Development of Nereid-UI: A Remotely Operated Underwater Vehicle for Oceanographic Access Under Ice

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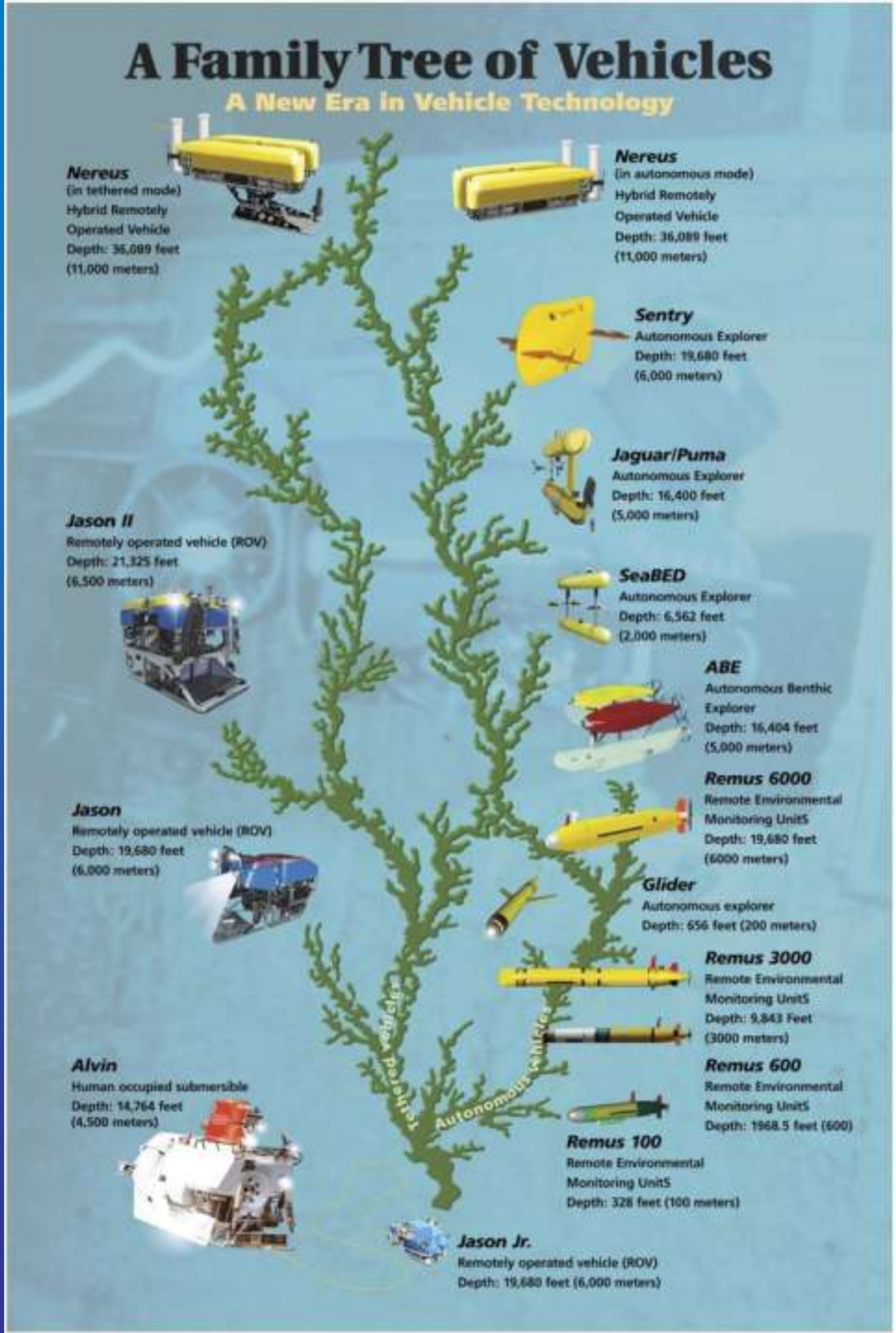
Photo courtesy S. McPhail, NOC

Woods Hole Oceanographic Institution

World's largest private ocean research institution

~900 Employees, 143 Scientific Staff
$160M Annual Budget

- Biology
- Chemistry
- Geology
- Physical Oceanography
- Engineering
- Marine Policy



WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Deep Ocean Oceanography:
The *D.S.V. Alvin 4500m Submersible*

Ph.D. Student James Kinsey

Image Credit: Rod Catenach © WHOI

Crew:	3 = 1 pilot + 2 scientist
Depth:	4500m (6,500m soon)
Endurance:	6-10 Hours
Speed:	1 m/s
Mass:	7,000 Kg
Length:	7.1m
Power:	81 KWH
Life Support:	72 Hours x 3 Persons
Dives:	>4,700 (since 1964)
Passengers:	>14,000 (since 1964)

Jason II ROV

Specifications:

Size: 3.2 x 2.4 x 2.2 m

Weight 3,300 kg

Depth 6,500 m

Power 40 kW (50 Hp)

Payload: 120 Kg (1.5 Ton)

First Dive: 2002

Dives: >600

Dive Time: >12,500 Hours*

Bottom Time: >10,600 Hours*

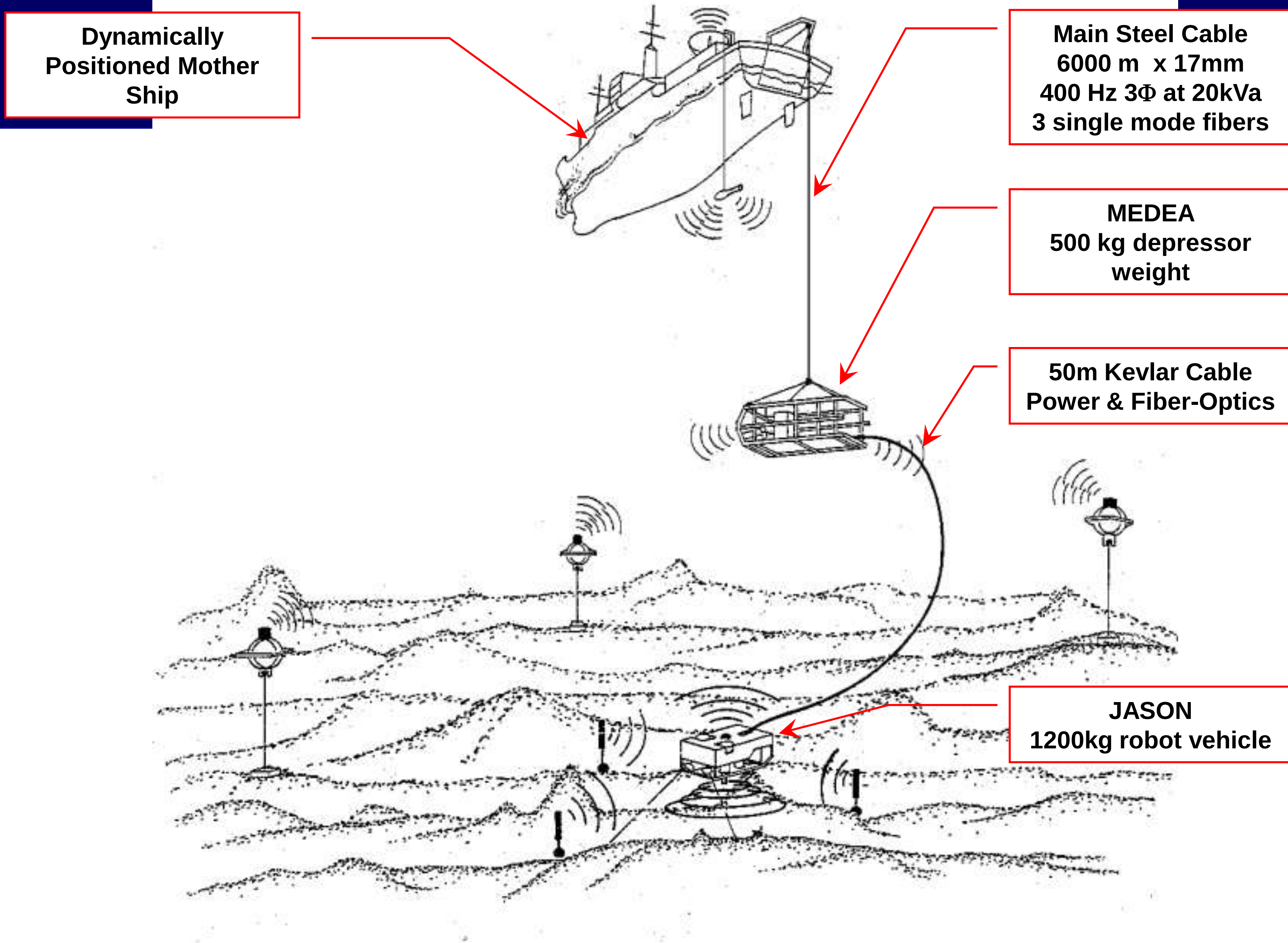
Longest Dive: 139 Hours*

Deepest Dive: 6,502 m*

Distance: >4,800 km*

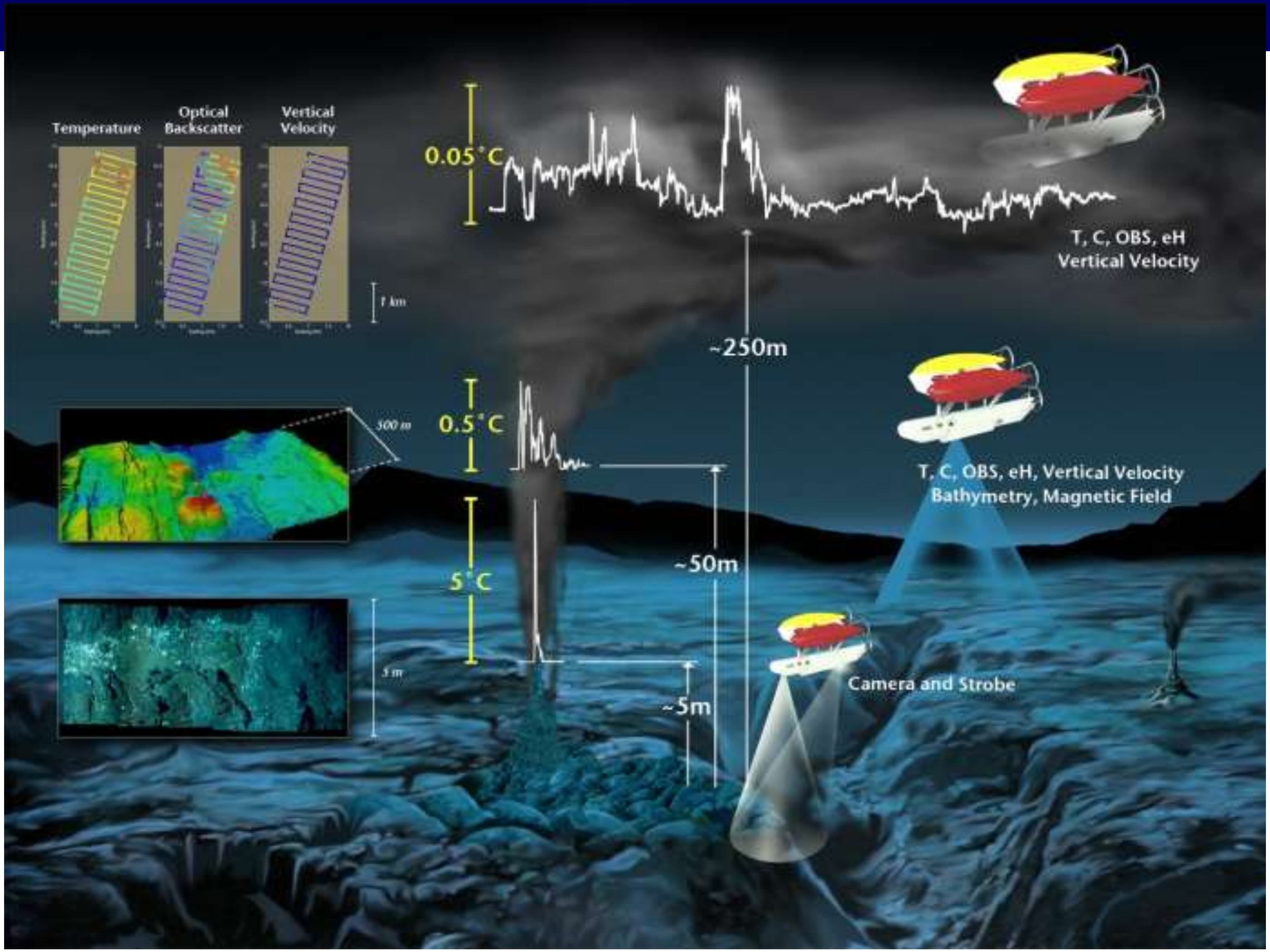
* As of Feb, 2012

Electric thrusters, twin hydraulic manipulator arms.



Dynamically Positioned Mother Ship
Main Steel Cable 6000 m x 17mm 400 Hz 3Φ at 20kVa 3 single mode fibers
MEDEA 500 kg depressor weight
50m Kevlar Cable Power & Fiber-Optics
JASON 1200kg robot vehicle

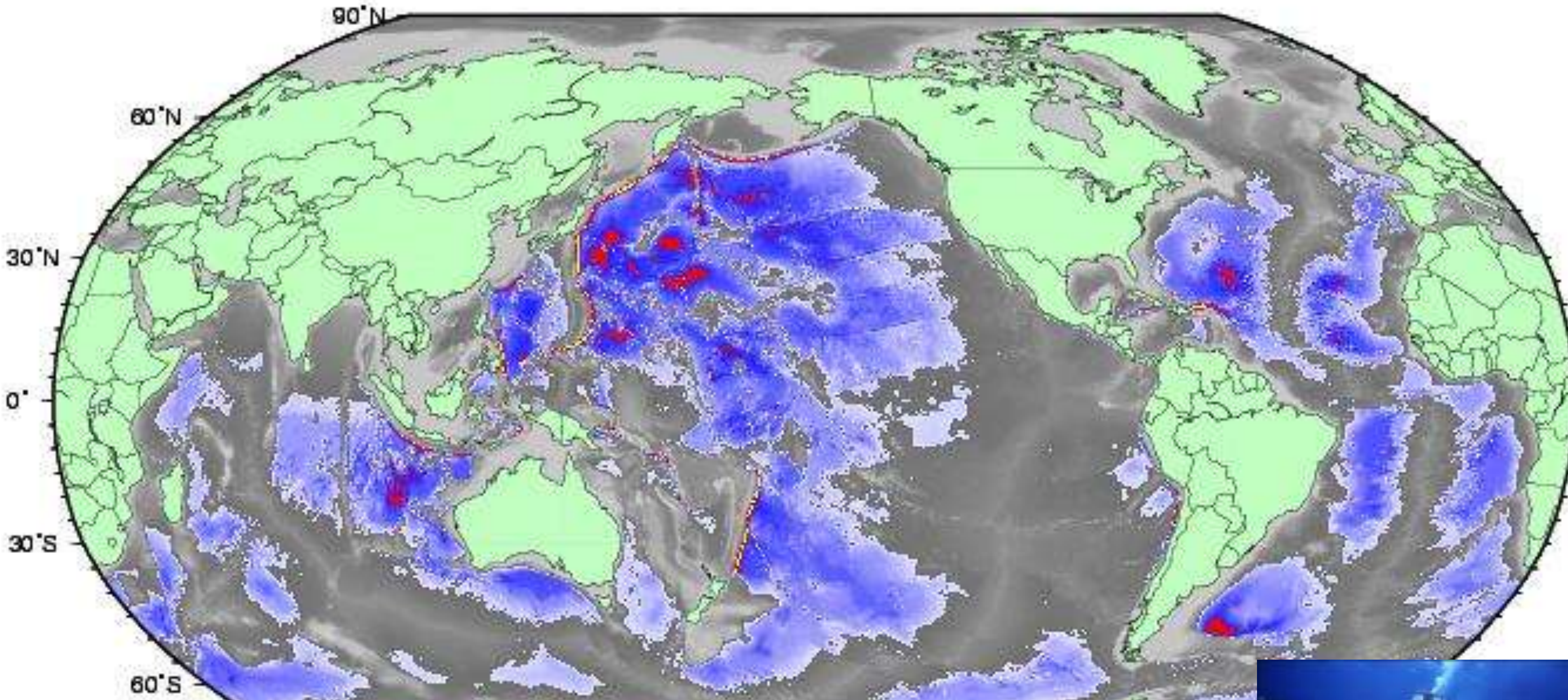
The Autonomous Benthic Explorer (ABE)

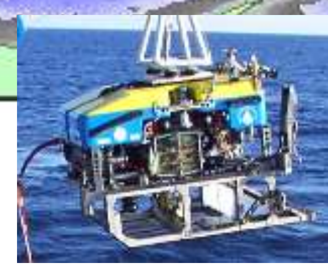


Vent discoveries in the Lau Basin (near Fiji), Southern Mid-Atlantic Ridge, Southwest Indian Ridge.

