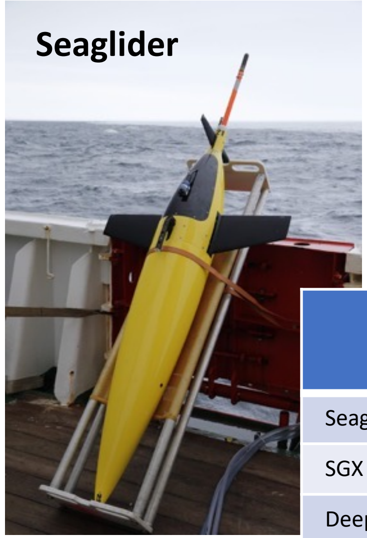
Networked Autonomous Systems for Persistent, Year-Round Arctic Observing – the Arctic Mobile Observing System Program

Craig Lee, Luc Rainville, Jason Gobat, Sarah Webster (APL-UW)
Lee Freitag (WHOI)

Background: The Integrated Observational Platforms Group

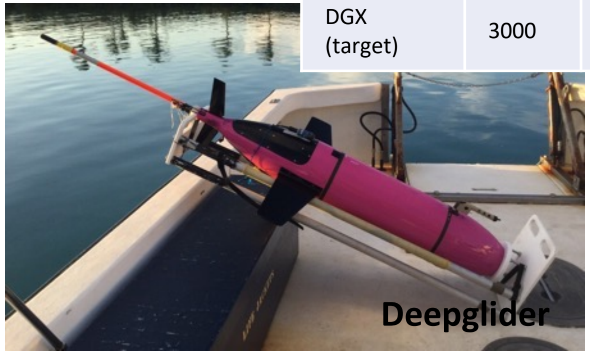
Applied Physics Laboratory, University of Washington

- Multi-scale ocean physics, interdisciplinary studies and technology development.
- Autonomous systems, mooring technologies, synoptic sampling.
- Tightly integrated basic research and technology development.
- Developers of Seaglider family of long-endurance underwater gliders.
- Seaglider Support Center.

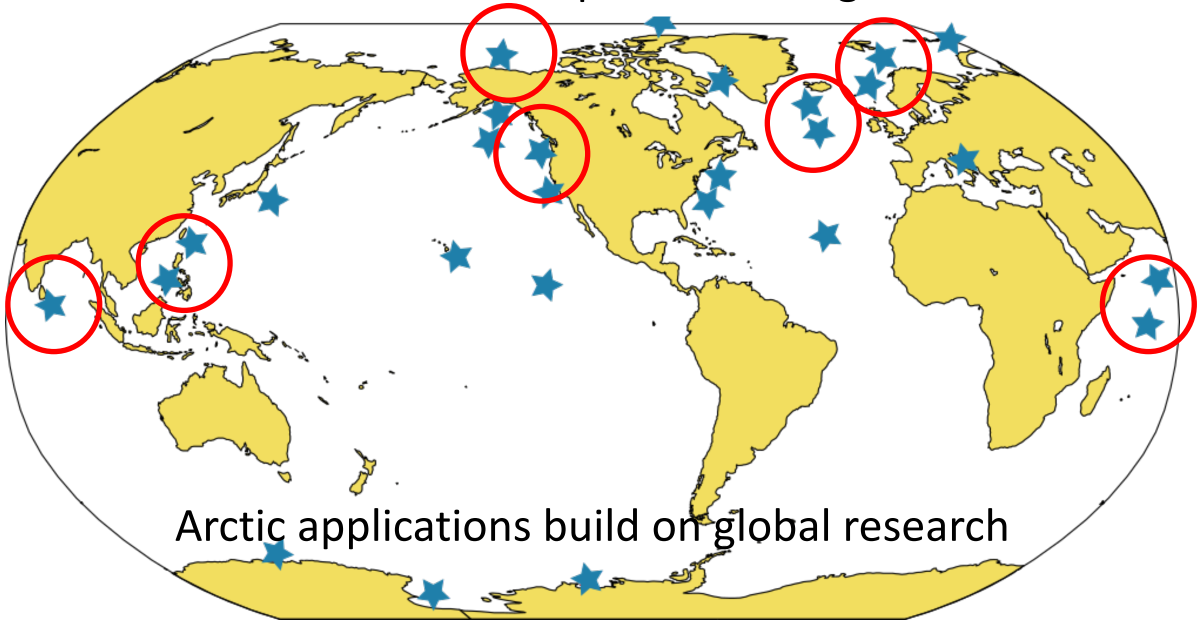


Seaglider Long-Endurance UUVs

	Max depth (m)	Energy Capacity (MJ)	Buoyancy Range (cc)	Mass (kg)
Seaglider	1000	18.1	850	52
SGX	1000	29.8	850	72
Deepglider	6000	17.5	1125	88
DGX (target)	3000	28.5	1500	75



APL-UW IOP Group Science Programs



Craig Lee, Jason Gobat, Luc Rainville, Leah Johnson, Kyla Drushka, Geoff Shilling, Ben Jokinen, Mike Johnson, Laura Crews

ONR Major Arctic Research Initiatives (2012 – present)

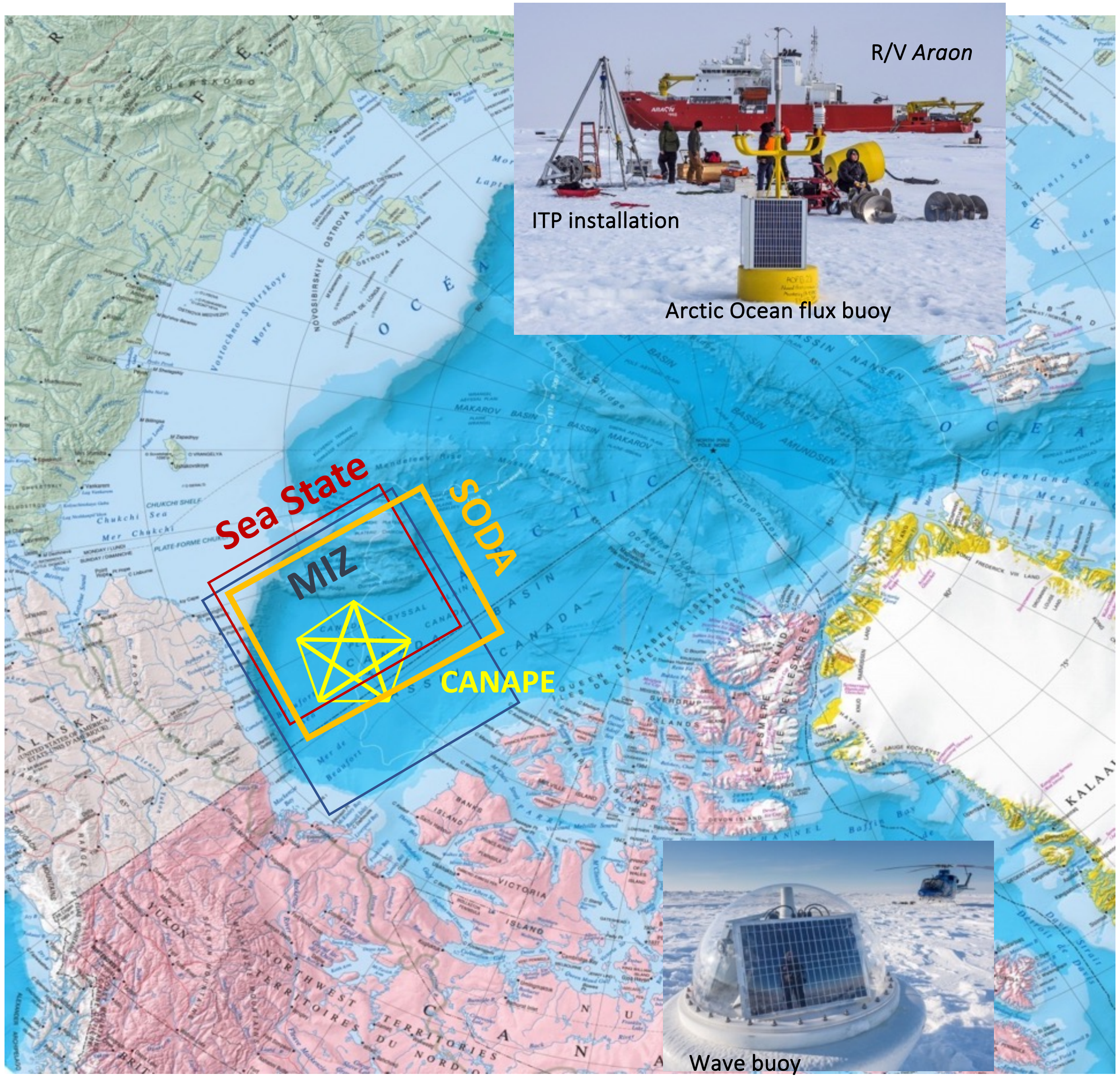
2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Office of Naval Research Arctic and Global Prediction and Acoustics Programs														
Marginal Ice Zone (MIZ)														
	Waves and Sea State													
			CANAPE (acoustics)											
				Stratified Ocean Dynamics (SODA)										
							Arctic Mobile Observing System (AMOS)							
							CAATEX (acoustics)							
							Sea Ice Dynamics Experiment (SIDEX)							
											Arctic Argo Pilot			

