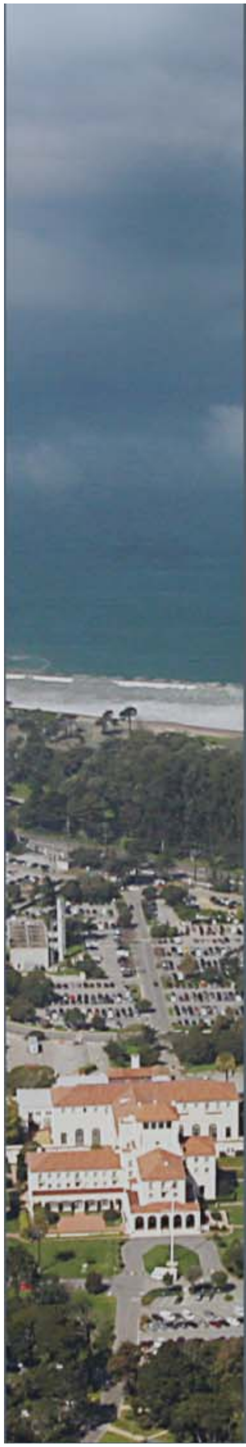

International Symposium on
EXPO 2012 Yeosu Korea
World Ocean Forum 2010
Nov 15-17, Busan, Korea

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Unmanned Undersea Vehicle (UUV) for Naval Science/Technology and Operations

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Outline

- Why UUV?
- Fundamentals of UUV
- UUV Dynamics and Control
- Key Technology Issues
- UUV – an Effective Marine Remote Sensing Technology
- Future …

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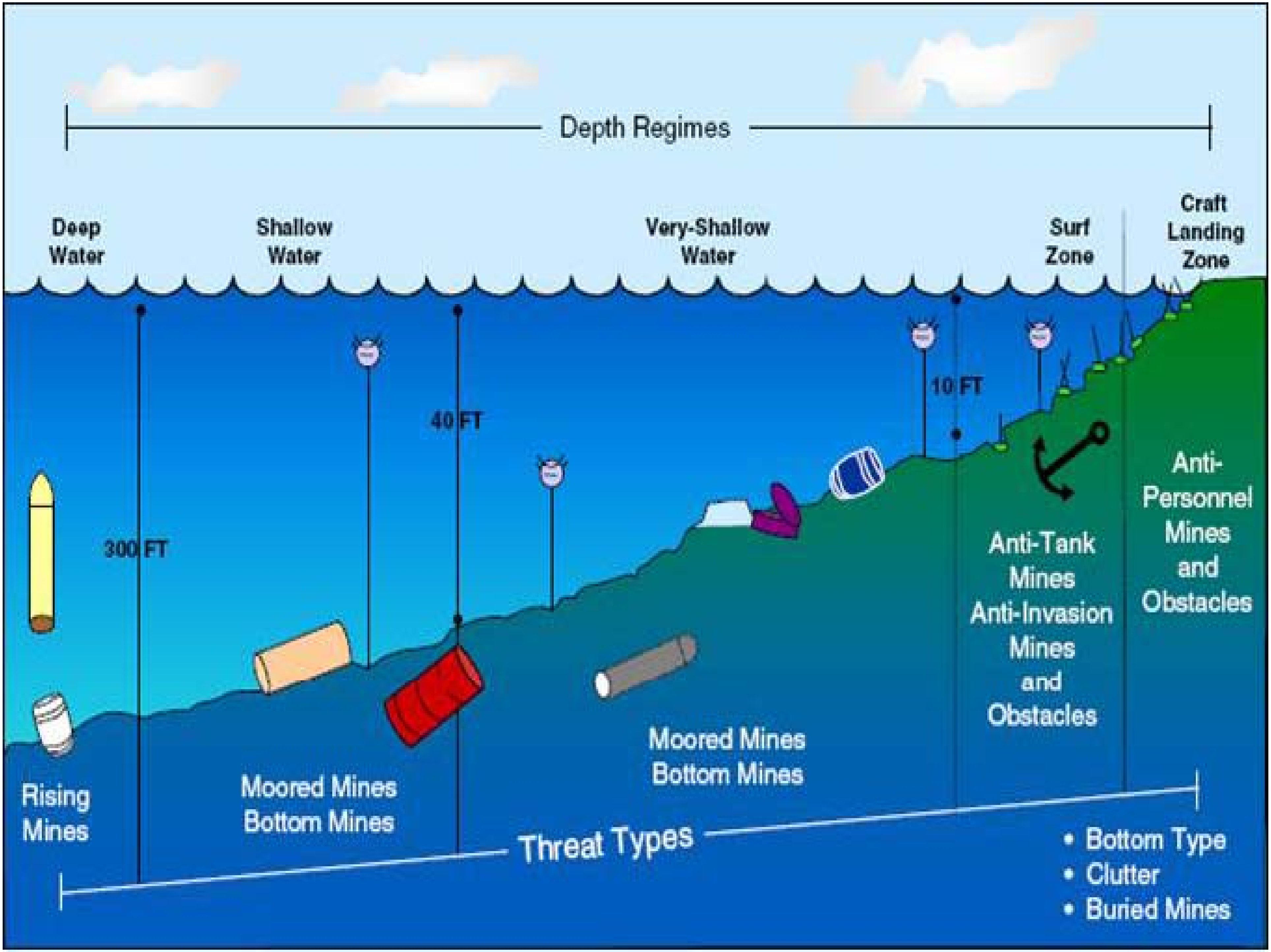
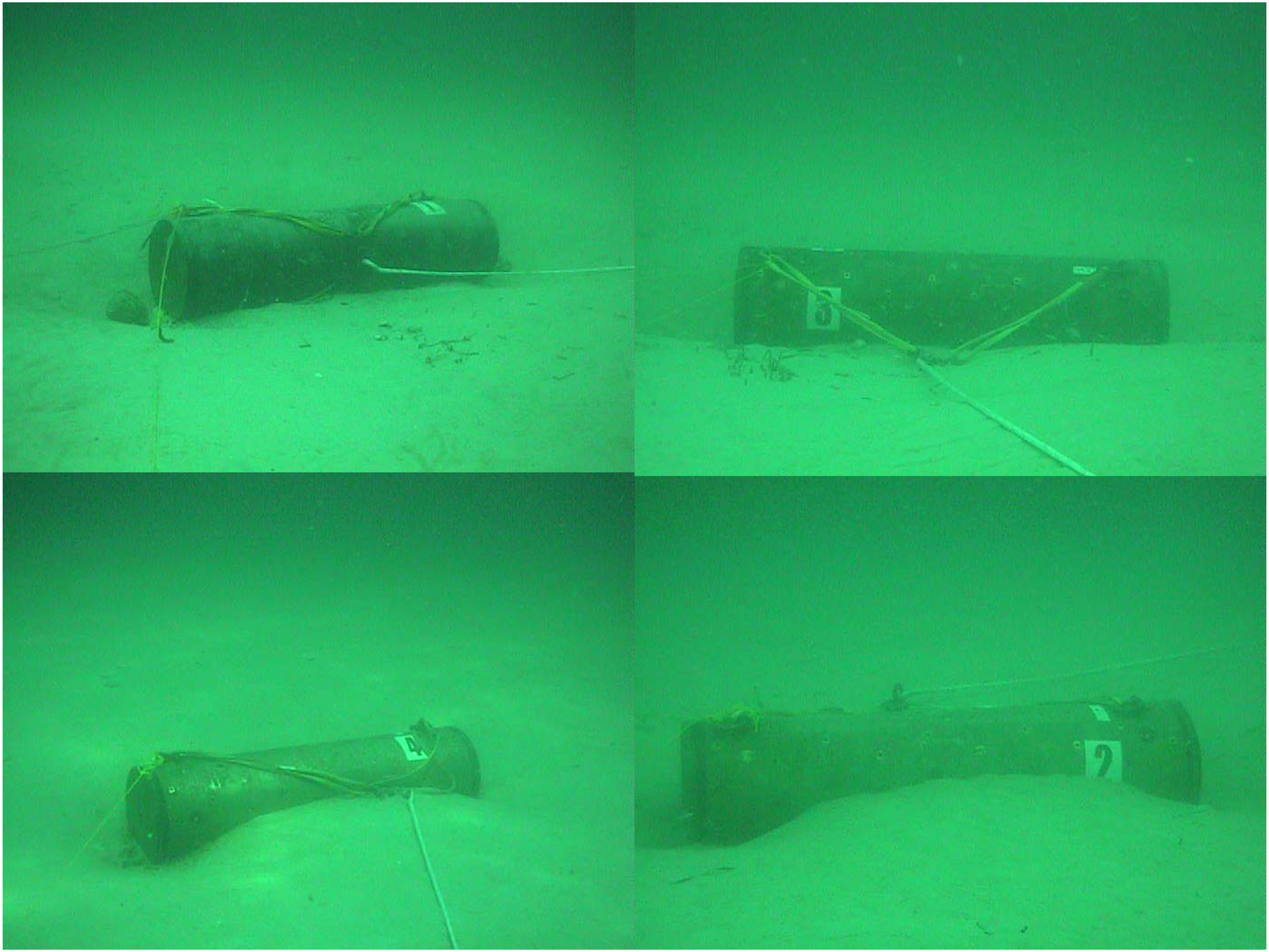
Why UUV?

Mine Countermeasure (MCM)
Antisubmarine Warfare (ASW)
as examples


Depth Regimes
Deep Water
Shallow Water
Very-Shallow Water
Surf Zone
Craft Landing Zone
300 FT
40 FT
10 FT
Rising Mines
Moored Mines Bottom Mines
Moored Mines Bottom Mines
Anti-Tank Mines Anti-Invasion Mines and Obstacles
Anti-Personnel Mines and Obstacles
Threat Types
• Bottom Type
• Clutter
• Buried Mines


3
4
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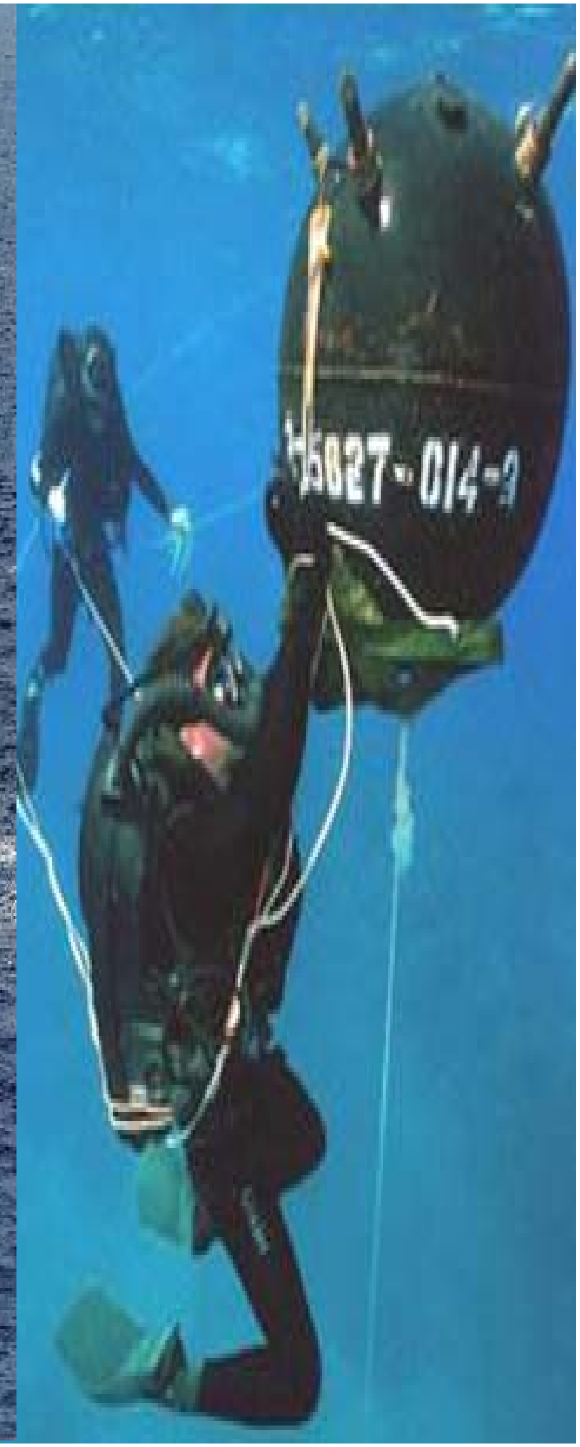
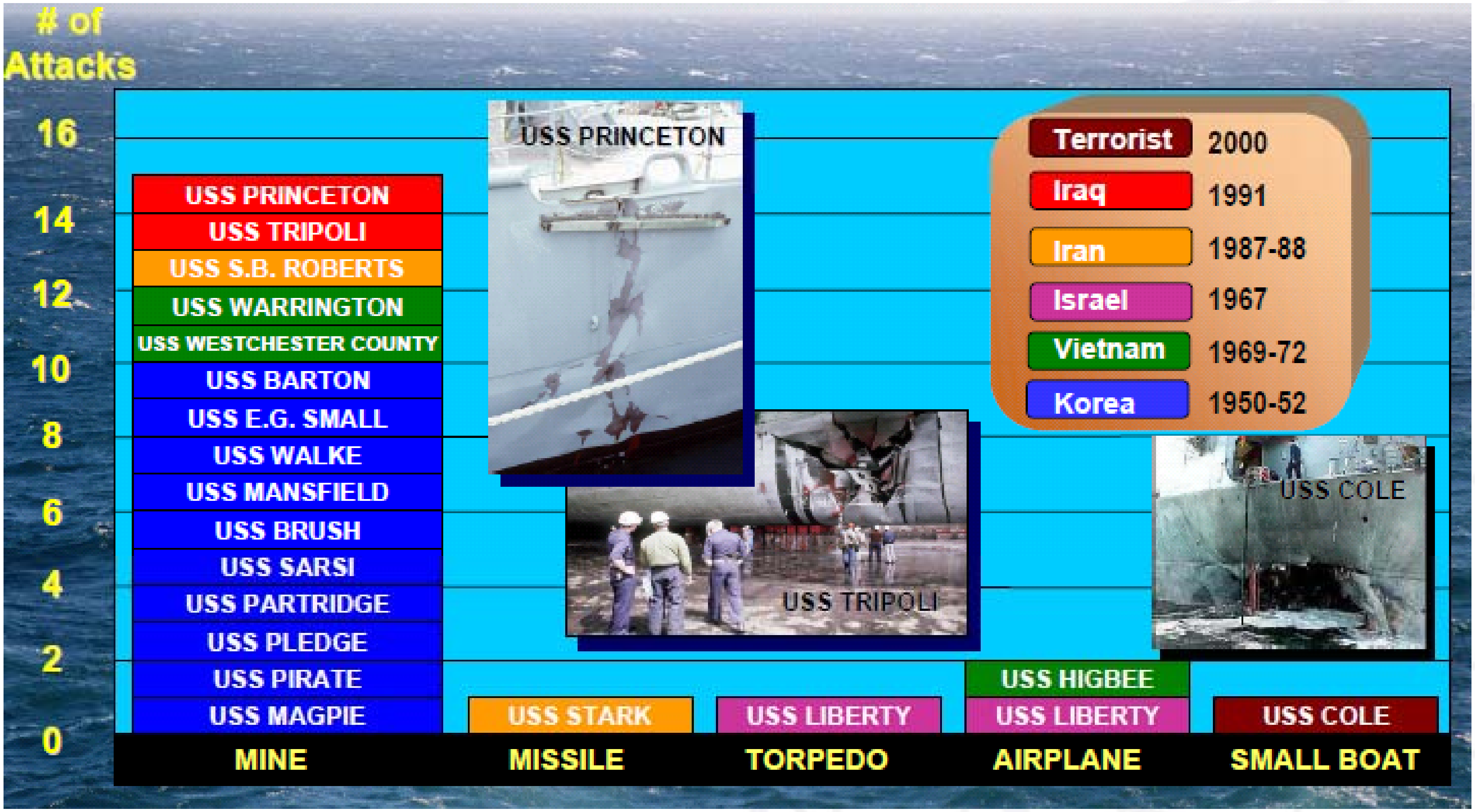


U.S. vs. MINES

- Of the 18 US Navy ships that have suffered battle damage in the last 50 years, 78 per cent was as a result of mines.