(German, Yoerger, et al, 2004)

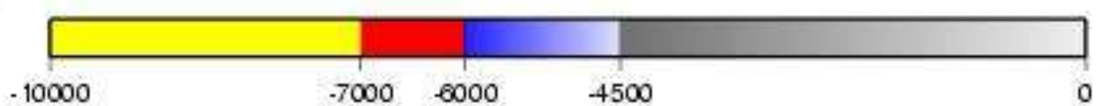
SPAWAR Systems Center San Diego

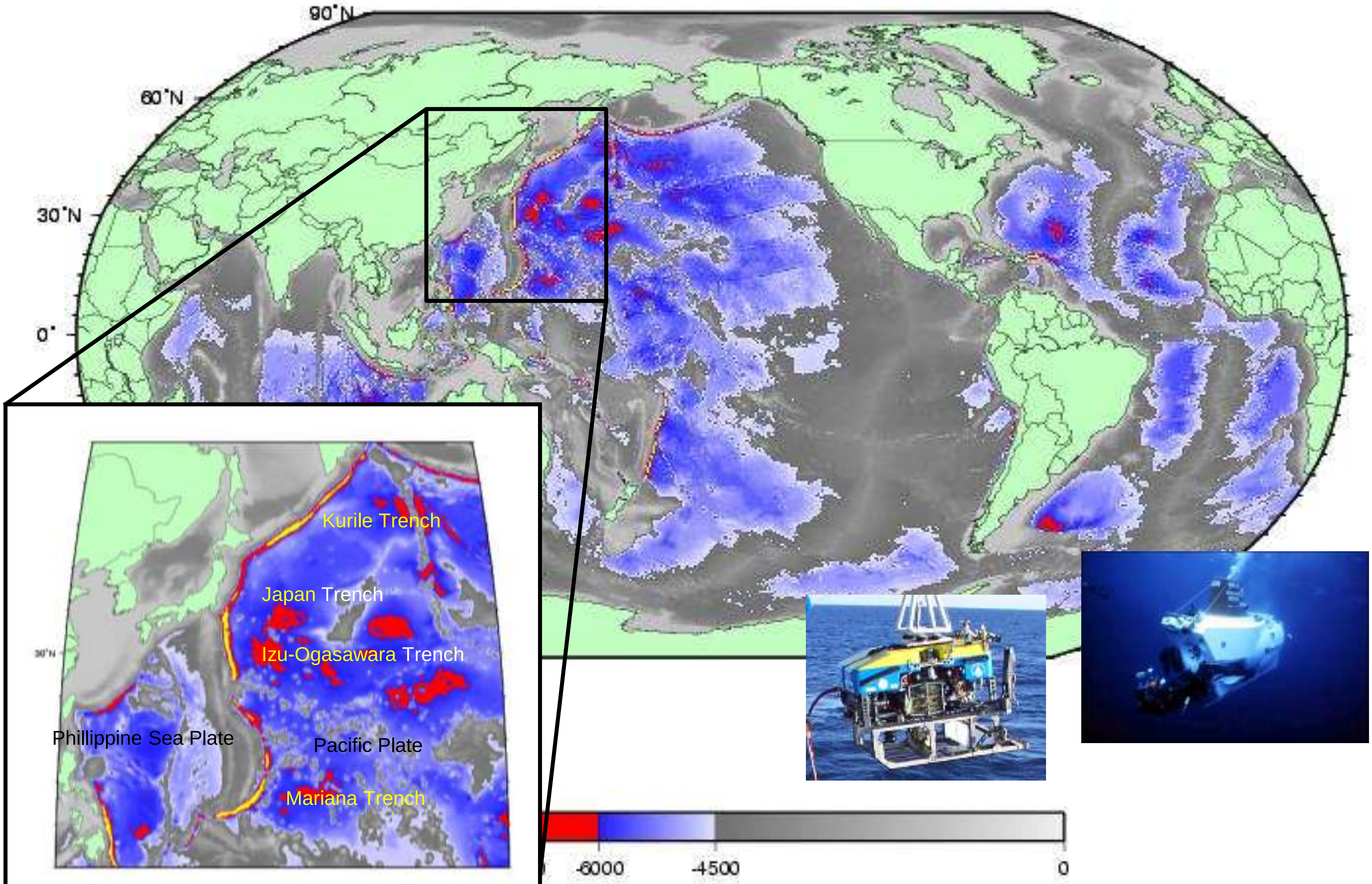


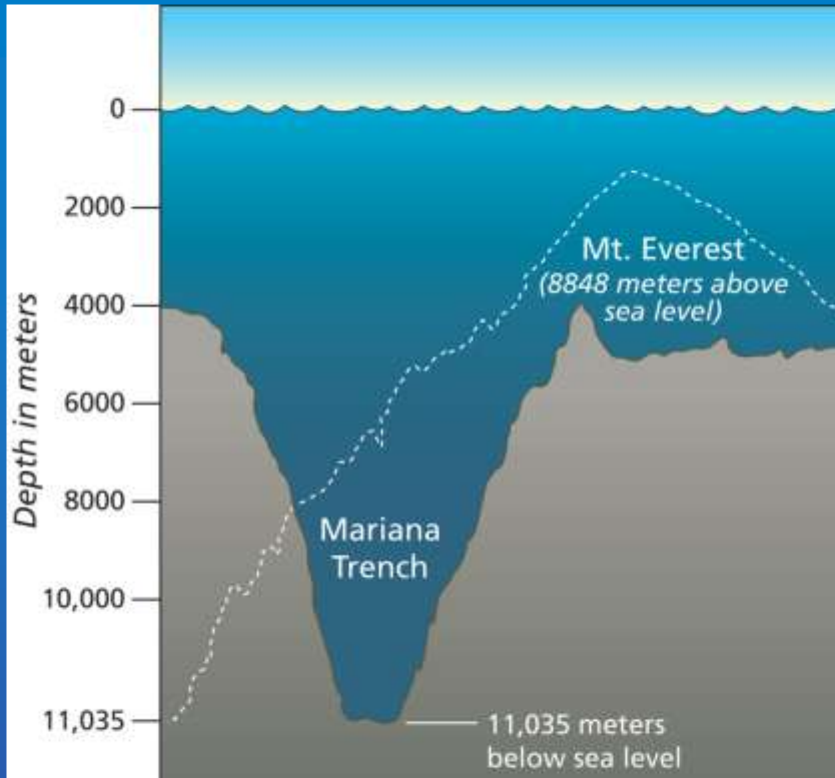


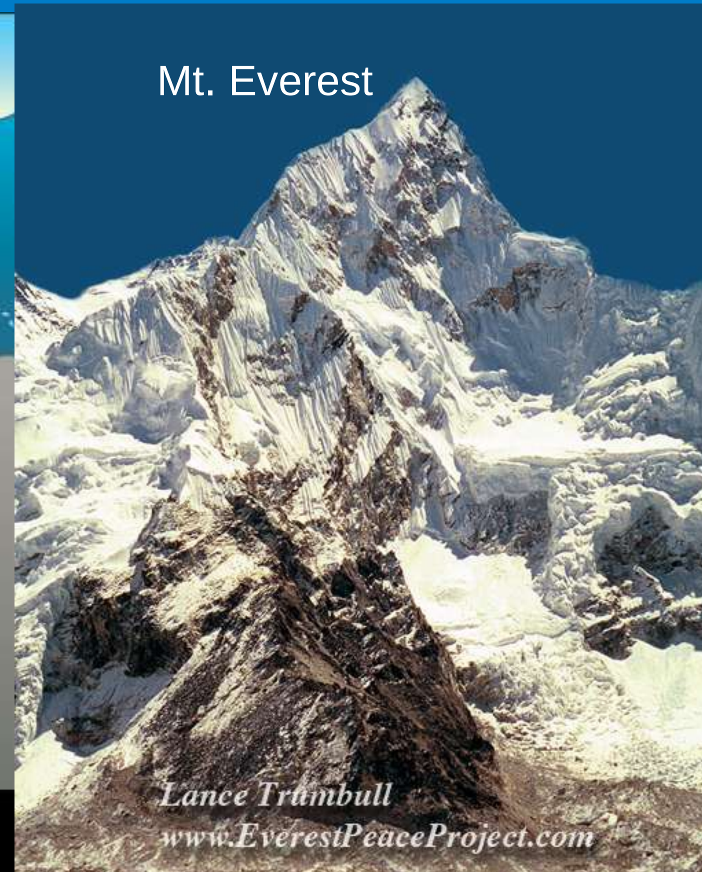
Global Ocean depth chart

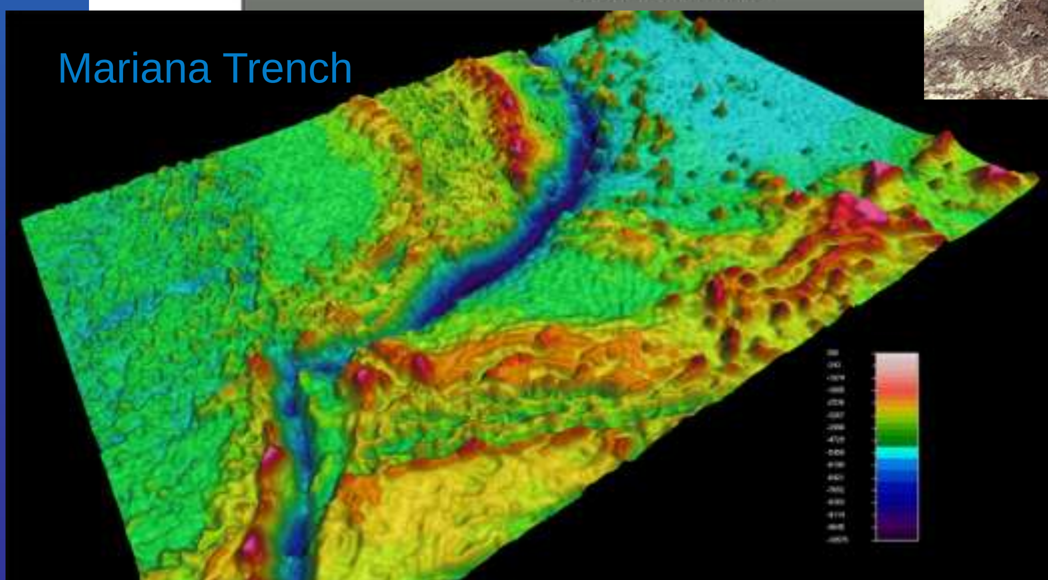
Robinson projection




90°N
60°N
30°N
0°
Kurile Trench
Japan Trench
Izu-Ogasawara Trench
Phillippine Sea Plate
Pacific Plate
Mariana Trench
-6000
-4500
0





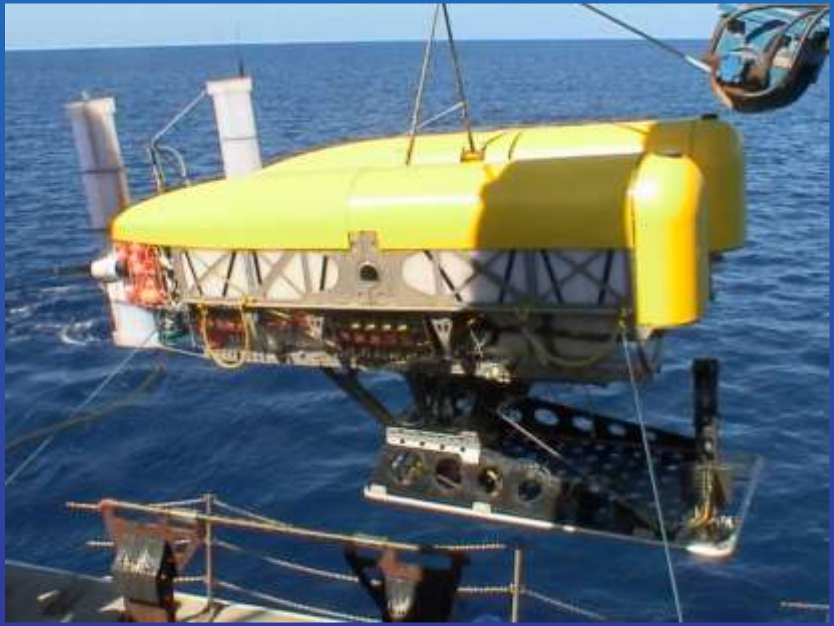


How to visit the deepest part of the ocean in a cost-effective way?

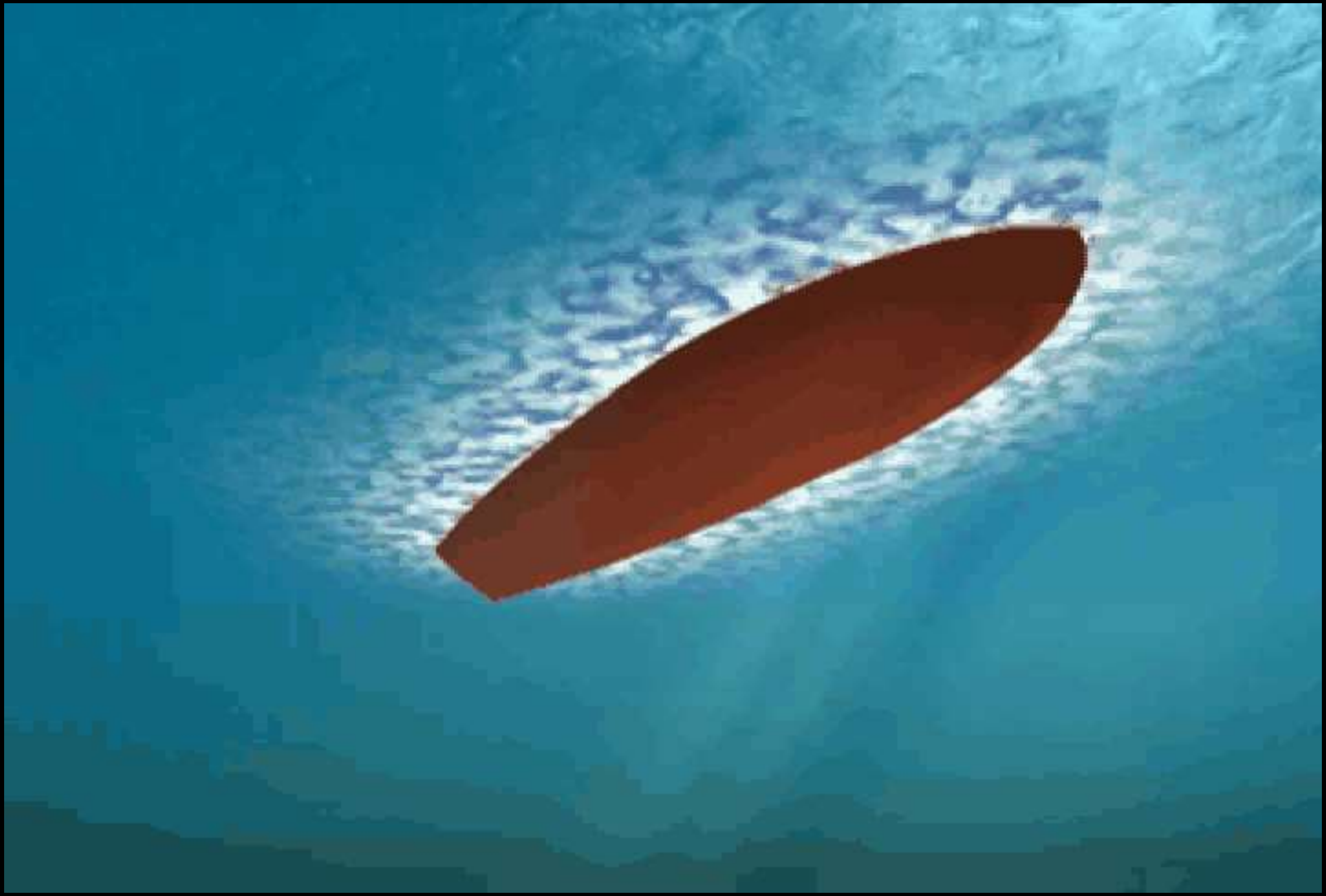
11,000 Meters an Easier Way

- A Hybrid cross between autonomous and remote-controlled undertwater vehicle
    - Untethered autonomous underwater vehicle (AUV) for mapping
    - Tethered remotely operated vehicle (ROV) for close inspection, sampling and manipulation

- New Class of vehicle intended to offer a cost effective solution for survey/sampling and direct human directed interaction with extreme environments through the use of new technologies



The *Nereus* Hybrid Remotely Operated Vehicle



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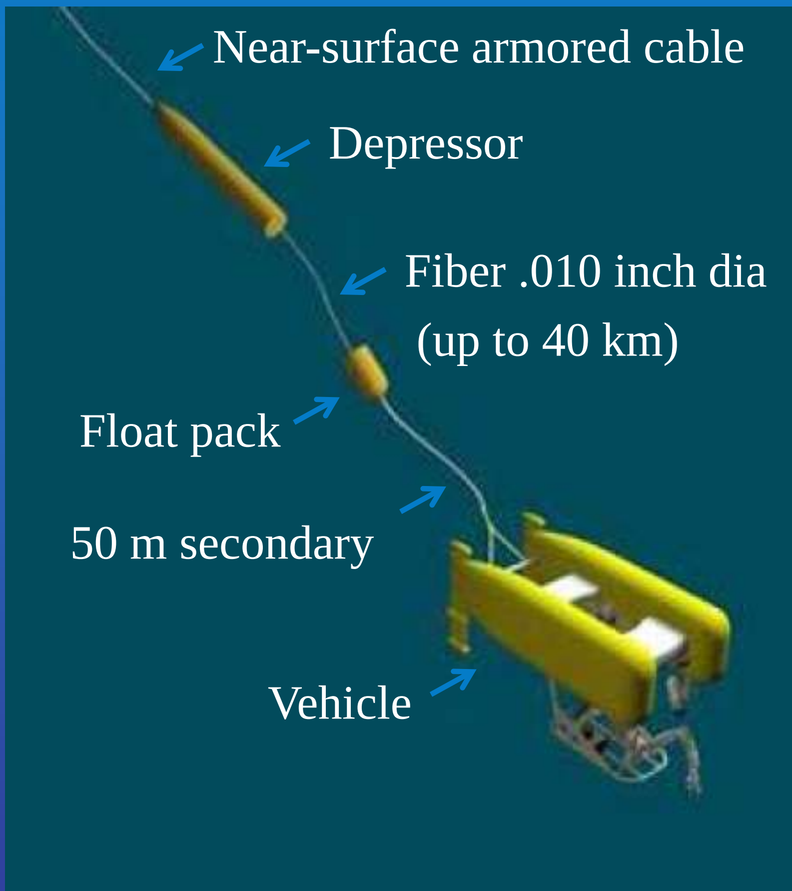
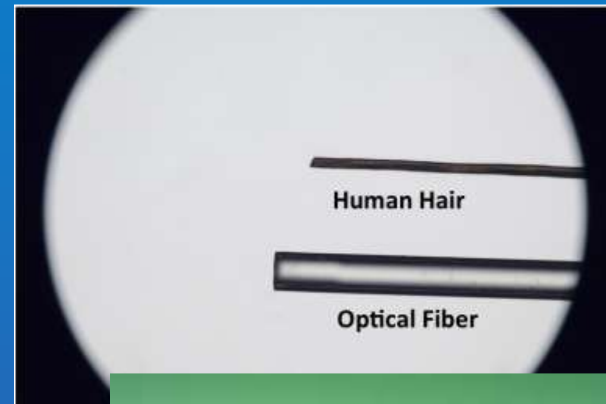
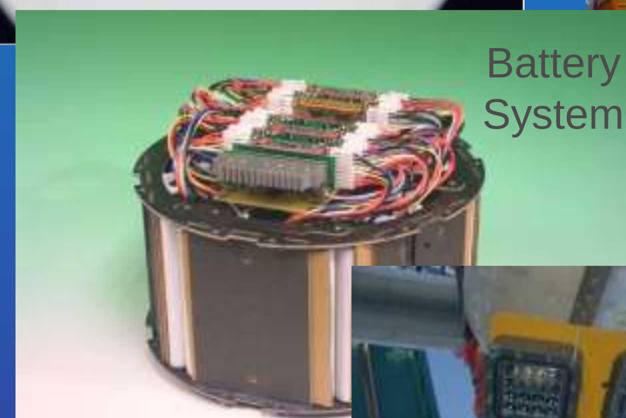
Antecedent Technology:
Nereus 11 km Hybrid Underwater Vehicle