Marginal Ice Zone (MIZ)
Sea ice evolution during summer melt-out.
Special MIZ issue of Elementa, 2016 and https://apl.uw.edu/project/project.php?id=miz

Arctic Sea State (Sea State)
Surface Wave and Sea Ice Evolution during freeze-up.
Special section in the JGR Oceans and https://apl.uw.edu/project/project.php?id=arctic_sea_state

Stratified Ocean Dynamic of the Arctic Ocean (SODA)
Upper ocean dynamics and stratification across an annual cycle.
https://apl.uw.edu/project/project.php?id=soda

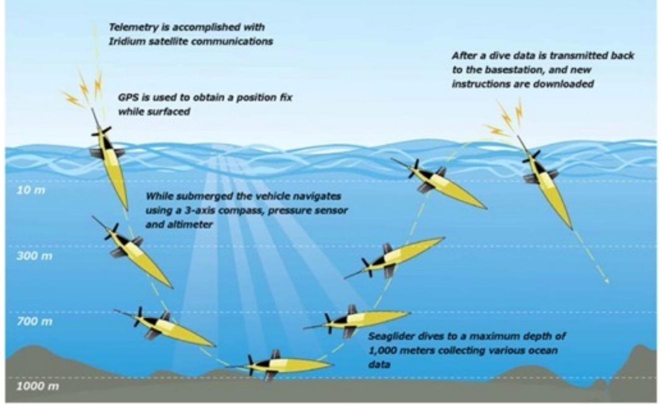
Arctic Mobile Observing System INP
Technology development – Persistence, long-endurance autonomy, acoustic geolocation and communications, networked systems.



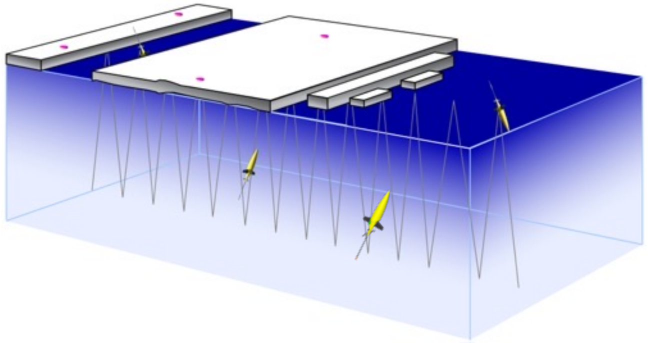
Acoustic Nav & Comms for Autonomous Platforms in Ice-covered Environments

Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Lee Freitag (WHOI)

OPEN WATER – SATELLITE ACCESS

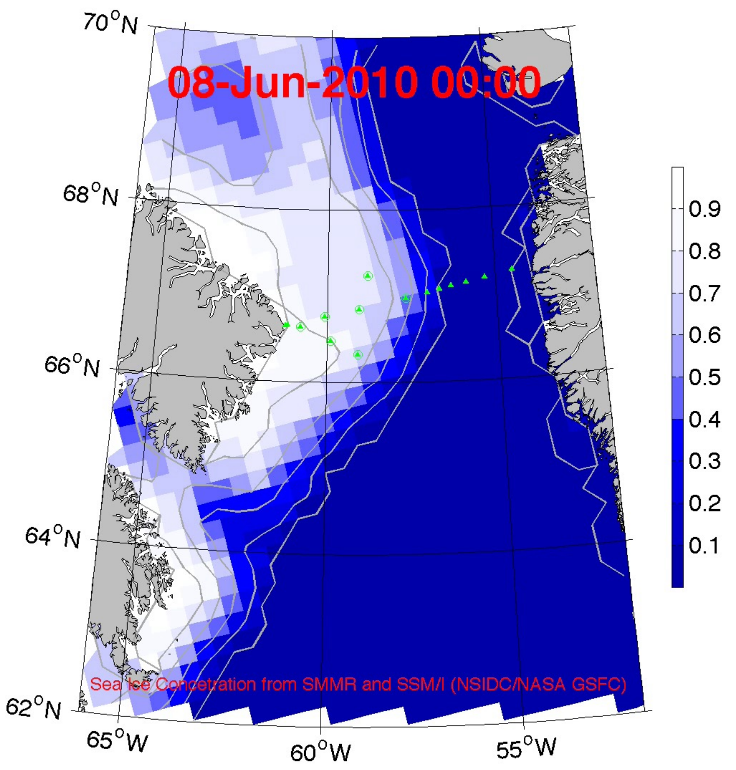


ICE – SATELLITE SERVICES BLOCKED



- Acoustic nav & comms – underwater GPS.
- Operate for months, years without human intervention.

SEAGLIDER ACOUSTIUC NAV, BAFFIN BAY (2010)



Surface ducting in many polar regions limits LF acoustic range to ~100 km.

Warm Pacific layer in Beaufort creates sound channel, allows long-range (500 km) propagation.

CURRENT STATE ACOUSTIC NAV & COMMS

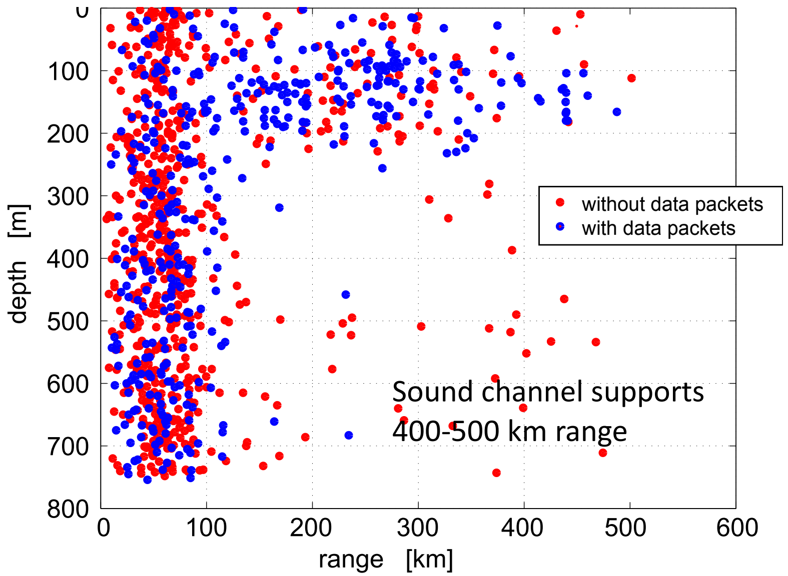
10 kHz: short-range acomms and localization.

260 Hz, 780 Hz: Fixed sources, geolocation.

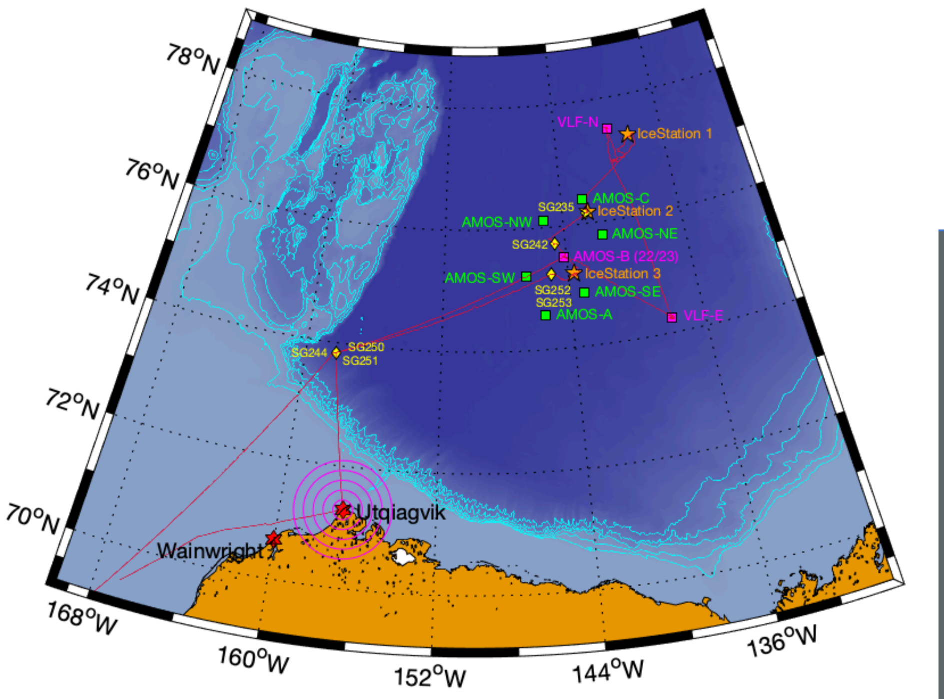
900 Hz: Fixed and mobile sources, geolocation, limited acomms.