• Why defeat the mine/maritime IED?

USS Samuel. B. Roberts (FFG-58)

Mine Cost: $1,500 vs. Repair Cost: $96 M

USS Tripoli (LPH-11)

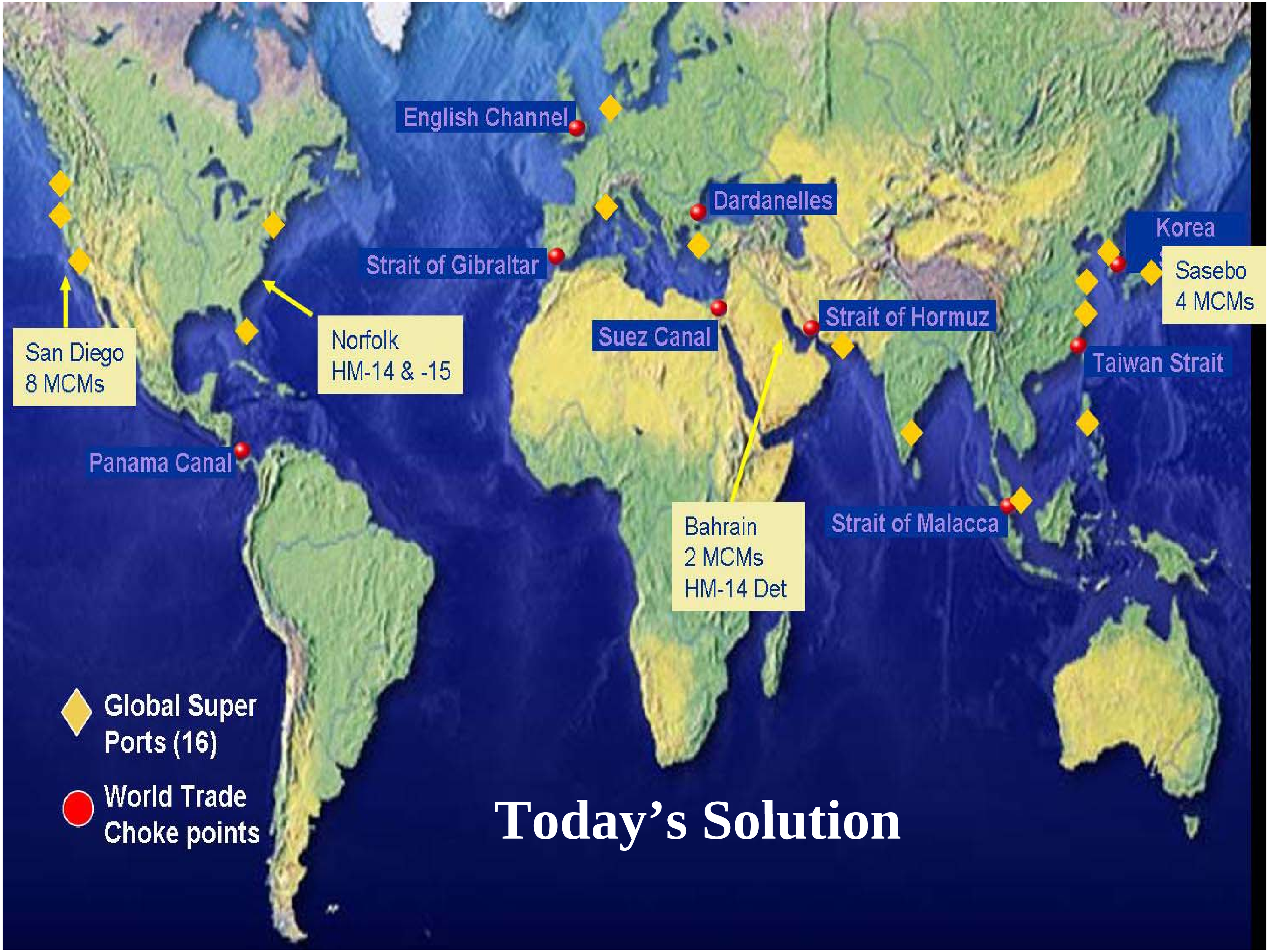
Mine Cost: $1,500 vs. Repair Cost: $3.5 M

USS Princeton (CG-59)

Mine Cost: $10,000 vs. Repair Cost: $24 M

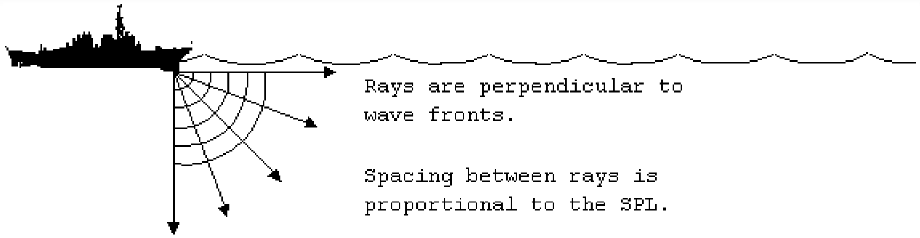
Economy and Security

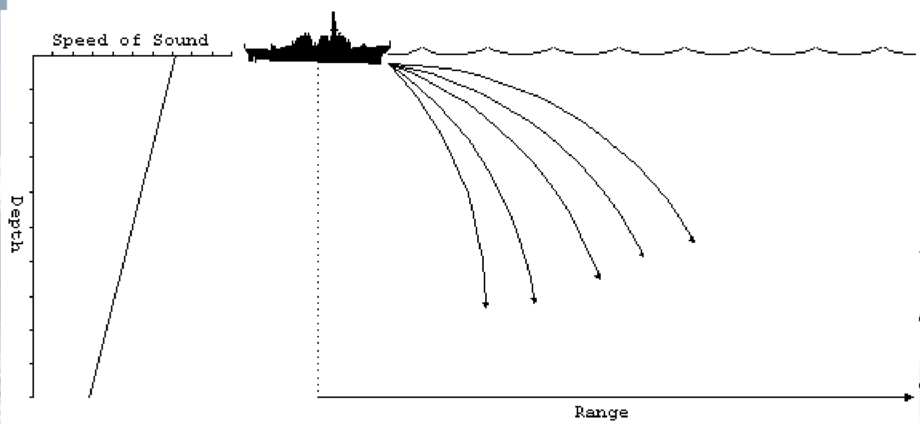
Port	$Million/day
Los Angeles	278.9
Long Beach	269.0
New York	221.6
Houston	118.9
Seattle	88.5
Charleston	86.3
Hampton Roads	77.8
Oakland	68.5
Baltimore	56.4
Tacoma	53.4

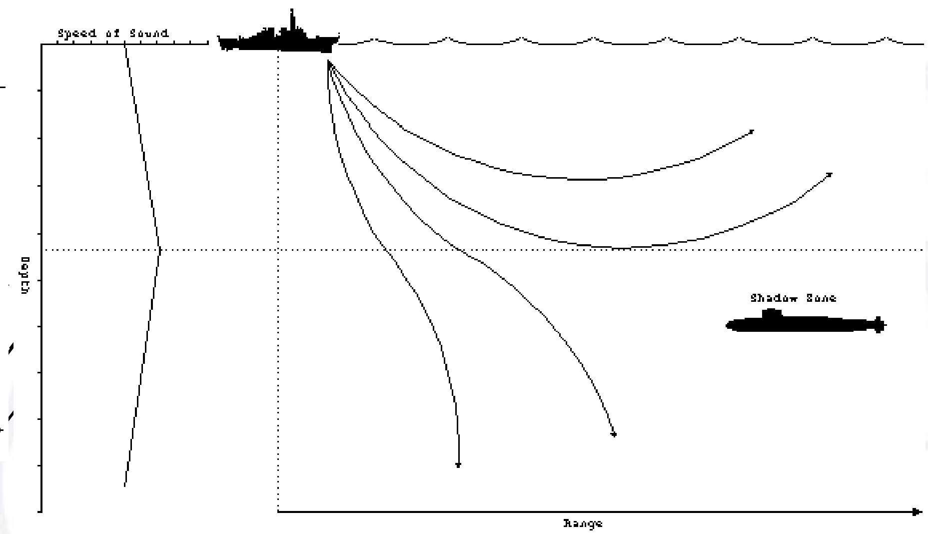

English Channel
Dardanelles
Korea
Strait of Gibraltar
Sasebo
4 MCMs
Strait of Hormuz
Suez Canal
Taiwan Strait
San Diego
8 MCMs
Norfolk
HM-14 & -15
Panama Canal
Bahrain
2 MCMs
HM-14 Det
Strait of Malacca
Global Super Ports (16)
World Trade Choke points
Today's Solution

ASW Success Foundation

Underwater Acoustics







$$\nabla^2 p(\vec{r},\omega) + \frac{\omega^2}{c^2(z)} p(\vec{r},\omega) = 2k_0^2 \mu(\vec{r}) p(\vec{r},\omega)$$

$$\mu(\vec{r}) = \frac{\delta c(\vec{r})}{c_0}$$

•→

•Stochastic or Deterministic Perturbation

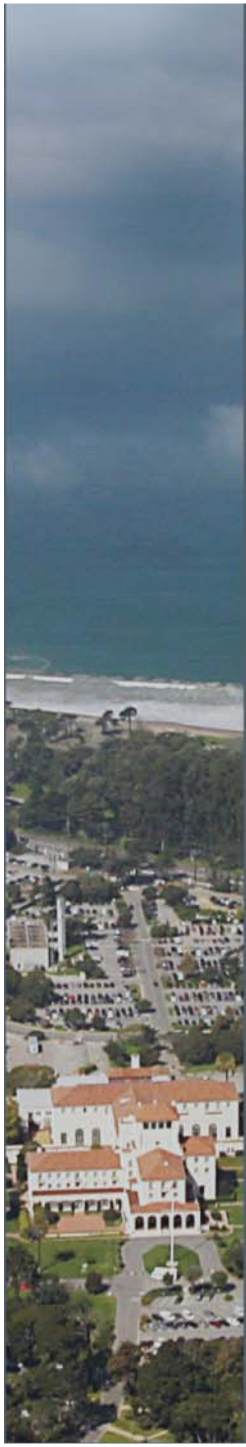
Urgent scientific problem

- What is the temporal-spatial variability in littoral environment (sediment, sound sped profiles, …)?

- → UUV is the ultimate solution.

UUV Capabilities

- entering a hostile area and gathering as much information about the surroundings as possible
- quickly identifying safe paths as well as identify mined areas
- gathering , transmitting, or acting on all types of information
- engaging bottom, volume, surface, air or land targets
- ……



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Fundamentals of UUV

UUV

Hull

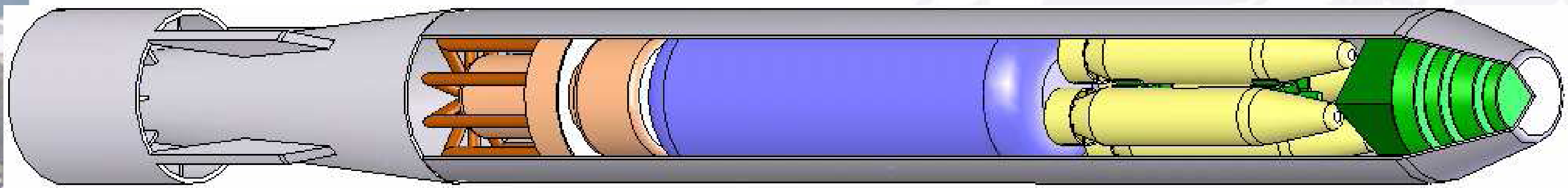
(fins)

Storage

(battery)

Sensor

(sonar)



Thrust

Engine

(propulsion)

•(rocket)

•

Background of UUV

- 90% of International Trade in Sea Lane
- Tactical Considerations
- Secure Future Leading Edge Technology
- Boosting Industrial Impacts
- Academic, Industrial and Military Interests

UUV Missions

- Intelligence, surveillance, and reconnaissance
- Mine countermeasures (MCM)
- Anti-submarine warfare (ASW)
- Inspection/identification
- Communication/navigation network node
- Amphibious warfare
- Port and force defense
- Special operations

Advantages of UUV

- Autonomy
- Risk Reduction
- Low Profile
- Deployability
- Environmental Adaptability
- Persistence
- Low Cost
- Enable Missions that cannot be performed by manned systems

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UUV Application

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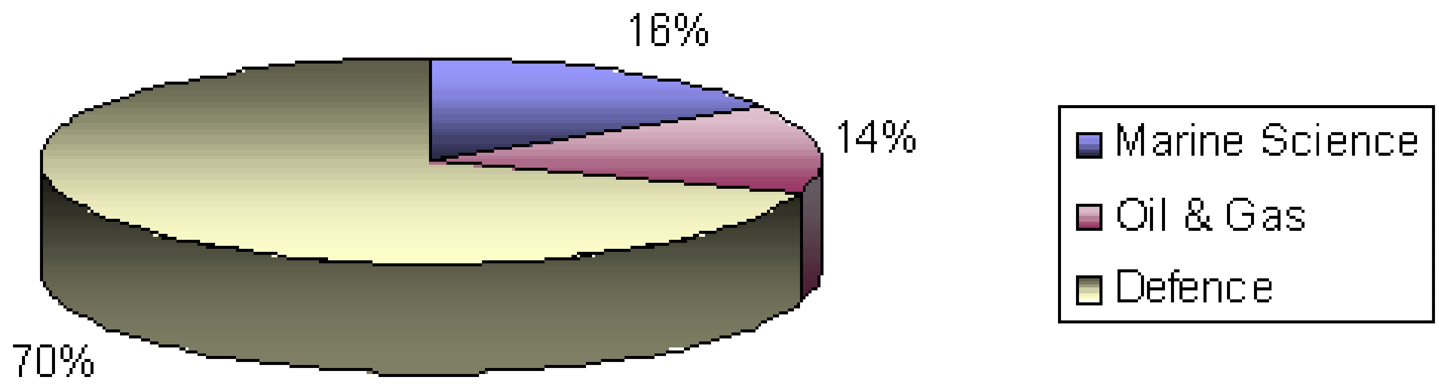
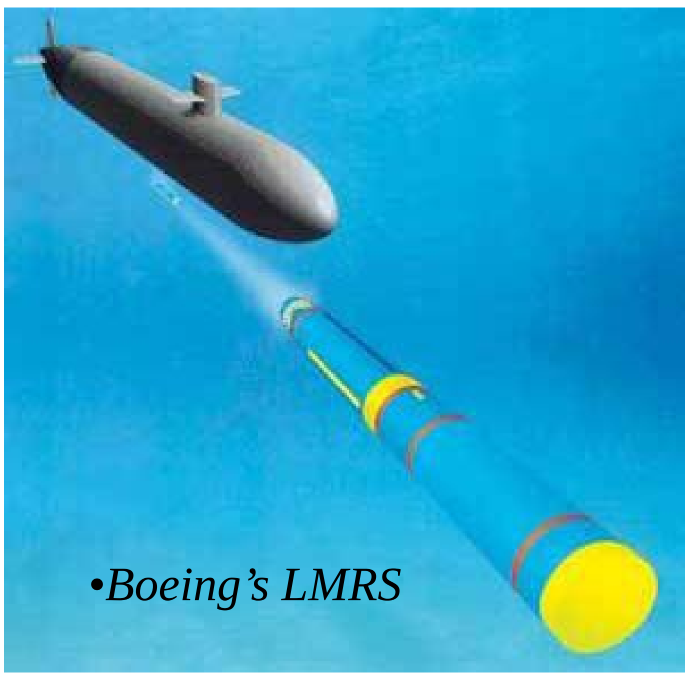
CAVR



- *Source: visiongain 2007*

Navy Autonomous Undersea Vehicles (AUVs)

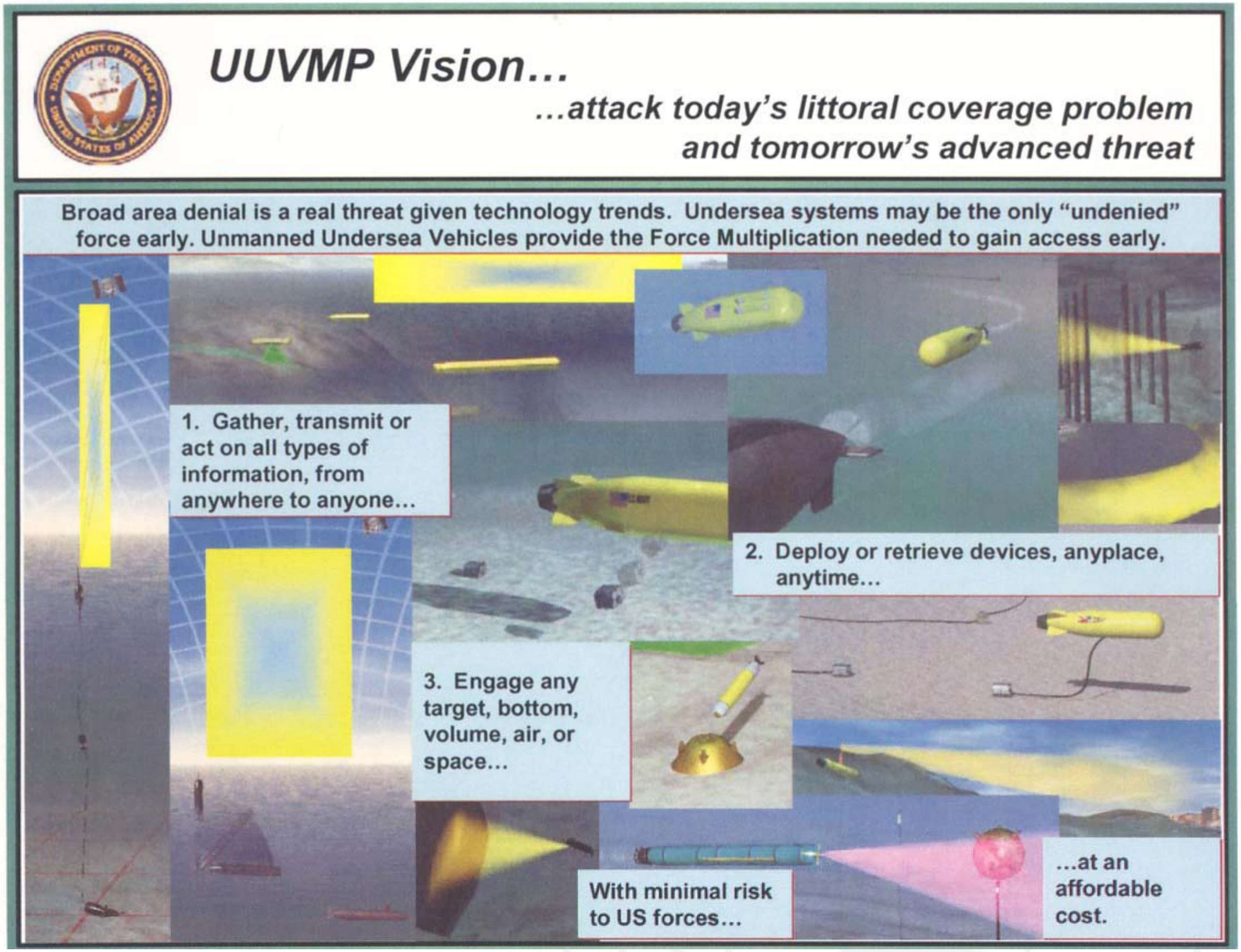


•Boeing's LMRS

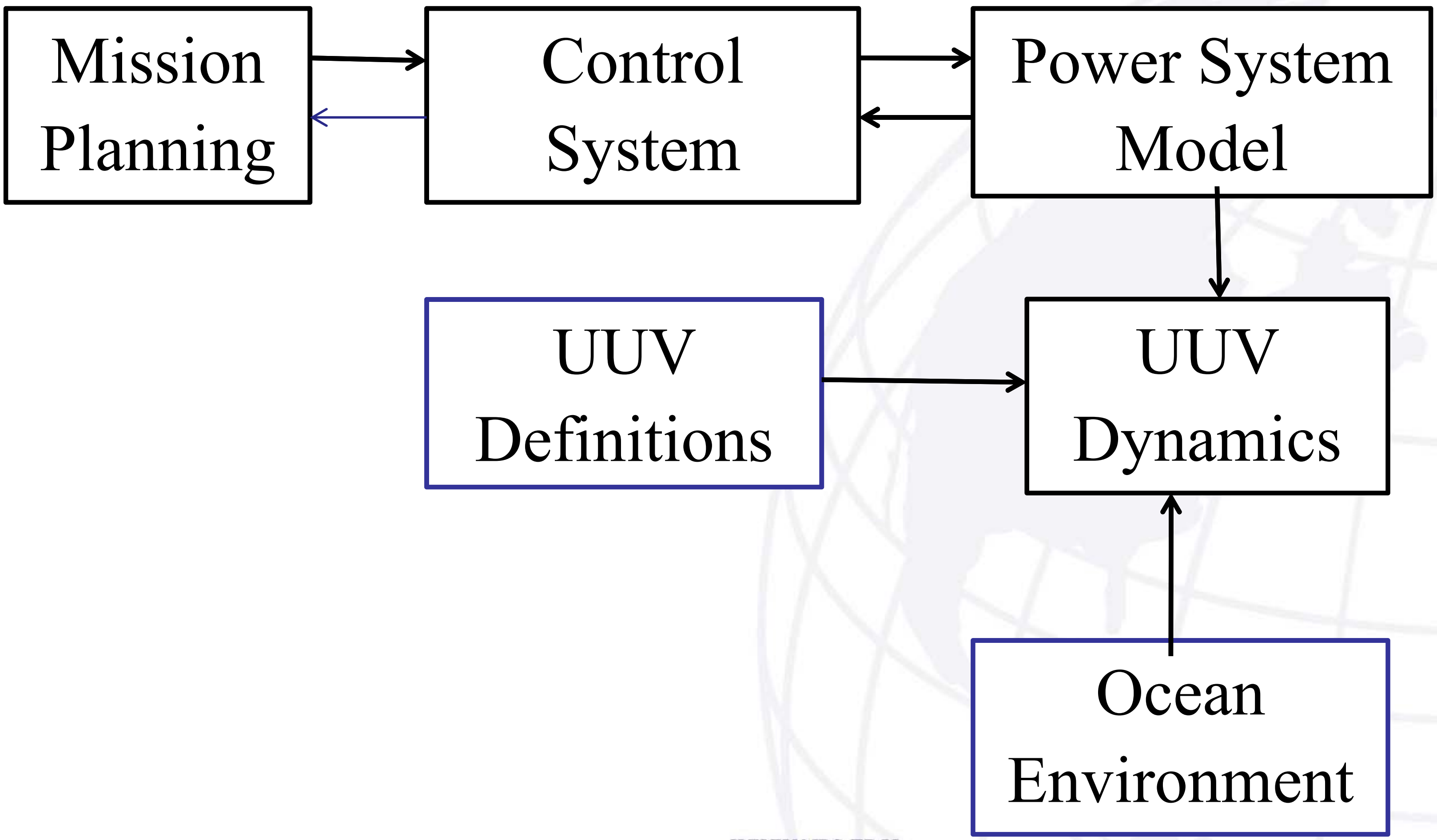
•Talisman from BAE

•Carrying variable payloads

Navy UUV Master Plan (2004)



A UUV System


Mission Planning
Control System
Power System Model
UUV Definitions
UUV Dynamics
Ocean Environment

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UUV Dynamics and Control

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Center for Autonomous Vehicle Research CAVR

6 DOF Equation

$$X_f = m\left[\dot{u}_r - v_r r + w_r q - x_G\left(q^2 + r^2\right) + y_G\left(pq - \dot{r}\right) + z_G\left(pr + \dot{q}\right)\right] + (W - B)\sin\theta$$

$$Y_f = m\left[\dot{v}_r + u_r r - w_r q + x_G\left(pq + \dot{r}\right) - y_G\left(p^2 + r^2\right) + z_G\left(pr - \dot{q}\right)\right] - (W - B)\cos\theta\sin\phi$$

$$Z_f = m\left[\dot{w}_r - u_r q + v_r p + x_G\left(pr + \dot{q}\right) + y_G\left(qr + \dot{q}\right) - z_G\left(p^2 + q^2\right)\right] + (W - B)\cos\theta\cos\theta$$

$$K_f = I_x\dot{p} + \left(I_z - I_y\right)qr + I_{xy}\left(pr - \dot{q}\right) - I_{yz}\left(q^2 - r^2\right) - I_{xz}\left(pq + \dot{r}\right)$$
$$+m\left[y_G\left(\dot{w} - u_r q + v_r p\right) - z_G\left(\dot{v}_r + u_r r - w_r p\right)\right]$$
$$-\left(y_G W - y_b B\right)\cos\theta\cos\phi + \left(z_G W - z_B B\right)\cos\theta\sin\phi$$

$$M_f = I_y\dot{q} + \left(I_z - I_x\right)pr - I_{xy}\left(qr - \dot{p}\right) + I_{yz}\left(pq - \dot{r}\right) + I_{xz}\left(p^2 + r^2\right)$$
$$-m\left[x_G\left(\dot{w} - u_r q + v_r p\right) - z_G\left(\dot{u}_r - v_r r + w_r Q\right)\right]$$
$$+\left(x_G W + x_B B\right)\cos\theta\cos\phi + \left(z_G W - z_B B\right)\sin\phi$$

$$N_f = I_z\dot{r} + \left(I_y - I_x\right)pq - I_{xy}\left(p^2 - q^2\right) - I_{yz}\left(pr + \dot{q}\right) + I_{xz}\left(qr - \dot{p}\right)$$
$$+m\left[x_G\left(\dot{v}_r + u_r r - w_r p\right) - y_G\left(\dot{u}_r - v_r r + w_r q\right)\right]$$
$$-\left(x_G W - x_b B\right)\cos\theta\sin\phi - \left(y_G W - y_B B\right)\sin\theta$$

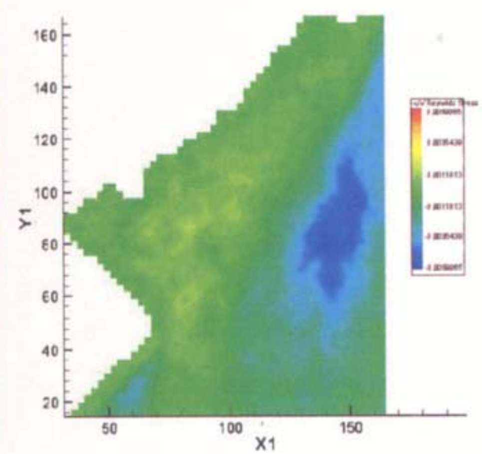
Variables in 6-DOF Model

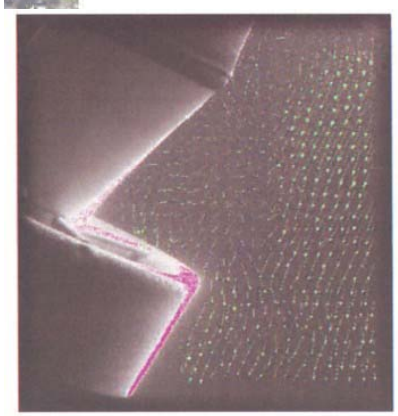
I_x, I_y, I_z	Mass moment of inertia terms
u_r, v_r, w_r	Component velocities for a rigid body fixed system with respect to the water
p, q, r	Component angular velocities for a rigid body fixed system
x_B, y_B, z_B	Positional difference between center of buoyancy and the geometric center
x_G, y_G, z_G	Positional difference between the center of gravity and the geometric center
B	Buoyancy
W	Weight
$\delta_r(t)$	Delta Rudder function

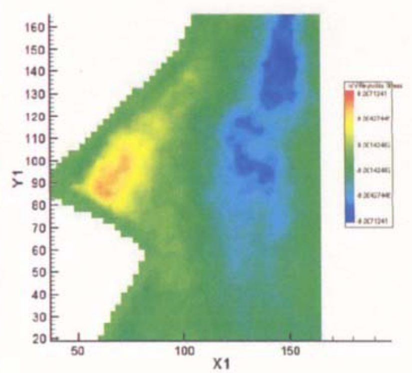
Characteristics and Challenges in UUV Dynamics

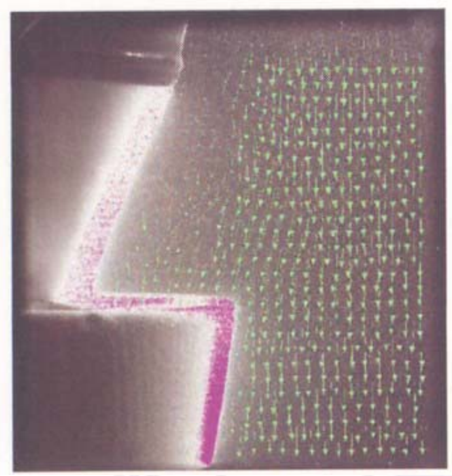
- The ocean is dense; so the lift (buoyancy) is easy to achieve.
- High pressures in the ocean depths increase UUV complexity and cost.
- Drag, lift, and torque coefficients need to be determined.
- Oceanic motions affect UUV especially in shallow water regions since UUV moves slow (few knots).

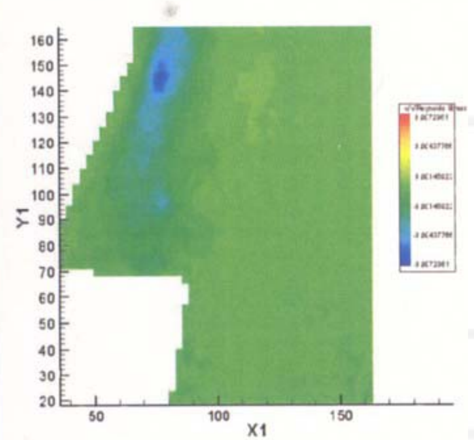
Particle Image Velocimetry (PIV)











(Ackermann and von Ellenrieder, OCEANS 2006)

Diagnostic-Photographic Method

$$C_d = 0.02 + 0.35 e^{-2\left(\alpha - \pi/2\right)^2} \left(\frac{\text{Re}}{\text{Re}*}\right)^{0.2} + 0.008\Omega \sin\theta$$

$$C_l = \begin{cases} 0.35 \sin(\theta_1) \left(\frac{\text{Re}}{\text{Re}*}\right)^{0.2} & \text{if } \alpha \le \frac{\pi}{2} \\ 0.1 \sin(\theta_2) - 0.015\Omega \left(\frac{\text{Re}}{\text{Re}*}\right)^{2} \sin\left(\theta_2^{0.85}\right) & \text{if } \alpha > \frac{\pi}{2} \end{cases}$$

$$\theta_1 = \pi \left(\frac{2\alpha}{\pi}\right)^{1.8}$$

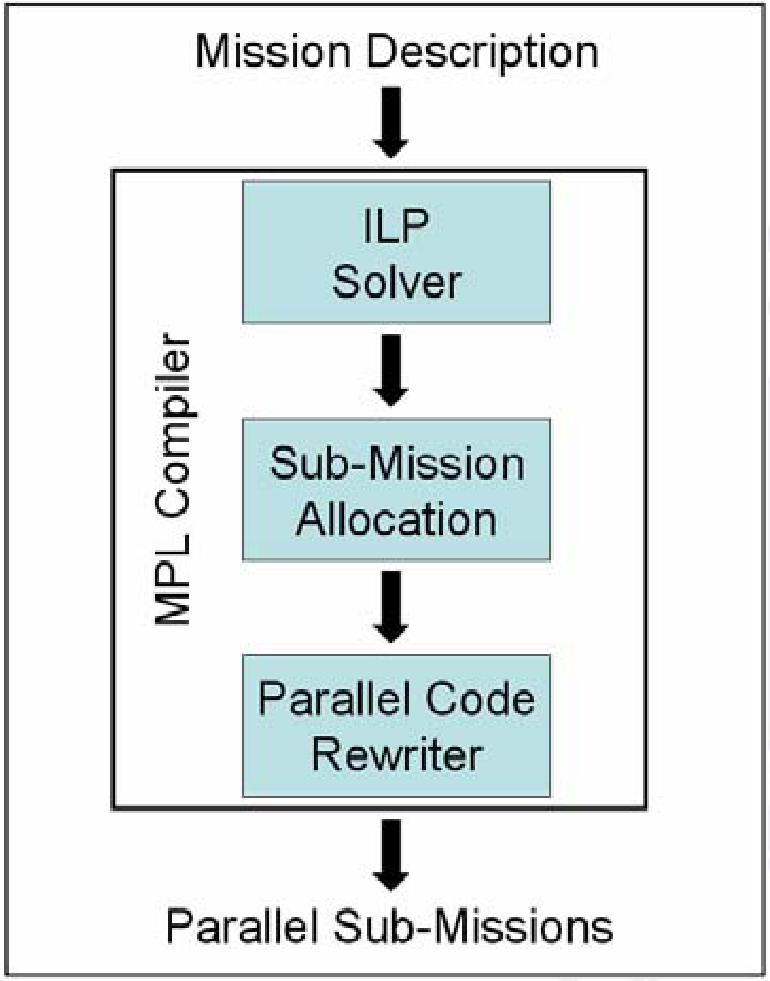
$$\theta_2 = 2\pi \left(\frac{2\alpha}{\pi} - 1\right)^{0.7}$$

$$C_m = \begin{cases} 0.07 \sin(2\alpha) \left(\frac{\text{Re}*}{\text{Re}}\right)^{0.2} & \text{if } \alpha \le \frac{\pi}{2} \\ 0.02 \sin(2\alpha) \sqrt{\left(\frac{\text{Re}}{\text{Re}*}\right)} & \text{if } \alpha > \frac{\pi}{2} \end{cases}$$

$$\theta \equiv \left(\pi^{2.2} - \left(\pi - \left|\pi - 2\alpha\right|\right)^{2.2}\right)^{\frac{1}{2.2}} \text{sign}(\pi - 2\alpha)$$

(Chu et al. Journal of Applied Mechanics, 2010)

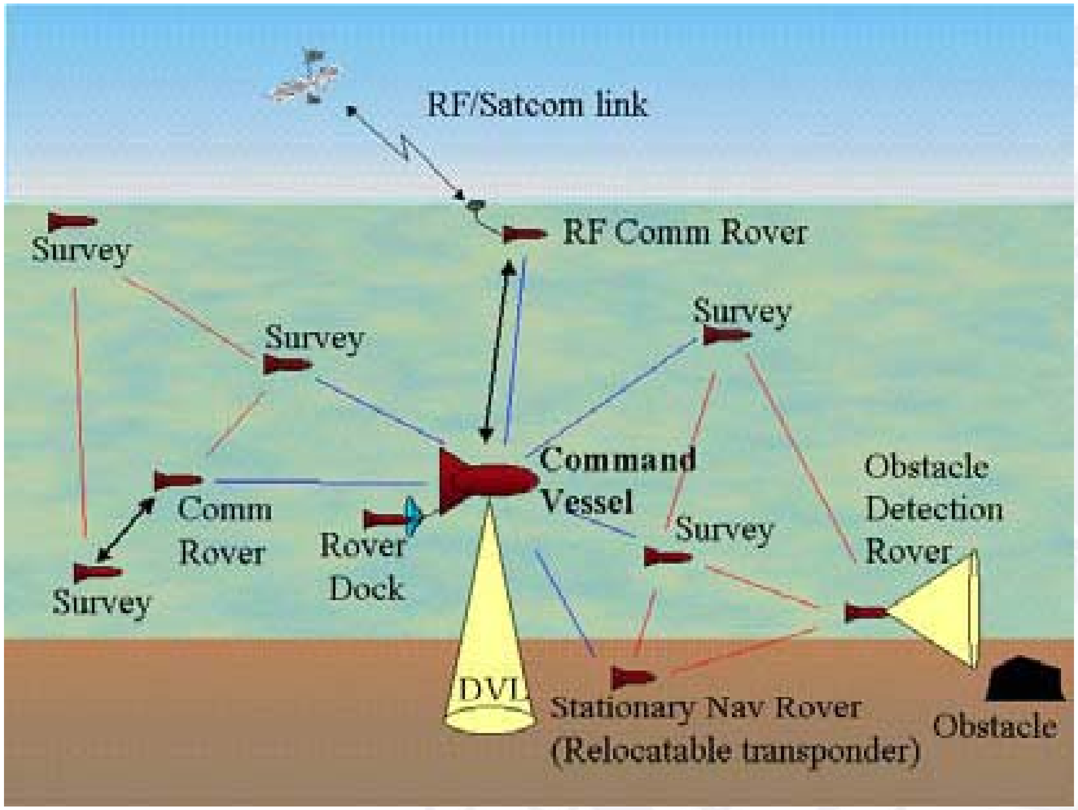
Mission Parallelization for a Group UUVs



integer linear programming (*ILP*)

Giger et al. (2007)

Multi-UUV Positioning/Communication



Acoustic → everybody listening (Bourgeois & McDowell, 2002)

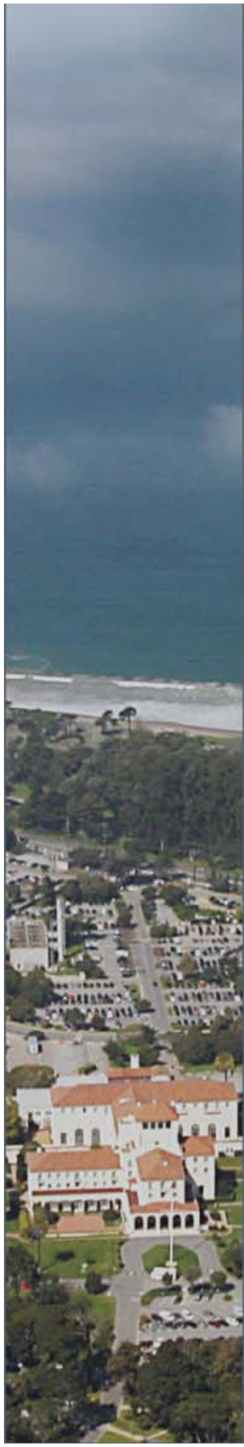
Laser → 200 m distance

Solving the Navigation Problem

- Return to a predetermined waypoint for a position fix

- Use Inertial Navigation System (INS) with GPS, Doppler Velocity Log (DVL)

- Use acoustic long-base-line (LBL), short-base-line (SBL), ultra-short-base-line (USBL) ← prior installation of beacon array



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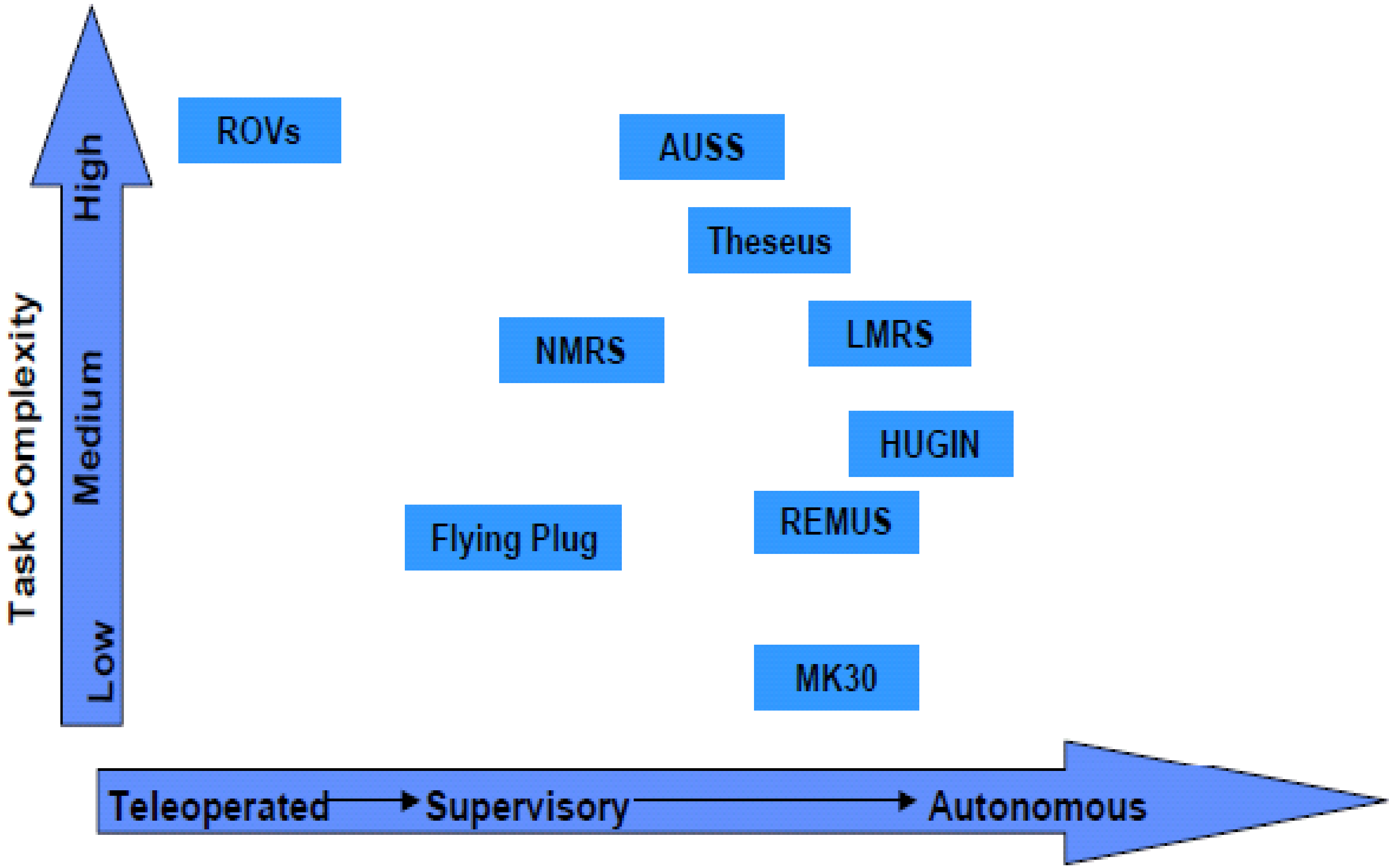
Key Technologies of UUV

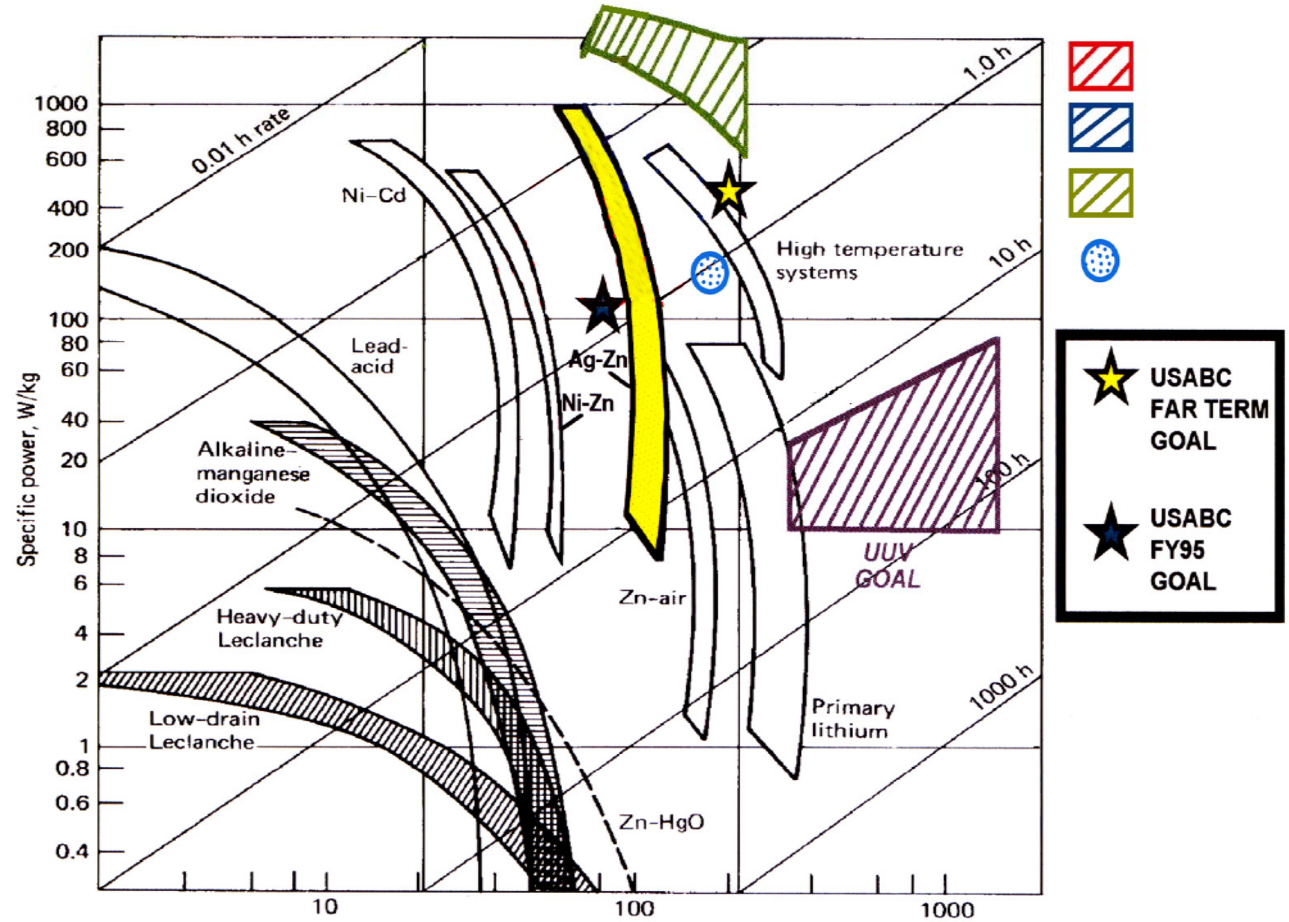
- System Autonomy
- Energy and Endurances
- Network Communications
- Materials, Platform and Structure
- Stealth Capability
- Interoperatability

UUV Comparison Factors

- Power/endurance
- Launch/recovery time
- Maneuverability
- Coverage rate
- Positioning
- Communications (bandwidth)
- Intelligence


Task Complexity
High
Medium
Low
ROVs
AUSS
Theseus
NMRS
LMRS
HUGIN
Flying Plug
REMUS
MK30
Teleoperated
Supervisory
Autonomous

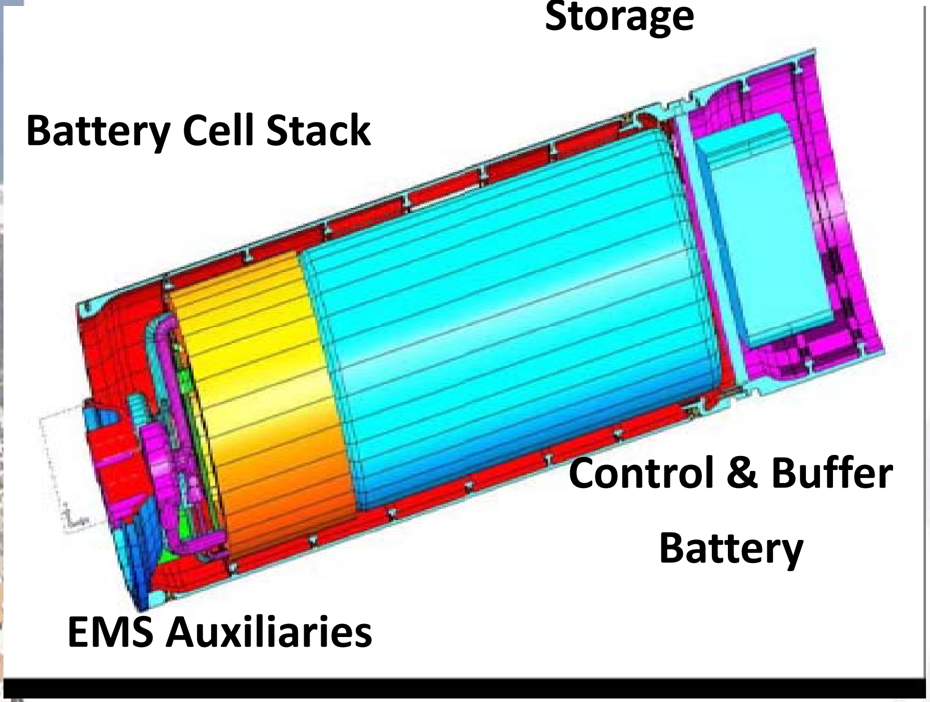
UUV Energy Needs



Specific Energy (W/kg)

- Source: David Linden Handbook of Batteries (1995)

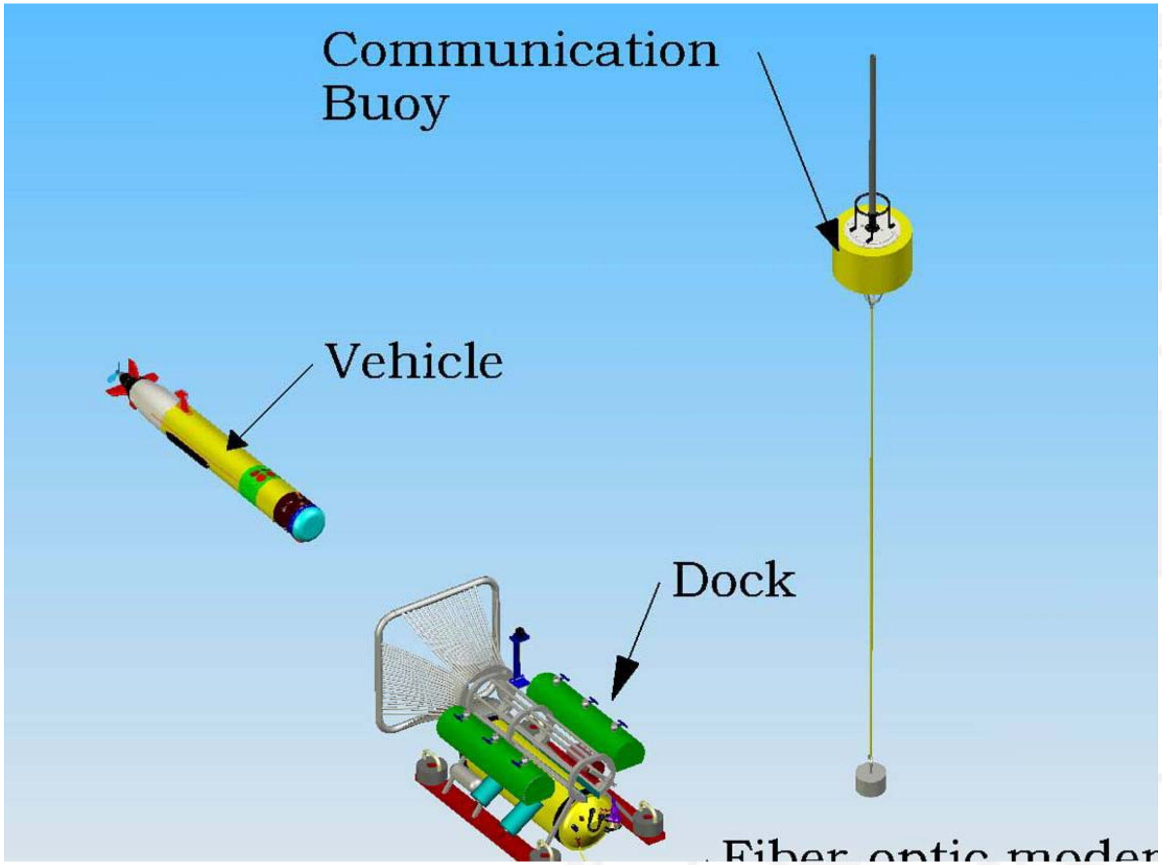
Air-independent Fuel Cells for UUVs (NUWC)



- Longer UUV missions as a result of higher energy density
- Faster turn-around time between missions (less down time)
- Decreased cost and increased safety versus primary lithium batteries
- Use of logistics fuels or even biodiesel

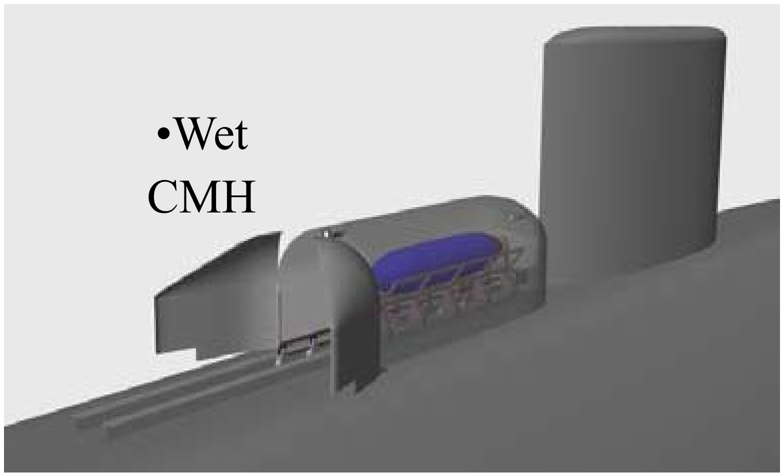
- For 21" UUV, available volume / mass: 189 L / 209 kg

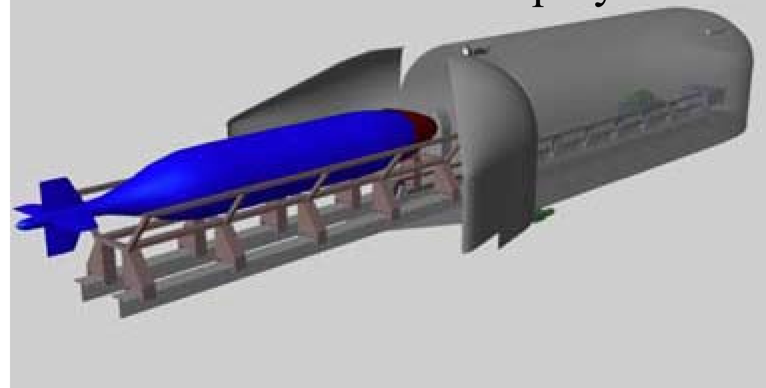
Docking System (from Allen et al., WHOI)



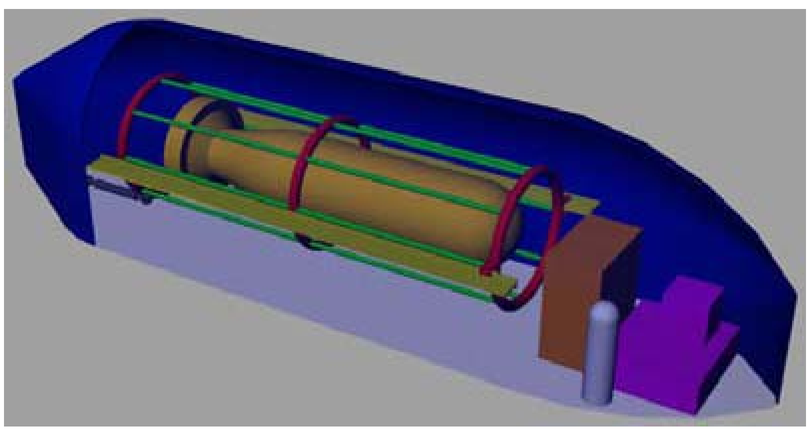
Launch and recovery

Casing Mounted Hangar (CMH) in Submarine

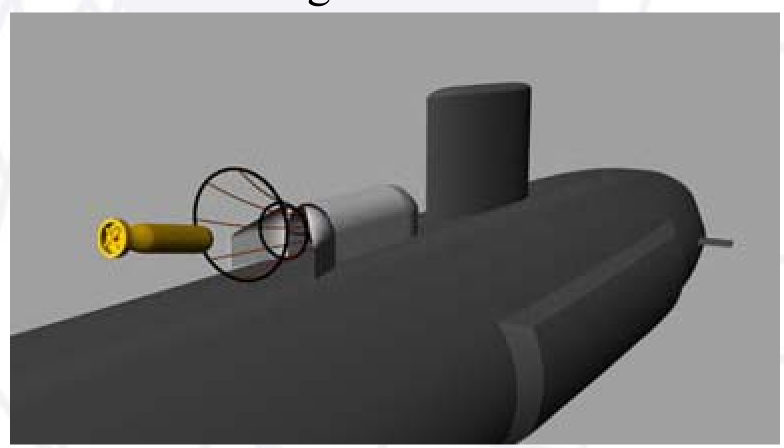

•Wet CMH

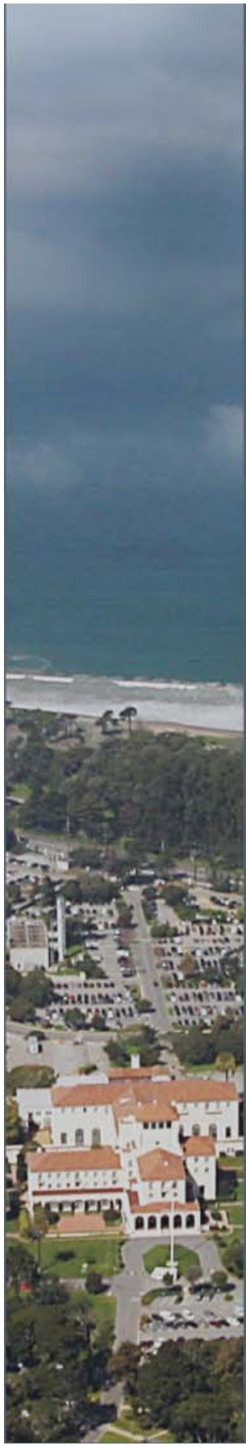

•Wet CMH with UUV Deployed

•AUV Secured in Wet CMH



•AUV Docking to Wet CMH





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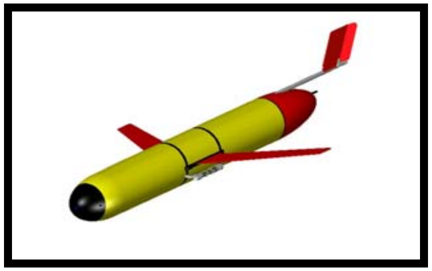
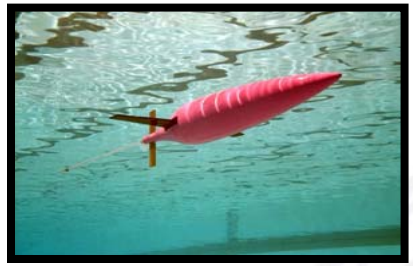
UUV – an Effective Marine Remote Sensing Technology

- to acquire high quality data of a prescribed area in reasonably fast time

(1) Glider → Increasing the endurance:
Power is needed only in ascending (changing the volume), but not in descending (gravity driven).

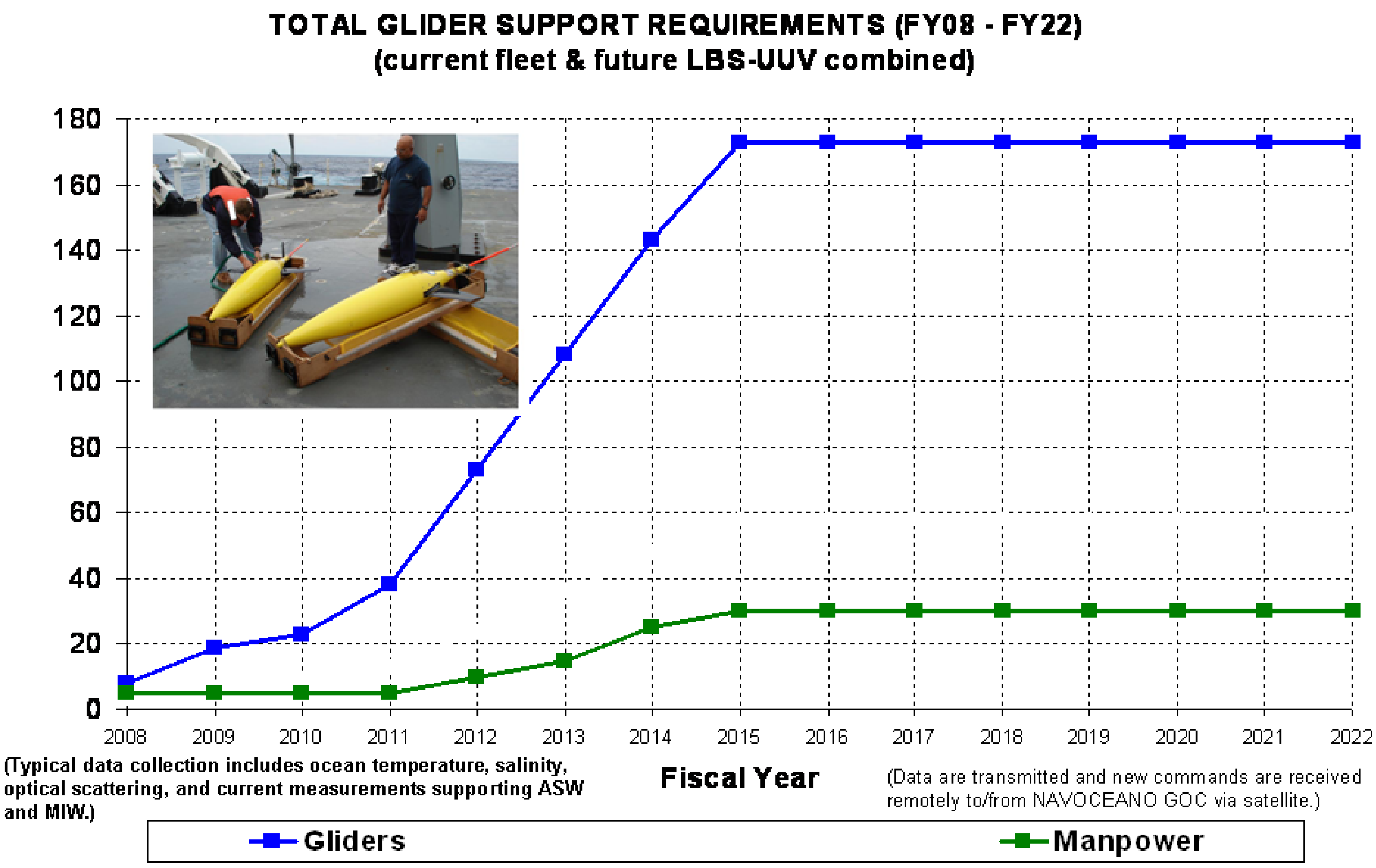
(2) Needs surveillance for gliders

Glider Specs

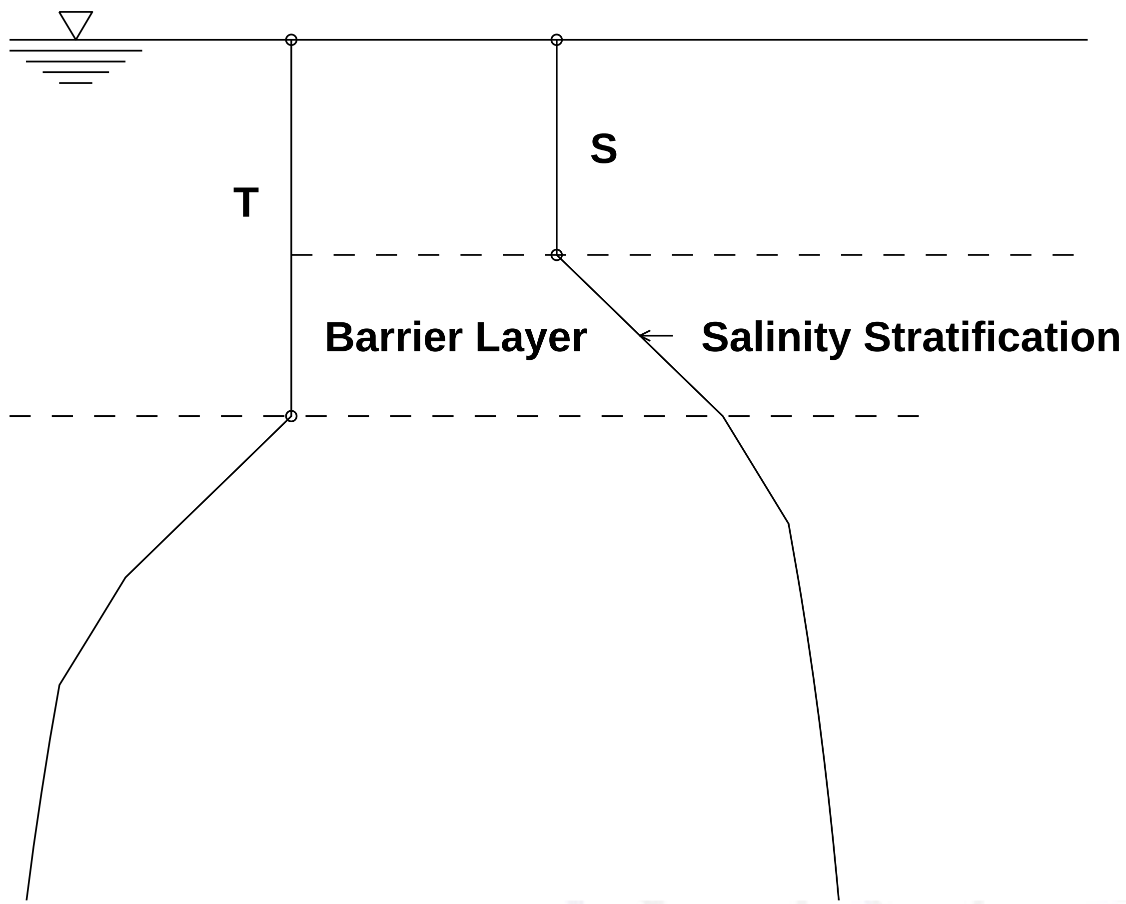
	Slocum Glider	SeaGlider	Spray Glider
	Webb Research	APL/UW	Scripps Institute
			
•Steering	Active Rudder	Roll / Bank	Roll / Bank
•Depths	4 to 200 m (option: 1000)	30 to 1000 m	30 to 1500 m
•Horiz. Speed	0.5 knots	0.5 knots	0.5 knots
•Nominal			
– Endurance	30 days	6 months	6 months
– Range	600 - 1500 km	4000 km	4500 km
•Power	Alkaline	Lithium	Lithium
•Hull Dia.	21 cm	30 cm	20 cm
•Length	1.5 m	2.8 m (w/1-m antenna)	2.15 m
•Weight	123 lb	110 lb	114 lb
•Comms	Iridium satellite phone	Iridium satellite phone	Iridium satellite phone

- Speed ~ 0.3 ms^{-1}
- Endurance: up to 6 months
- GPS navigation at surface
- 2-way satellite communications (Iridium)
- Measurements
  - Conductivity, temperature and pressure
  - Current velocities
  - Vertical velocity
  - Turbulence

Projected Glider Fleet Growth
in the Naval Oceanographic Office



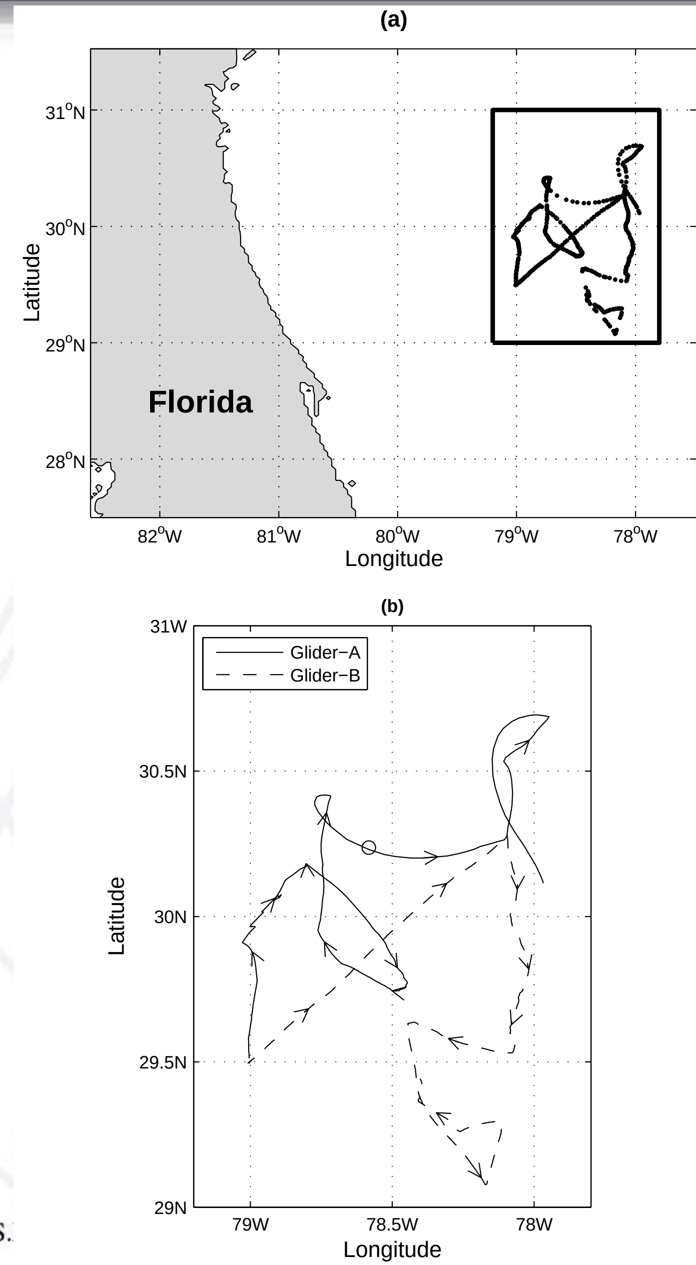
Barrier layer → heat exchange with deep layer → SST → climate change



Detection of Barrier Layer in the North Atlantic near Florida coast using Seagliders (Chu and Fan, 2010)

Solid Curve → Glider A

Dashed Curve → Glider B



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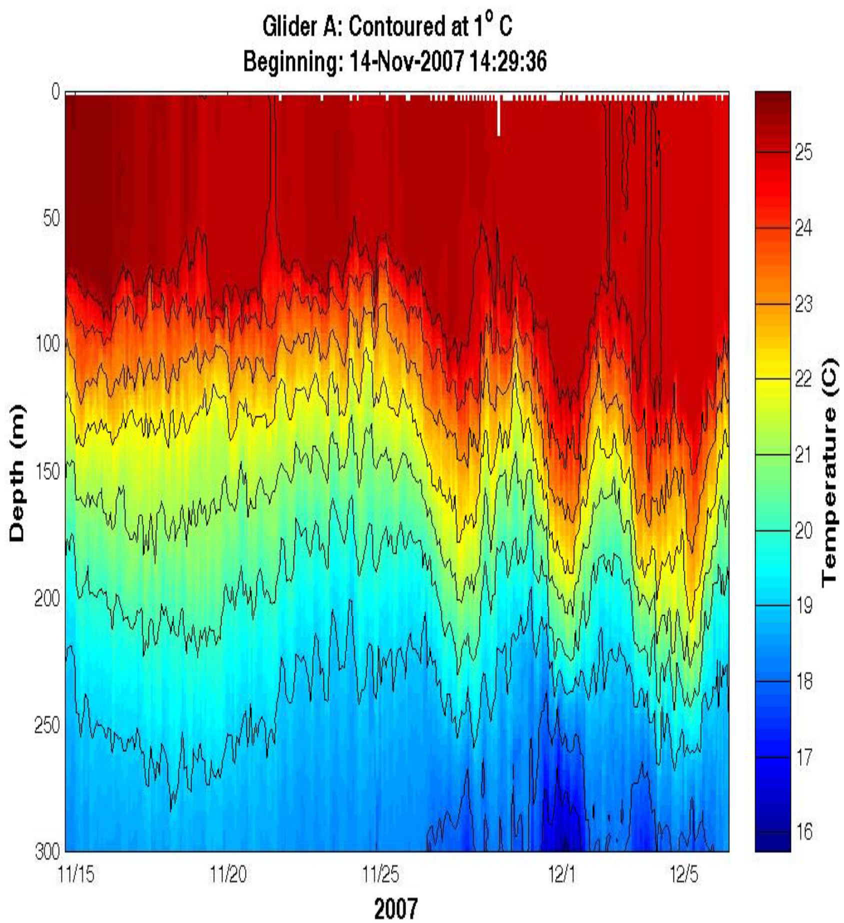
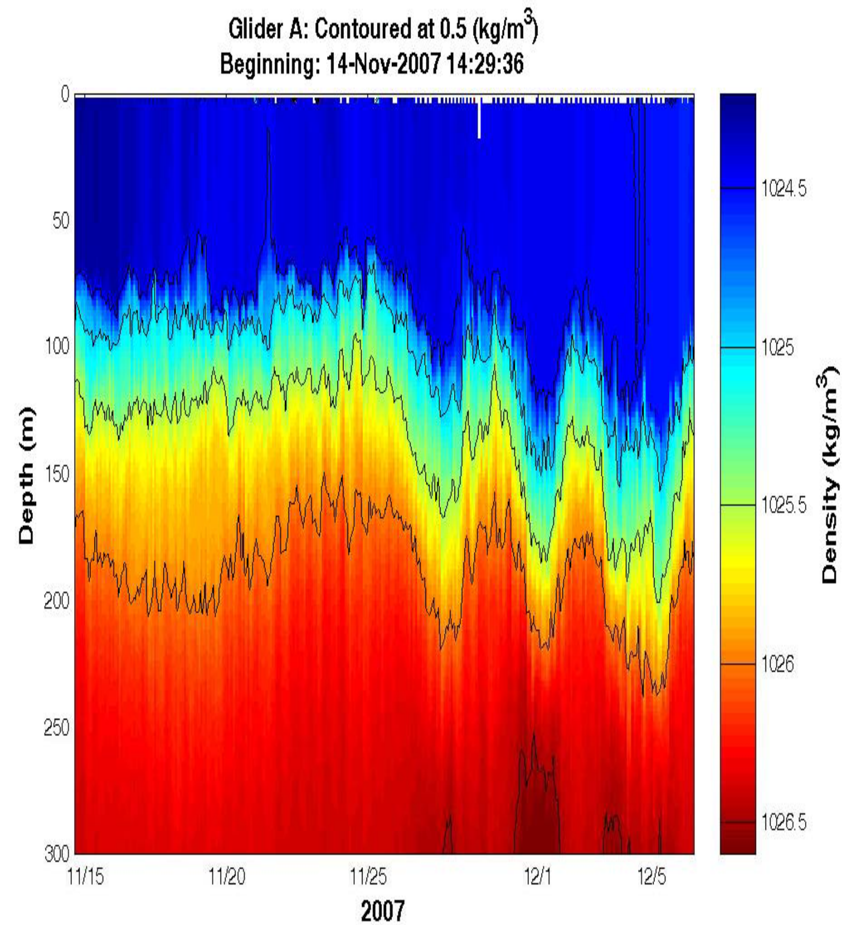
Time-depth cross section of temperature and density (Glider A)





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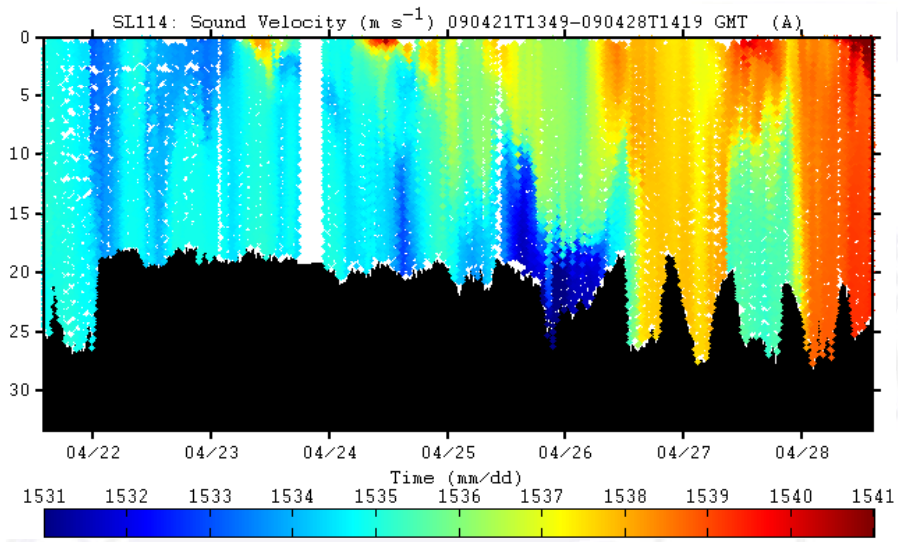
Glider Products – Sound Speed

- Sound speed used for MCM shipboard sonar
- MCMs stop every four hours to conduct a BSP cast
- Gliders measure same information, can be used by MCMs in immediate vicinity



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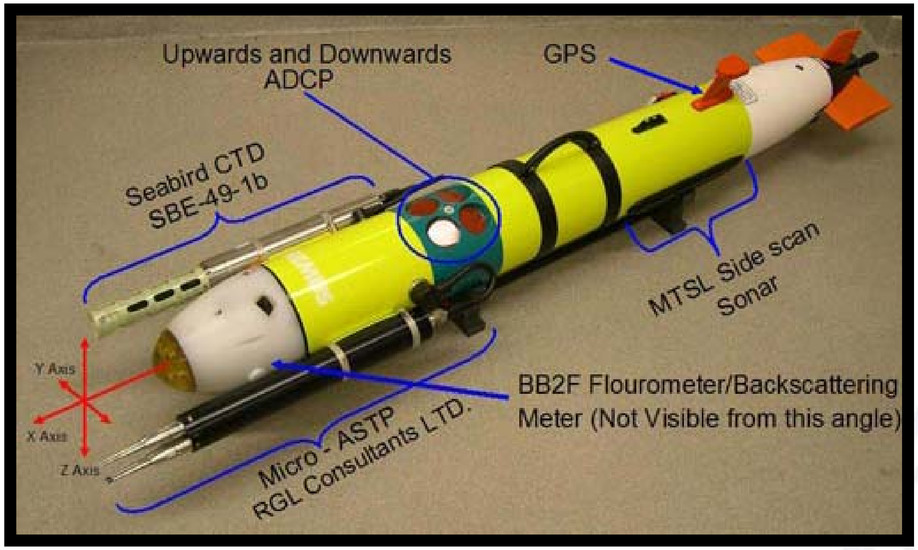
REMUS (50-100 watts)

- **Oceanographic Sensors**
- **Chemical Sensors**
- **Acoustic Communications**
- **Hull Inspection Camera Suites**

- **7.5”Diameter**

•SMAST T-REMUS & Its Sensor Suite



•Goodman (2005)

Equipments	Sensors	Signal	Sampling rate(Hz)	Location
RMMS	thrust probe	*dv/ds, dw/ds, v, w*	500	left nose cove(exterior)
	FP07 thermistor	*dT/ds, T*	500	left nose cove(exterior)
	pressure transducer	*dP/ds, P*	500	left nose cove(interior)
	Accelerometer	*ax, ay, az*	500	left nose cove(interior)
Seabird CTD		*T, S and D*	16	right nose cove
BB2F	Backscattering Meter	$Beta_{470}$ and $Beta_{700}$	1	left nose
	Fluorometer	*Chl a*	1	left nose
ADCP		*u,v*	0.2	middle

•T-REMUS AUV and Key variables:

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- CTD
- Buoyancy frequency

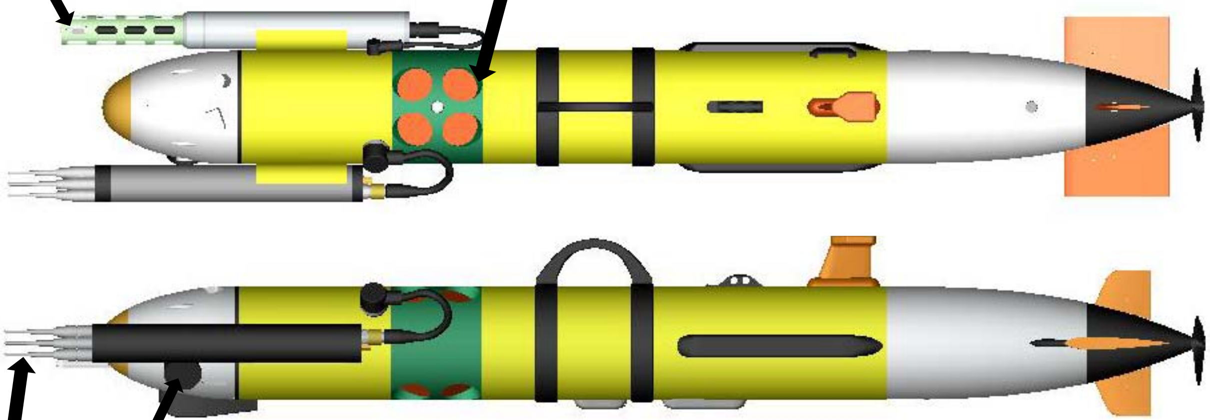
$$N = \sqrt{-\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}}$$

- ADCP
- Mean velocity shear

$$s = \frac{\partial u}{\partial z}$$

- Gradient Richardson Number

$$Ri = \frac{N^2}{\left(\partial \bar{u}/\partial z\right)^2} = \frac{N^2}{s^2}$$



- Turbulent Velocity w_{turb}

$$w_{turb} = \left(\varepsilon / N\right)^{1/2}$$

- Goodman (2010)

- ECO BB2F Backscattering Meter and Fluorometer
- Chlorophyll *a*

- Shear Probe
- Dissipation Rate

$$\varepsilon = \nu < \frac{\partial u_i}{\partial x_j}\frac{\partial u_i}{\partial x_j} >= \frac{15}{2}\nu < (\frac{\partial v}{\partial x})^2 >$$

- Buoyancy Reynolds Number

$$\mathrm{Re}_b = \frac{\varepsilon}{\nu N^2} = \frac{\kappa_\rho}{\nu \Gamma} = \left(\frac{l_B}{l_\nu}\right)^{4/3}$$

- Eddy Diffusivity

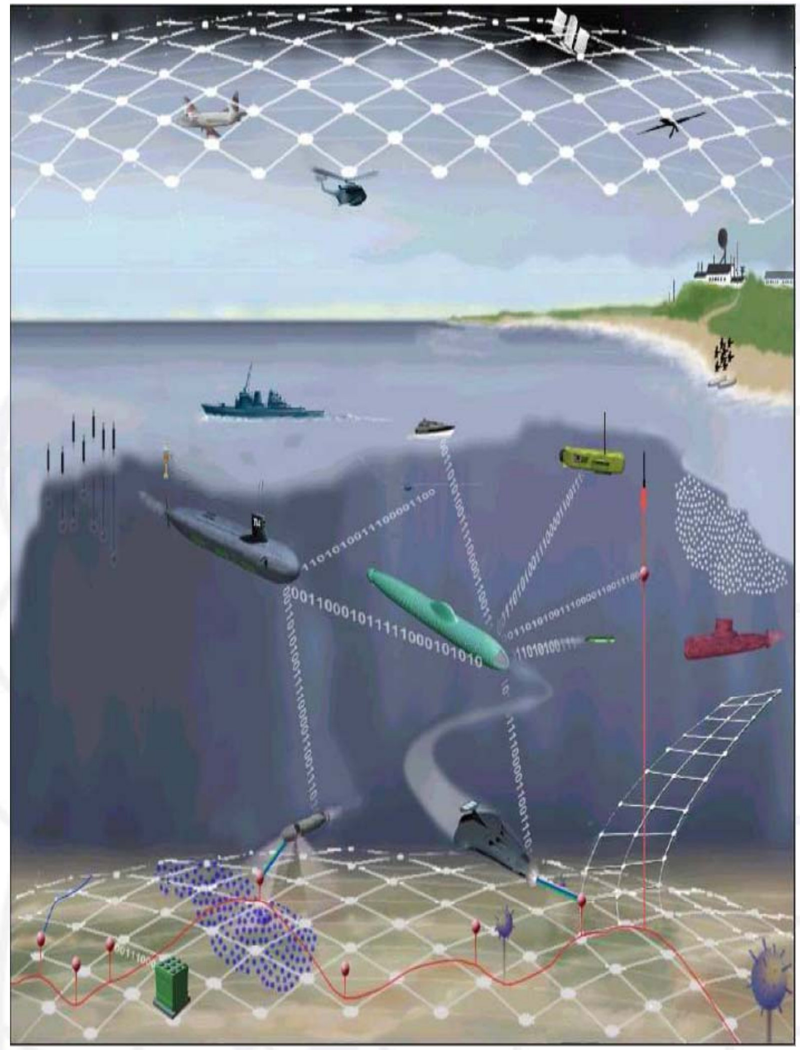
$$\kappa_\rho = \frac{<\rho' w'>}{|\frac{d\bar{\rho}}{dz}|} = \frac{\Gamma \varepsilon}{N^2} = \Gamma \nu \mathrm{Re}_b$$

$$\Gamma \approx .2$$

(6) Future …

- Systematic and Effective National Research and Development
- Core Technology Selection
- Optimized and Effective UUV System Configurations
- Synergy Effects over National Unmanned System Researches

Communication and Sensor Technology

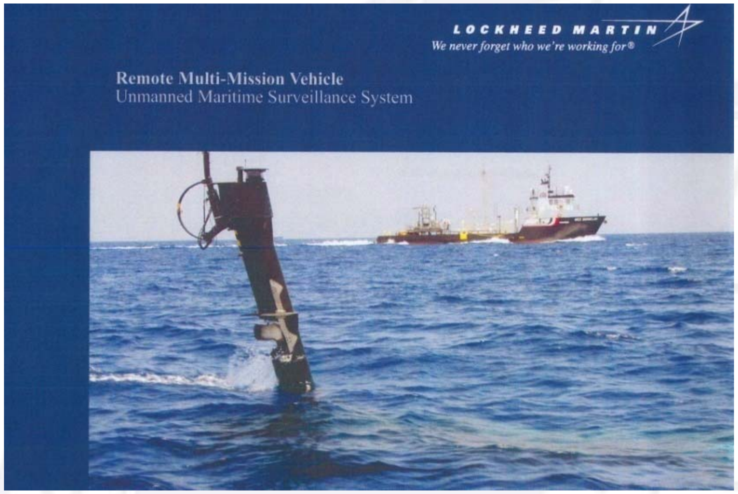


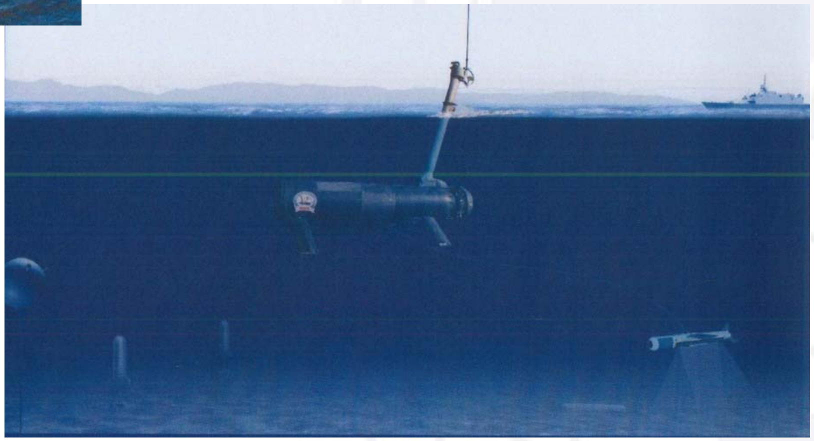
Archerfish Mine Disposal System (UK Navy)

•mine-seeking expendable neutraliser

•up to four times faster than conventional remotely-controlled mine disposal vehicles.

Remote Minehunting System (RMS)





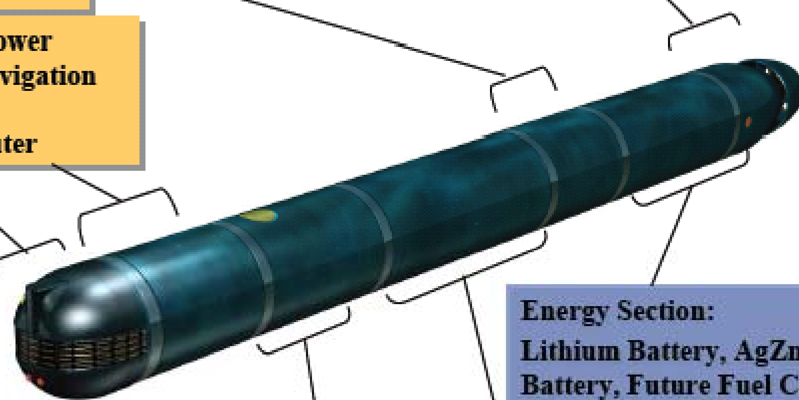
Conceptual 21” Diameter Mission Reconfigurable UUV

Propulsion Section: Trust Vectored Pumpjet, Control Surfaces, Recovery and Handling System, Future Integrated Motor Propulsor

Ballast and Trim Section: Pump, Valves, Aft Tank

Electronics and Control Section: Power Distribution, Vehicle Computer, Navigation System, Communications System, Payload/Vehicle Integration Computer

Nose Section: FLS, Acoustic Communications System



Energy Section: Lithium Battery, AgZn Battery, Future Fuel Cell

Mission Payload Section: 5 Cubic Feet with Standard Interfaces

Forward Auxiliary Section: SATCOM & GPS Antennas, Antenna Mast, Anchor, Forward Ballast Tank

- 20.95 Inches OD, 240 Inches Long
- Weight = About 2800 lbs
- Speed = 3 to 8 knots
- Sortie Reliability Ps = 0.953
- Sortie Duration = up to 40 Hours
- Sortie Reach = 75 - 120 NM
- Full Impulse Launch Capable

MRUUVS Overview

- **Initial Capability: Conduct autonomous, clandestine MCM and ISR missions at significant standoff distances with IOC for MCM in 2016**
  - Launch and recovery from SSN 688/688I/774 classes (Threshold)
  - Leverage host platform mobility and dwell time
  - Extend stealth and sensor reach into operating areas that are not otherwise accessible
  - Complement host SSN sensors to enable simultaneous coverage at multiple sites
- **Major MRUUVS components**
  - DE -- Deployed Equipment
  - MRUUV -- reconfigurable vehicle and modular payload
  - NDE -- Non Deployed (support) Equipment

- **Follow-on capability increments: Oceanography, Information Operations and MASINT**

AN/BLQ-11 Long-term Mine Reconnaissance System (LMRS)

- **L&R Test #1 - USS OKLAHOMA CITY (SSN 723) September 2005**
  - Recovery arm extensions at depth
  - INU alignments from shipboard navigation system using both UUVs
  - UUV impulse launch and powered up
  - SSN / UUV operation validated
  - Shadow Submarine algorithm performance verified
- **L&R Test #2 - USS SCRANTON (SSN 756) January 2006**
  - UUV impulse launch and powered up
  - 24 runs performed by UUV#1 and UUV#2
  - Repeated demonstrations of SSN breaking UUV out of station-keeping and achieve shadow submarine
  - Demonstration of UUV safely break-off from H&D and open SSN in a reliable, repeatable manner
  - UUV maintained shadow submarine position through a 180° turn
  - UUV successfully docked to Recovery Arm
- **L&R Test #3 Planned Summer 2007**
  - Demonstrate successive UUV launch and recovery end to end operation

Left Click Image to run video. Page

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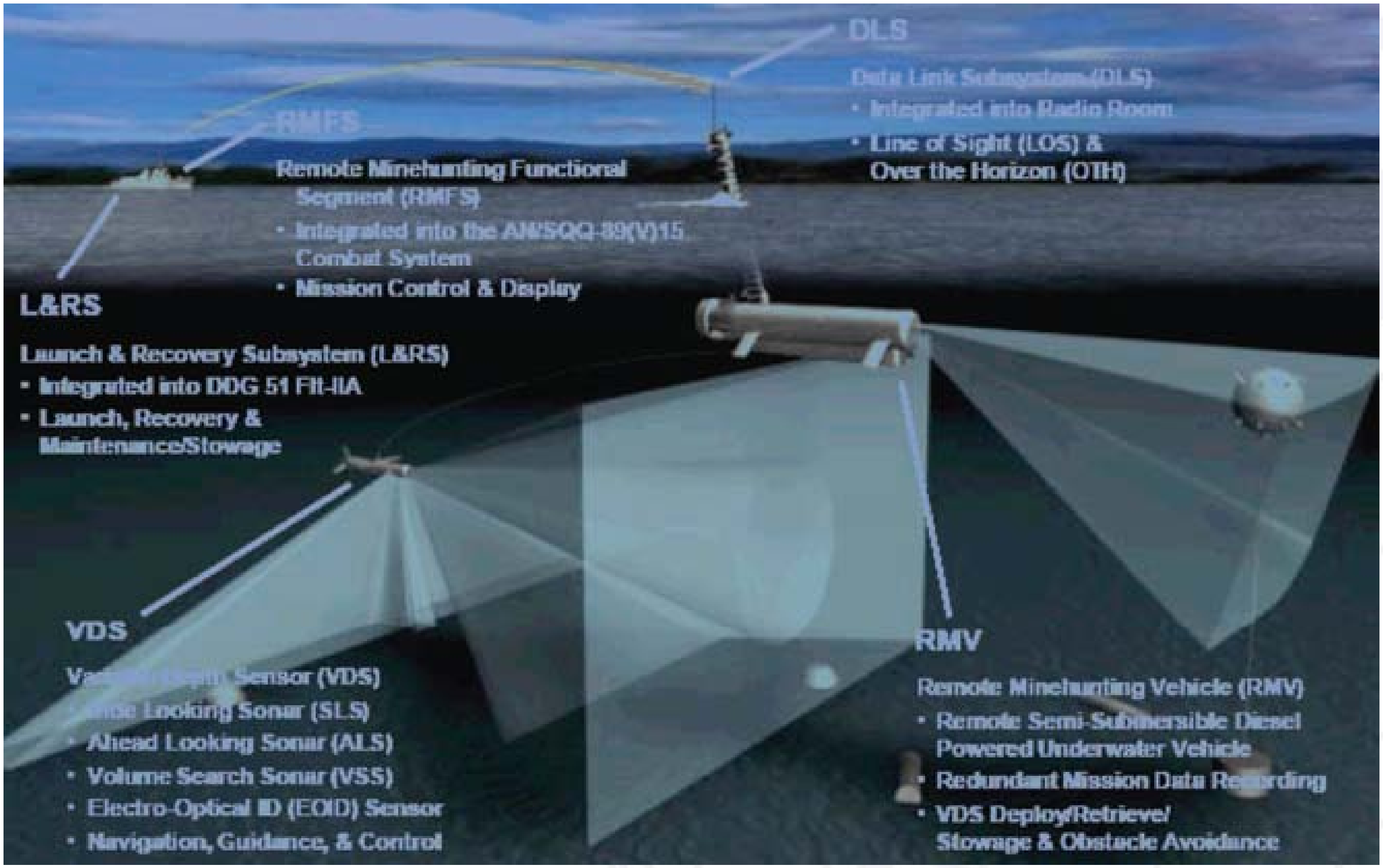
POSTGRADUATE
SCHOOL

Center for Autonomous Vehicle Research
CAVR

The AN/WLD-1 RMS in Operation



•SOURCE: Image courtesy of the Lockheed Martin Corporation

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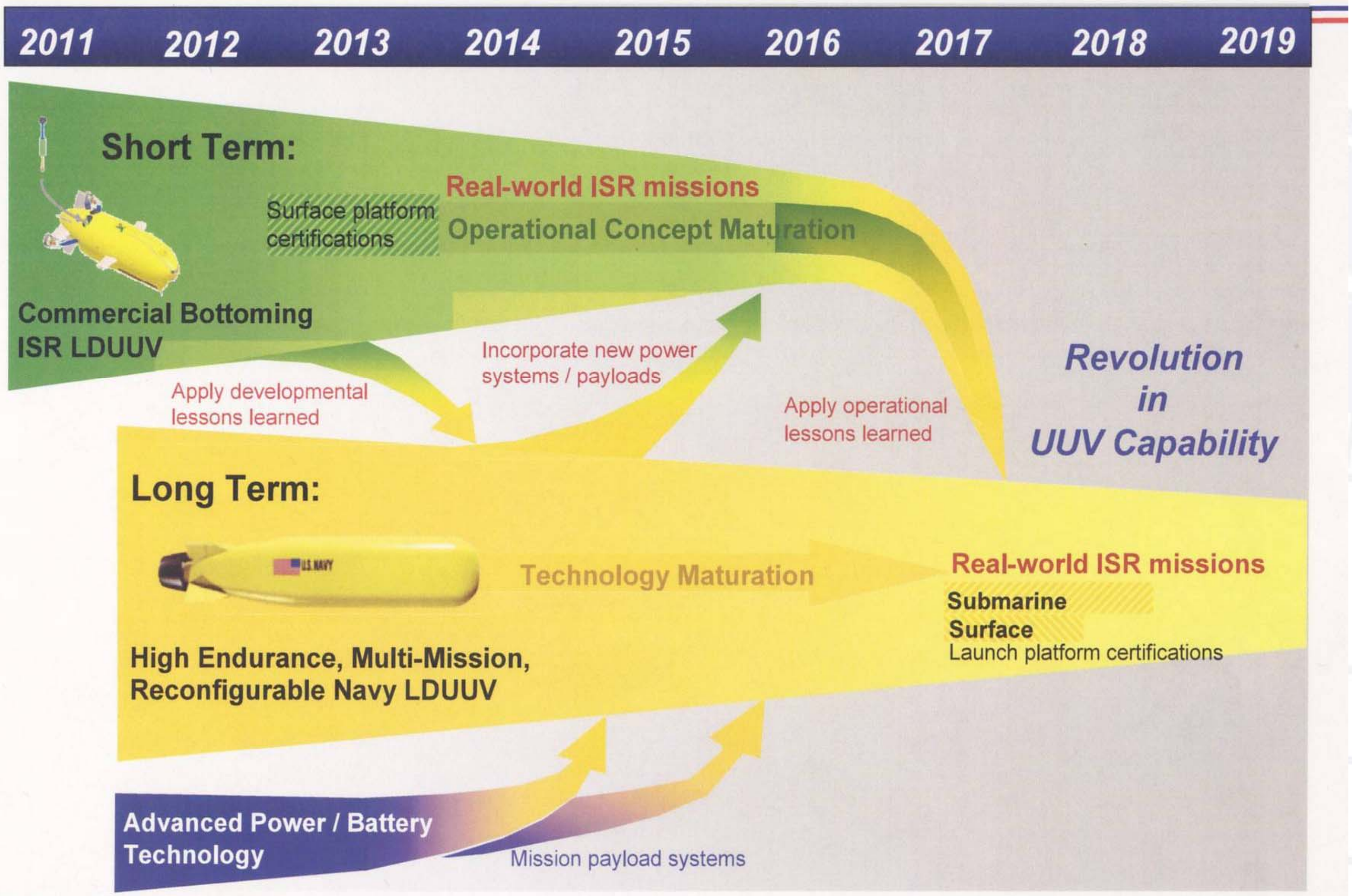
UUV ISR Roadmap
"Path to Persistence"



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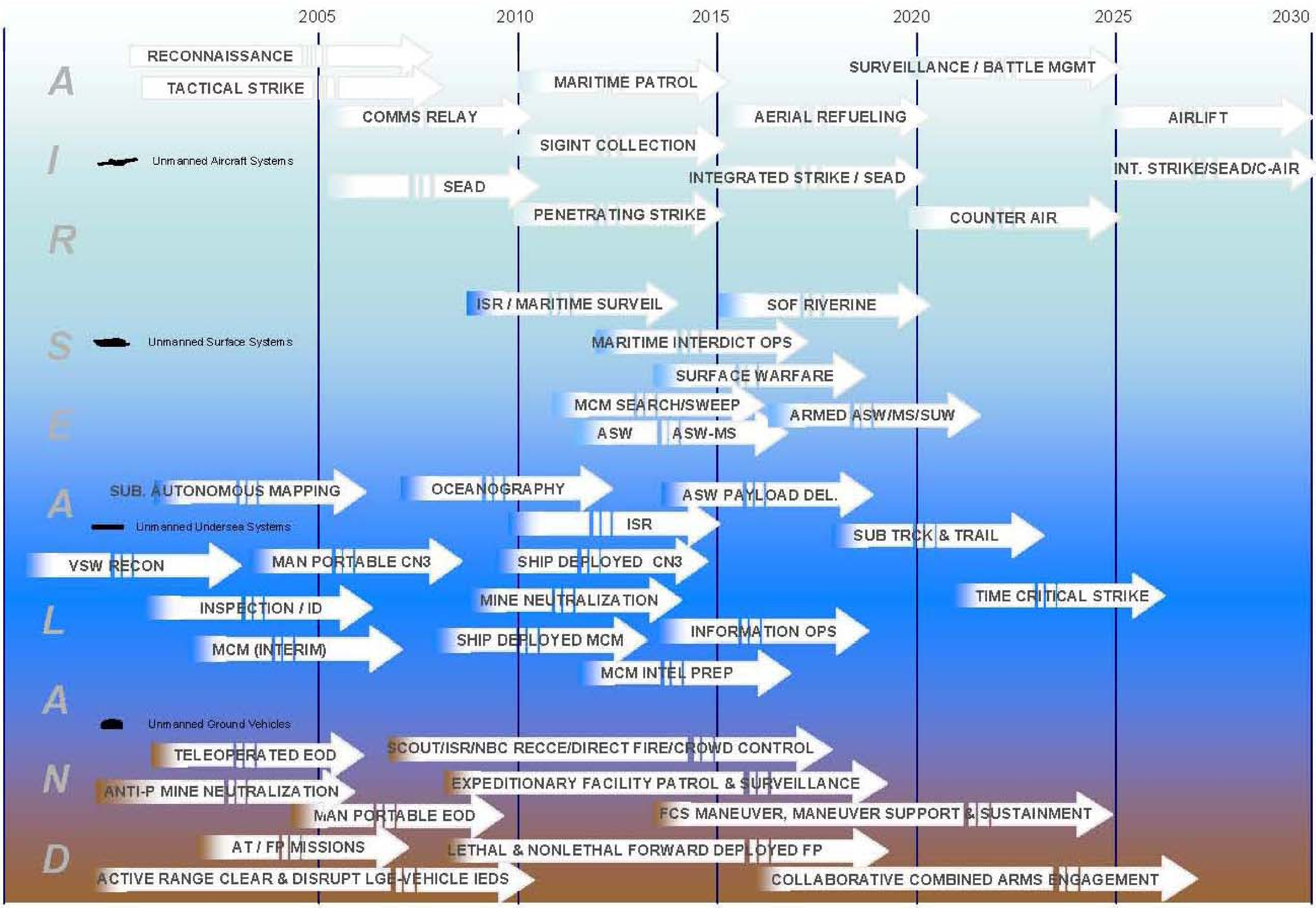
Unmanned Systems Roadmap 2007-2032



Suggestion

Korean Version of UUV Master Plan is needed.

Thank you very much for your attention !!

Questions?