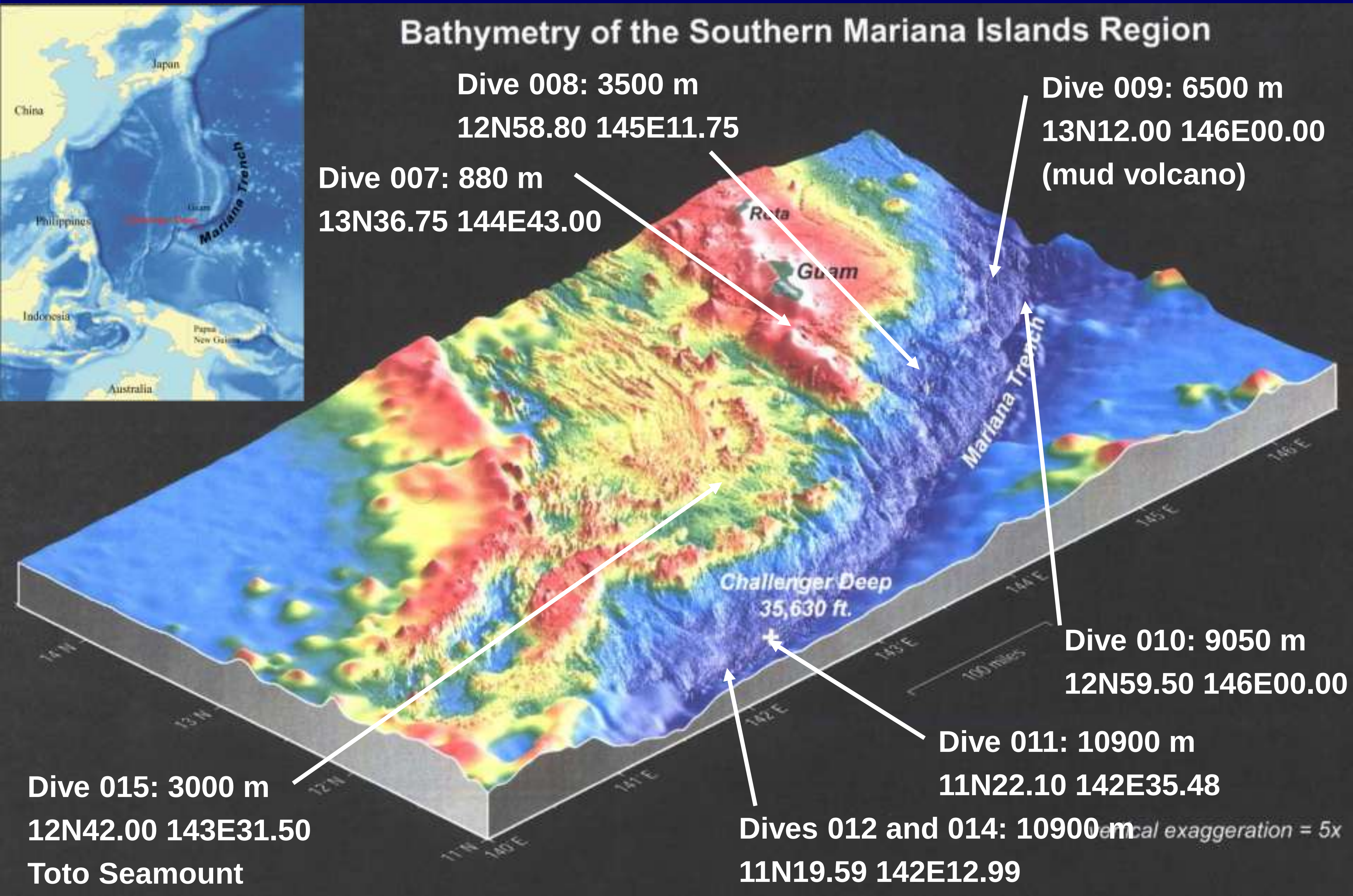




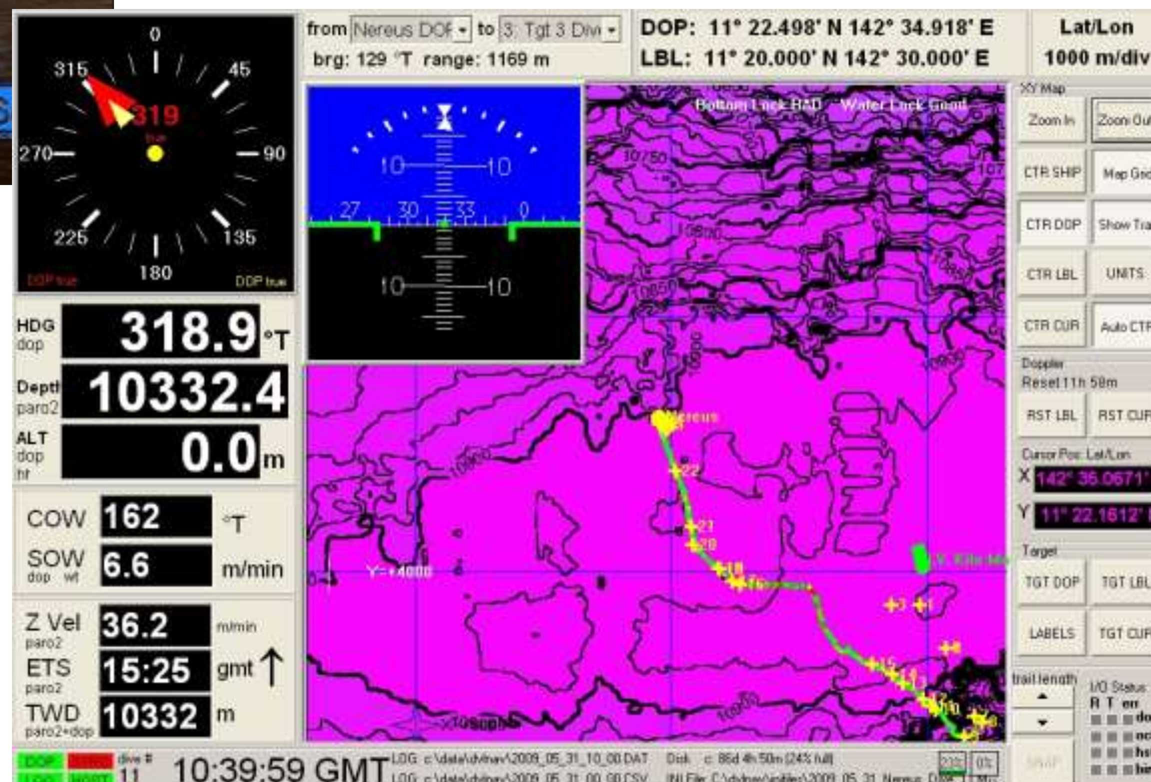
Micro-Fiber Tether System



Nereus 2009 Mariana Expedition



Nereus Dive 11 to 10,903 m Depth



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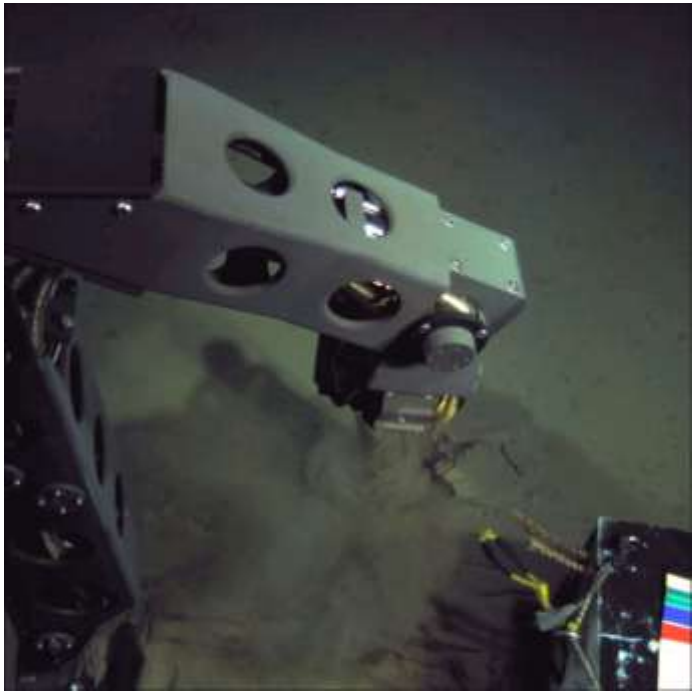
Nereus Sampling



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Nereus Sampling

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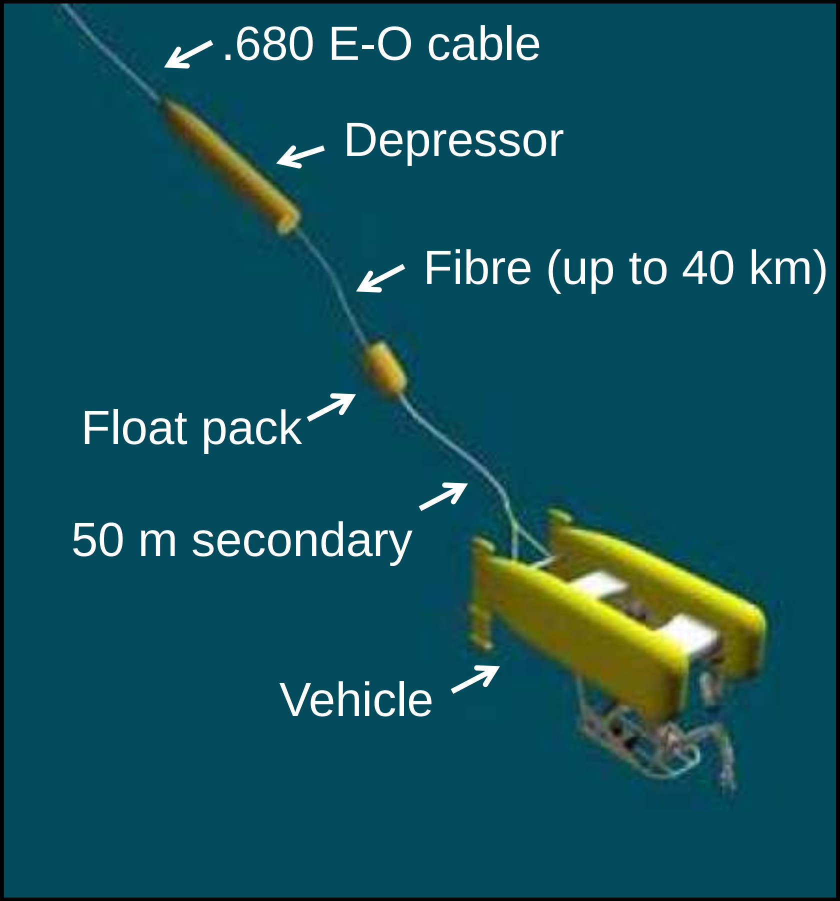
Light Fibre Tether Concept



- High bandwidth (GigE) communications
- Unconstrained by surface ship
- Operable from non-DP vessels

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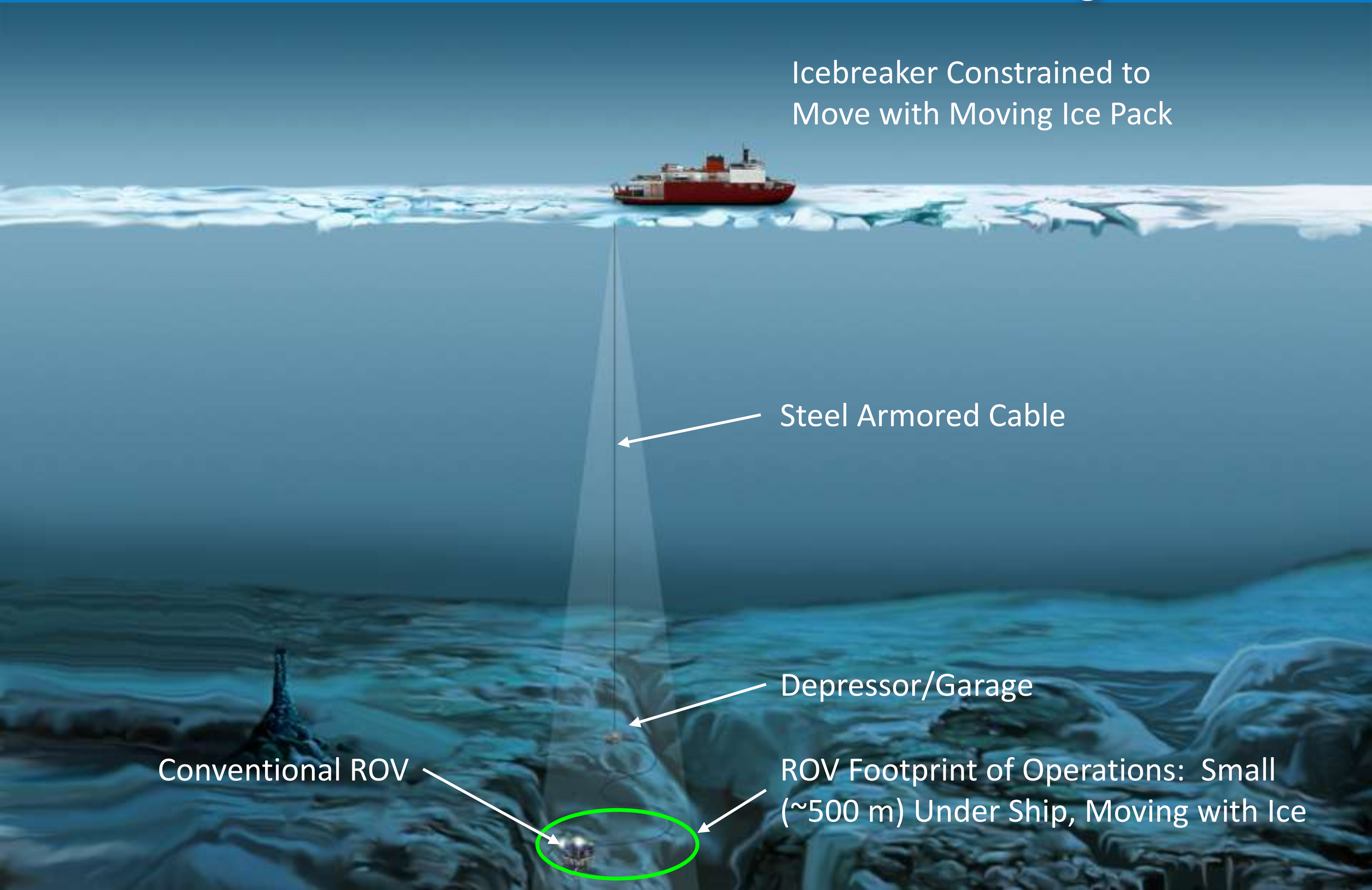
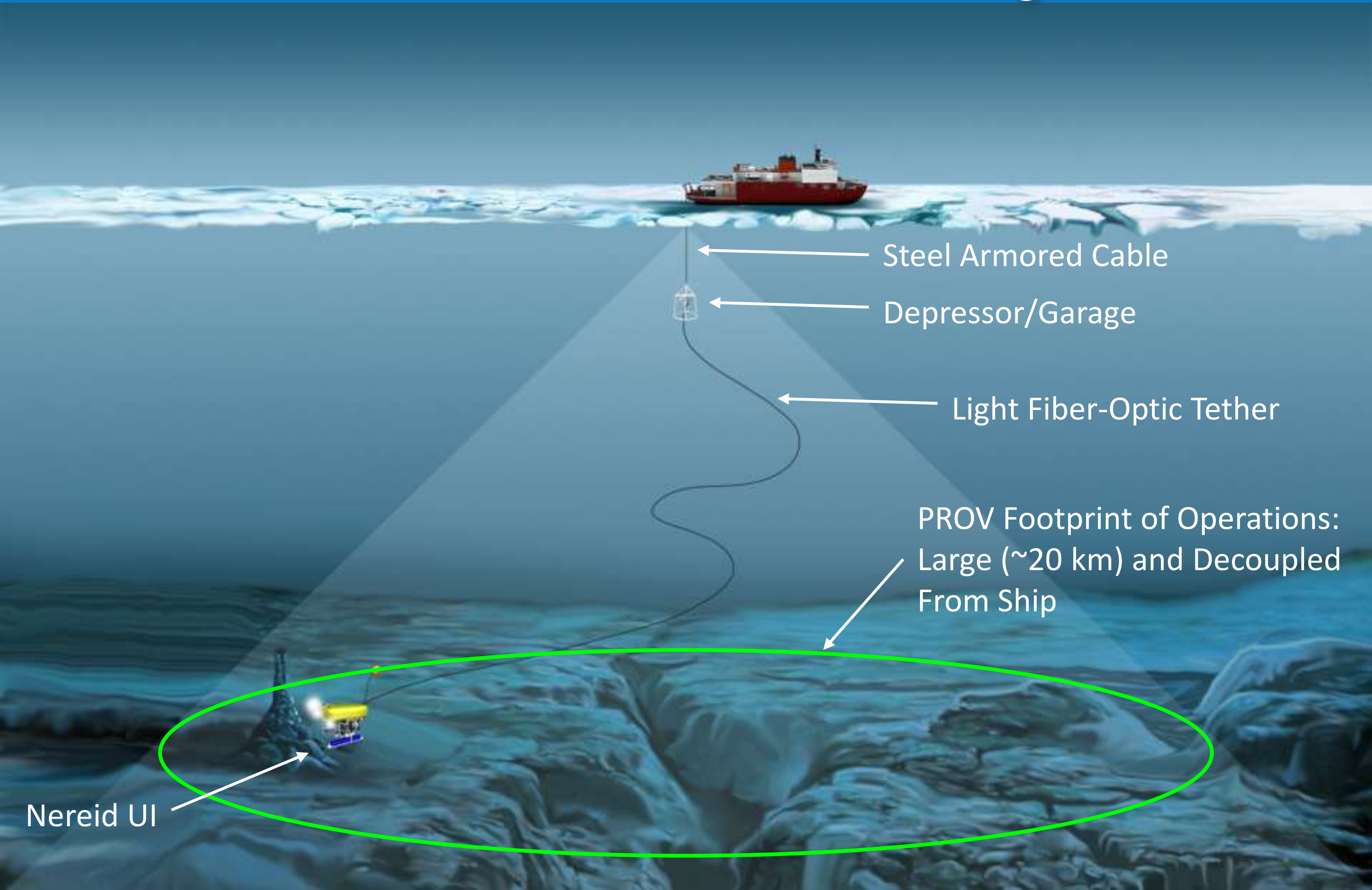
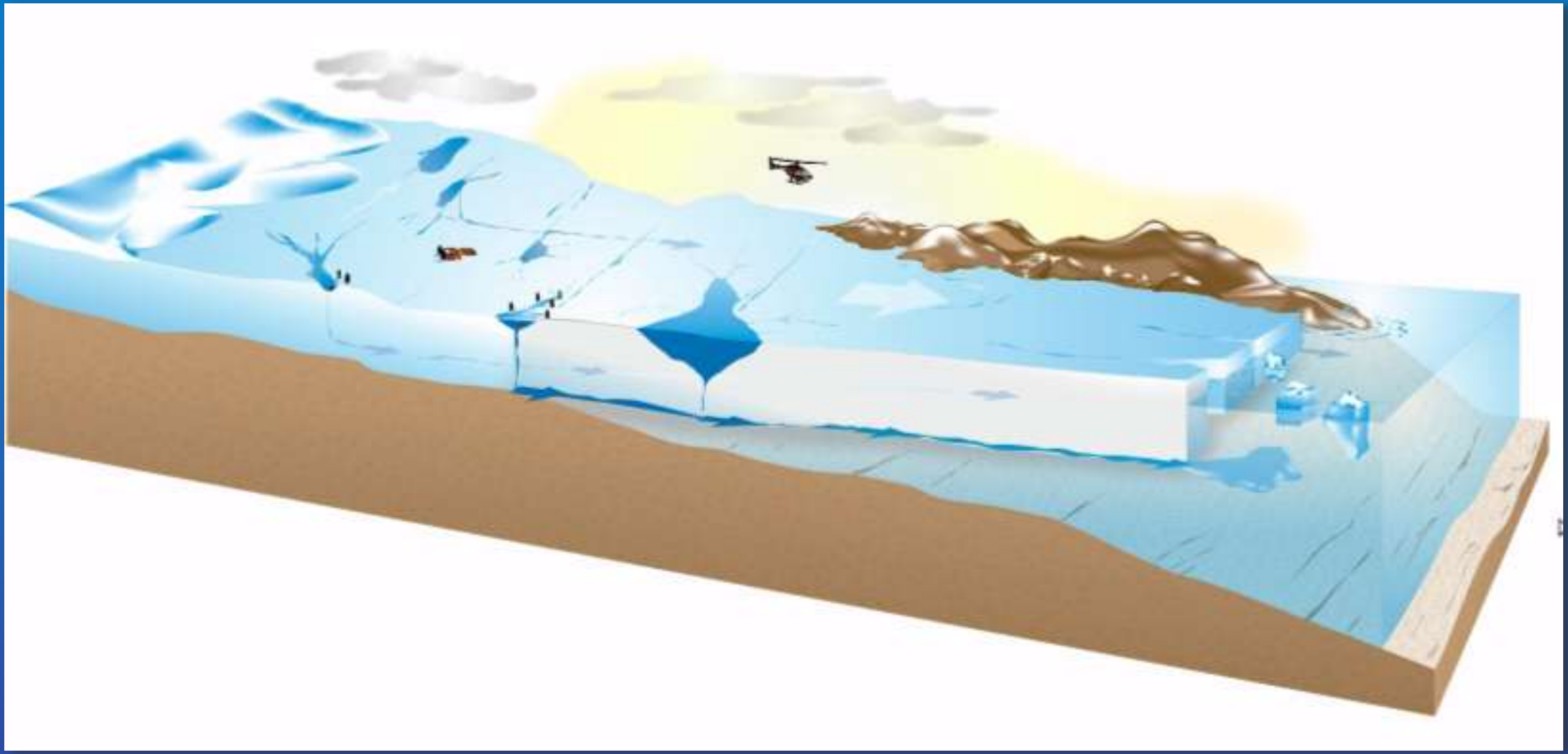
Problem: Conventionally Tethered ROV Operations from Icebreaker in Permanent Moving Ice