35 Hz: Fixed sources, long-range geolocation.

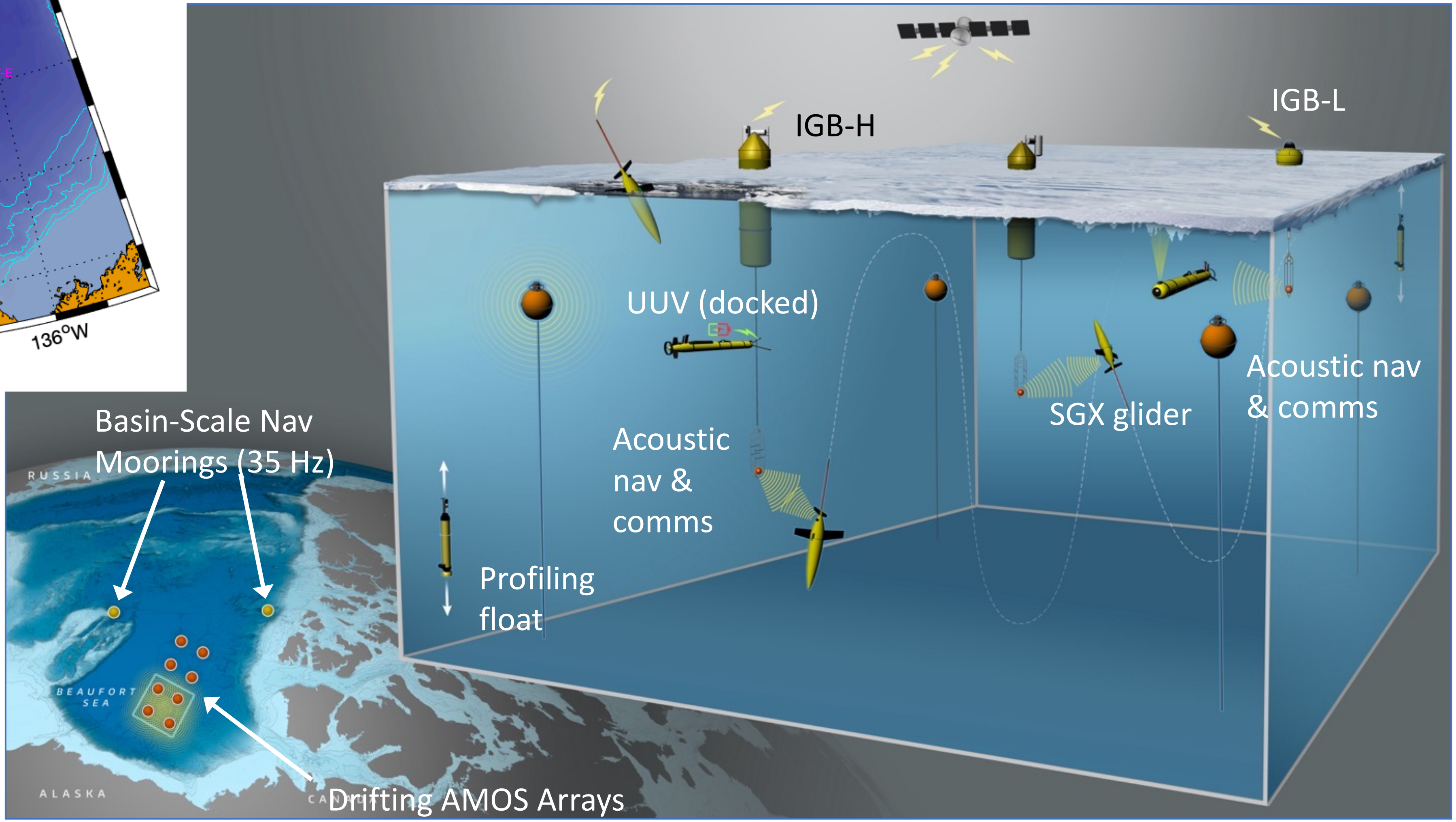
Glider Receptions vs depth and range



Arctic Mobile Observing System (AMOS)



- Persistent , year-round sampling.
- Networked for communication and data telemetry.
- Basin-scale acoustic geolocation.



Ice-mounted Gateway Buoys

IGB Light & Heavy

Acoustic navigation sources

Drifting & Moored 900 Hz

Moored 35 Hz

Long-endurance gliders

Profiling floats (Argo)

Uncrewed Underwater Vehicles

AMOS Navigation, Communication and Networking

Geopositioning

- Moored and drifting (IGB-H, IGB-L) LF (900 Hz) provide regional coverage.
- Moored VLF (35 Hz) provide basin-scale coverage.

Communication

- IGB-H, IGB-L, REMUS, moorings carry LF (900 Hz) to provide low-bandwidth, two-way acomms at 100s of km.
- Gliders and floats can receive 900 Hz, but cannot transmit.
- IGB-H, IGB-L, REMUS, gliders, floats carry 10 kHz systems to provide two-way data transfer at 1s of km.
- Potential expansion of 10 kHz to include moored data depots.

Extensive network and autonomy allow platforms to interact, exchange data.

