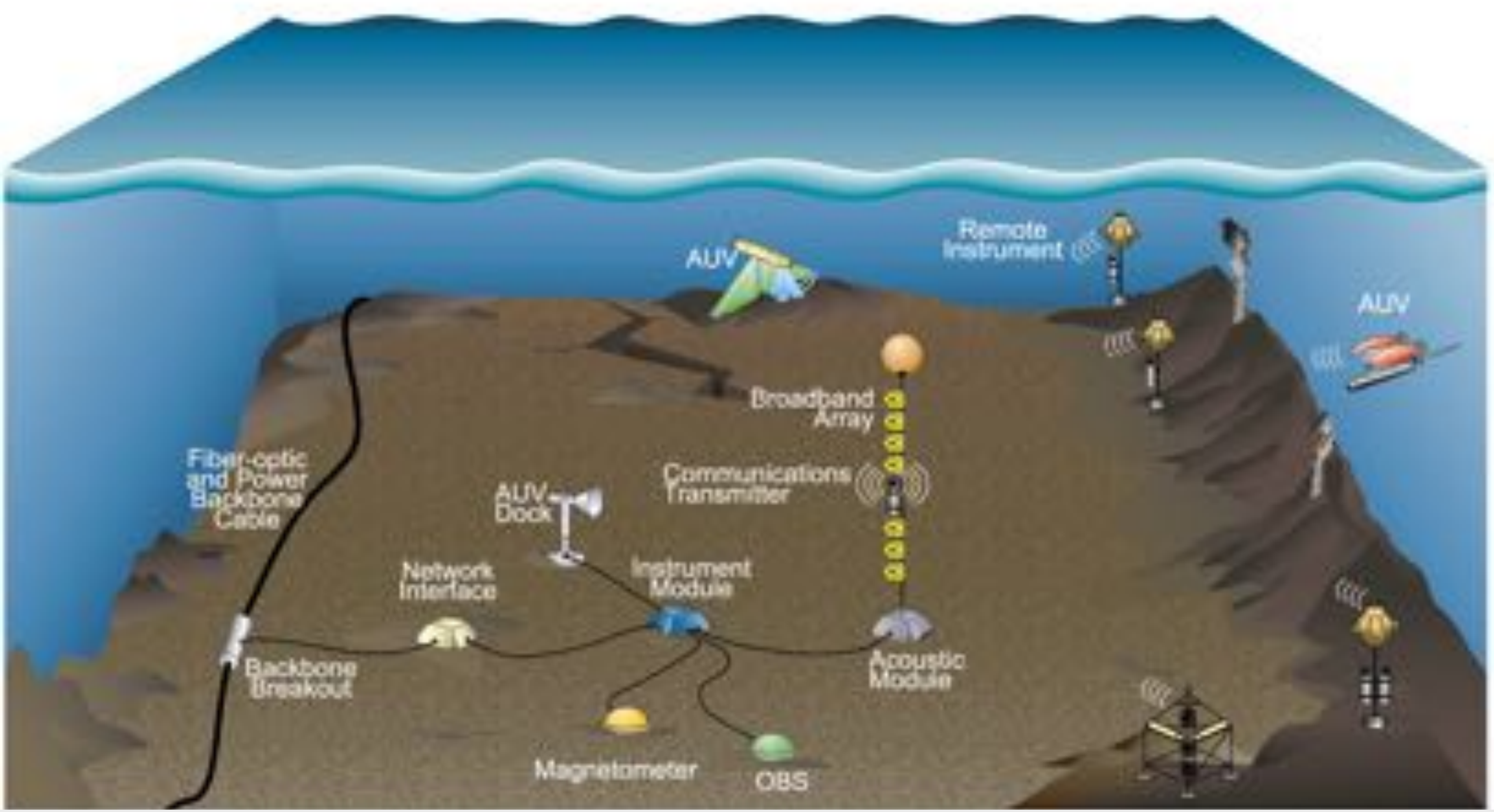


ESONET



NEPTUNE Canada

AUVs on Observatories



(courtesy Lee Freitag, WHOI)

Slide Courtesy of J.G.Bellingham

Hybrid ROV /AUV

Nereus

Weight on land: 2,100 kg

Payload capacity: 25 kg

Maximum speed: 3 knots

Battery: Rechargable lithium ion. 6 KW in both main pressure housing and tool pressure housing

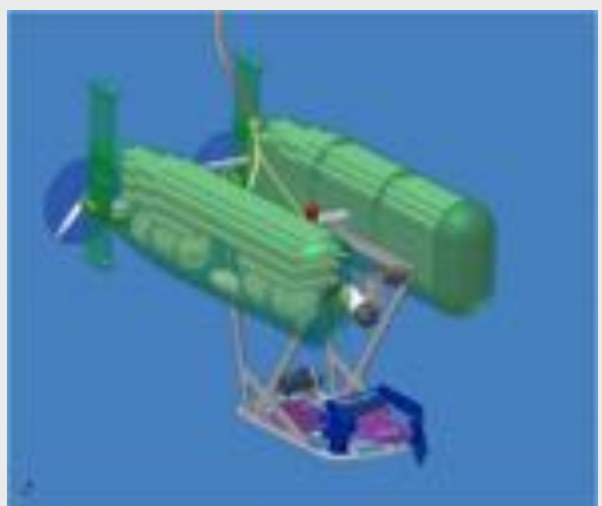
Thrusters: 2 aft, 2 vertical, 1 lateral

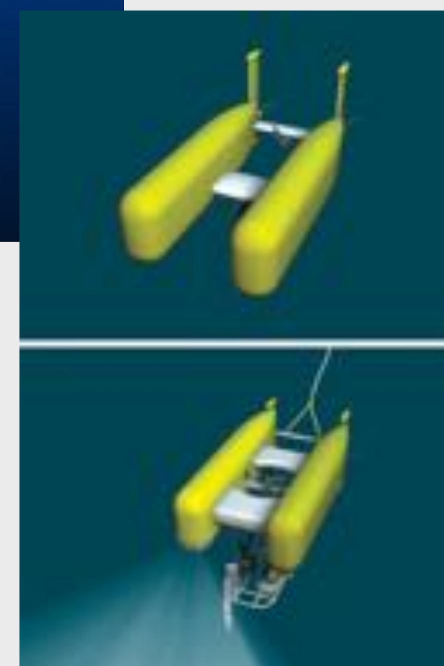
Lights: variable output LED array, strobes

Manipulator arm: Kraft TeleRobotics 7-function hydraulic manipulator

Sonar: scanning sonar, forward look and profile, 675 KHz

Sensors: magnetometer, CTD (to measure conductivity, temperature, and depth)





Images Courtesy of WHOI

AUV Docking

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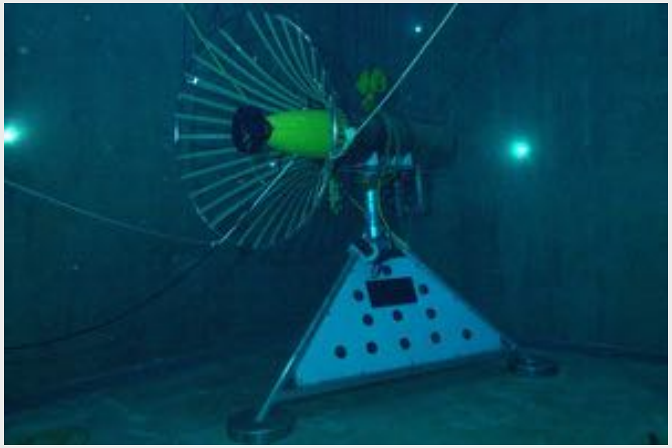
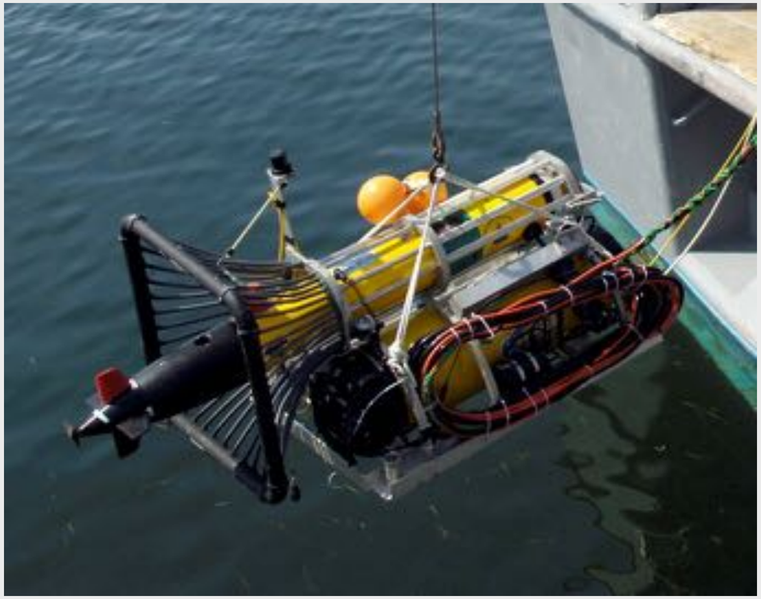
- Underwater garage
  - Power available to re-charge batteries
  - Communications to shore for data download and new mission upload
  - Securely park AUV



MBARI Dorado Dock



WHOI REMUS Dock

Kawasaki Marine Bird Dock

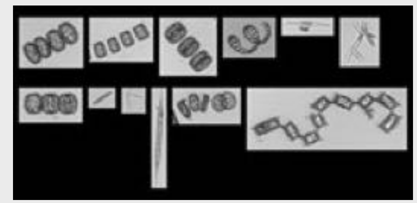
WHOI Odyssey Dock

Integrated Multiplatform Operations - AOSN

Slide Courtesy of J.G.Bellingham

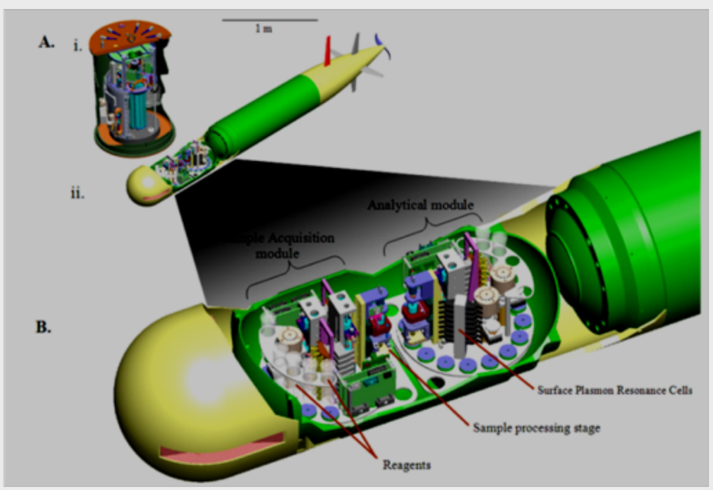
Advanced Sensors

- Insitu Genomic Identification
  - Environmental Sample Processor (ESP) identifies microorganisms and their gene products in situ
  - Smaller version ESP designed for use on Tethys provides mobile platform for identifying toxicity
- Insitu Microbe Identification
  - Flow Cytometer
    - SeaFlow: 0.5 - 20 Micron
    - FlowCam 10 - 60 Micron

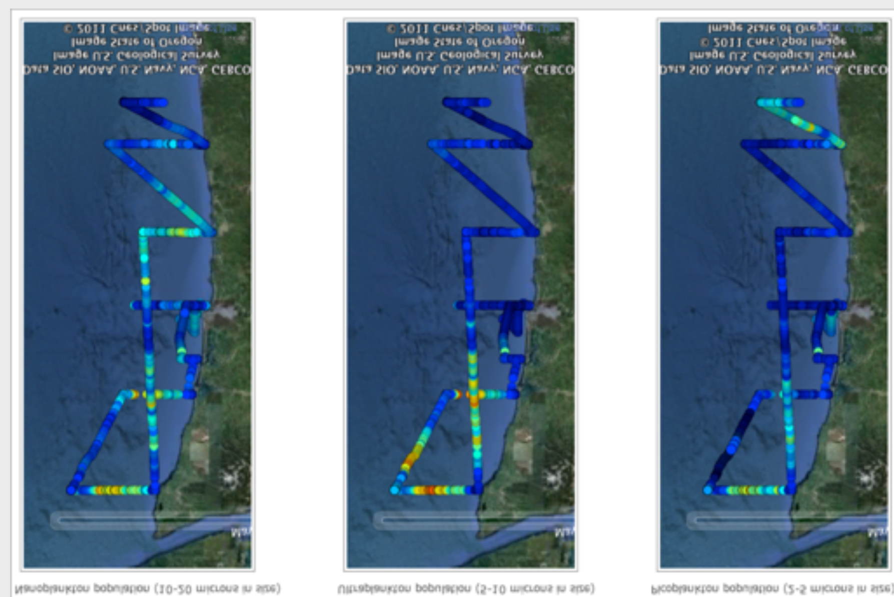


Fluid Imaging FlowCam

B.)



3rd generation ESP on LRAUV
Chris Scholin, MBARI



UW SeaFlow

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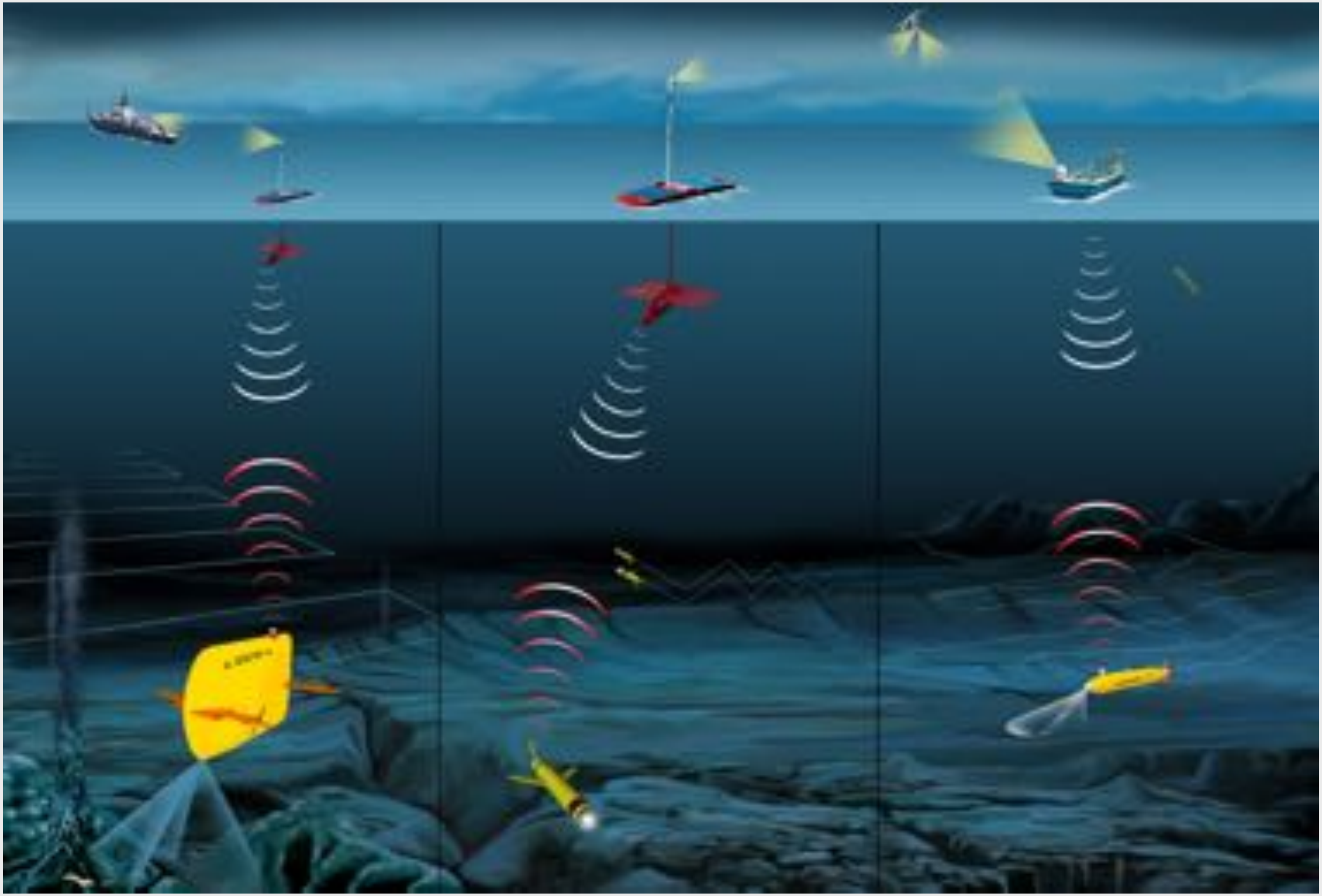
Oil Field Technology Gaps

	Overall Program Lifecycle TDS Level								
Technology	2010	2011	2012	2013	2014	2015	2016	2017	2018
Geophysical Survey	9	9	9	9	9	9	9	9	9
Environmental Survey	9	9	9	9	9	9	9	9	9
Pipeline Inspection AUV (sonar)	6	7	8	8	9	9	9	9	9
Structural facility survey GVI	5	6	7	8	8	8	9	9	9
Pipeline Inspection (full)	3	3	4	5	6	7	8	9	9
Advanced Facility inspection	[illegible]	3	3	4	5	6	7	8	9
Field resident inspection	[illegible]	3	3	3	4	5	6	7	8
Light intervention	[illegible]	[illegible]	3	3	4	4	5	6	7
Field resident light intervention	[illegible]	[illegible]	[illegible]	3	3	3	4	5	6
Under ice resident	[illegible]	[illegible]	[illegible]	[illegible]	3	3	4	5	6

CHEVRON’S LONG-TERM AUV VISION
Bill Gilmour

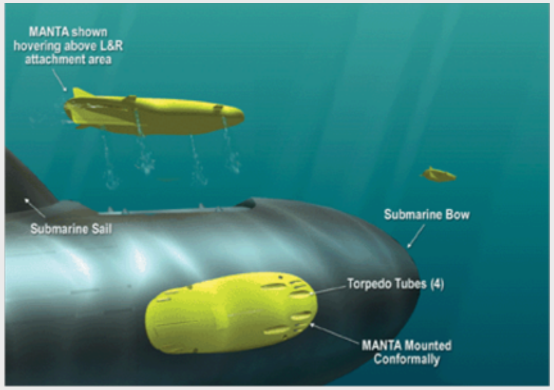
Future Vision: Reduce Reliance on Ships



Chris German, WHOI - presented at AUV2012

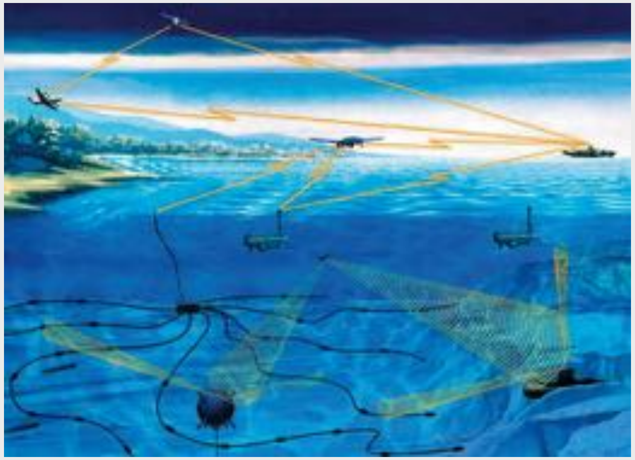
Concept AUVs and Gliders

Future applications look interesting…

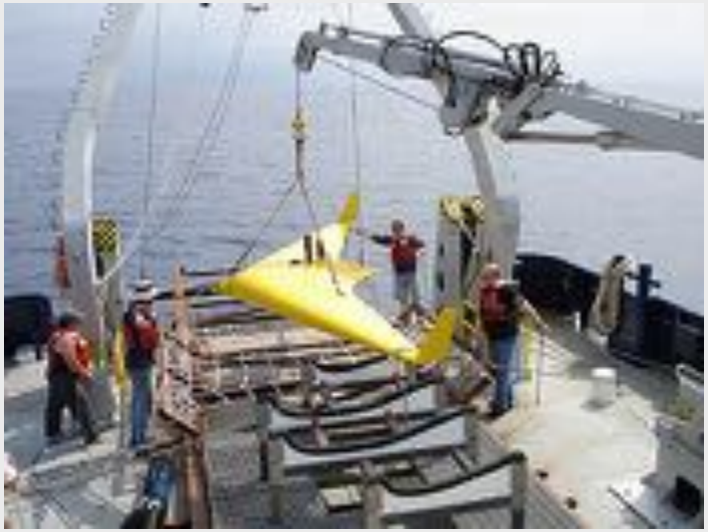


NUWC Manta

Teledyne Webb Thermal Glider



Multi-vehicle operations is a major thrust for the military and science!



ONR-Scripps Liberdads Xray Glider

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Looking to the Future…

- Multi-platform observation systems are now in development and some operations
- Prediction systems and ocean observatories are likely to make heavy use of mobile platforms
- Communications difficulties creates a needs for mixed levels of autonomy
- Seafloor observatories provide potential power and communication infrastructure for observation systems
- Engineering of such complex systems in infancy