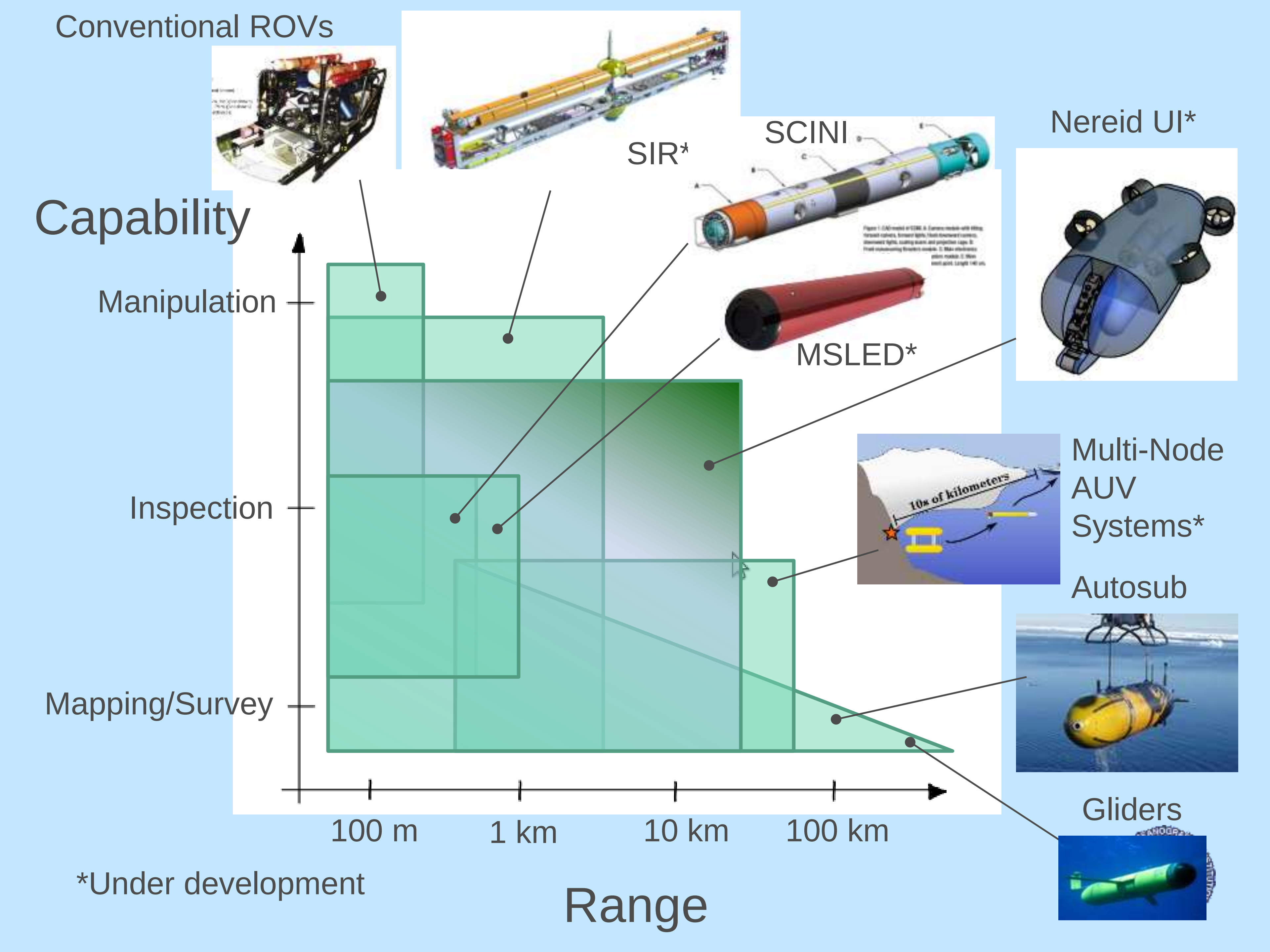
Solution: Light-Tethered Nereid Operations from Icebreaker In Permanent Moving Ice



The Under-Ice Scientific Imperative



- Near-Ice Inspection and Mapping
- Boundary Layer Investigations
- Grounding Line Inspection
- Sediment Sampling
- Ice Shelf Cavity Physical Oceanographic Mapping
- Instrument Emplacement*

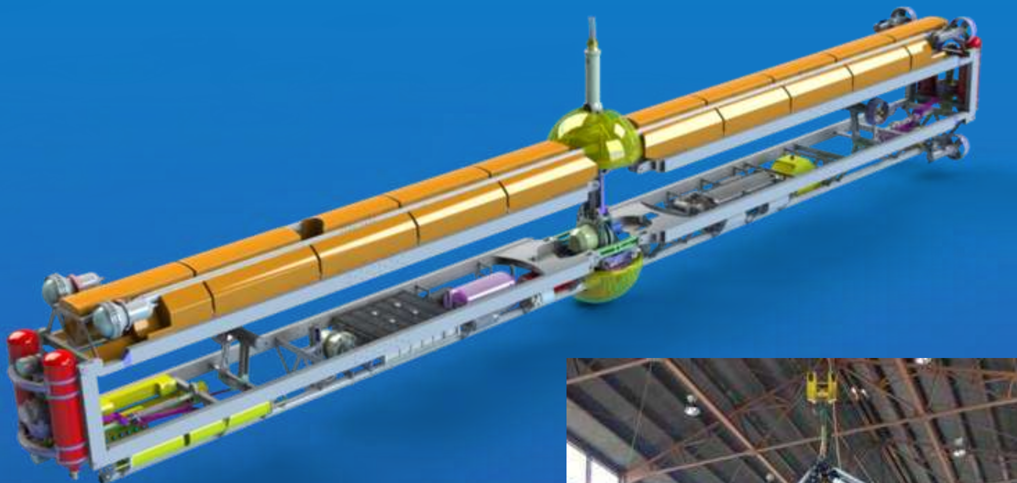


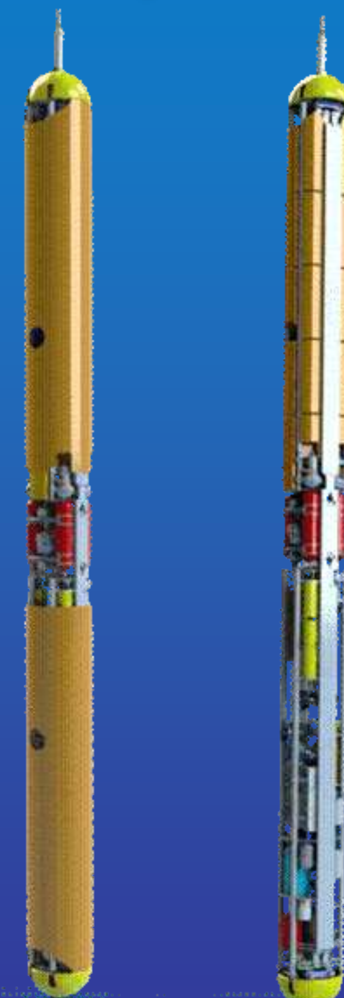
Conventional ROVs
SIR*
SCINI
Nereid UI*
MSLED*
Capability
Manipulation
Inspection
Mapping/Survey
Multi-Node
AUV
Systems*
10s of kilometers
Autosub
Gliders
100 m
1 km
10 km
100 km
Range
*Under development

Under-Ice Vehicle Systems

- Specialized hybrid AUV/ROV systems
- Conventional AUVs
- Conventional ROVs

Sub-Ice ROVer (SIR)

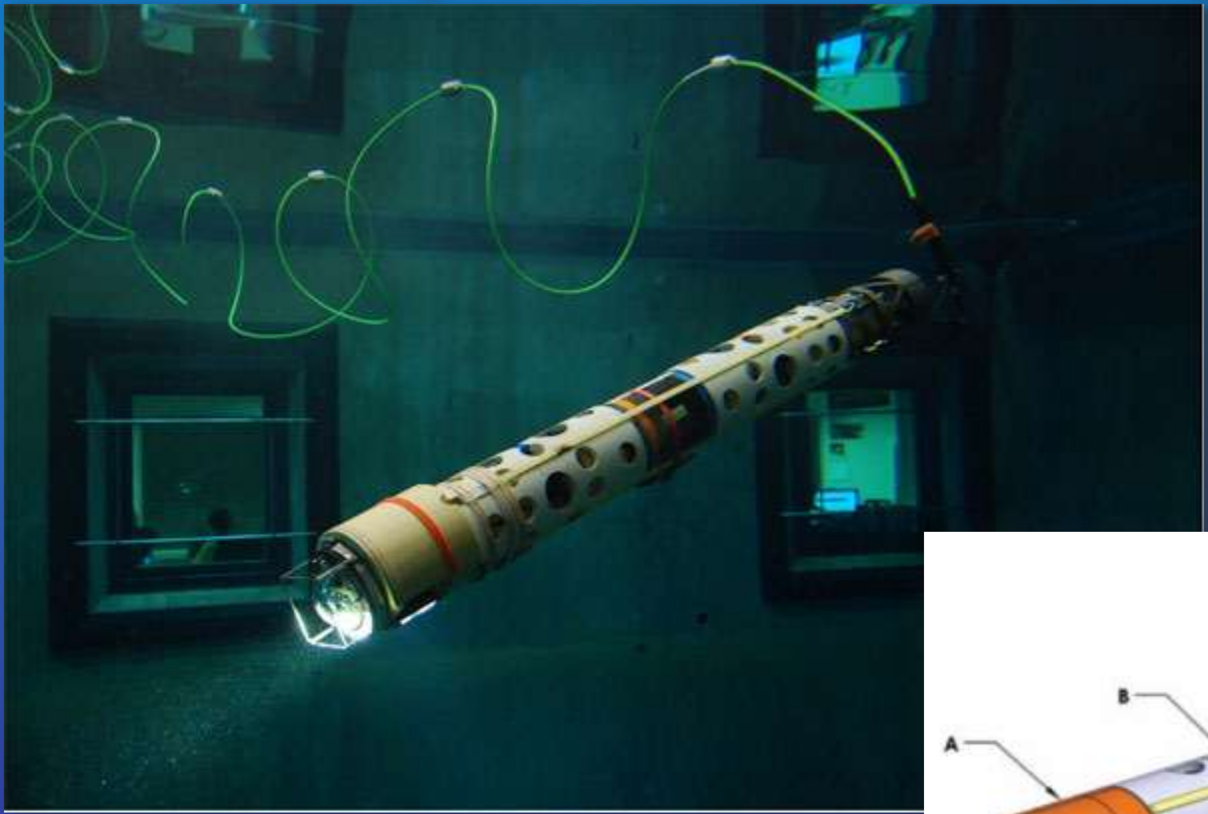




For through-ice-shelf deployment via ~70-75 cm bore holes.
Max diameter 55 cm in "folded" configuration.
Unfolds into ROV configuration.
Under development. 1500 m.
Missions: Optical imaging, acoustic imaging, PO,

Vogel et al. (2008), "Subglacial environment exploration – concept and technological challenges for the development and operation of a Sub-Ice ROVer (SIR) and advanced sub-ice instrumentation for short and long-term observations", In *Proceedings IEEE/OES Autonomous Underwater Vehicles*

Submersible Capable of under Ice Navigation and Imaging (SCINI)



15 cm diameter for deployment through 20 cm holes drilled in sea ice.
300 m depth rated.

Missions: Optical imaging, acoustic imaging, and PO.

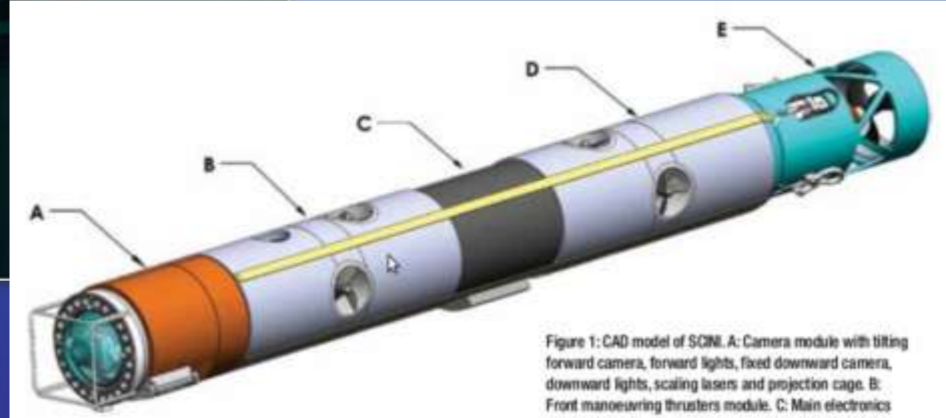


Figure 1: CAD model of SCINI. A: Camera module with tilting forward camera, forward lights, fixed downward camera, downward lights, scaling lasers and projection cage. B: Front manoeuvring thrusters module. C: Main electronics housing. D: Rear manoeuvring thrusters module. E: Main thruster module and tether attachment point. Length 140 cm, diameter 15 cm, weight 18.5 kg.

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

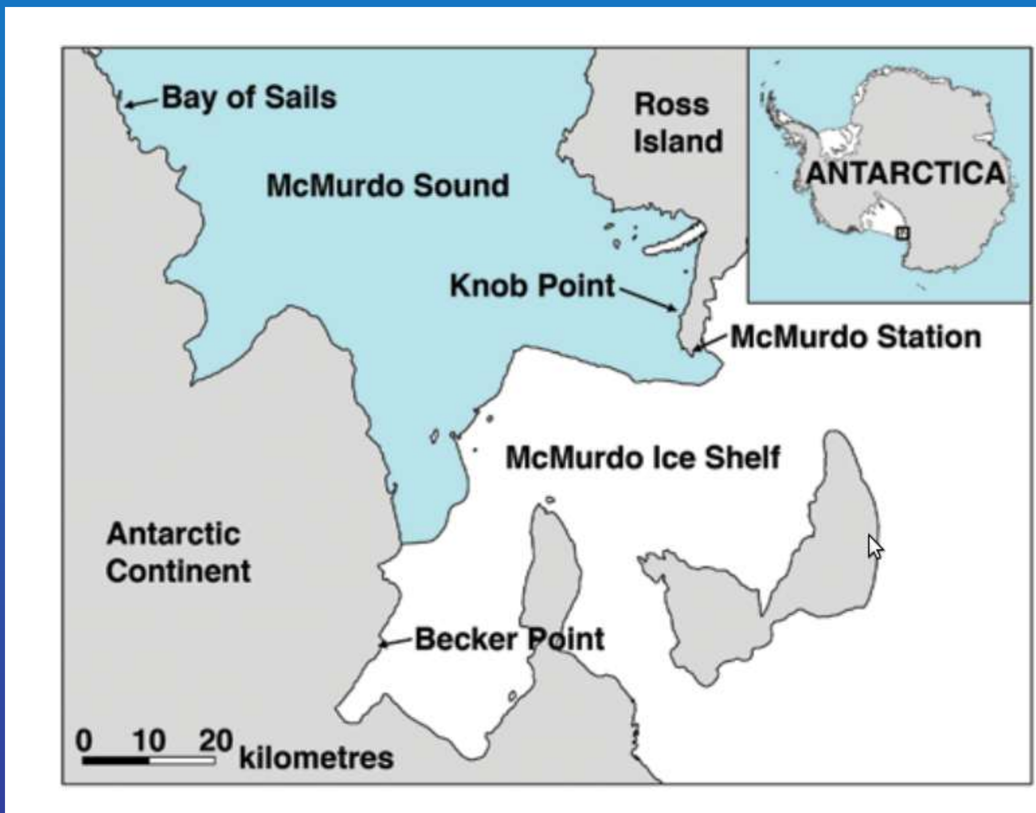
SCINI: Logistics

Figure 12: Walking to the survey site from the Becker point field camp. The entire SCINI ROV setup weights less than 350 kg and can be person-hauled by three or more people, on two sledges.

1930

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

SCINI: McMurdo Sound



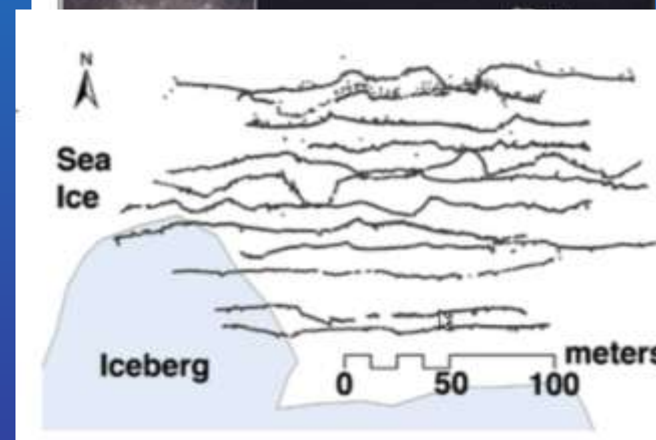
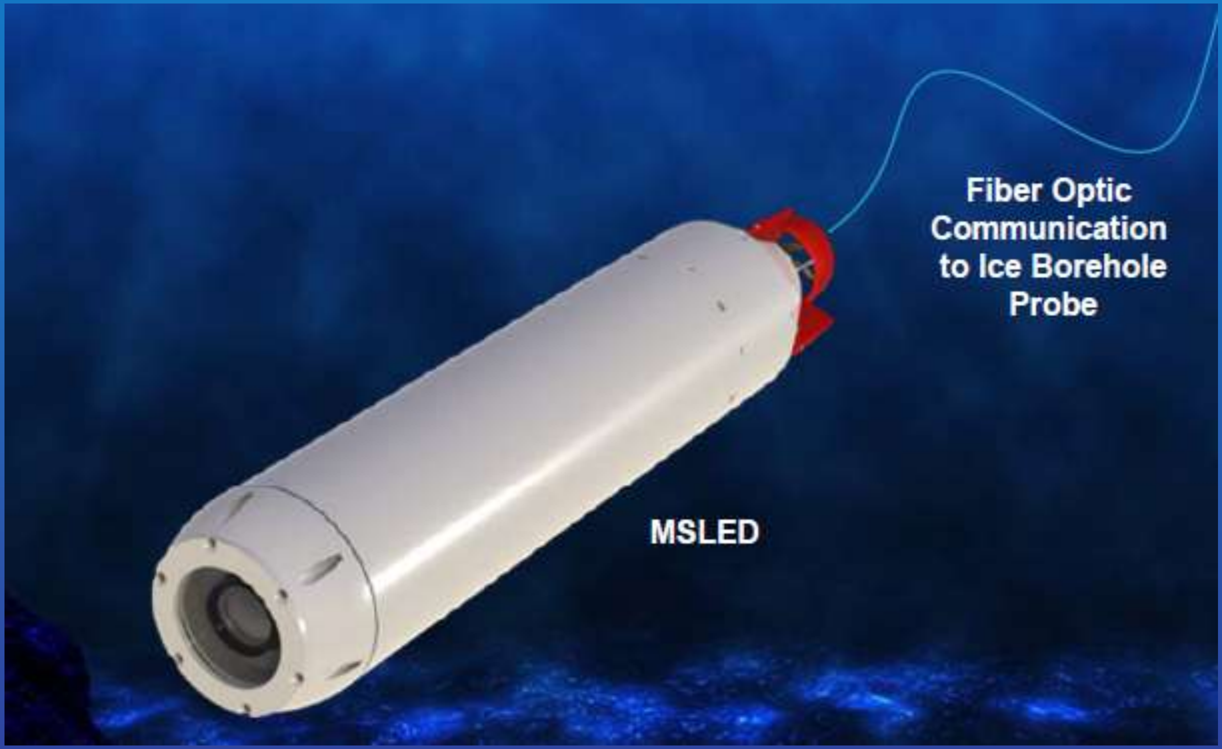


Figure 11: The ROV navigation tracklines from transects surveying the seafloor disturbance near one iceberg in Bay of Sails. Dots off the transect lines indicate bad navigation returns, demonstrating the importance of frequent returns to successfully maintain heading. Iceberg outline at sea ice level was obtained with a handheld GPS unit. The depth of the transects was between 30 m and 38 m.

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology

Micro-Subglacial Lake Exploration Device (MSLED)

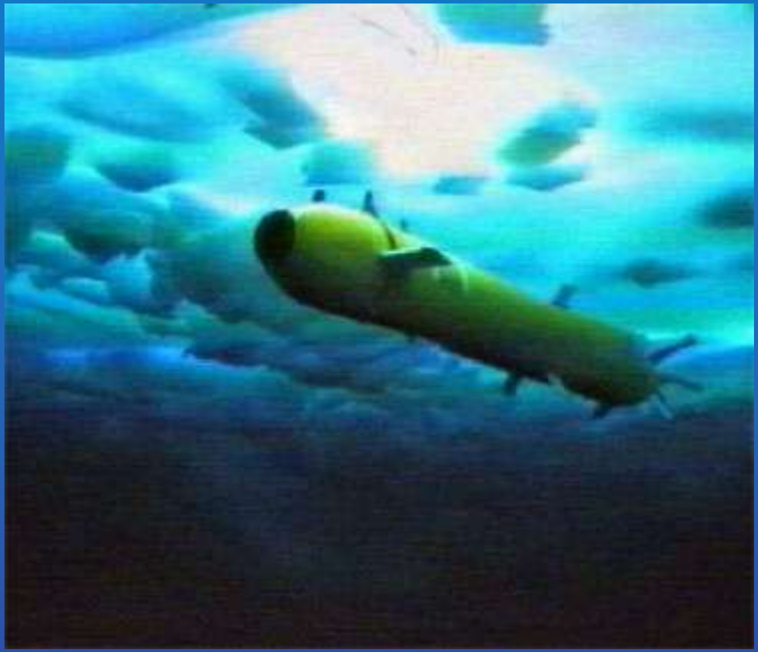


8 cm x 70 cm for deployment through bore holes drilled in ice.
1,500 m depth rated.
Camera, CTD
Fiber-optic tether
2 hour endurance

Missions: Optical imaging and PO.

A. Behar (2011) Micro Subglacial Lake Exploration Device (MSLED). Eighteenth Annual West Antartic Ice Sheet Initiative (WAIS) Workshop, 2011

Theseus AUV



1.27 m x 10 m for long-endurance fiber-optic cable deployment.
8,000 kg
1,300+ km range
2,000 m depth rated.

Fiber-optic tether deployment.

More recent versions of Theseus developed by ISE for Canadian UNCLOS Arctic bathymetric survey operations.

J. Ferguson et. Al. (1999), Theseus AUV-two record breaking mission, Sea Technology (40)2:65-70, 1999.

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Stone Aerospace *Endurance*

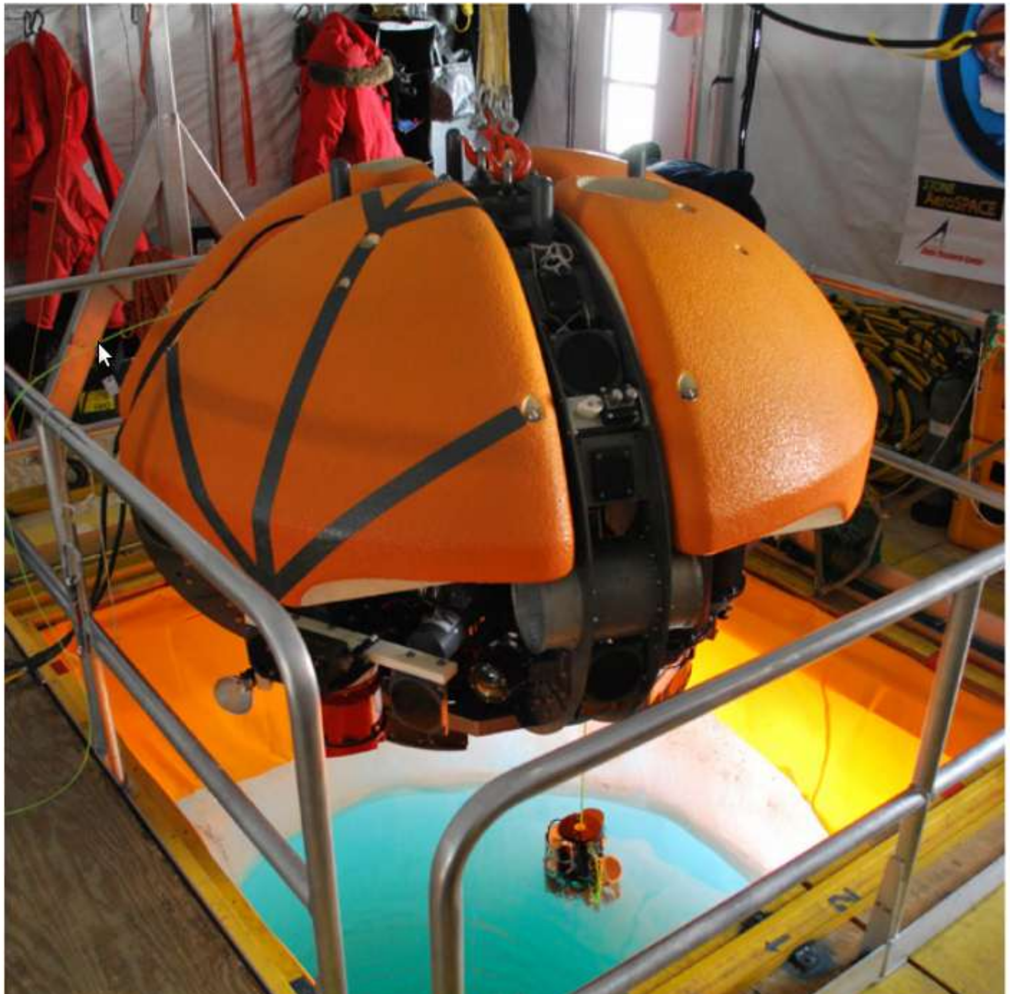
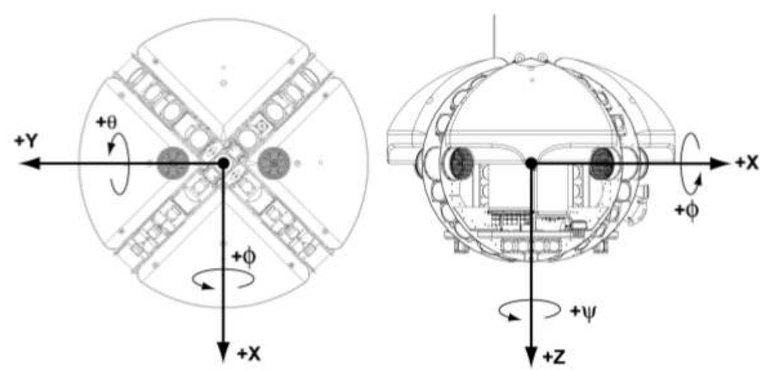


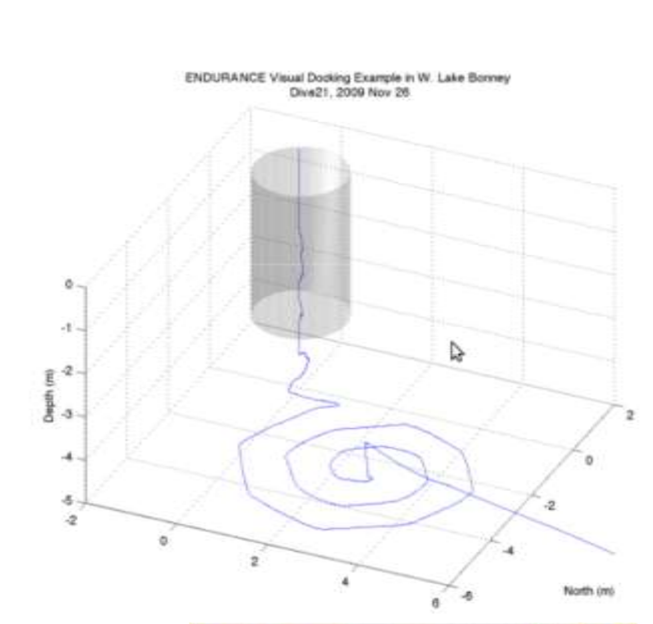
Table 1: ENDURANCE vehicle specifications

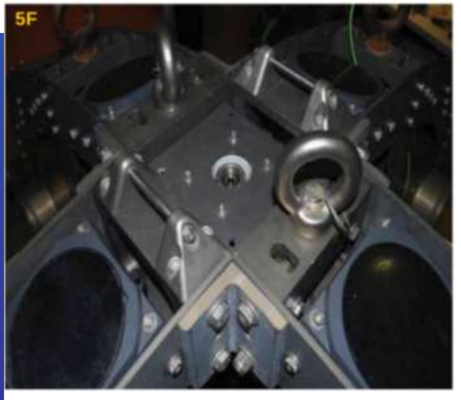
Dimensions	Ellipsoid major axis (diameter): 2.13 m Ellipsoid minor axis (height): 1.52 m
Mass	1.3 t including science payload
Depth rating	1000 m (excluding payload)
Onboard power	2 × 2.5 kW h lithium-ion rechargeable battery packs
Thrust	6 electric thrusters @ 110 N nominal thrust
Service range	5 km
Maximum transit speed	0.3 m/s
Cruise speed	0.24 m/s
Onboard instrumentation	Honeywell inertial measurement unit (IMU) RDI Doppler velocity log (DVL) 2 Paroscientific pressure depth sensors 32 Imagenex 100 m sonars 24 Imagenex 200 m sonars Imagenex DeltaT multi-beam sonar Sonardyne inverted ultra-short baseline (USBL) transceiver



Richmond et al. (2011), "Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project", UUST'11

Stone Aerospace *Endurance*





Stone et al. (2009), "Sub-ice exploration of West Lake Bonney: Endurance 2008 mission," In Proceedings UUST'09.

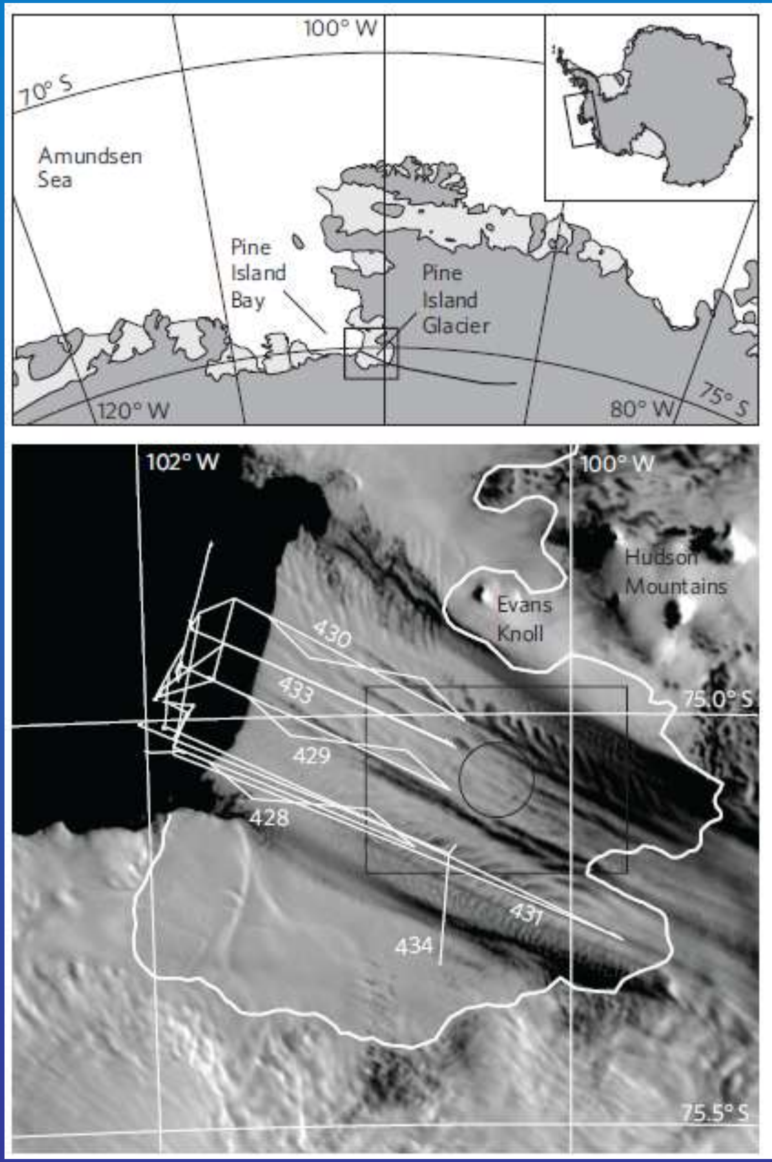
Richmond et al. (2011), “Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project”, UUST’11,.

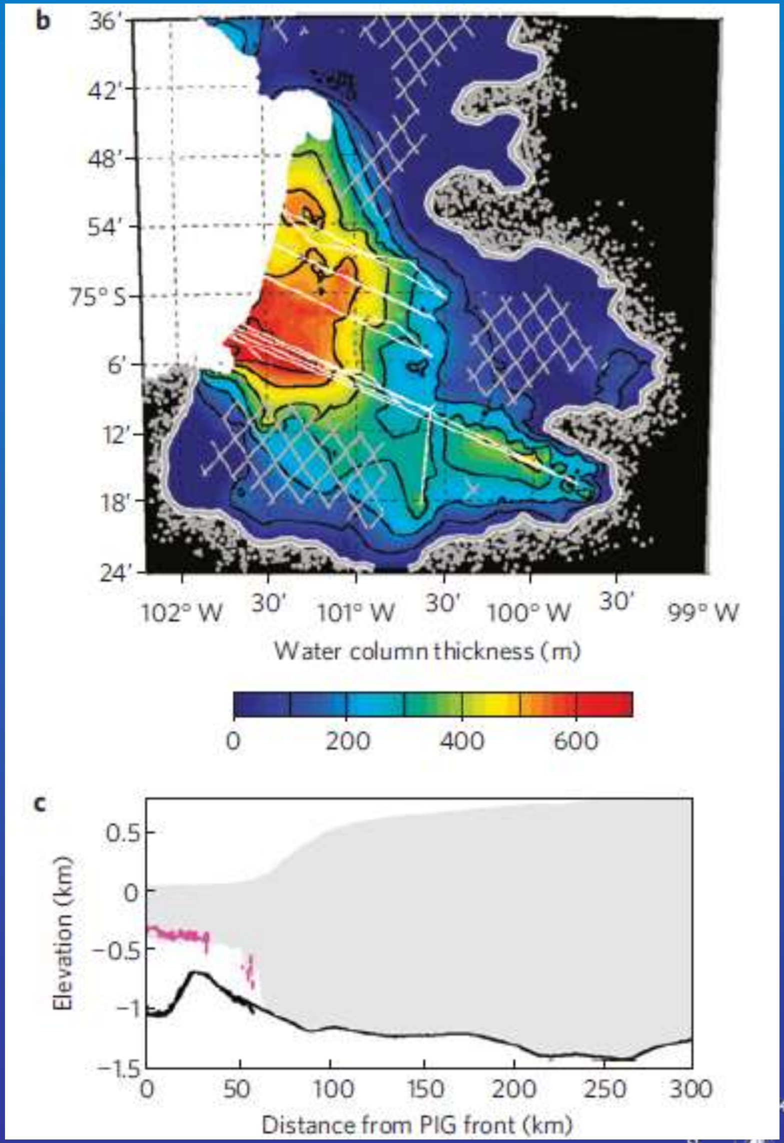
Autosub 3

400 km range
1,600 m depth
7 m x 1 m
3000 kg
Missions: Acoustic survey and PO survey.

Jenkens et al. (2010), “Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat”, Nature Geoscience, June 2010.

Autosub 3



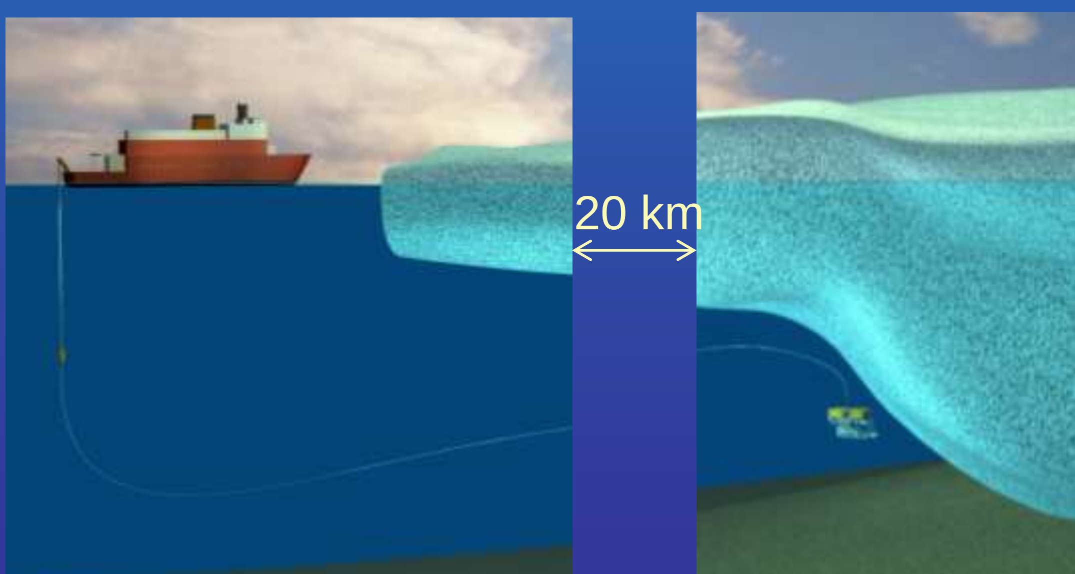


Jenkens et al. (2010), "Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat", Nature Geoscience, June 2010. (Results of January 2009 operations from R/V N. B. Palmer)

PROV Concept of Operations

Mission:

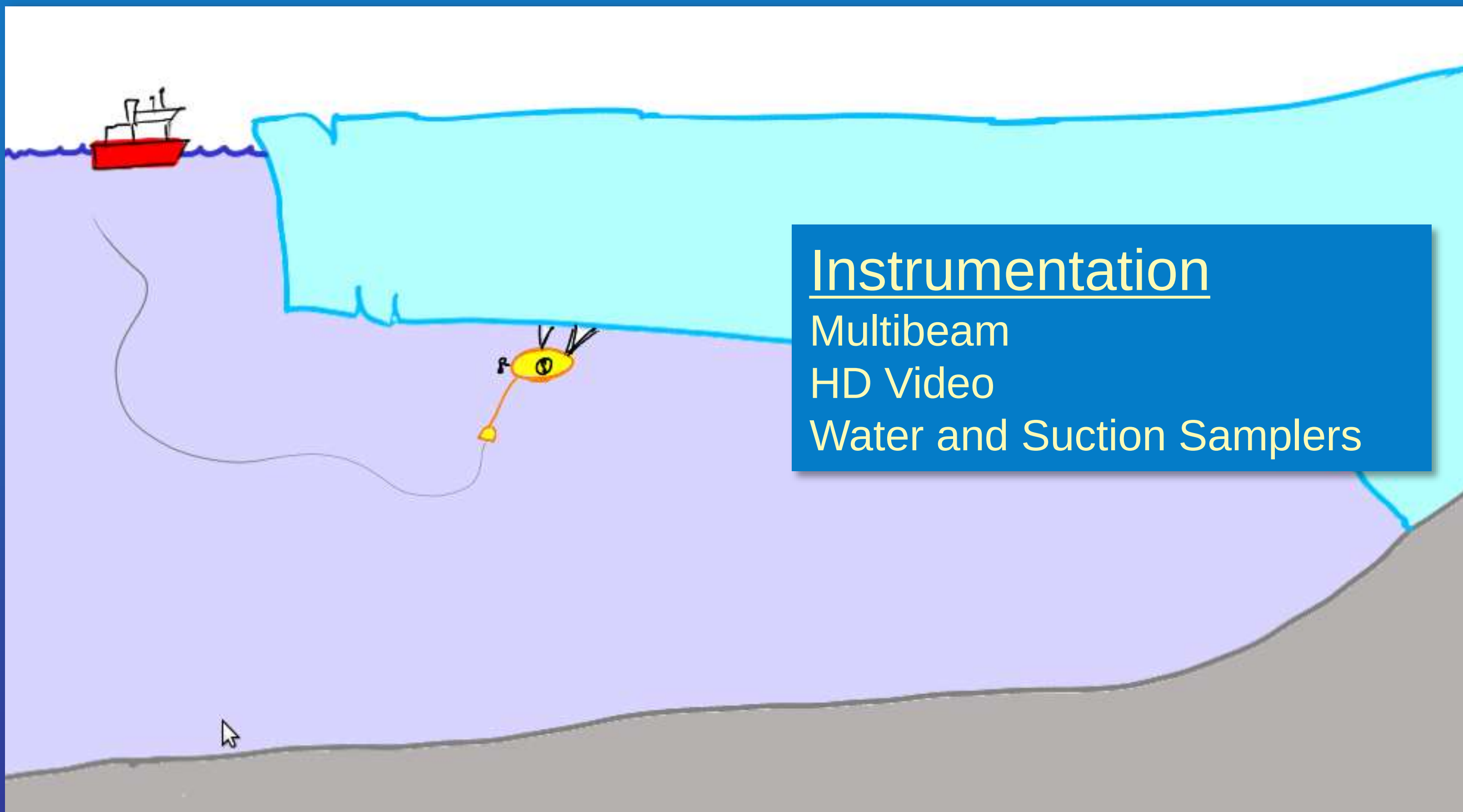
- Penetrate under **fixed ice** up to 20 km as a tethered vehicle while supporting sensing and sampling in close proximity to the under-ice surface
- Return safely to the ship



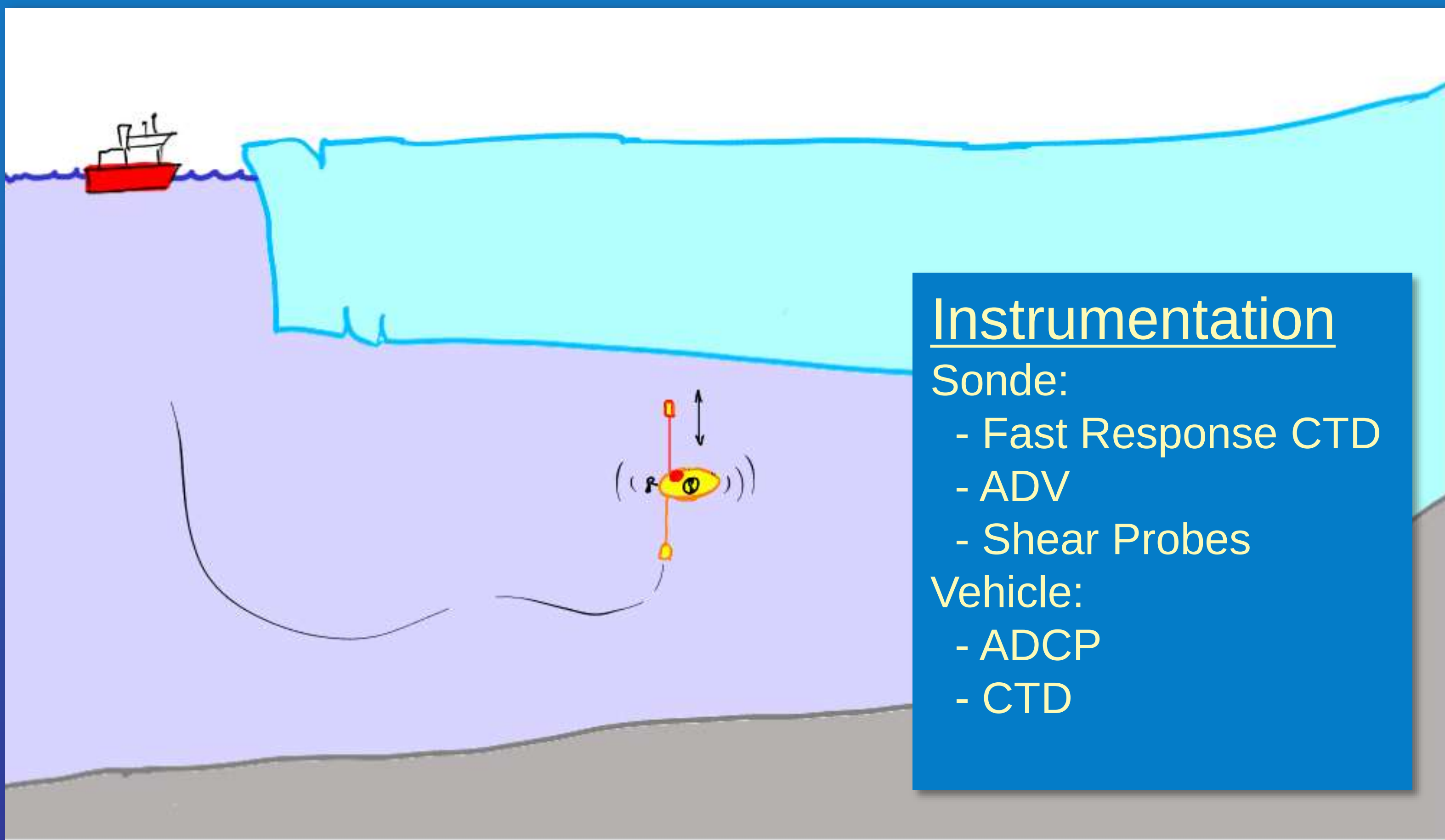
Notional Concept of Operations:

- Install acoustic Nav/Comms as required near ice-edge
- Deploy from vessel at ice edge as tethered system
- Transit to ice-edge and begin survey activities under-ice to the maximum range of the tether.
- Complete mission and return to the vessel as an AUV and recover onboard in open water

Use Case 1: Near-Ice Inspection and Mapping



Use Case 2: Boundary Layer Investigations

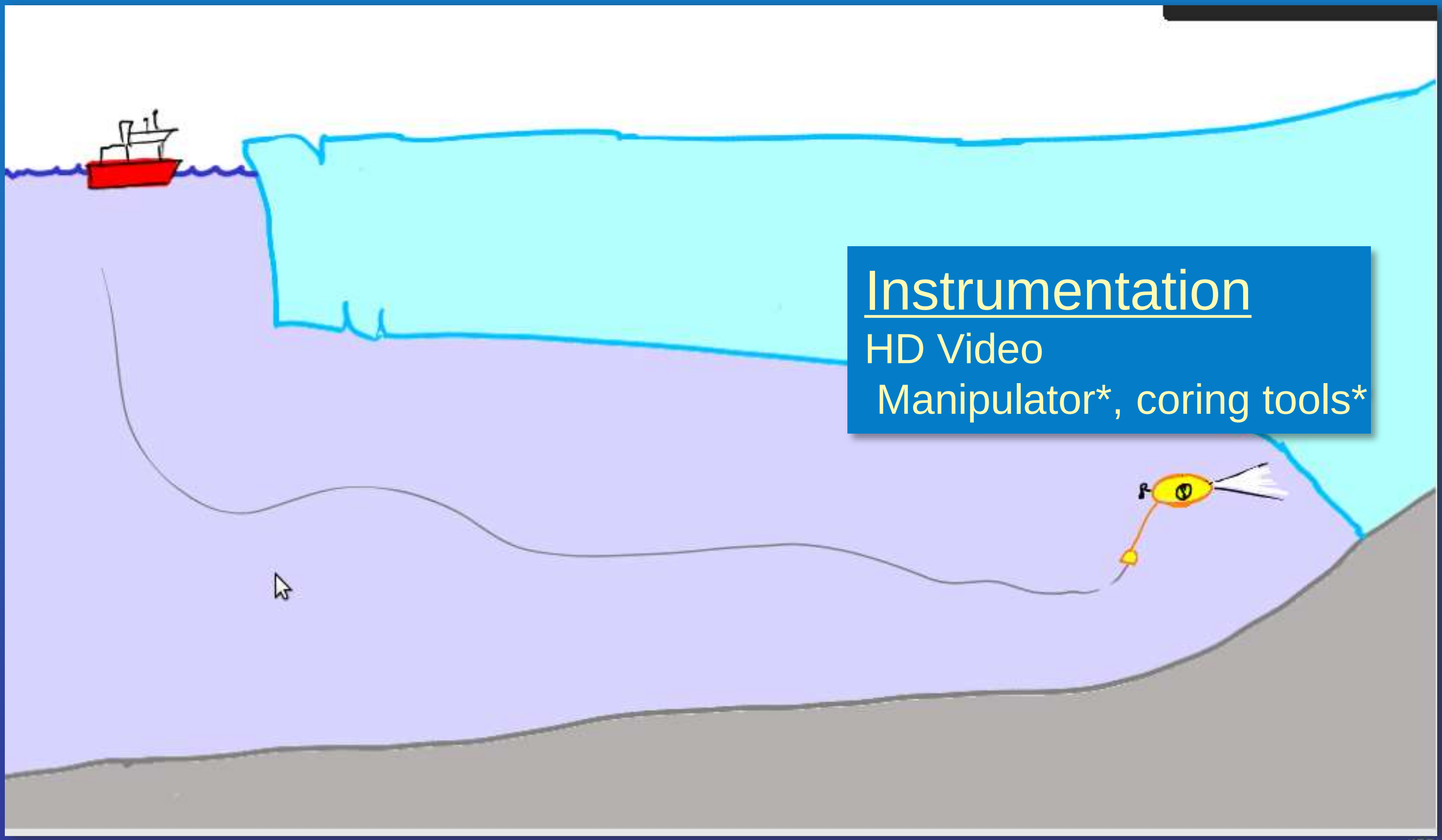


Instrumentation

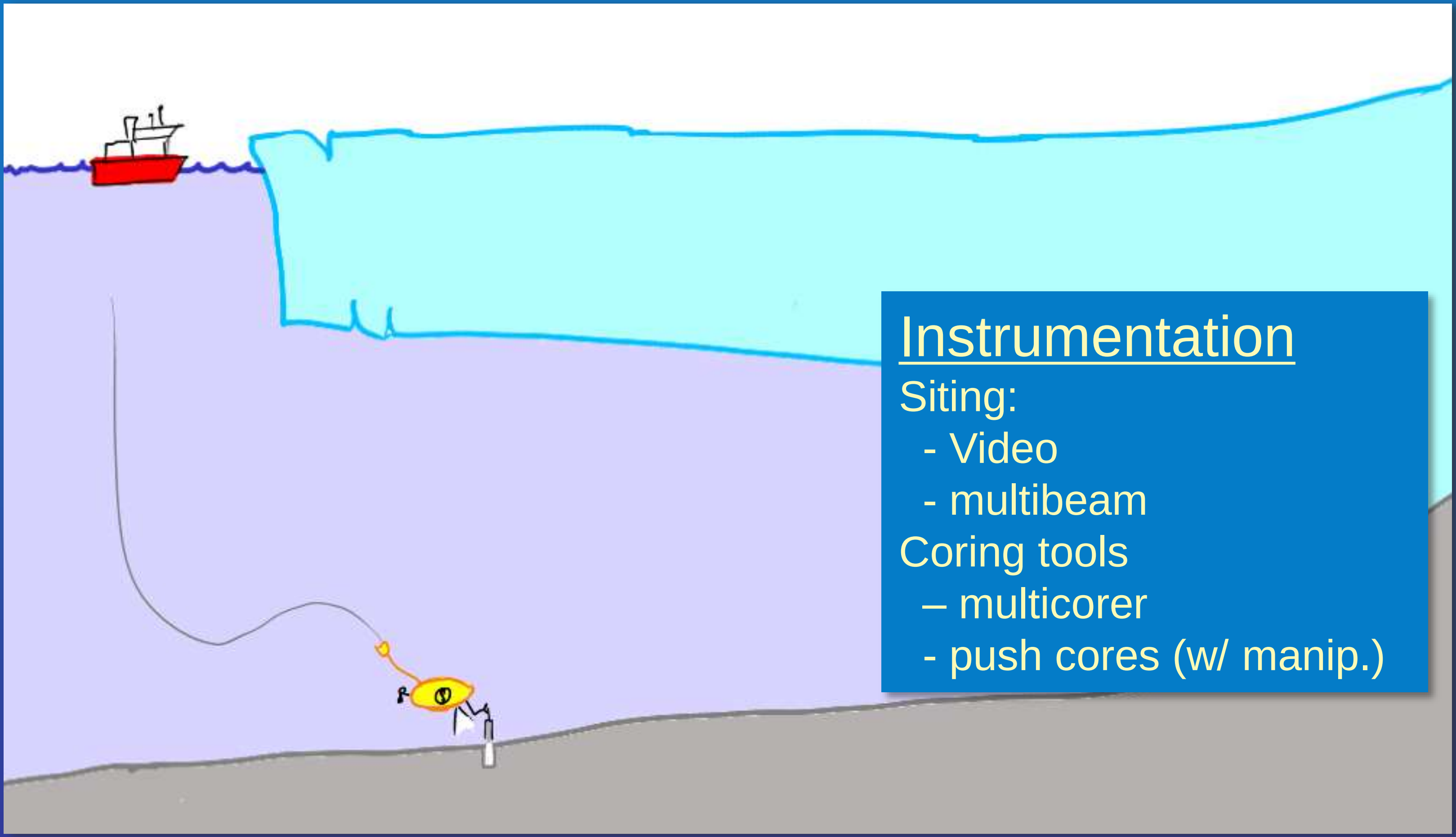
Sonde:
- Fast Response CTD
- ADV
- Shear Probes

Vehicle:
- ADCP
- CTD

Use Case 3: Grounding Line Inspection



Use Case 4: Sediment Sampling

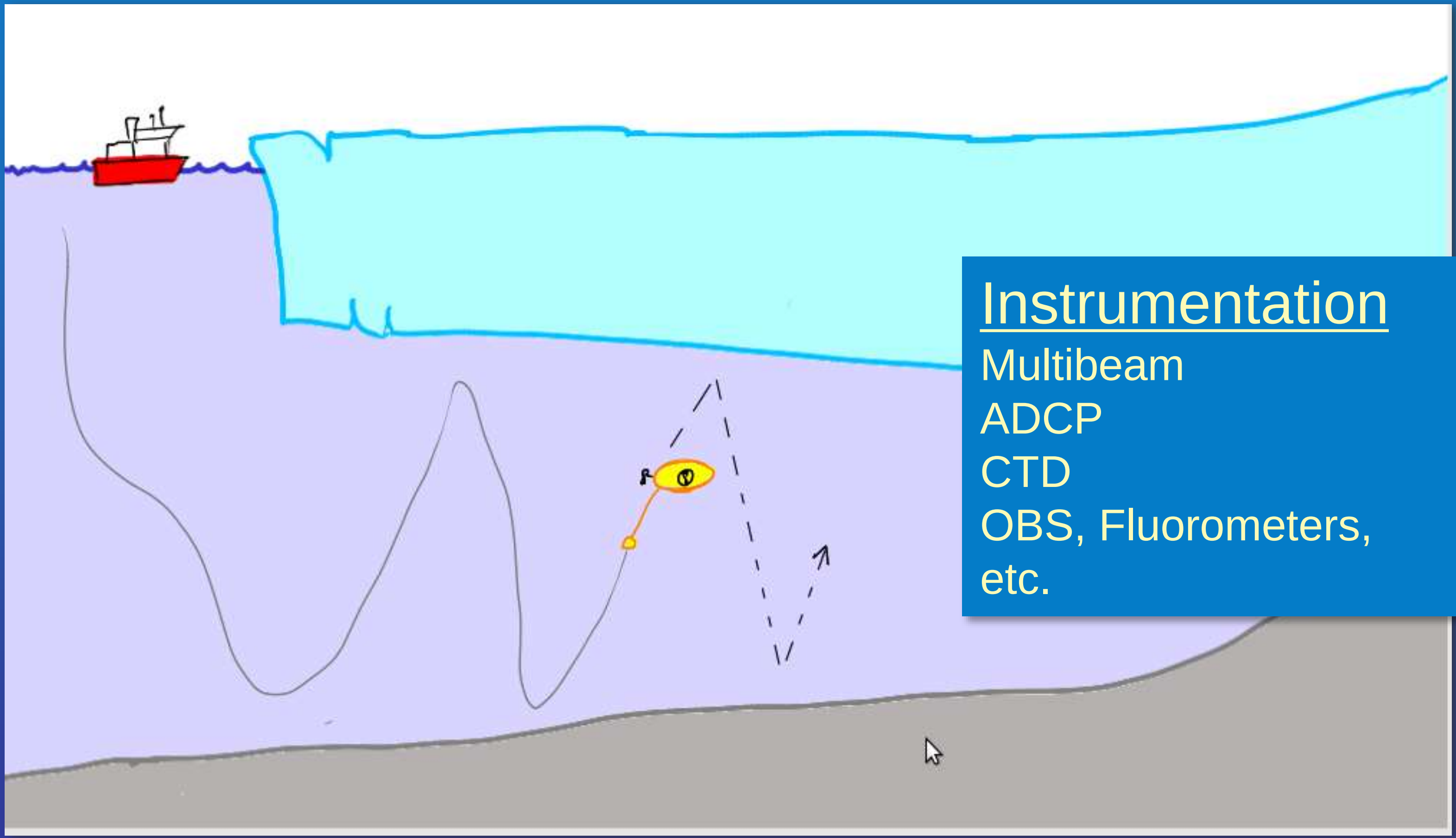


<u>Instrumentation</u>

Siting:
- Video
- multibeam

Coring tools
– multicorer
- push cores (w/ manip.)

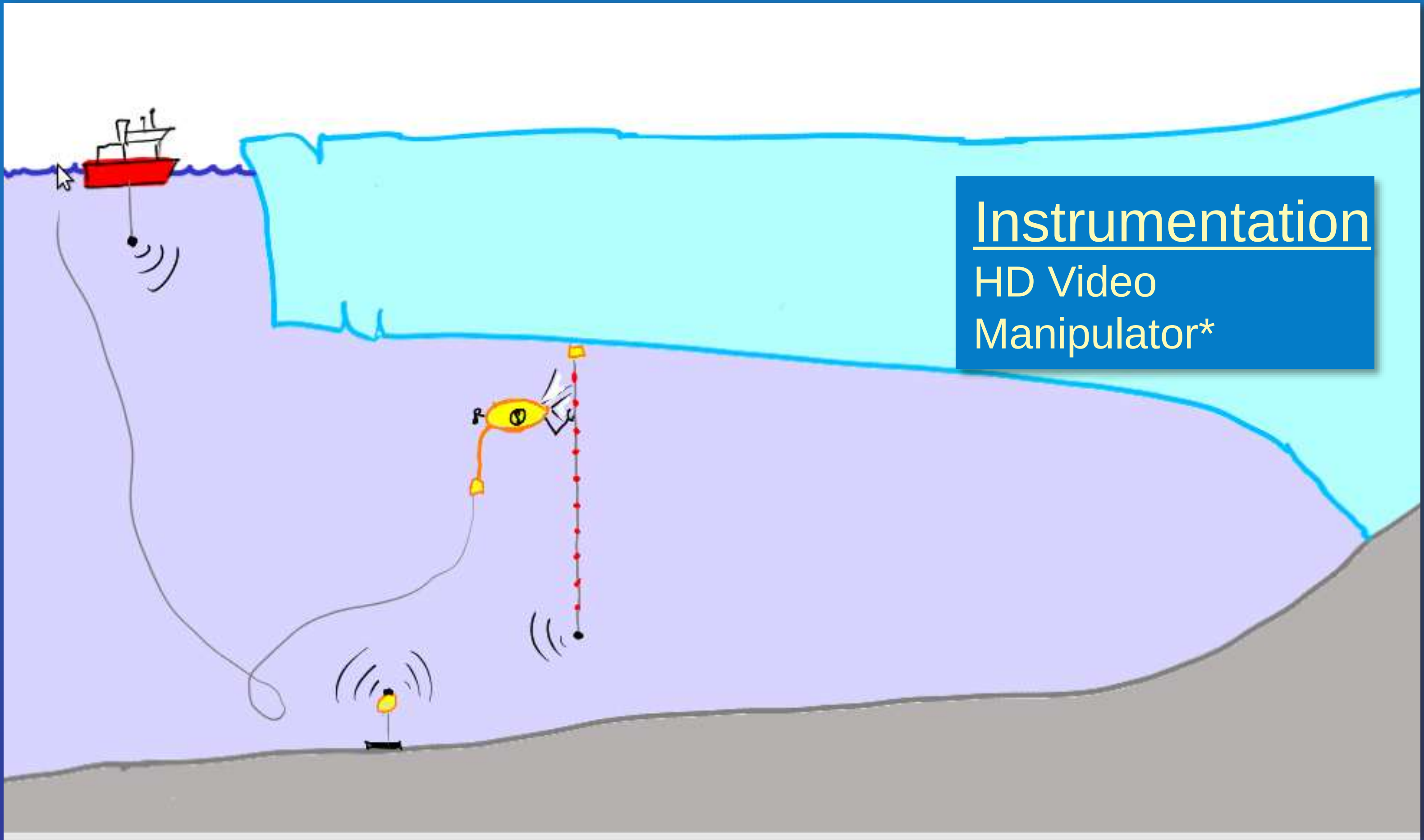
Use Case 5: Ice Shelf Cavity Physical Oceanographic Mapping



Instrumentation

Multibeam
ADCP
CTD
OBS, Fluorometers, etc.

Use Case 6: InstrumentDeployment/Recovery*



Design Parameters

- Bathymetry -> Depth rating
- Ice Draft -> Maneuverability/Sensing
- Water column structure -> Need for, and capacity of VBS
- Circulation and Tides -> Minimum speed
- Sea-Ice and Sea State -> LaRS complexity
- Phenomena -> Special design considerations
- State of Knowledge -> Conservatism in design
- Logistics -> Special design considerations, field-planning

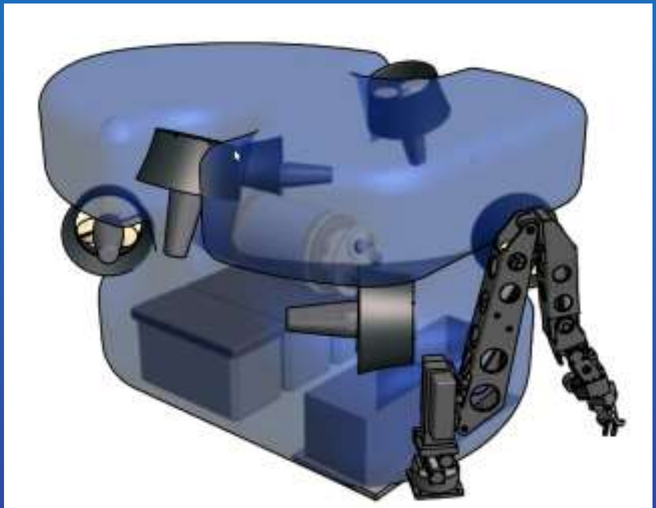
- Regions Studied:
  Antarctic Ice Shelves
  Greenland Glaciers
- Assumptions:
  Ship-based, open-water launch/recovery, sub-type for through-ice deployment

Design Constraints: Antarctica

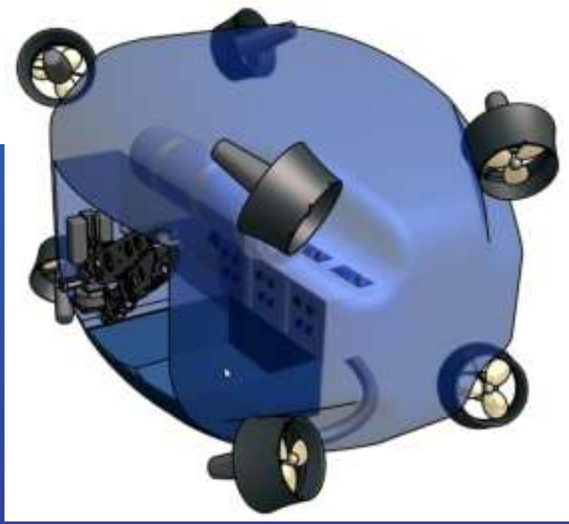
- Bathymetry -> Depth rating: 1500 m
- Ice Draft -> Maneuverability/Sensing: mission-driven/??
- Water column structure -> Need for, and capacity of VBS: mission-driven, potential for creative solutions
- Circulation and Tides -> Minimum speed: 0.5 m/s
- Sea-Ice and Sea State -> LaRS complexity: simple, AUV-like
- Phenomena -> Special design considerations: minimize entrained volume, thermally couple as much as possible, pre-launch washdown
- State of Knowledge -> Conservatism in design: reliability-driven
- Logistics -> Special design considerations: What can be learned from small, proxy vehicles?

Nereid-UI: Design Concepts

Flatfish



Conventional

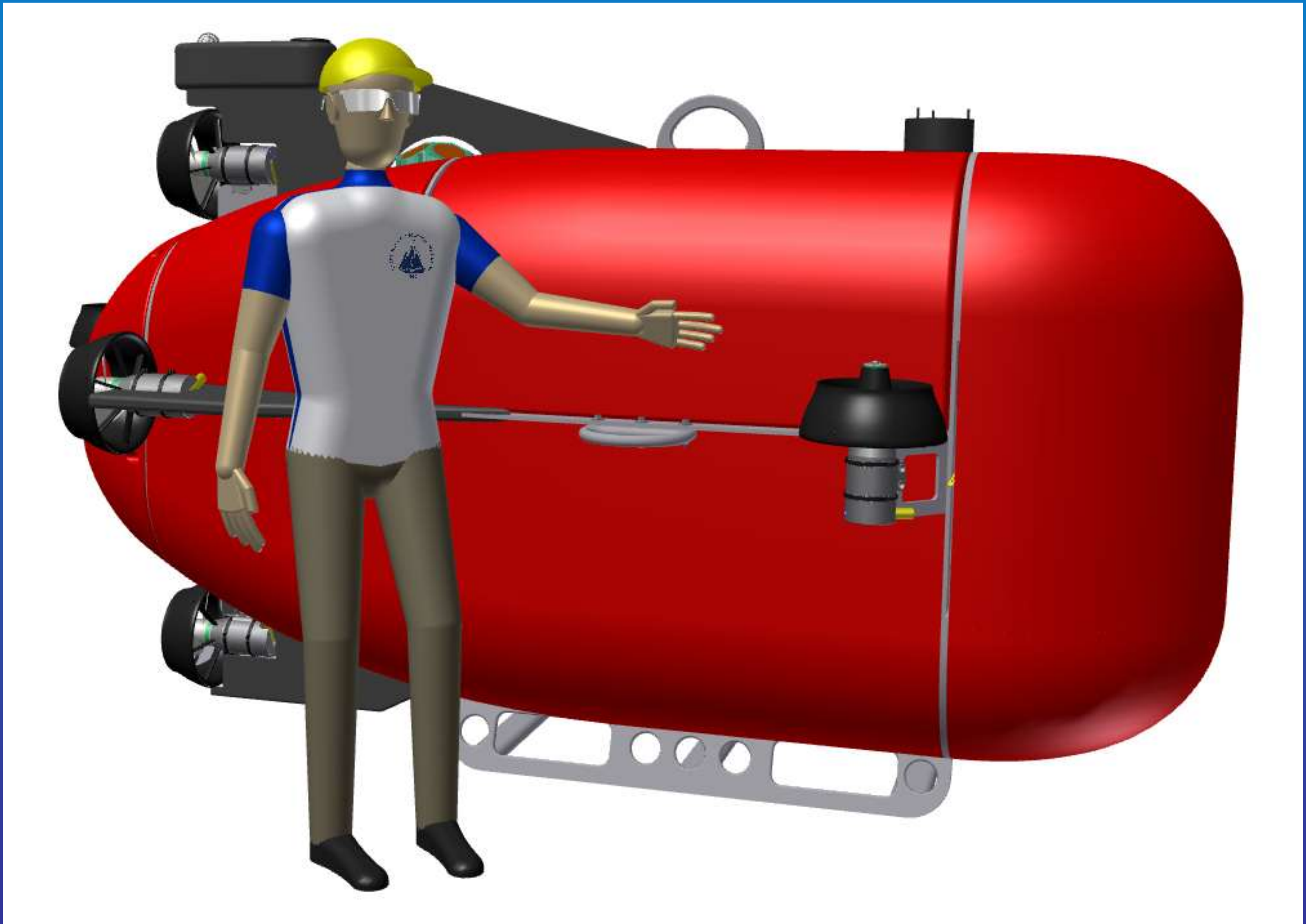


Crab

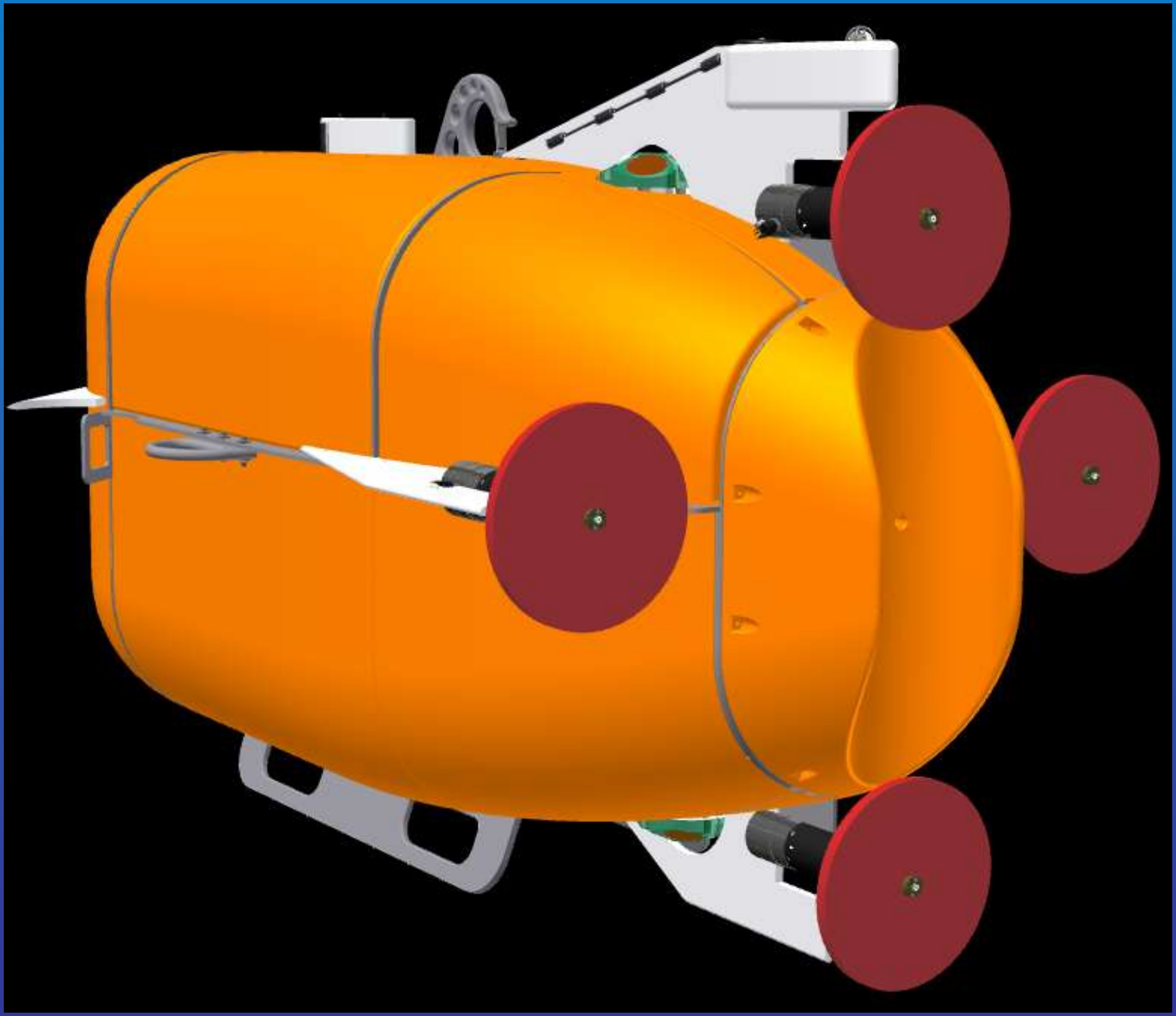
Nereid-UI: Specifications

Performance	Range	20 km max horizontal excursion from launch point
	Displacement	1,800 kg
	Depth Rating	1,500 m
	Battery	19 kWhr Li-Ion
	Manipulator	6-DOF Electro-Hydraulic (provisional)
	Sample Payload	20 kg
Navigation	Inertial	IXSEA PHINS
	Acoustic	300 kHz up/down ADCP/DVL; LF (3.5 kHz) communications; Imaging sonar for obstacle avoidance
	Pressure/Depth	Paroscientifc pressure sensor
Telemetry	Tether	20 km fiber-optic Gb Ethernet expendable tether
	Acoustic	LF (3 kHz) 20-300 bps acoustic telemetry to/from ship HF (10-30 kHz) acoustic telemetry to seafloor instruments
Imaging	Optical	Real-time HD color video; high-resolution digital still; LED lighting
	Acoustic	R2Sonic 2020 or better, mounted up or down on per-mission basis.
Chem/Bio Sensors	Chemical	Seabird CTD; pH; OBS
	Biological	Photosynthetically Active Radiation (PAR); Chlorophyll; Turbidity; Dissolved Oxygen
Auxiliary Payload		20 kg Up to 500Whr (affects range)

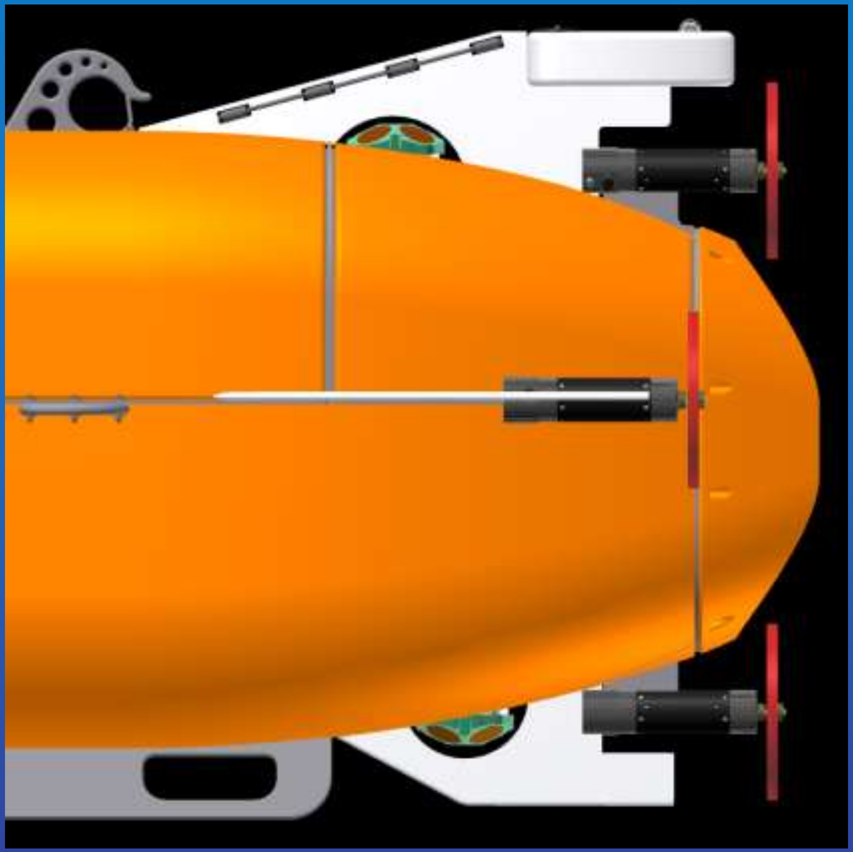
Nereid UI: Final Design



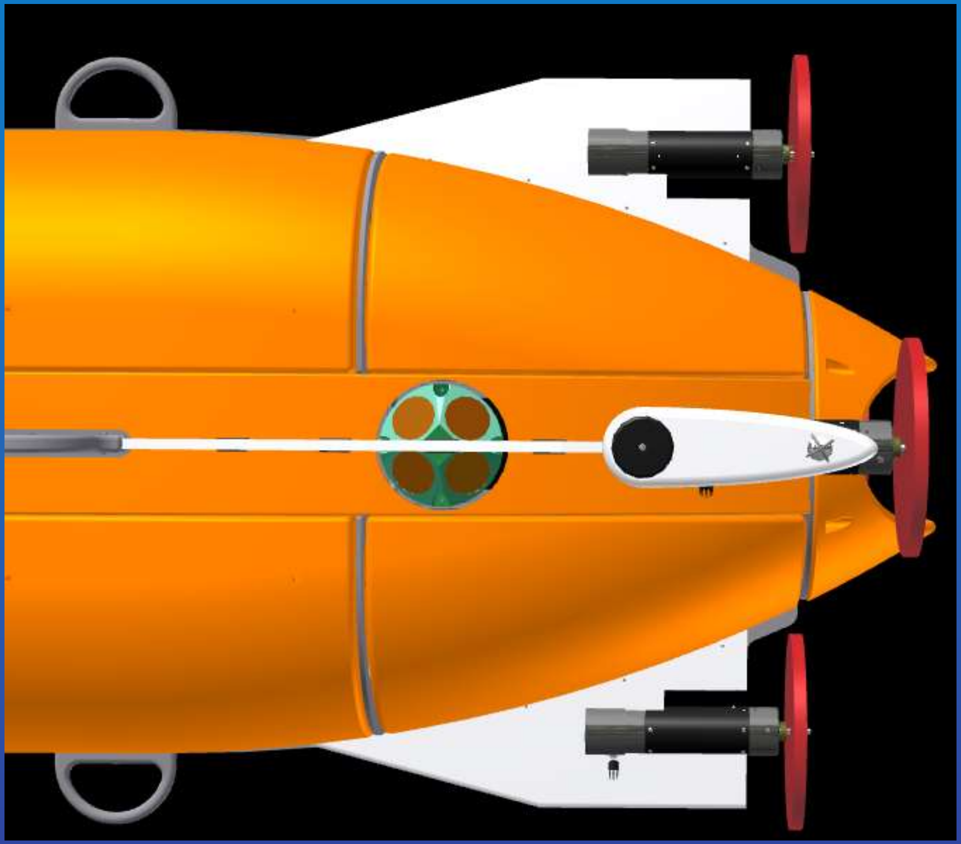
Nereid UI: Final Design



Nereid UI: Final Design



Side

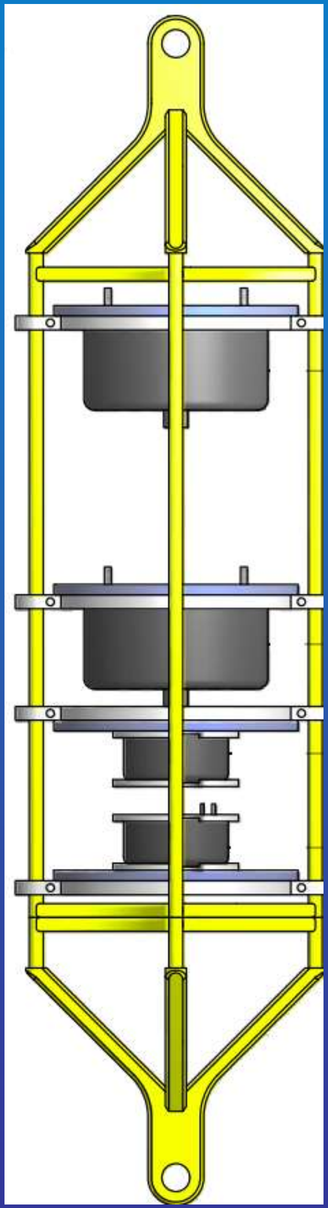


Top

Design for Reliability/ Fault-Tolerant Control/Design

Photo courtesy S. McPhail, NOC

Acoustic Communications and Navigation

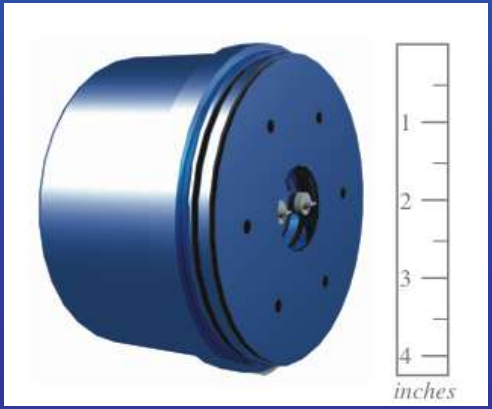


Short range, 10 kHz

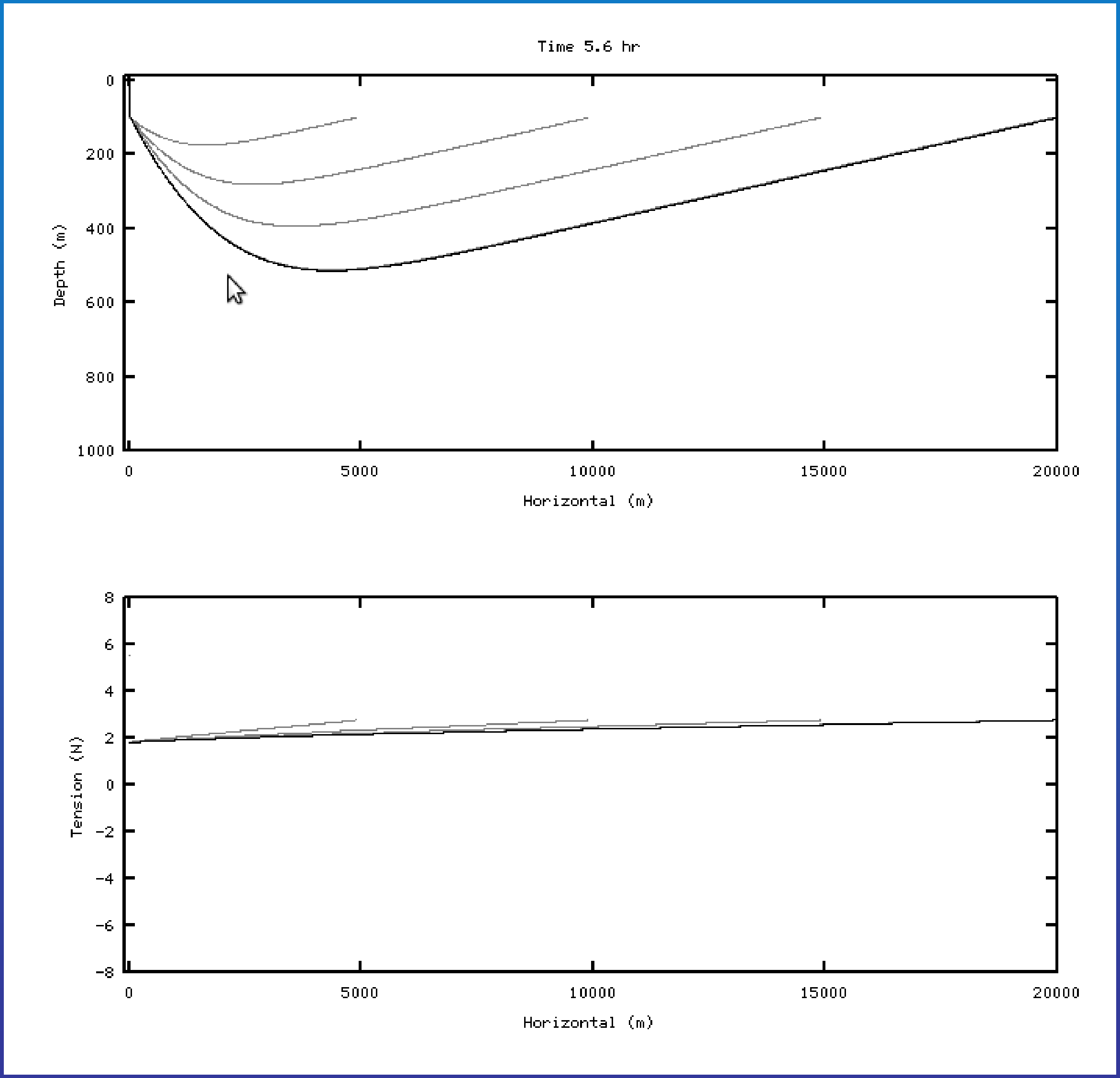
- ITC 3013 (hemispherical coverage)
- Use for 5-8 km horizontal and similar for slant range in deep water, depending on propagation conditions.
- Data rate/efficiency 100-1000 bps, 4-40 bits per joule.

Long range, 3 kHz

- ITC 2002 (slight toroidal beam-pattern)
- Use for up to ~20 km, path dependent performance.
- Data rate/efficiency: ~50-100 bps, 2-4 bits per joule.



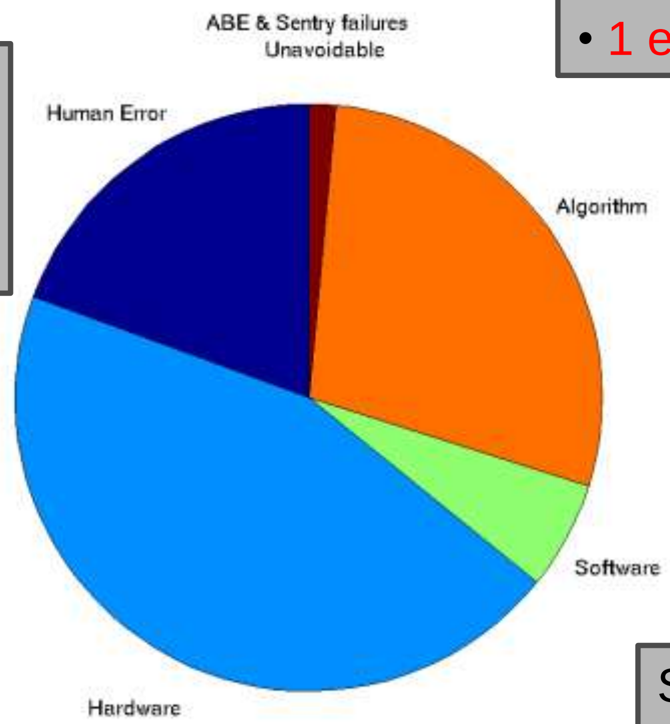
Fiber Tether Sink-rate Simulation



ABE and Sentry failures in 350 dives

Human error
- 3 setup
- 7 mission programming
- 2 incorrect ballast

Unavoidable
- 1 entanglement



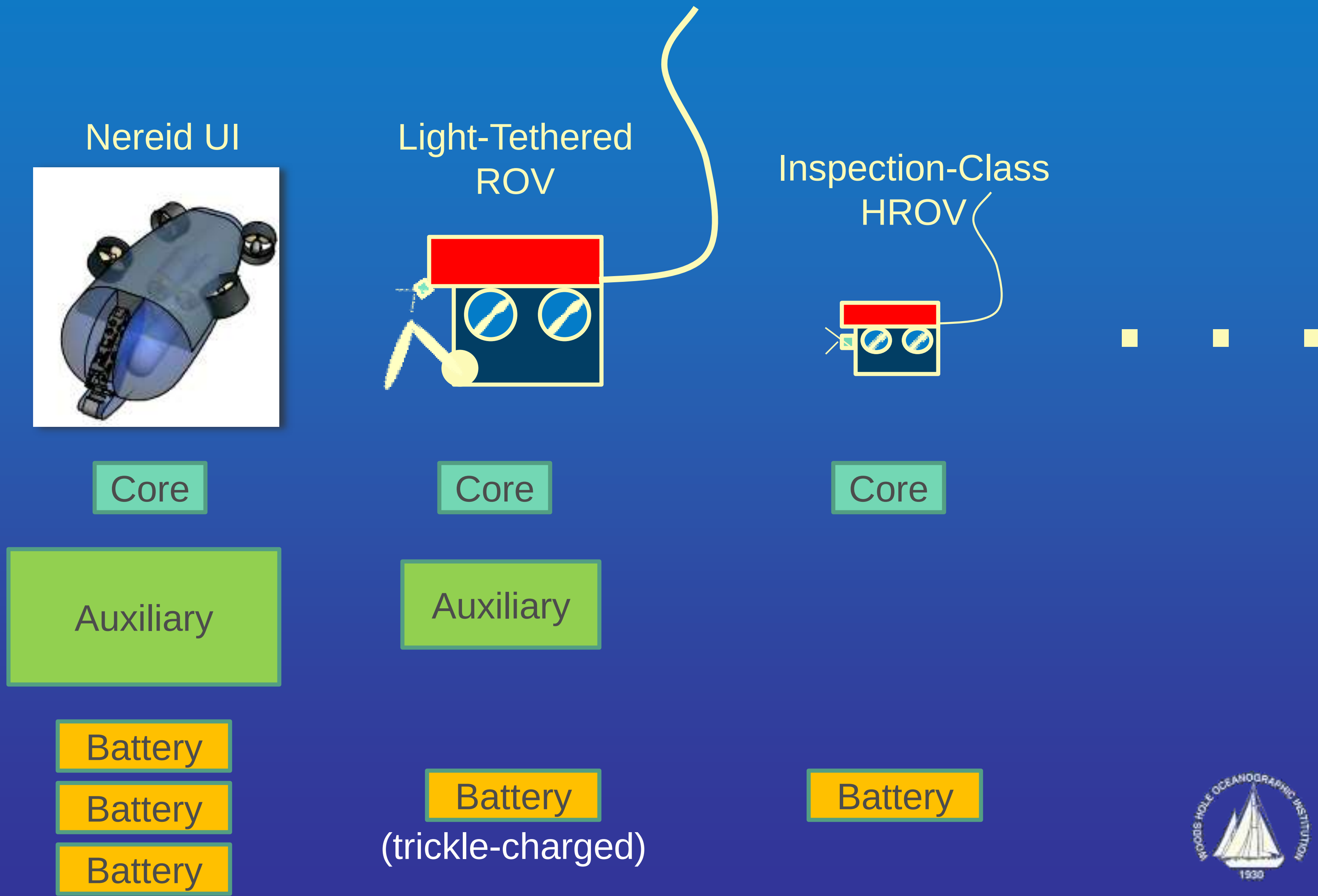
Algorithm
- 5 bottom-following
- 9 abort process
- 5 lbl

Software
- 2 inadequately tested change
- 2 programming blunder

Hardware
- 4 lbl elec/acoustics
- 2 connector failure
- 2 faulty battery
- 7 release failure
- 13 (4) Thruster elec/mechanical
- 1 computer failure

23 FATAL UNDER ICE

Mobility/Autonomy Core



Come-Home Capability

- Act upon loss of tether
- Timeout before Bailout
- Standown
- Home Acoustically
- Breadcrumbs
- Deadman Initiation
- Constant Depth
- Top-Follow
- Bottom-Follow
- Visualize Bailout
- Recall Election

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Conclusions

- More detailed exploration under permanent fixed ice will be enhanced by the Nereid Under Ice vehicle and lead to important new knowledge difficult to gather with autonomous systems having limited bandwidth communications
- Both operational and scientific techniques developed during this project should be of interest to those contemplating missions on other planets
- Teaming of human explorers to robotic tools over high bandwidth links promises most efficient of resources

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