- Persistent , year-round sampling.
- Networked for communication and data telemetry.
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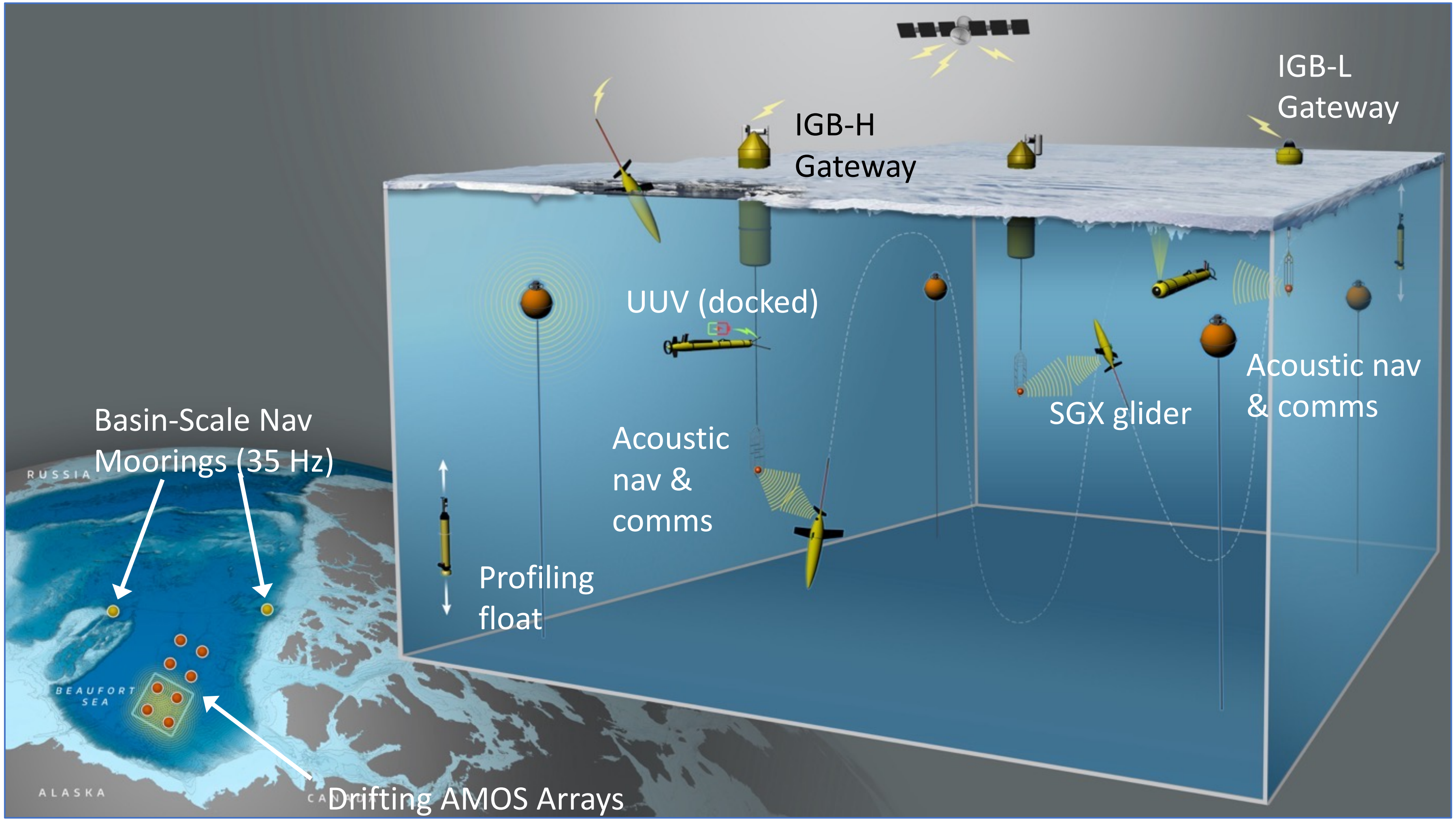
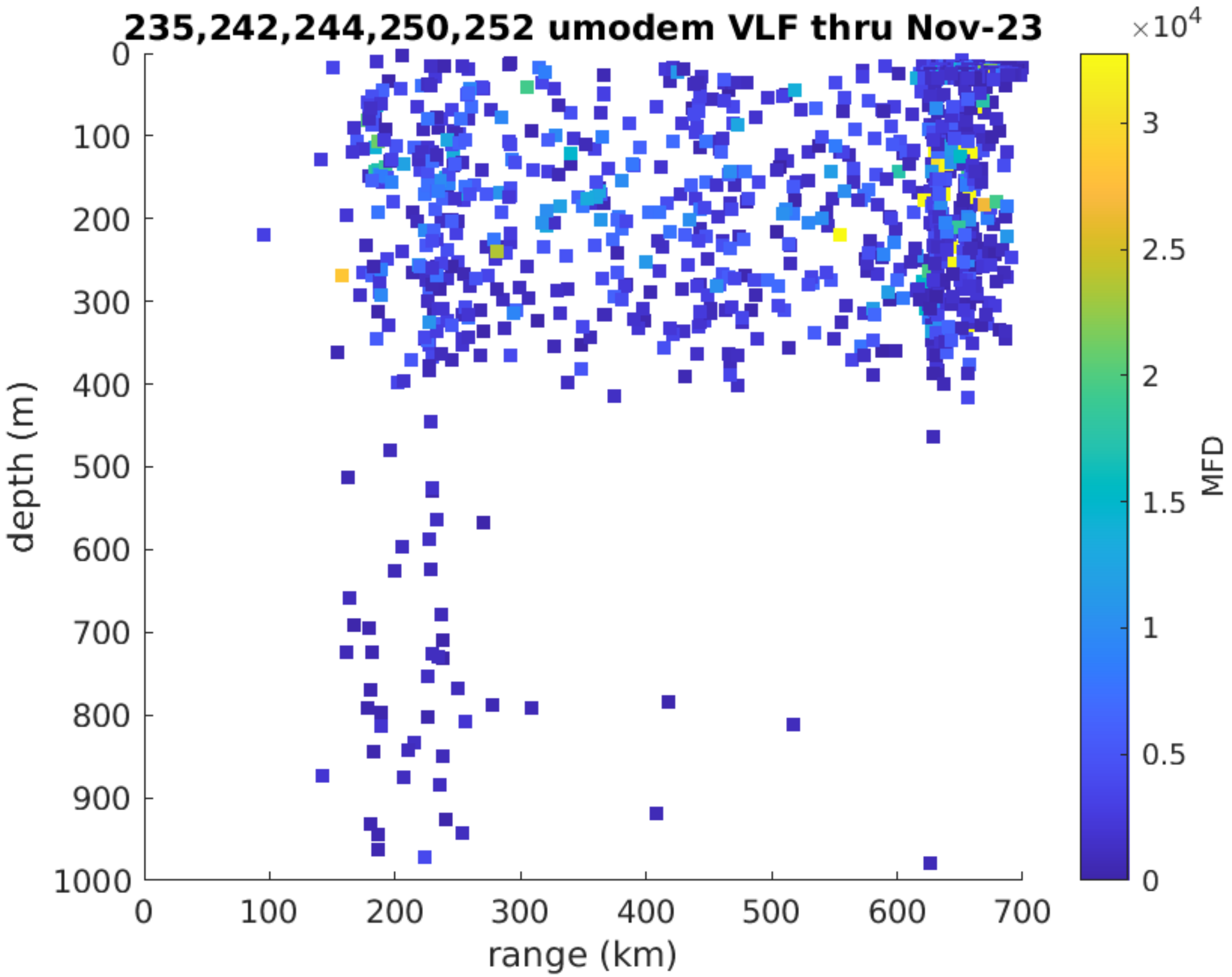
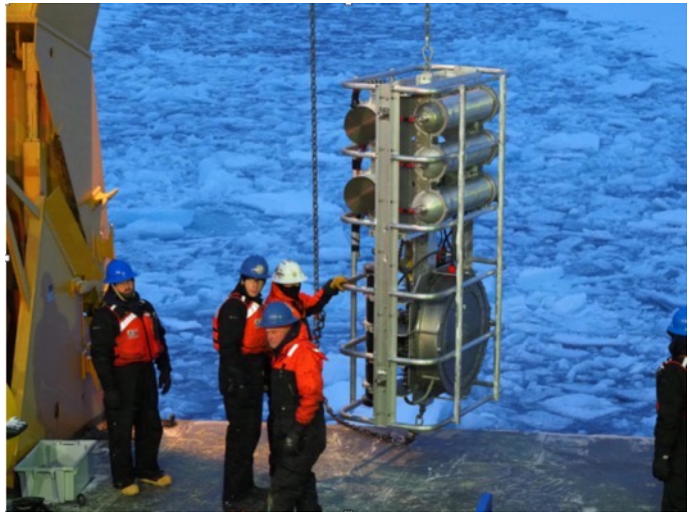


35 Hz VLF Geolocation Developments

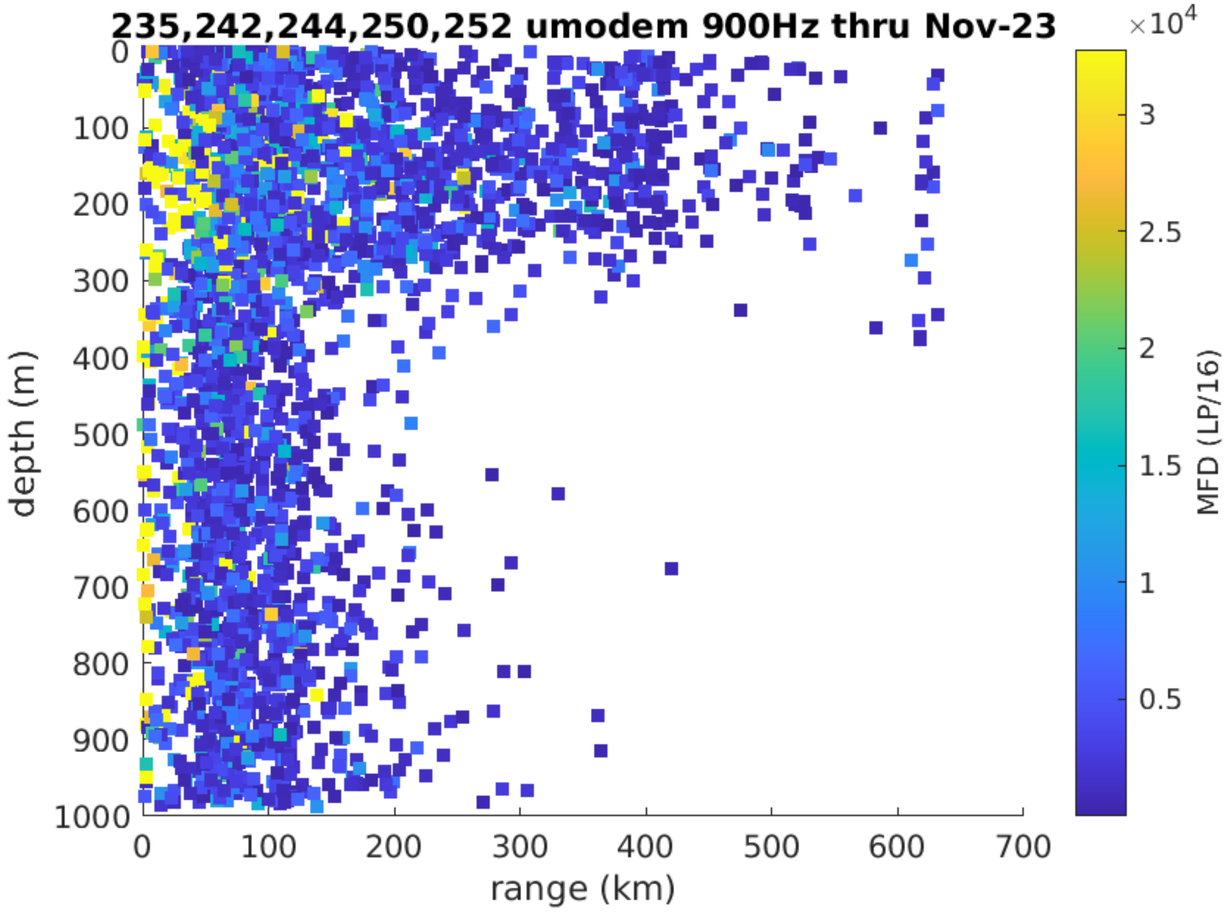
Lee Freitag (WHOI), Jason Gobat, Craig Lee (APL-UW), Matt Dzieciuch (SIO)

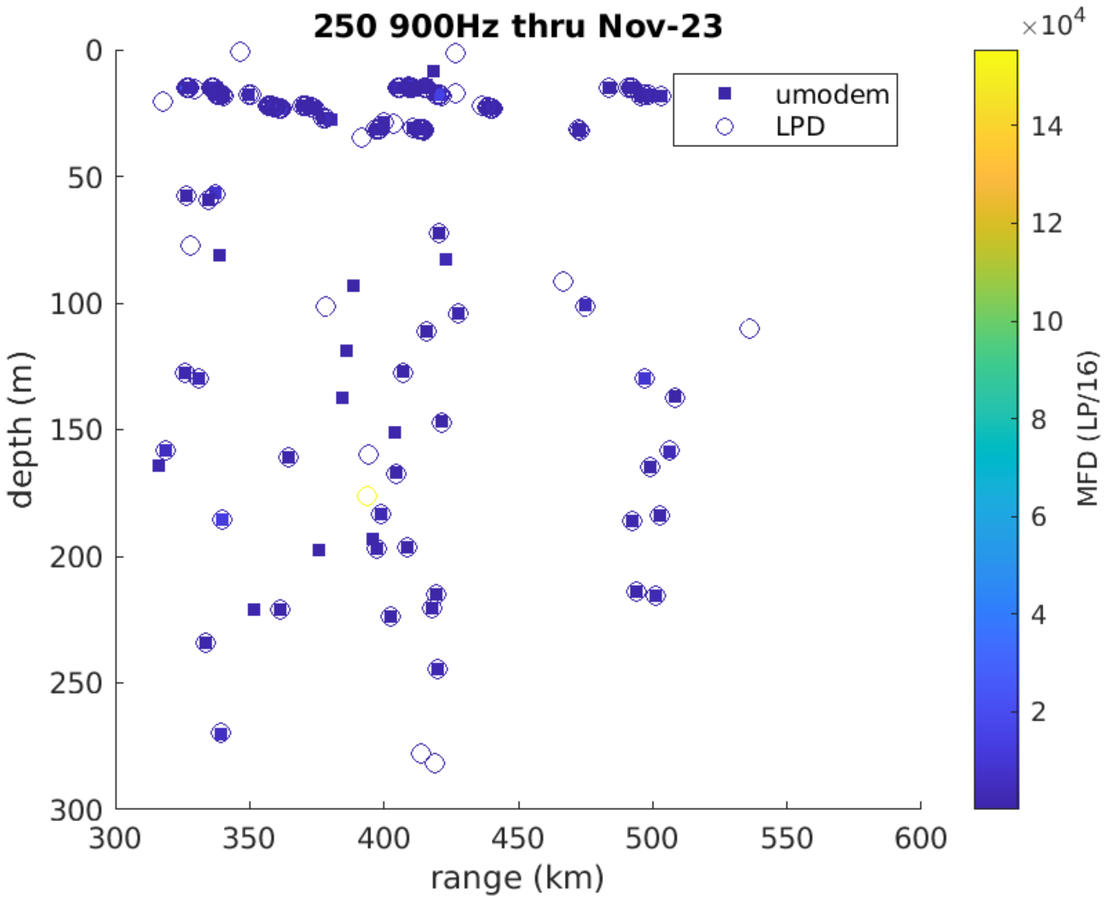


- Package 35 Hz VLF source for year-long deployments with more frequent broadcasts of shorter signals.
- 35 Hz, NTE 190 dB.
- 1-4 broadcasts per day.
- Local testing followed by central Beaufort deployment on a single mooring in summer 2022.
- Range tests with SGX gliders in autumn 2022.
- Deployed two-element array in 2023 to provide geolocation in Beaufort Sea. Currently in operation providing geolocation for floats and gliders.



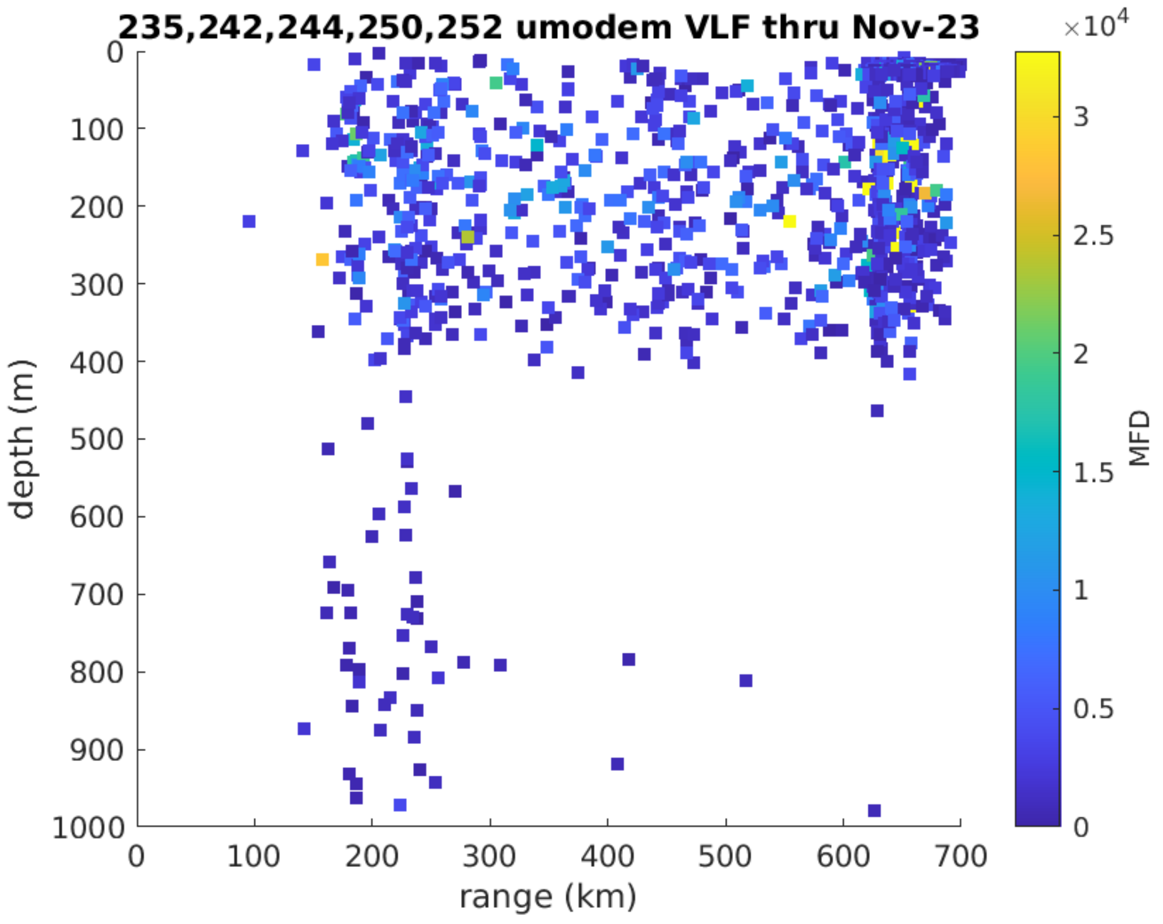
900 Hz (LF) – MicroModem and LDP Receptions

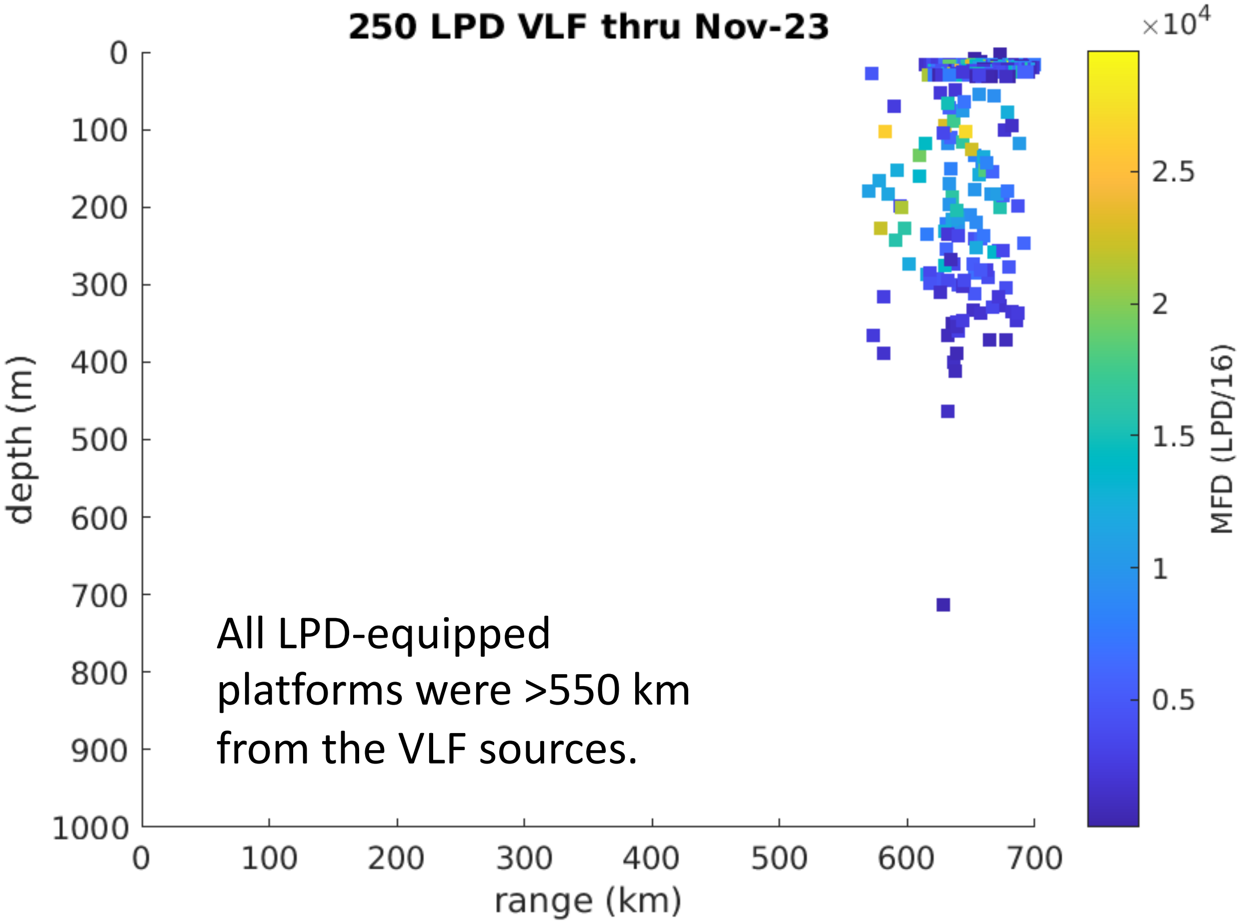




LPD = Low-Power Detector. Low-power/low-cost navigation receiver (no acomms) developed for AMOS and Arctic Argo. Alternative to more capable WHOI MicroModem system.

35 Hz (VLF) – MicroModem and LDP Receptions





All LPD-equipped platforms were >550 km from the VLF sources.

SGX Gliders in the Beaufort Sea – Year-Long Missions

Craig Lee, Luc Rainville and Jason Gobat (APL-UW)

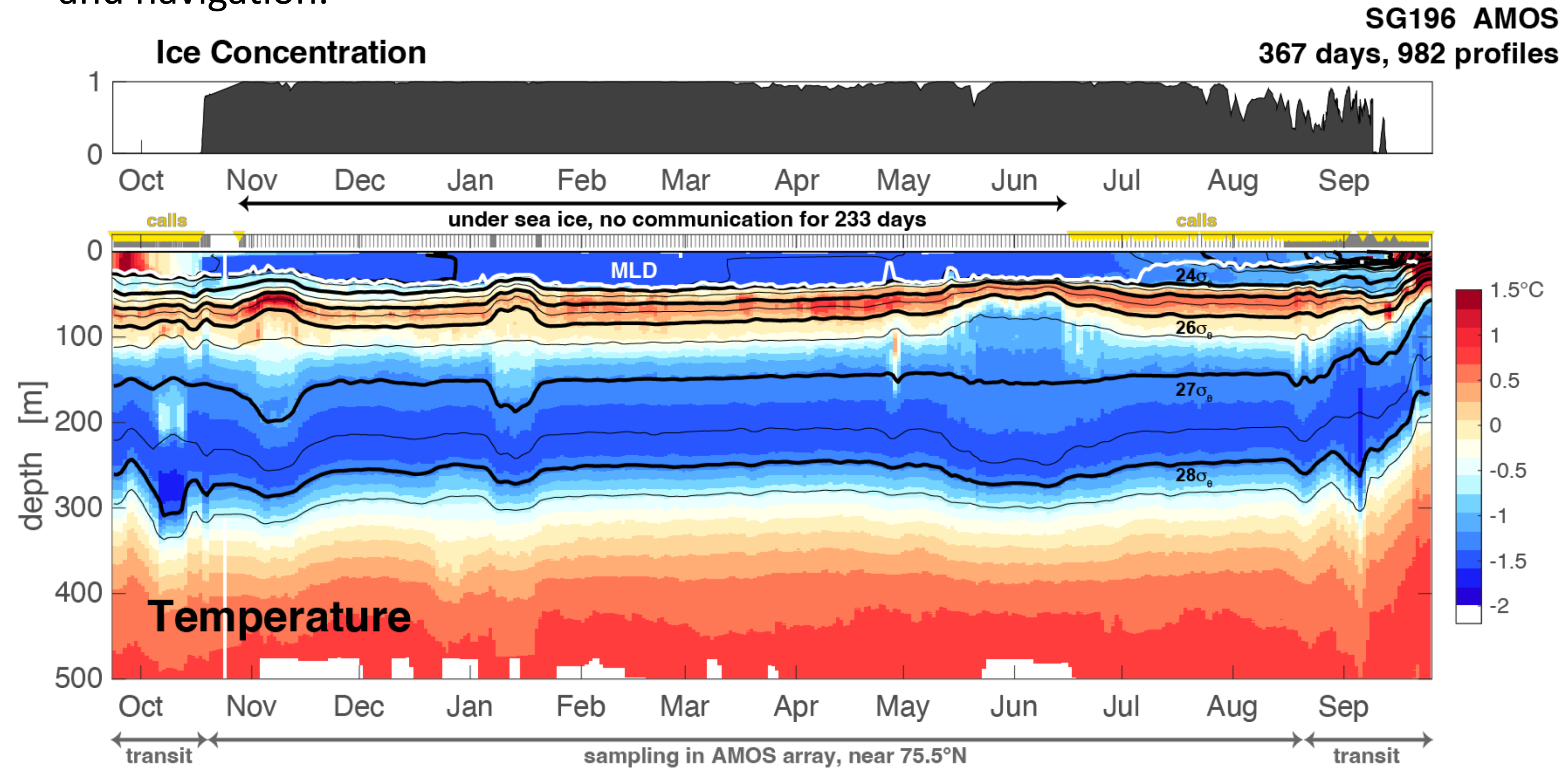
SG196: 23 Sept 2019 to 24 Sept 2020

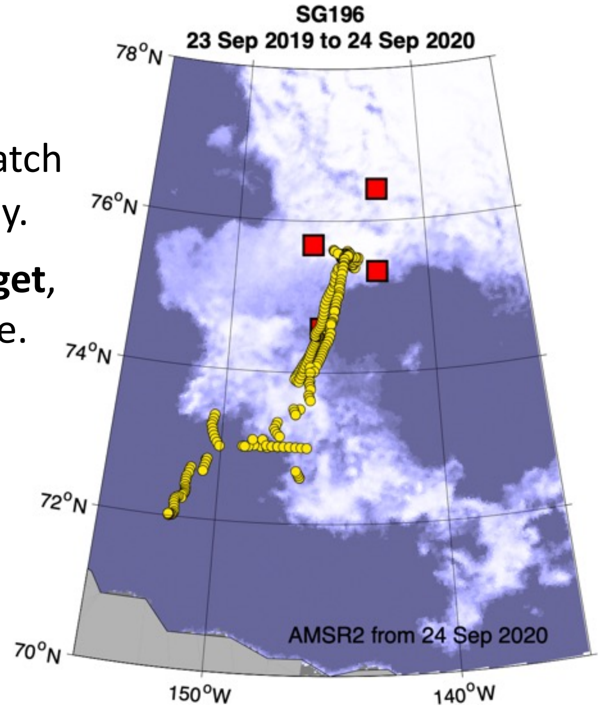
- 367 days, 982 profiles
- **233 consecutive days** under sea ice - fully-autonomous operation, diving once per day.
- Moored 900 Hz broadband acoustic array for localization and navigation.

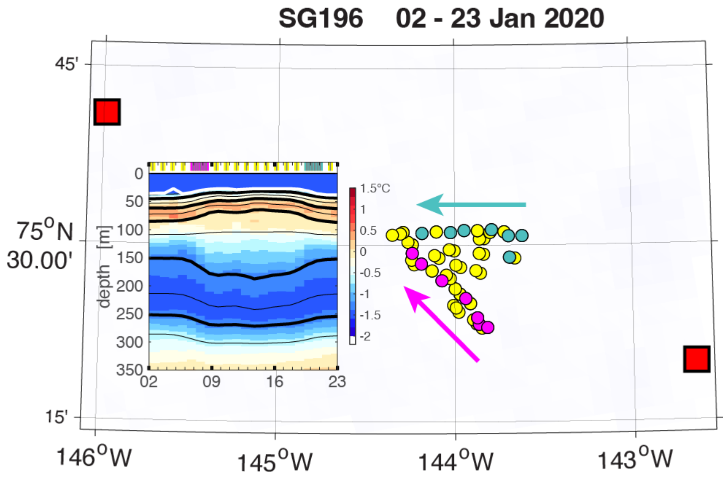
Commanded to hold position (virtual mooring).

Reposition when outside of watch circle by diving more frequently.

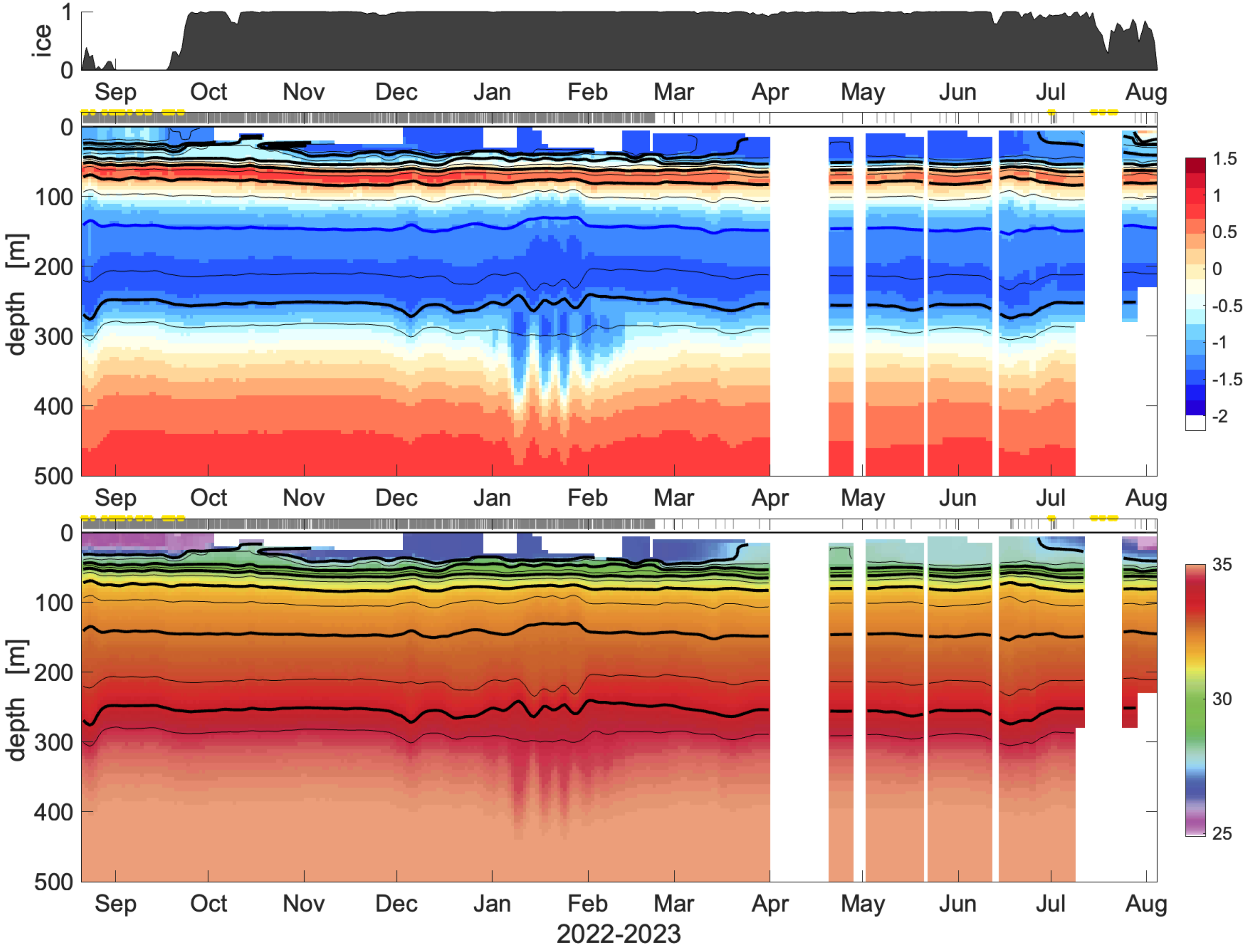
Remained within **20 km of target**, except during Jan eddy passage.





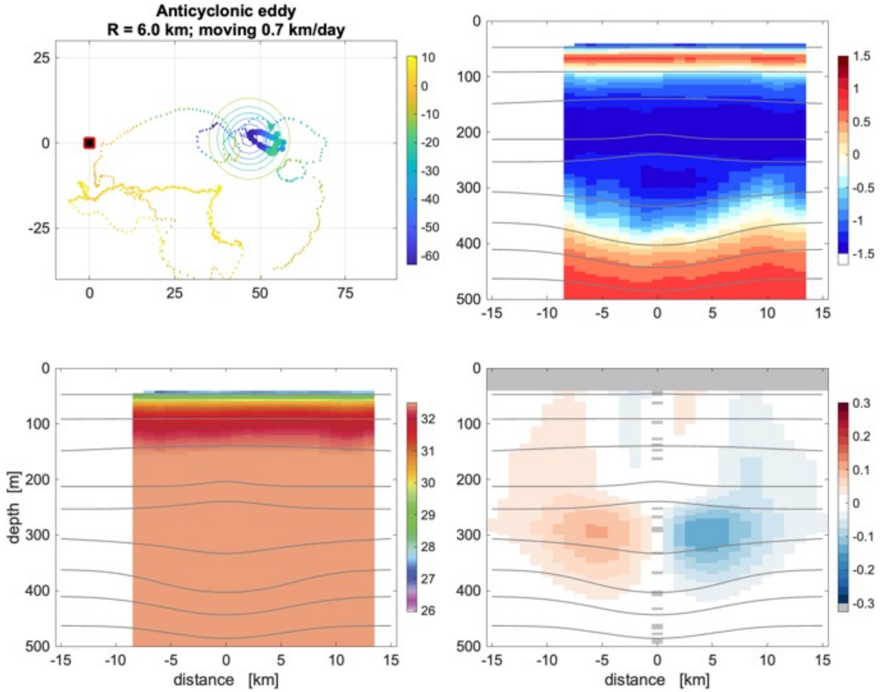


SG240 – Year-Long Over-Winter Sampling



- Deployed with IGB-H.
- Followed, then broke off to transit to center of array.
- 281 days operating under ice, without contact.
- Sharp isopycnal deflections mark transits across eddies.

Eddy Sampling Example

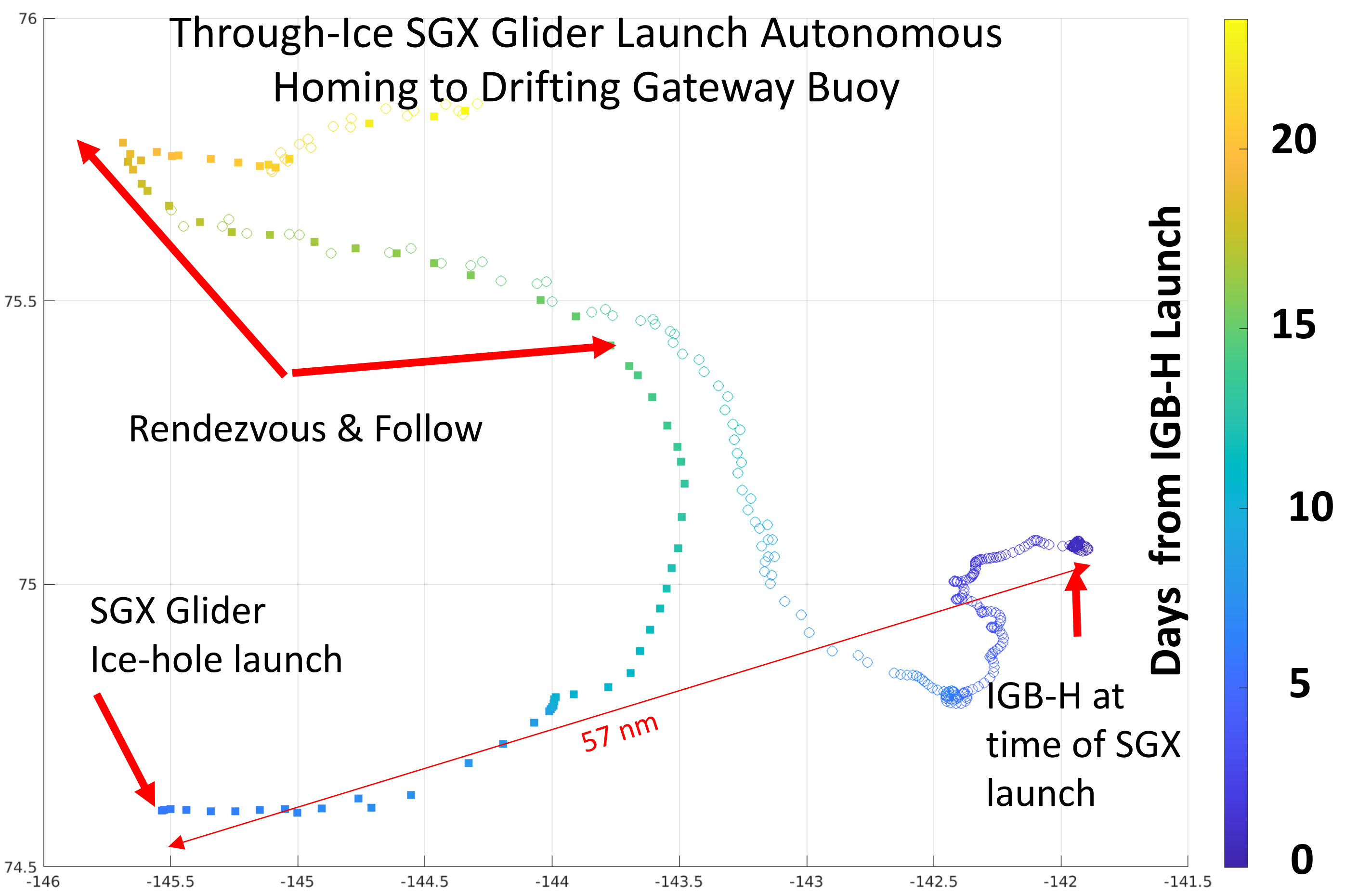


Putting the Pieces Together – The AMOS Network

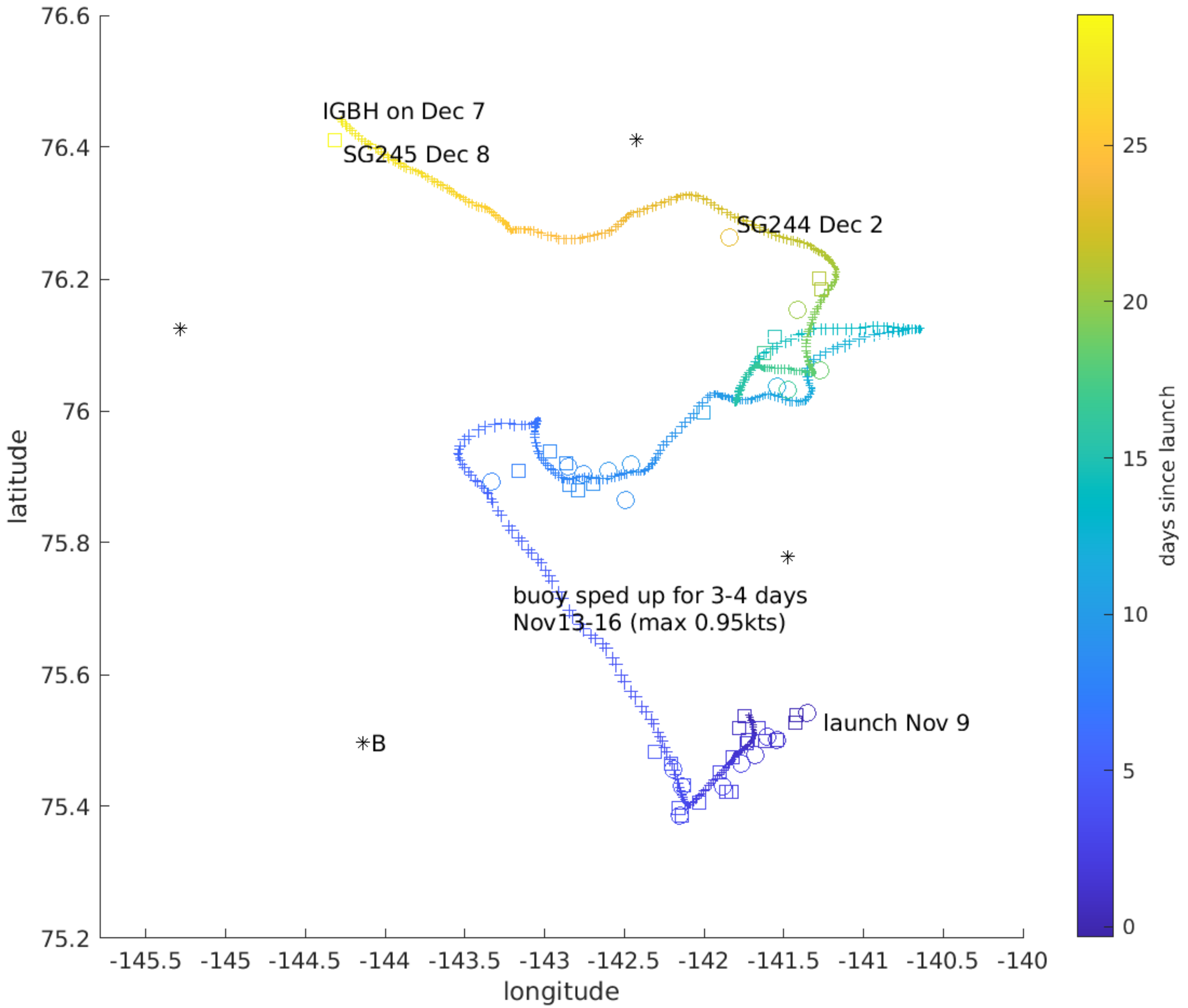
SG241 Autumn 2022

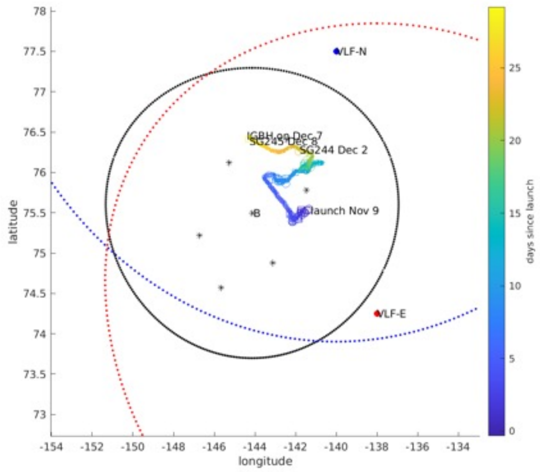
- Fully-autonomous ice-hole deployment.
- Homing, rendezvous, follow and mission re-target all fully autonomous – no human interaction/intervention.
- Glider homes based on positions communicated by IGB-H.
- Glider transmits data to IGB-H for exfil, receives commands.
- Identical demonstrations with IGB-L as target/gateway.

Integrated Nav, