From Concept to Operational System – The Idea, Development and Operation of Autonomous Underwater Gliders

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marum
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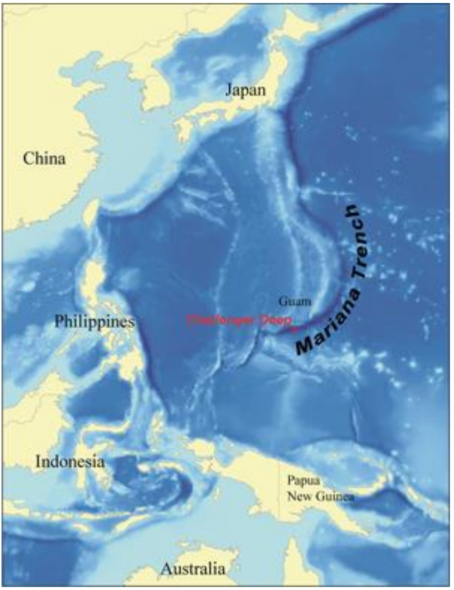
Outline

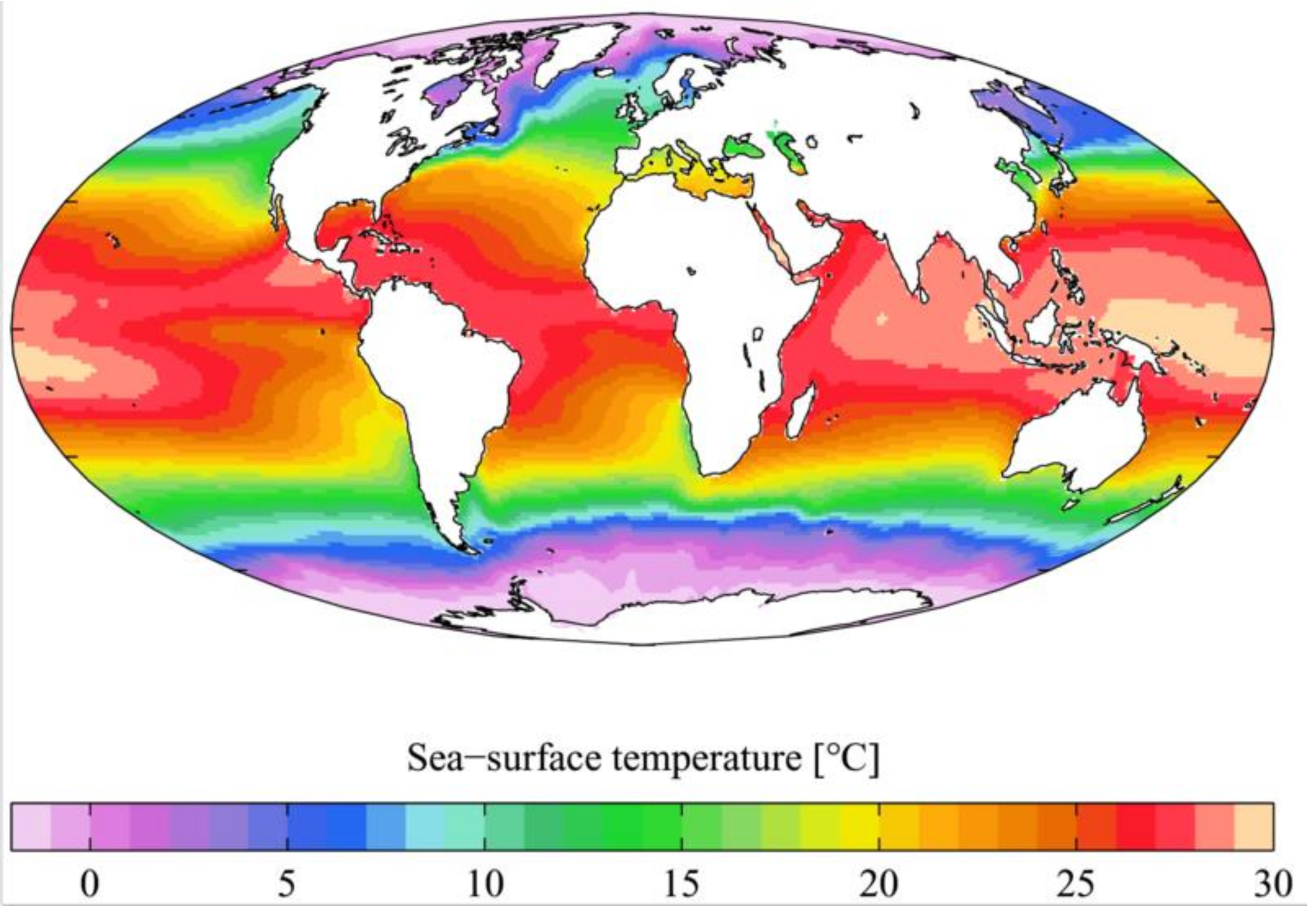
- Some information about the oceans
- Overview of underwater vehicles
- Design cycle
- Range and endurance
- Underwater gliders
  - Concept
  - Operations
- Components
- Questions?

Ocean

- Size: 362 Mio km^2 (71% of the Earth surface)
- 3% ice covered
- Depth
  - Average 3750m
  - Deepest point 11,033m (Challenger Deep, Mariana's Trench)



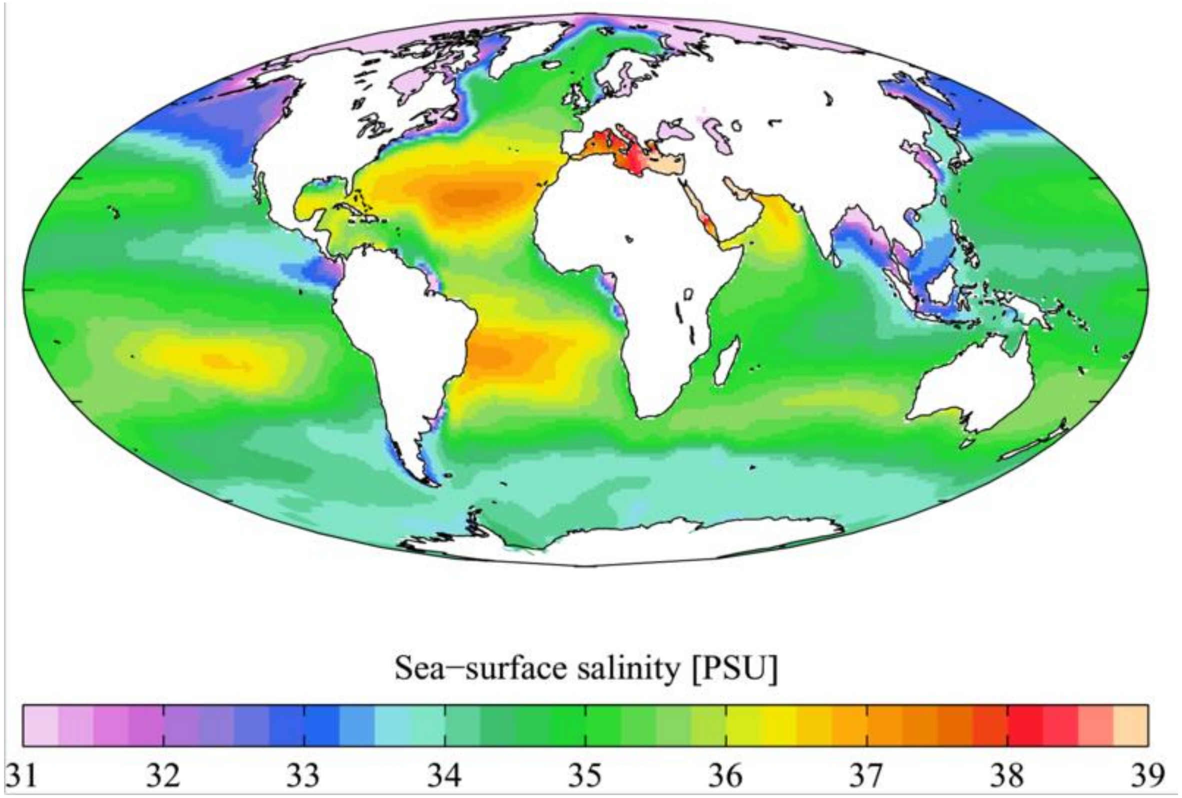
Sea Surface Temperature



Annual mean sea surface temperature from the World Ocean Atlas [http://www.nodc.noaa.gov/OC5/WOA05/ 2005].

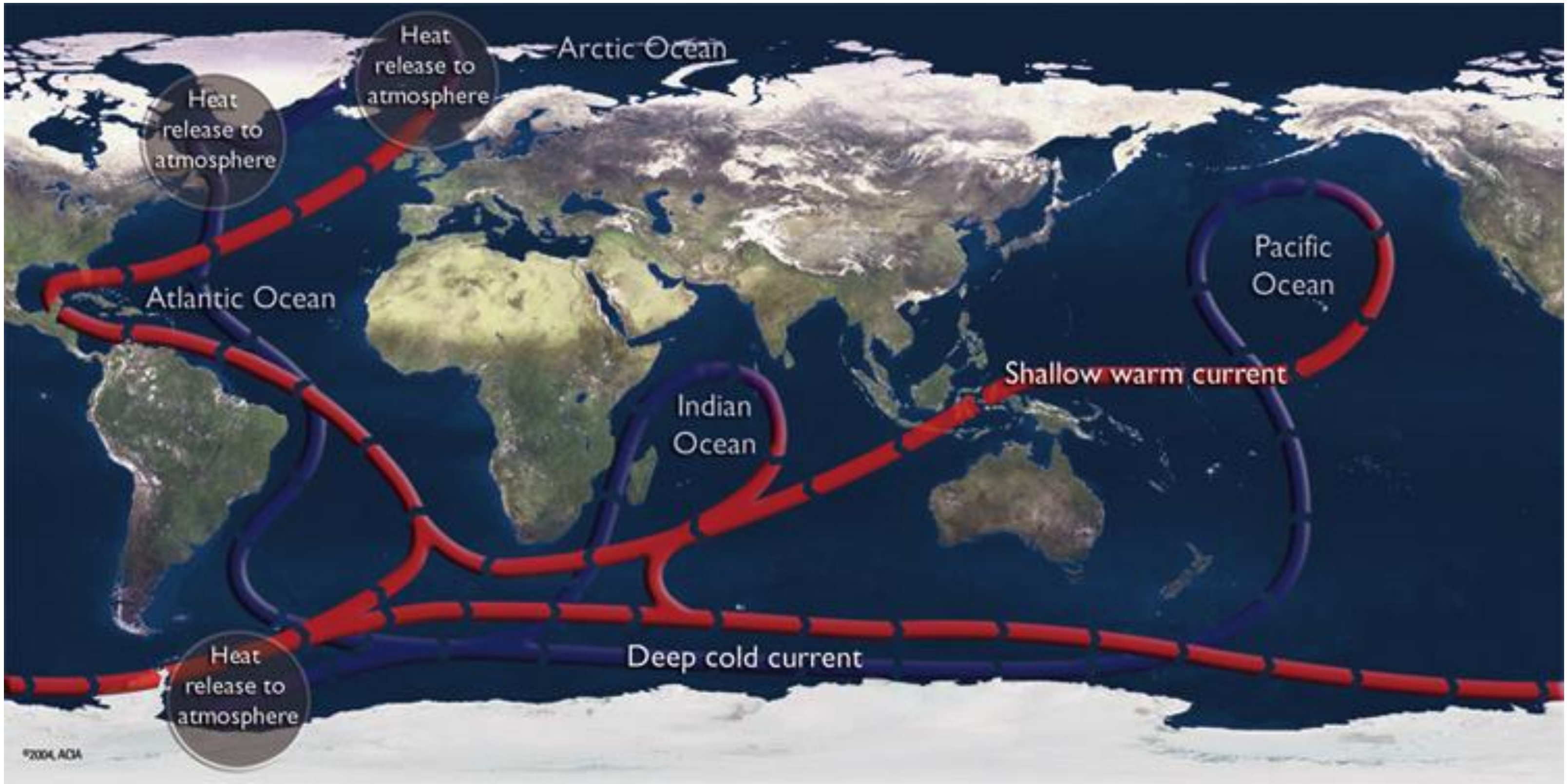
Ocean Salinity

The international thermodynamic equation of seawater – 2010:
Calculation and use of thermodynamic properties
Manuals and Guides 56
Intergovernmental Oceanographic Commission



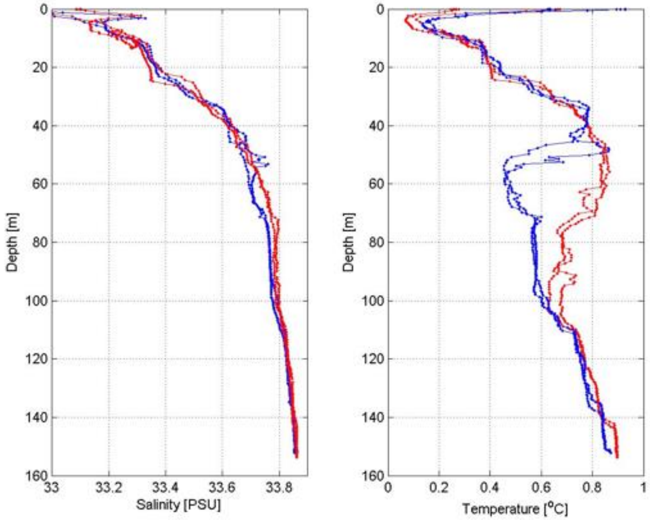
Annual mean sea surface salinity from the World Ocean Atlas
[http://www.nodc.noaa.gov/OC5/WOA05/ 2005

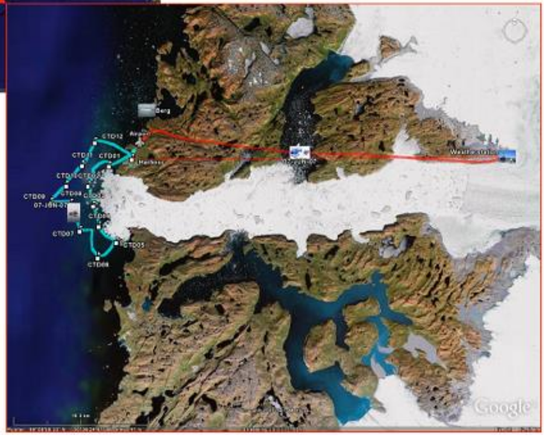
Ocean Circulation



Conception Bay& Greenland

- Temperature Range
  - -1.5°C to 16°C
- Density
  - ~1026kg/m

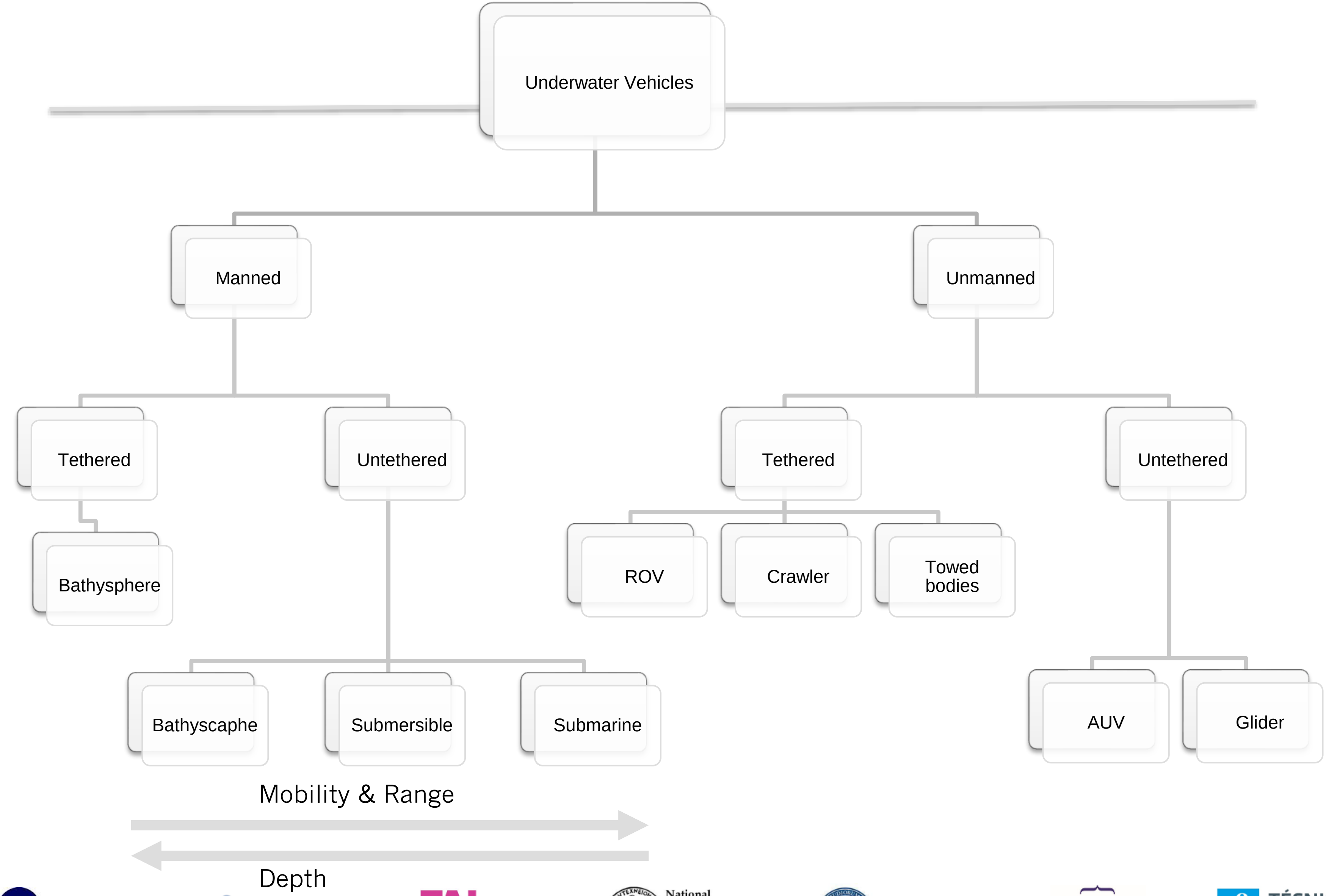




Marine Systems Unit

Underwater Vehicles

- From submersibles to underwater gliders



- Underwater Vehicles
  - Manned
    - Tethered
      - Bathysphere
    - Untethered
      - Bathyscaphe
      - Submersible
      - Submarine
  - Unmanned
    - Tethered
      - ROV
      - Crawler
      - Towed bodies
    - Untethered
      - AUV
      - Glider

Mobility & Range →

← Depth

Trieste Bathyscaphe (Deep Boat)

Research Vessels: Submersibles - Trieste

Department of Navy Press Release

February 1, 1960

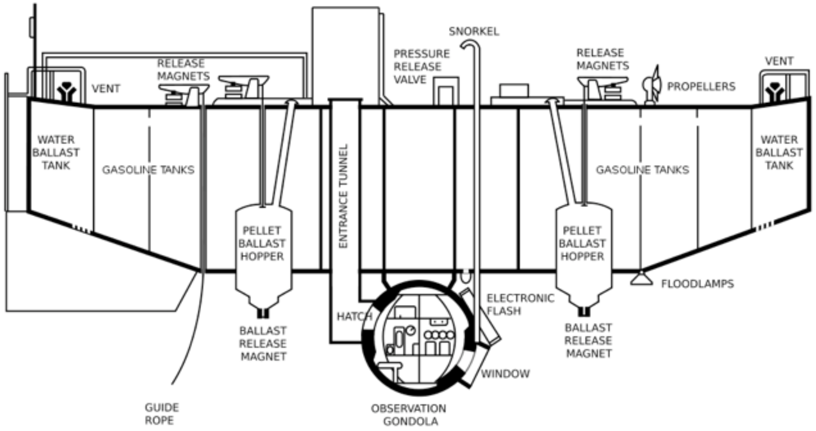
ABOARD THE USS LEWIS OFF GUAM--(NAVNEWS)--The Navy's bathyscaph Trieste again set a world's diving record when she probed 37,800 feet (10,911 m) to the depths of the Marianas Trench, deepest known hole in the world's oceans, Jan. 23.

Lt. Don Walsh of San Diego, Calif., and Swiss scientist Jacques Piccard, operating from this destroyer escort, made the descent. No difficulties were experienced during the dive, during which the Trieste was subjected to a pressure of 16, 883 pounds per square inch (more than a thousand times greater than the pressure at sea level).

This depth program has been named "Project Nekton" and, according to a Navy announcement, provides "scientific knowledge of sunlight penetration, underwater visibility, transmission of man-made sounds, and marine geological studies." The Trieste had previously made two record-setting dives, the last on Jan. 7 when she descended to 24,000 feet.

There was light outside the Trieste until about 800 feet, according to Lt. Walsh. At about 6000 feet, the chill from the water forced both men to don warmer clothing. The entire descent required 4 hours and 48 minutes. Once done, about 20 minutes was spent on the bottom making observations and recording data. Lights enabled the men to see living and moving objects. The return trip to the surface was made in 3 hours and 17 minutes.

ADM Arleigh Burke, Chief of Naval Operations, sent congratulations to the two men. He termed their record-breaking feat an accomplishment that " may well mark the opening of a new age in exploration of the depths of the ocean which can well be as important as exploration in space has been in the past."



GENERAL ARRANGEMENT DRAWING OF TRIESTE, CA. 1959

Manned Submersibles


Tourist Submarine

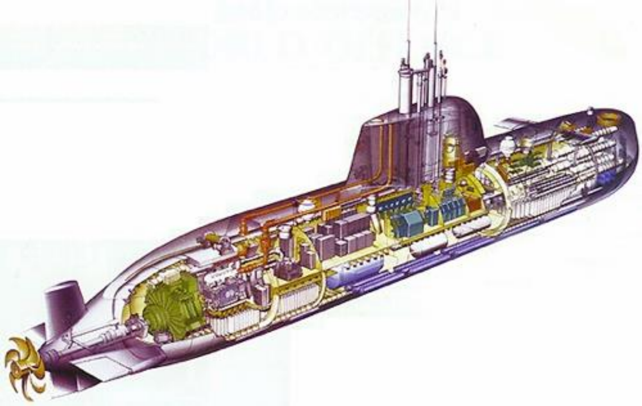
Jiaolong Submersible (China) 7,000m


New Alvin Submersible (USA) 6,500m

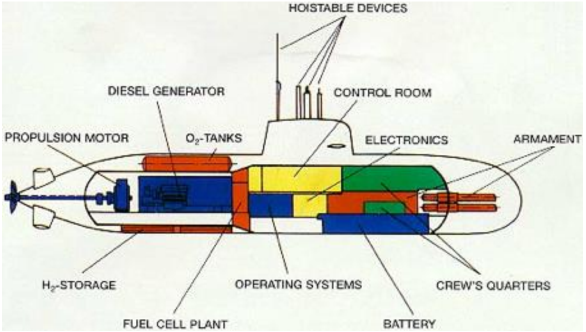
ALVIN Submersible (USA) 4,500m


MIR I & II Submersible (Russia) 6,000m

Submarines



Fuel-cell / Diesel electric Submarines
U214 Type
Depth: >200m
Submerged Range: 1200NM
Length: 70m



Diesel electric Submarines
Victoria Class (Canada)
Depth: >200m
Range: 8,000NM (snorkling 30%)
Length: 70m

Submarines Cont'd

Seawolf class (US)
Nuclear powered fast attack submarine
Length: 107m
Depth:?500m?

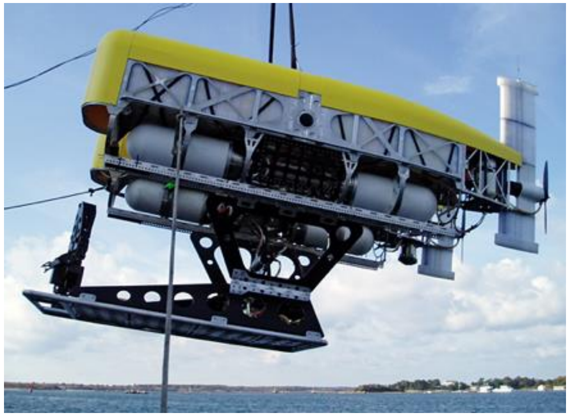
Typhoon class (Russia)
nuclear powered missile submarine
Length: 175m
Depth: ?400m?

Remotely Operated Vehicles (ROV)

Eyeball class ROV

Work class ROV (Compact car size)

Inspection class ROV system
ROV – Winch – Generator - Manipulator



HROV Nereus (WHOI)
Full Ocean Depth capable

Autonomous Underwater Vehicles (AUV)

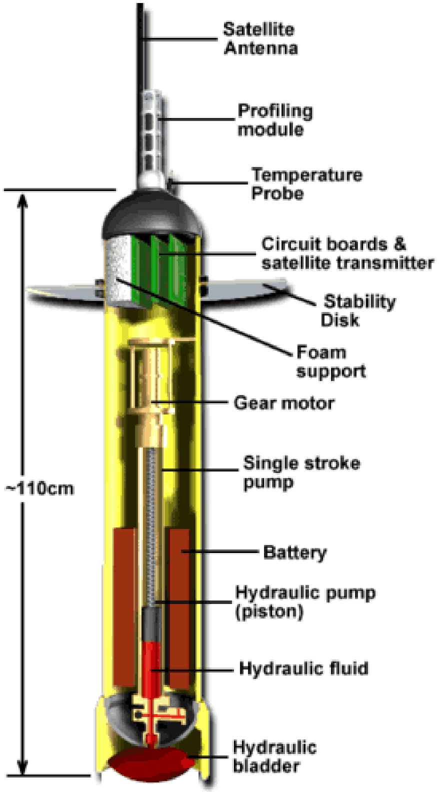
- **Propeller driven**
  - ❖ Torpedo shaped
    - Optimized for horizontal forward flight
    - Higher velocity
    - Higher altitude
  - ❖ Hovering vehicle
    - Stable platform
      - Imaging
      - Micro bathymetric surveys
    - Terrain following

Courtesy John Anderson DFO

Autonomous Benthis Explorer (ABE)

ARGO profiling floats

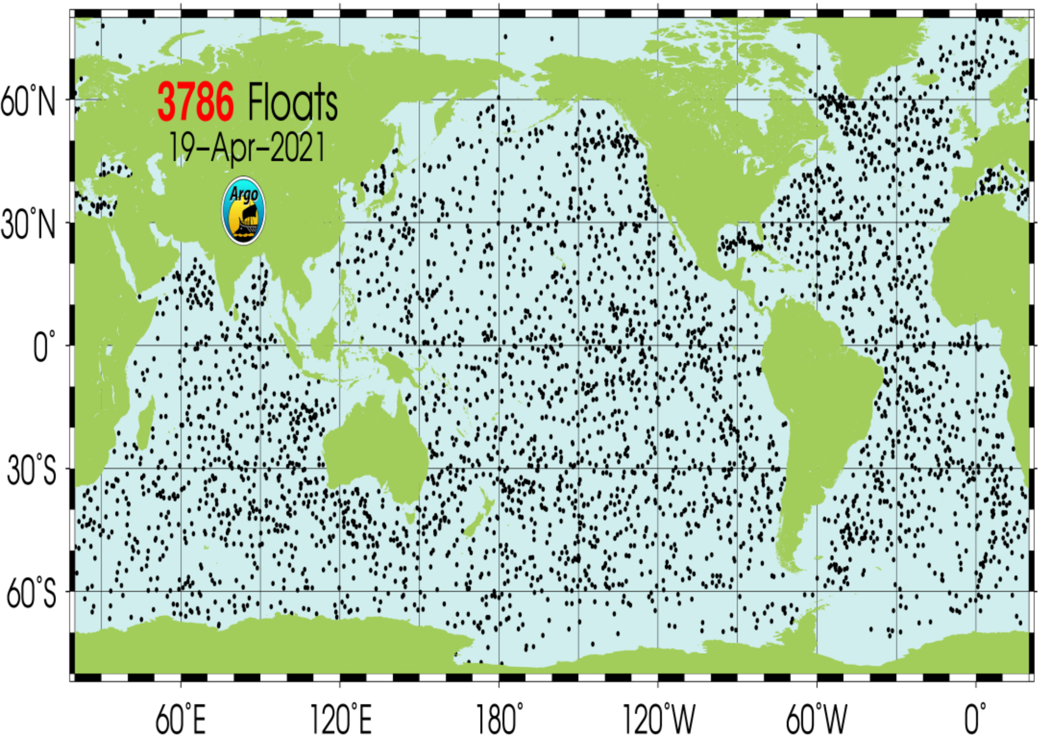
- Comprised of three subsystems:
  - Hydraulics: control buoyancy adjustment via an inflatable external bladder, so the float can surface and dive.
  - Microprocessors: deal with function control and scheduling.
  - Data transmission system: controls communication with satellite.
- Approx. Weight: 25 Kg
- Max. operating depth: 2000m (deepARGO 6000m)
- Crush depth: 2600m



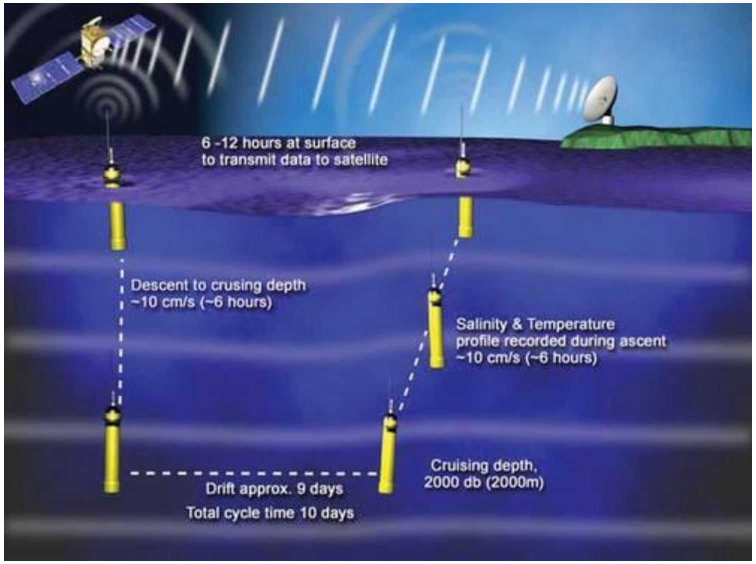
The three float models in use are the *PROVOR* built by MARTEC in France in close collaboration with IFREMER, the *APEX* float produced by Webb Research Corporation, USA and the *SOLO* float designed and built by Scripps Institution of Oceanography, USA.

Source:
http://www.argo.ucsd.edu/float_design.html

ARGO Profiling Floats (cont’d)



Position where floats have surfaced in the lat 30days.
Source: http://www.argo.ucsd.edu/



An Argo profiling float cycling through the water column. Graphic courtesy of National Oceanographic Centre Southampton http://www.soc.soton.ac.uk/JRD/HYDRO/argo/index.php

Slocum Mission

- Vision with a background
- Oceanography driven
- Provides specific specifications of what is desired or envisioned
- Did everything get accomplished?
- Requires a multi-disciplinary approach and knowledge across disciplines and fields

FEATURE

THE SLOCUM MISSION

Narrative and Illustration
By Henry Stommel

The payoff in increase of knowledge often is greatest the more unconventional the idea, especially when it conflicts with collective wisdom.

IT IS DIFFICULT to realize that twenty-five years have passed since I first came to the Slocum Mission Control Center on Nonamesset Island, one of the Elizabeth Islands, in 1996. I was a post-doc in physical oceanography, and the Department of the Environment had just acquired the island from the descendants of a sea captain prominent in the China trade of the early nineteenth century. The government acquired Nonamesset to establish the World Ocean Observing System [WOOS], a facility capable of monitoring the global ocean, using a fleet of small neutrally-buoyant floats called Slocums that draw their power from the temperature stratification of the ocean. Nonamesset Island was chosen partly because it is isolated from the mainland of Cape Cod, but mostly because it is close to the Woods Hole Oceanographic Institution, the Marine Biological Laboratory, and a thriving scientific community.

Nestling low in the hills is the Mission Control Center itself, with its satellite antennas. Along the beach, facing Buzzards Bay, there are a few houses for a small permanent staff. Most of the scientific staff commute from their homes in the Upper Cape area, reaching Nonamesset by a ferry. There is a large dock at the cove, but the one that the ferry uses is at Sheep-Pen Harbor on the Hole. There are no automobiles on the island. The buildings are connected by footpaths and there is a narrow-gauge railroad for moving supplies from the docks to the facilities. For the most part the island has been left undisturbed. It is in a pristine state of beauty, tranquil beyond the experience of those who swarm about on the mainland.

The Slocum float is named after Joshua Slocum, the Yankee skipper who first went around the world singlehanded in a small sailing vessel. There were Slocums on the Elizabeth Islands before, ever since Peleg Slocum of Dartmouth purchased Cuttyhunk, Nashawena and Penikese in 1693. Whether Joshua was related to them, I never have discovered. But my relationship with Slocums has a different genealogy—a scientific and technical one. Perhaps I should begin by saying what Slocums do.

They migrate vertically through the ocean by changing ballast, and they can be steered horizontally by gliding on wings at about a 35 degree angle. They generally broach the surface six times a day to contact Mission Control via satellite. During brief moments at the surface, they transmit their accumulated data and receive instructions telling them how to steer through the ocean while submerged. Their speed is generally about half a knot. There are military applications for them, but our work in WOOS is unclassified. We have a fairly large fleet of Slocums, about 1,000. Half are devoted to a program of routine hydrographic observation, much like the meteorologists' upper air network. The rest make soundings of temperature, salinity, oxygen, nutrients, and those geochemically important tracers that the geochemists have been clever enough to find automatic measuring devices and sensors for. The other half of the Slocum fleet is devoted to purely scientific purposes: special research programs carried out under the instructions of academic scientists, by contract. Slocums were originally designed with a 5-year lifetime, but many have been in continuous service at sea for more than 10 years. They are widely dispersed throughout the world's ocean.

Our WOOS center and the Slocum Mission had their start because of the growing concern with monitoring the environment: Is the ocean heating up? Where are the pollutants going? Can we construct theoretical models of the ocean circulation that are useful in predicting the direction of climate change? With a necessarily small fleet of research ships, how could numerous widely dispersed measurements throughout all depths of the ocean be obtained on a routine basis? In 1995, much of the oceanographic community had been involved for 15 years in the World Ocean Circulation Experiment (WOCE), exploring the general circulation of the ocean but still using the technology of the 80's. For example, one of the keystones of WOCE was the World Hydrographic Program (WHP), which used a single ship per year over a period of 12 years to survey 48 long hydrographic sections, with some repeats. Only six stations each day could be occupied, giving a very low rate of data acquisition compared to what the meteorologists were getting from their upper air network.

A really new method was needed, one that would provide subsurface data on a scale and at a frequency that matched what remote sensing by satellite provided for the sea surface. Multiplying the number of ships by a factor of 100 was economically out of the question. But a pioneering ocean engineer had a different vision of how to garner a harvest of data on a deep-ocean global basis, and this led, after a few vicissitudes, to the Department of the Environment's determination to support the Slocum Mission and the present deployment of Slocums throughout the world. It has been my career.

So here I am on a lovely October day sitting in the library of Mission Control overlooking Vineyard Sound. On the grass bank outside the window there is a flock of sheep grazing. I have the daily logbooks of those first deployments and experiments made in the early days of Mission Control before me on the

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Henry Stommel, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543.

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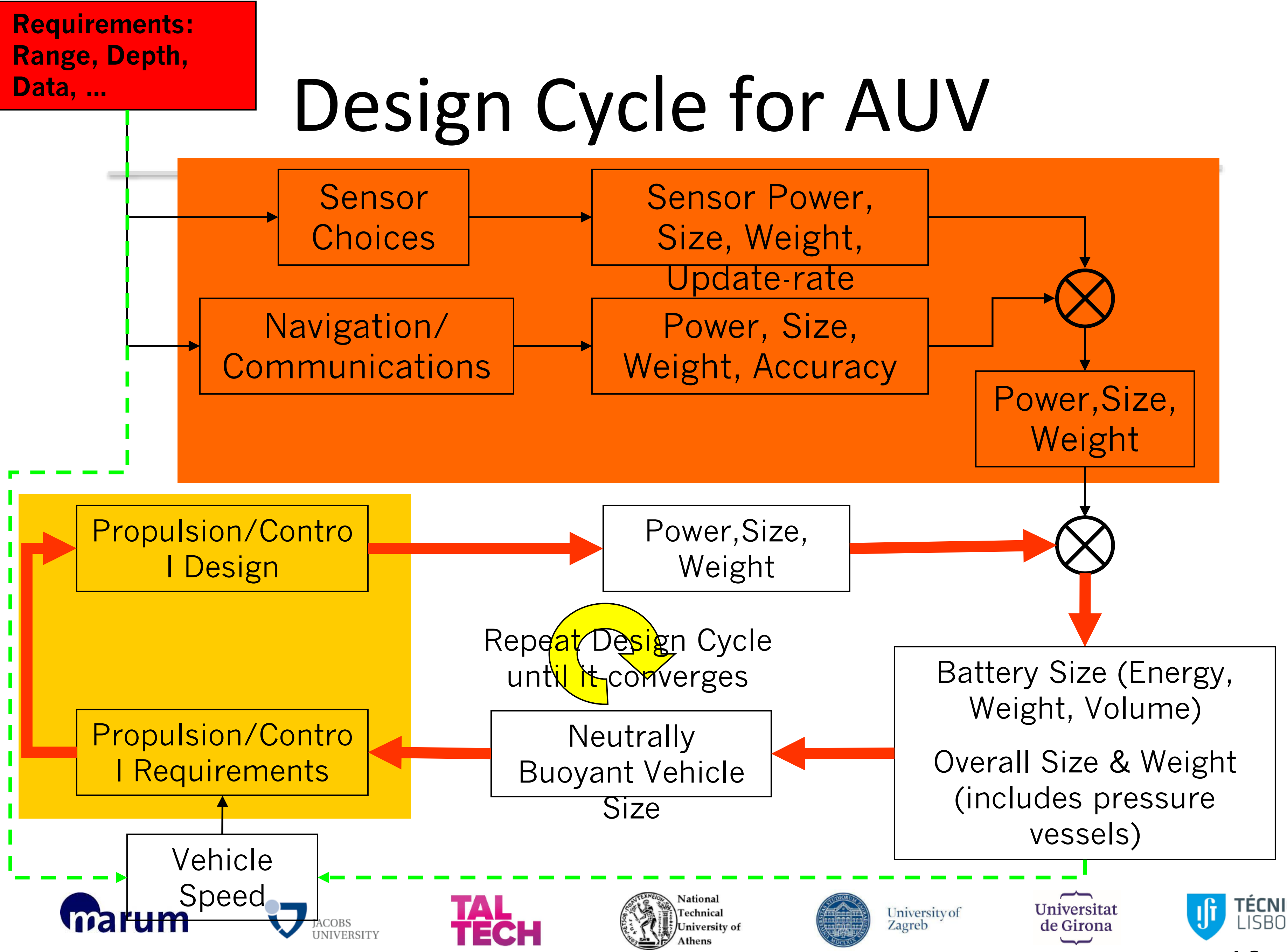
Design Cycle for AUV



Requirements: Range, Depth, Data, …

Sensor Choices

Sensor Power, Size, Weight, Update-rate

Navigation/ Communications

Power, Size, Weight, Accuracy

Power,Size, Weight

Propulsion/Control Design

Power,Size, Weight

Repeat Design Cycle until it converges

Battery Size (Energy, Weight, Volume)

Overall Size & Weight (includes pressure vessels)

Neutrally Buoyant Vehicle Size

Propulsion/Control Requirements

Vehicle Speed

Endurance and Range

- Loads
  - Hotel-load:
    - Everything but propulsion that is needed to run the vehicle
  - Pay-load
    - “Customer equipment”, usually sensors, sampler,…
  - Propulsive-load

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LOW POWER NAVIGATION AND CONTROL FOR LONG RANGE AUTONOMOUS UNDERWATER VEHICLES

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ABSTRACT

This paper discusses the ultimate limits to the range of conventionally powered deep ocean Autonomous Underwater Vehicles (AUVs). It is intended as an introduction to the unique problems of vehicles designed for speeds between 0.2 and 2 knots. We first present the relationship between range, size, non-propulsion energy requirements and flotation efficiency for vehicles using various common battery technologies. We then demonstrate that, at these speeds, the non-propulsion energy requirements severely limit the ultimate range. We next discuss strategies for implementing navigation and control systems at power levels of 0.1 to 1 Watt. We present systems which are based on existing technologies in use in various areas of oceanographic research but not generally utilized in the AUV community. We conclude that ocean-crossing AUV's of modest size are possible. To support this thesis, we present a design example of a vehicle suitable for economical monitoring of a hypothetical deep ocean dumpsite. This 3.5 m vehicle will have a range in excess of 6000 km at a speed of 0.5 m/sec.

KEY WORDS- AUTONOMOUS UNDERWATER VEHICLE, LOW POWER, LONG RANGE

1. INTRODUCTION- Why are we doing this?

Long range, slow moving Autonomous Underwater Vehicles (AUV's) appear to be an attractive solution to problems of environmental monitoring, geophysical exploration and military surveillance. Many authors have written enthusiastically and extensively about the potential applications of AUV's and we will not repeat their arguments here. Instead, we assume the reader is impatient to discuss the limitations to the range obtainable by AUV's based on current technology. We will demonstrate that, if the AUV can accomplish its mission while moving slowly, the range-limiting factor is the parasitic non-propulsion power requirements or "hotel" load. We will show that, if this overhead power is minimized, ranges sufficient to cross ocean basins are realizable.

Most of the AUV's developed in recent years are handicapped by large hotel loads, typically hundreds or even thousands of watts. This load includes the power for navigation, control, communication and environmental sensing instrumentation. We feel that inadequate attention has been given to reducing this component of the vehicle's power budget and to the intriguing class of slow ocean-crossing vehicles that then become possible. This paper presents proven examples of low power alternatives to current AUV navigation and control technology and offers some ideas on promising future technologies with the goal of reducing the hotel load to below one watt. Our goal is to explore the possibilities in this low power area of the AUV envelope and provide a starting point for the designer who is interested in investigating this realm. We try to cover a wide range of the pertinent topics and provide extensive references to the methods we present.

2. RANGE OF AUV's

We first present a relationship between the size of an AUV, its speed, battery energy density and range. It is derived from an energy balance and assumes square law drag over the speeds of interest. If all the battery energy of an AUV is devoted to propulsion (the hotel load is negligible), the range can be approximated by:

$$R=\eta\left(\frac{2(1-\sigma)V_0}{C_d S_0}\right)\frac{B_0 L}{u^2} \qquad (1)$$

where
R = range in meters
η = propulsion efficiency (assume 50%)
σ = specific gravity of buoyancy material
V_0 = 0.019, a volume coefficient
S_0 = 0.467, a surface area coefficient
C_d = 0.0064 drag coefficient based on wetted area
L = overall vehicle length, meters
u = velocity, m/sec
B_0 = energy density of batteries, J/kg

for example,

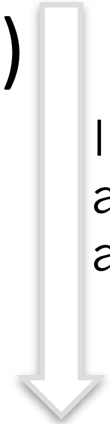
$Pb\text{-}H_2SO_4$, $B_0 = 0.112 \times 10^6$ J/kg
Alkaline, $B_0 = 0.443 \times 10^6$ J/kg
LiBr, $B_0 = 1.55 \times 10^6$ J/kg

Navigation

- Depth
- Magnetic heading
- Inertial systems
- Doppler velocity log (DVL)
- Acoustic baseline systems
- Terrain aided

Inertial Systems

- Attitude Heading Reference System (AHRS)
- Inertial Measurement Unit (IMU)
- Inertial Navigation System (INS)

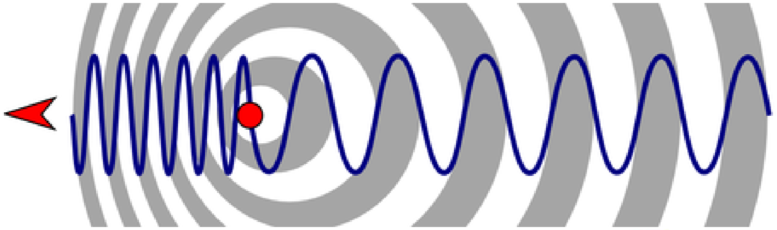


Increasing
accuracy
and cost

Doppler Velocity Log (DVL)

- Doppler effect (Christian Doppler, 1842)
- Provides speed over ground
- Acoustic Doppler Current Profiler (ADCP) speed of particles in the watercolumn

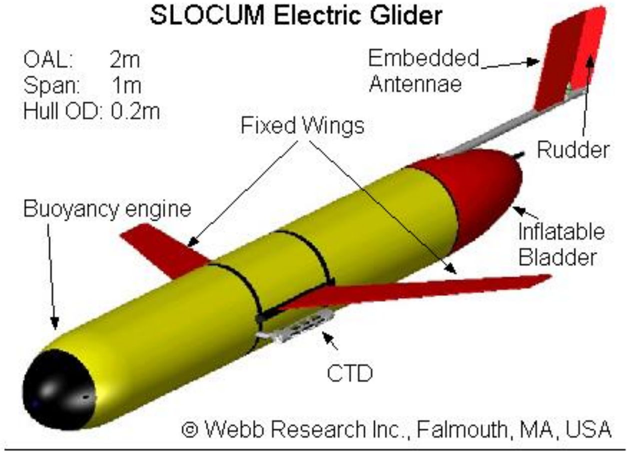
- c: wave speed [m/s]
- f: frequency [1/s]
- $T=1/f$ [s]
- λ: wave length [m]
- $c= \lambda/T$ with $T = \lambda/c$



Underwater gliders

Typical glider features:

- Buoyancy driven (e.g. variable volume/weigh
- Fixed wing and tail
- Attitude controlled by sliding and rolling inte
- Examples of operational gliders:
    - Slocum
    - Spray
    - Seaglider
- Achievements
    - Transatlantic crossings
    - Atlantic Circumnavigation (multi-stage)
    - 13 month glider endurance
    - Working on 6000m glider



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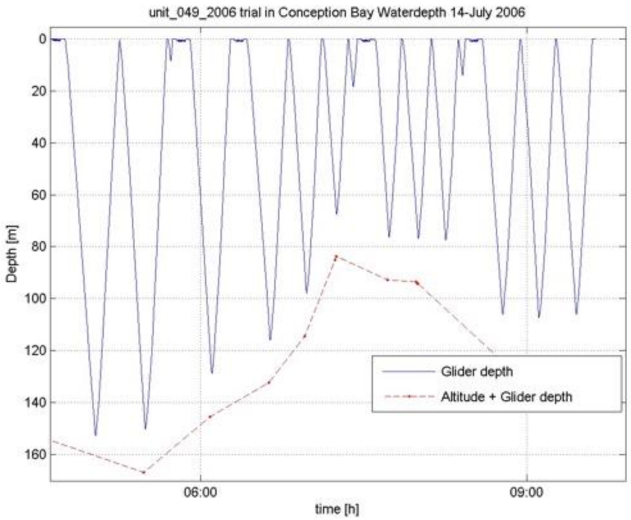
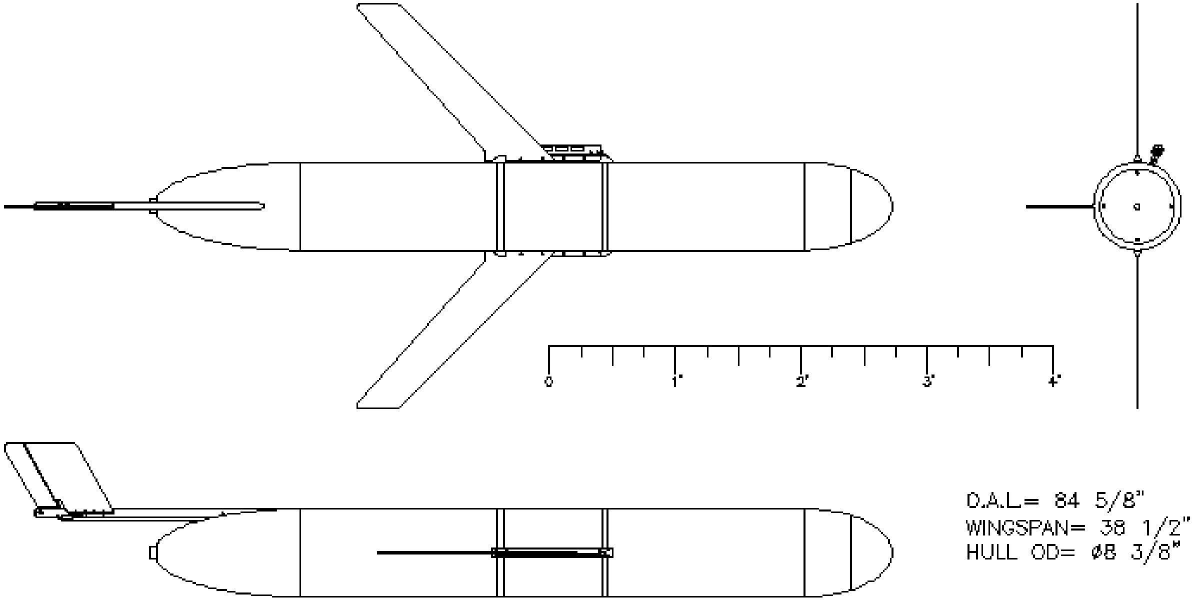


Underwater gliders (cont'd)

- Depth range 200m -1500m depending on model
- Navigation:
  - Surface: GPS
  - Sub-surface: ded reckoning, pressure depth, magnetic heading, attitude
- Low power sensor payload (selection):
  - CTD (standard)
  - Dissolved oxygen
  - Chlorophyll
  - Photosynthetic active radiation (PAR)
  - Ice-profiling sonar
  - Acoustic Doppler Current Profiler (ADCP)

The Slocum Glider

- WRC electric Slocum
- 1.5 m length, 50 kg
- 200 m depth
- 0.4 m/s horiz. speed
- 0.2 m/s vertical
- +/- 250 ccm ballast
- 9 kg moving mass
- Rudder



Sensors:

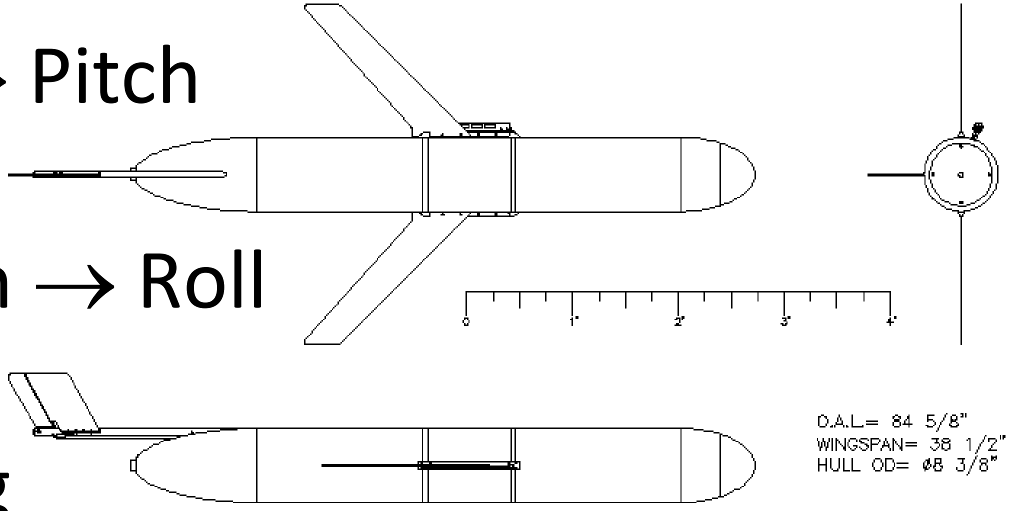
Heading, pitch, roll, depth, GPS, altimeter

Science sensors:

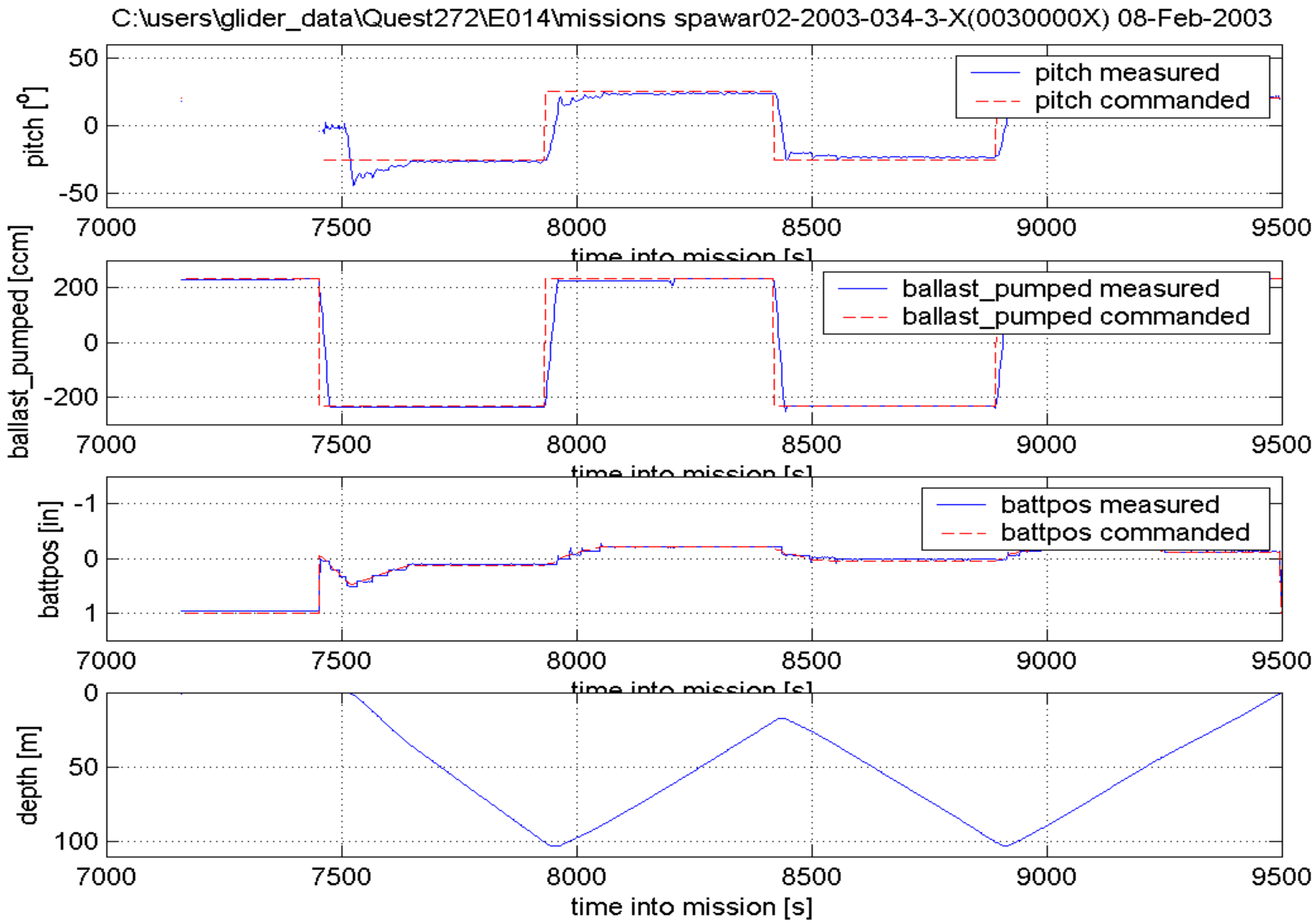
CTD, PAR, Fluorometer, others.

Low Level Control

- Ballast pump → Buoyancy engine
- Battery position → Pitch servo
- Battery orientation → Roll servo
- Rudder → Heading
- Bladder → Surface expression

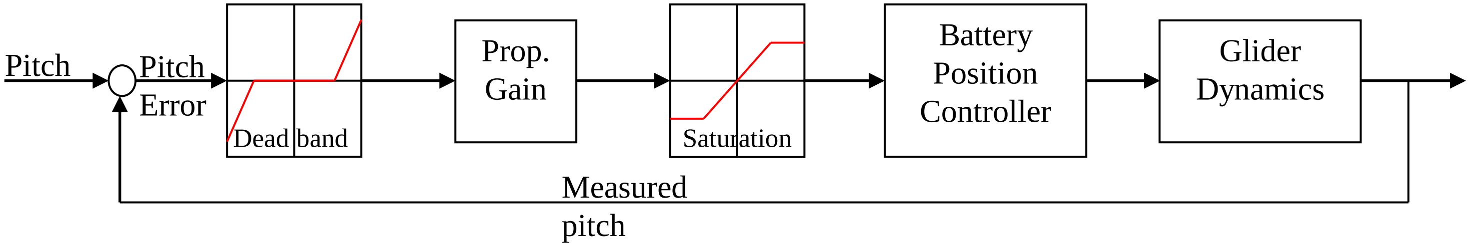


Glider dive performance

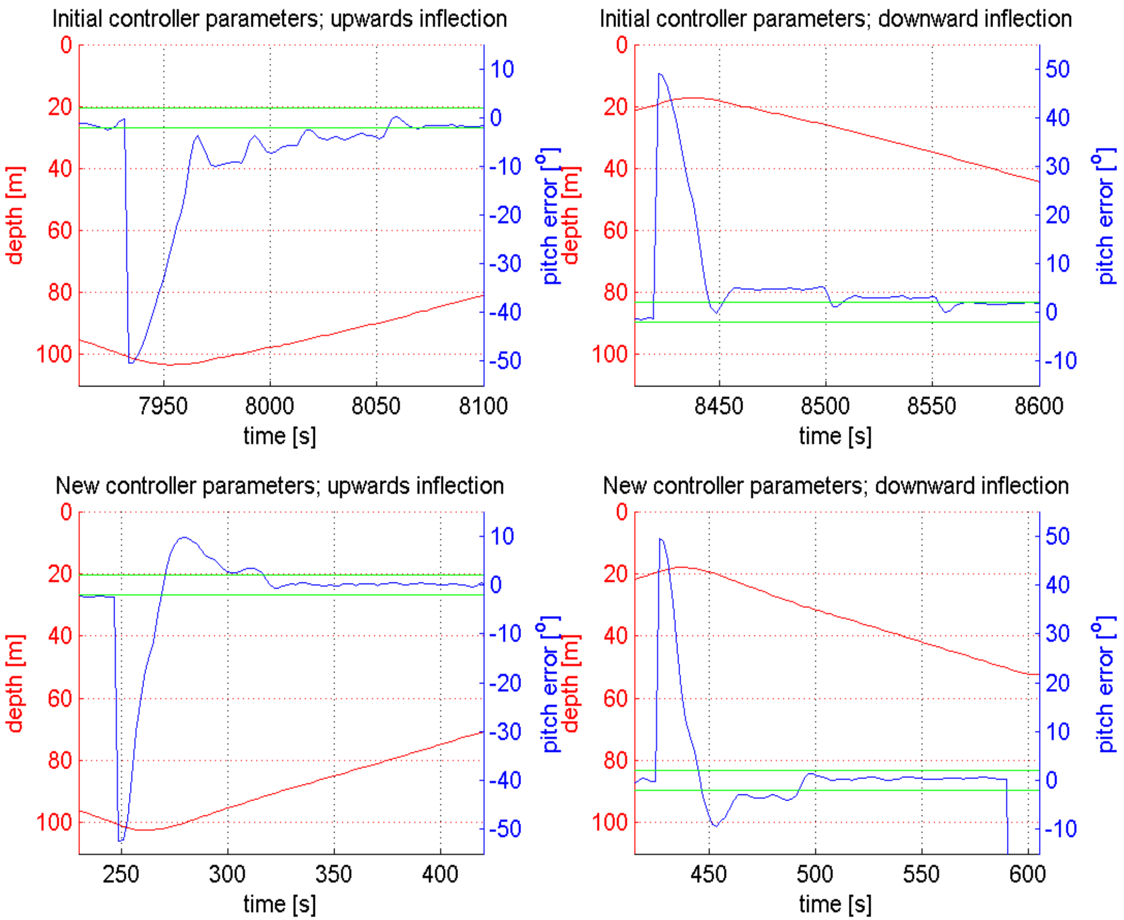


Pitch Control (during Dive)

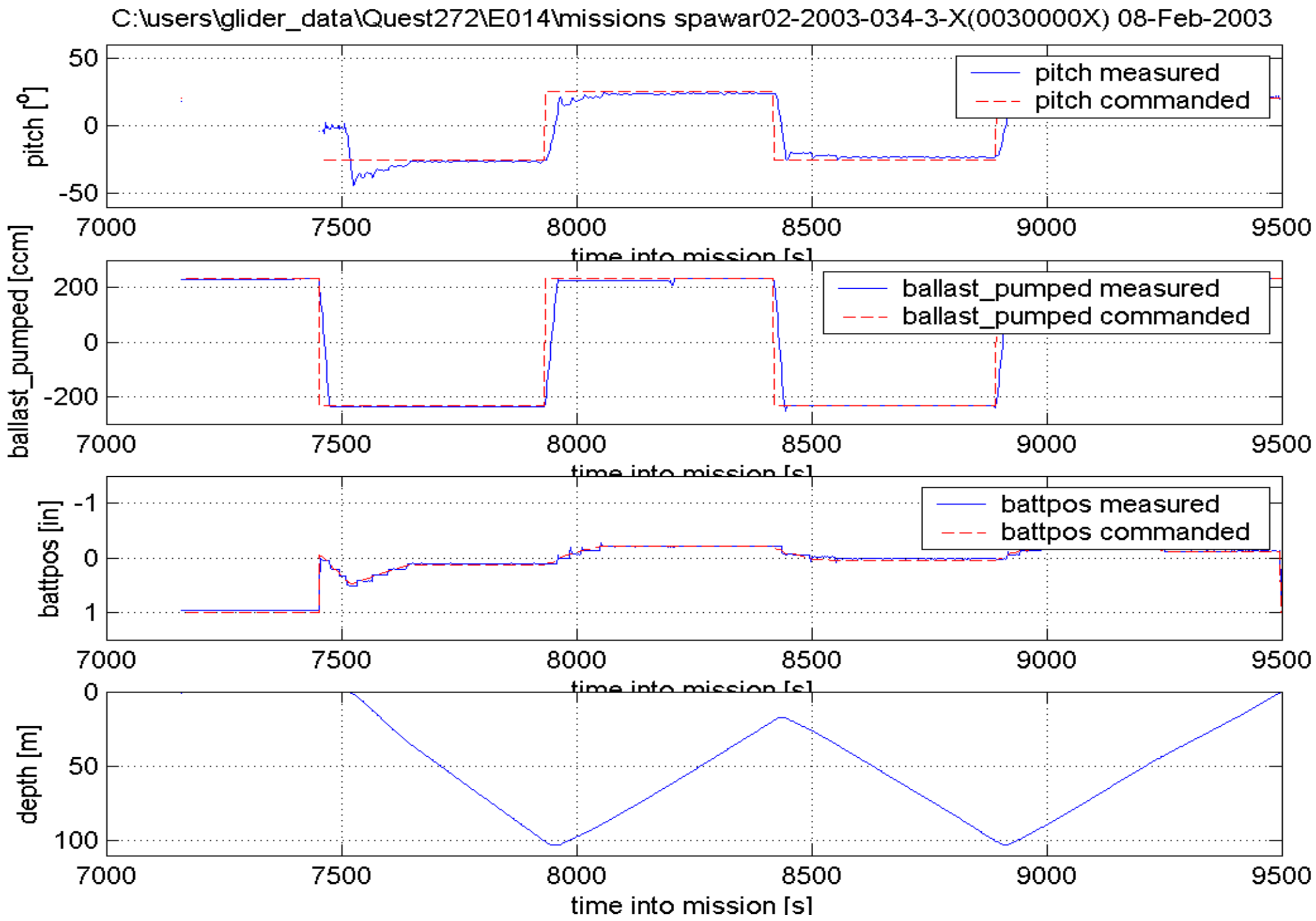
- 2 step
  - Main pitch actuation provided by ballast location (forward of the CG) →open loop
  - Fine tuning by servoing the battery position → closed loop



Pitch Controller Performance



Glider dive performance



Marine Systems Unit

Considerations for Controller/Actuator Implementations

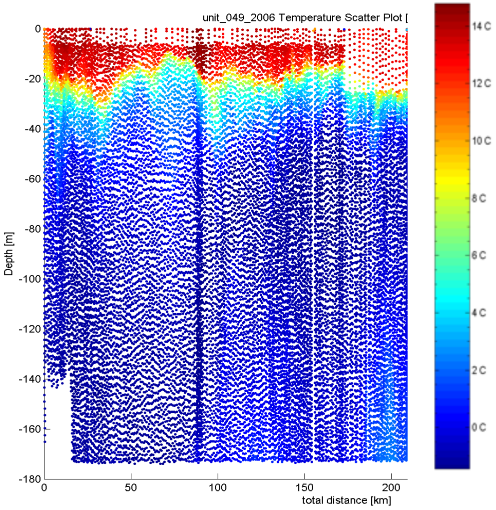
- Performance
  - Shallow vers. deep water operations
  - Roll vers. rudder
- Operational
  - Robustness of control
  - Power efficiency
  - Trimming of the vehicle

Glider deployment in Trinity-Conception Bay 2006

Total duration: 21 day

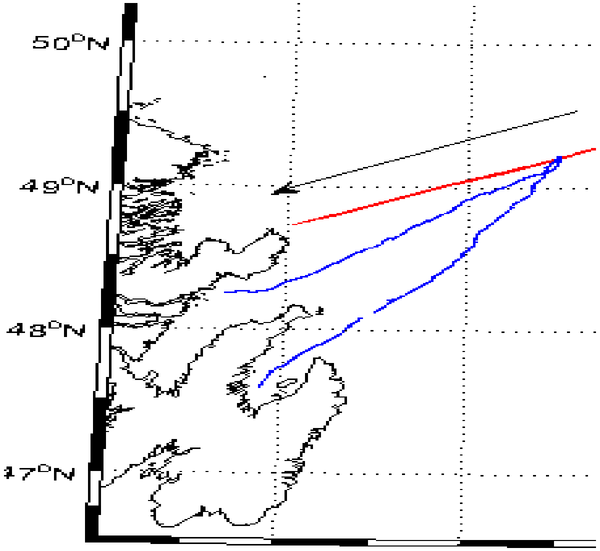
Distance covered: ~500km

Glider



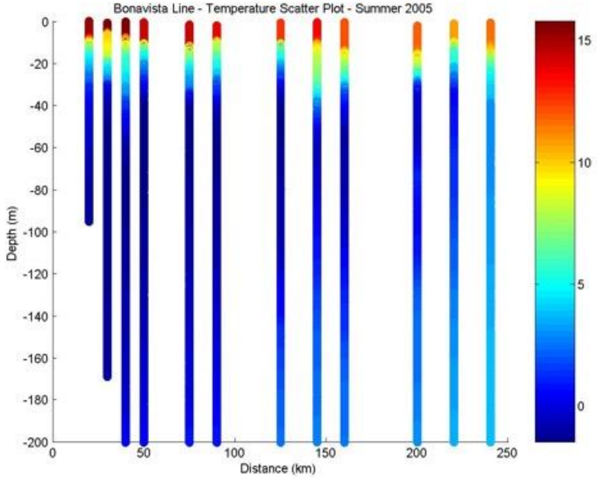
Separation ~ 0.5 km

Duration: 10 days



Glider track (blue) Ship track (red)

Ship stations



Separation ~ 15 km

Duration: 1-2 days

High Level Control

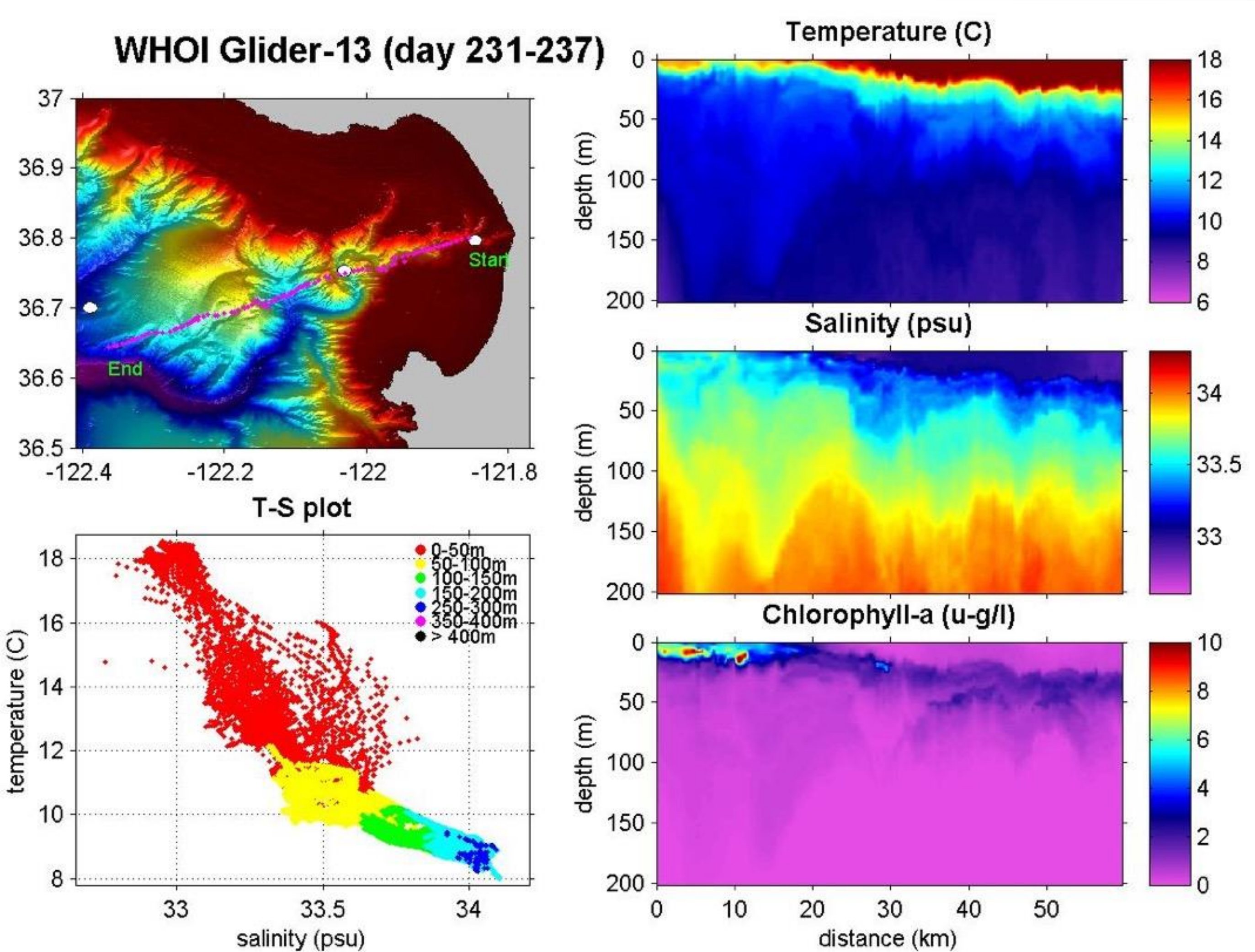
Results during 2003 Autonomous Ocean Sampling Network (AOSNII) field experiments in Monterey Bay

Research focus: Adaptive Sampling

Participants: MBARI, CalTech, Princeton University, Harvard, JPL, Scripps, WHOI, NPS, CalPoly, University of Miami, …

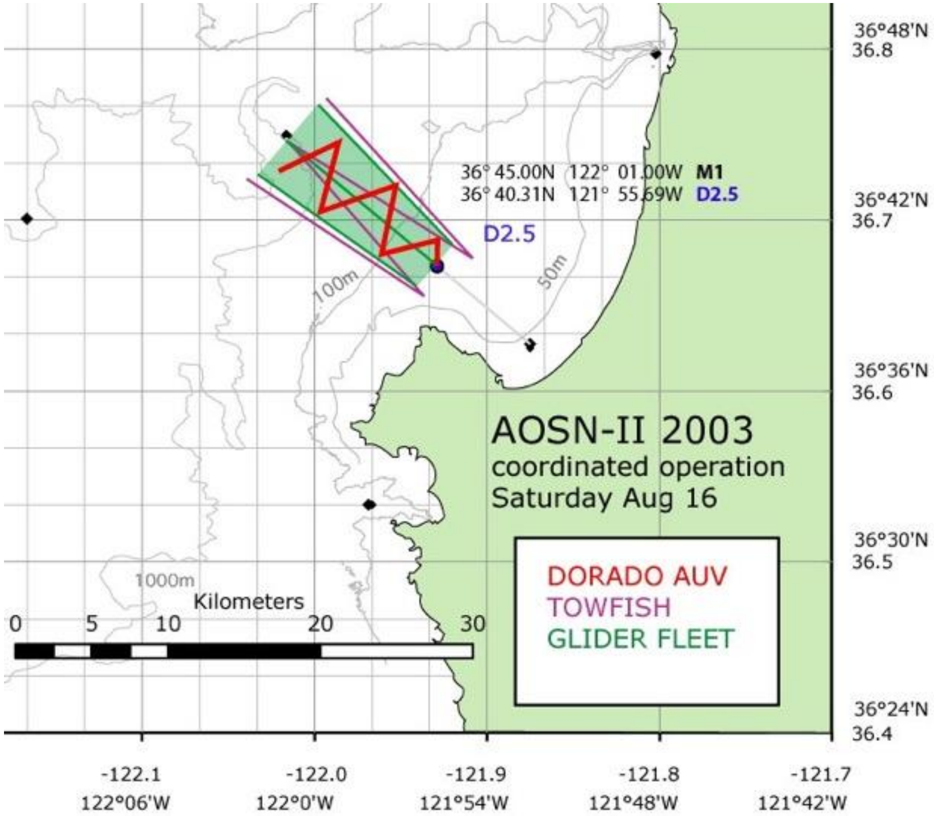
Sponsor: US Office of Naval Research

Glider Science Data



Coordinated Operations

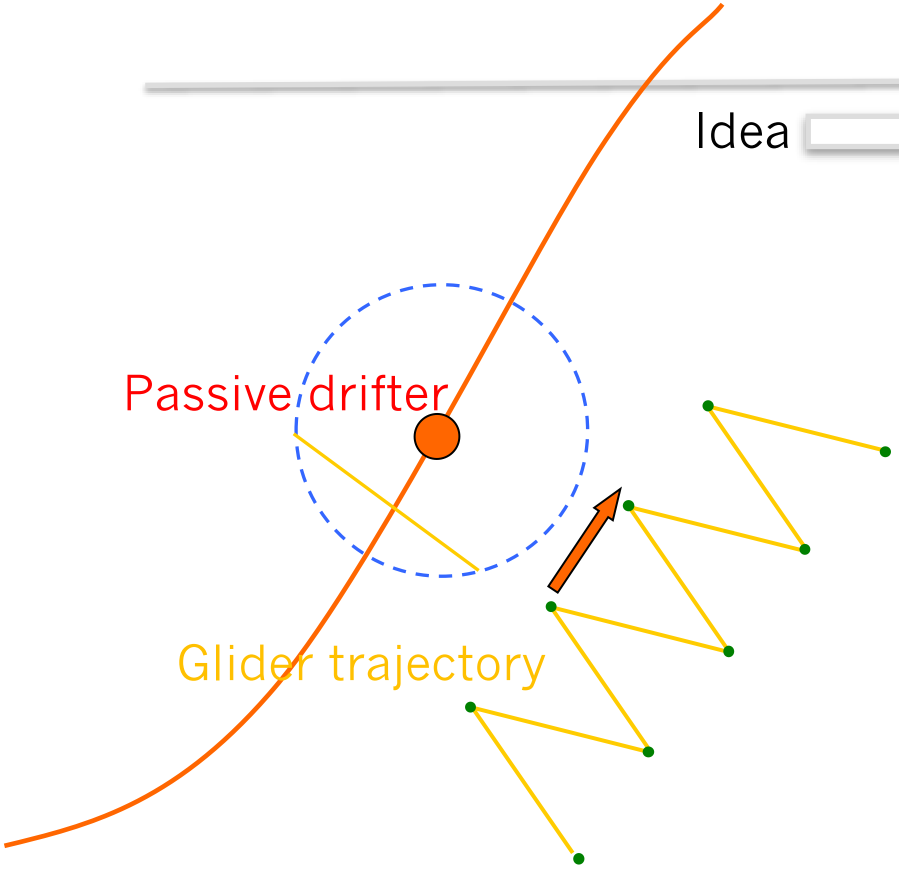
3 Glider, 1 Dorado AUV, 1 Towfish and 1 Drifter

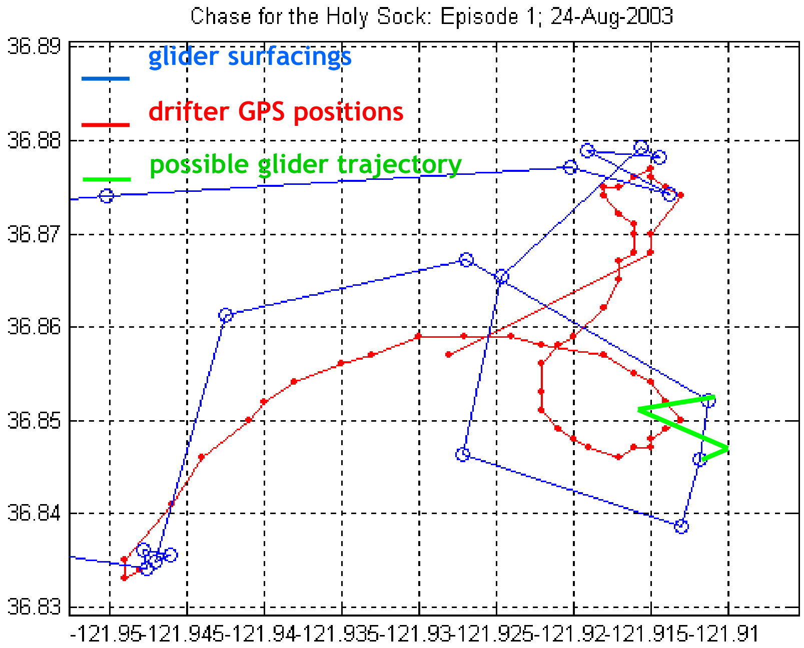


Coordinated (Cooperative?) Control

Drifter Tracking: 23-24 August, 2003 by Pradeep Bhatta and Ralf Bachmayer

Idea → Reality





- Estimation of drifter trajectory
- Adaptive scaling of radius

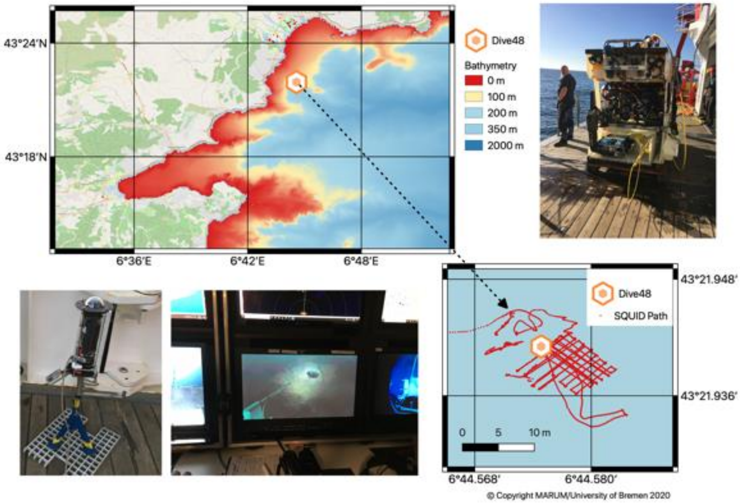
> Interesting perspective: Lagrangian (inside blue circle) vers. Eulerian frame of reference (Zig-Zag)

Sub-Systems

System	Manned	ROV	AUV	Glider
Surface Communications	Acoustic; Limited Bandwidth	High Bandwidth	Acoustic; Limited Bandwidth	None
Pressure Vessel	Large	Small	Medium	
Propulsion	Electric propeller drive	Multiple Electric/hydraulic propeller drives	Electric propeller drive Typ. Single propulsor	Buoyancy Engine
DAQ	Subsea	On support vessel	Subsea	Subsea
Navigation	Acoustic Navigation: Ultra Short Baseline, Short Baseline, Long Baseline Magnetic heading, pressure depth, ded reckoning, inertial navigation			
Obstacle Avoidance	Sonar based: single beam forward/downward looking, scanning, multi-beam On manned submersibles and ROV: visually using cameras and lights			
Control System	Direct human control auto depth and auto heading standard – moving towards more automatic control: Auto XY		Autonomous control system with minimal or no human interaction while submerged – waypoint/ trajectory control	
Sensors	Sonar: sidescan, multi-beam; sub-bottom profiler; Visual: cameras (multiple, HD, 3D coming); CTD; Chemical; Samplers: nets and pumps, sediment samplers (push corer)			
Power	Battery; fuel-cell; nuclear; sterling engine	From support vessel	Battery; Fuelcell	Battery; ocean thermal energy

Technology Evaluation at Sea

- RV Alkor
- Ligurian Sea 21.-24.2.2020
  - La Seine sur Mer, France – Malaga, Spain
- Equipment:
  - ROV MARUM SQUID
  - Optical Bottom node
  - Fly-out MiniROV (modified BlueROV hard
  - AUV MARUM Manatee (Skeleton)



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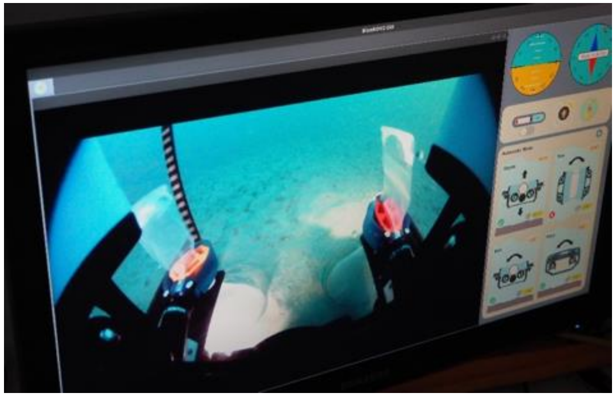
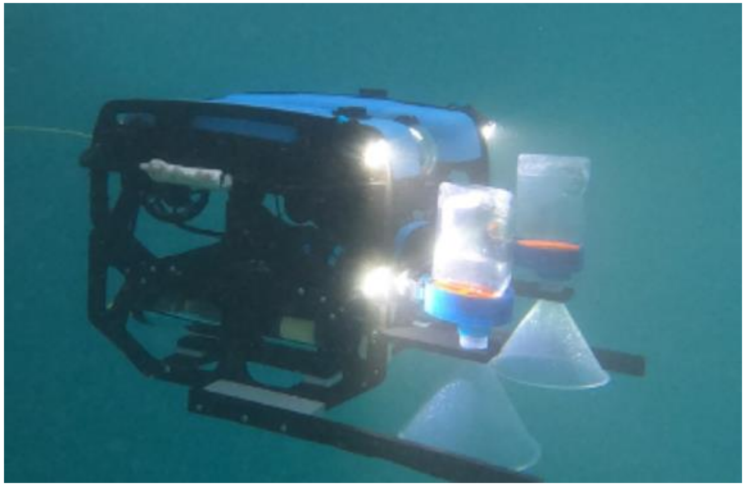
MiniROV for Gas detection and sampling in the North Sea: Challenges

- **Operating Regime in the North Sea**
  - **Tidal currents**: Managing operations in strong tidal regime
    - Predictive capabilities using Tidal models (OSU and BSH)
    - Improved and highly configurable control system (ROS based)
    - Heavy duty configuration with 8 thrusters (4V/4H)
    - Depressor weight deployment
  - **Low visibility**
    - USBL navigation
    - Multi-beam sonar
    - Auto depth and auto attitude controllers

➢ ***12 Dives with up to 2 h dive time in ~40 m water***





Credit: Miriam Römer, Pablo Gutierréz, Szymon Krupinski, Philipp Koschinsky, MSM98

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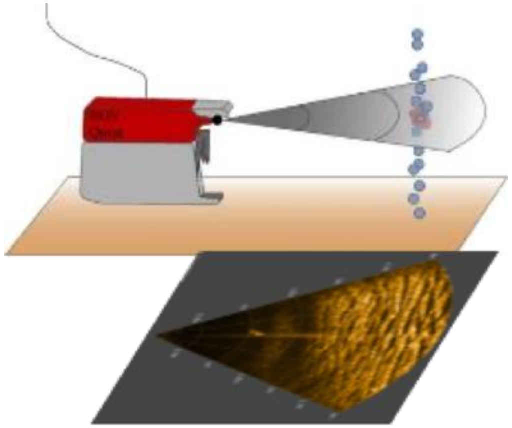
MiniROV for Gas detection and sampling in the North Sea: Challenges (cont'd)

- Gas bubble detection
  - Robust guidance through USBL system (after prior localization by ship borne sonar)
  - Forward looking multi-beam Sonar for bubble detection
  - ➢ ***Successful detection of gas bubbles***
- Gas sampling
  - Two single actuator funnel systems with soft valves (no overpressure)
  - Transparent sampling bags (not hermetically sealed)
  - Pilot assist systems – Automated attitude and depth control
  - ➢ ***Successful collection of gas bubbles***



Credit: Miriam Römer, Pablo Gutierréz, Szymon Krupinski, Philipp Koschinsky, MSM98

Any questions?

Contact:
rbachmayer@marum.de

- PS: Concerning the SLOCUM mission, the thermal engines are a reality.

- C. D. Haldeman, O. Schofield, D. C. Webb, T. I. Valdez and J. A. Jones, "Implementation of energy harvesting system for powering thermal gliders for long duration ocean research," *OCEANS 2015 - MTS/IEEE Washington*, Washington, DC, USA, 2015, pp. 1-5, doi: 10.23919/OCEANS.2015.7404559.

- Y. Chao, "Autonomous underwater vehicles and sensors powered by ocean thermal energy," OCEANS 2016 - Shanghai, Shanghai, China, 2016, pp. 1-4, doi: 10.1109/OCEANSAP.2016.7485367.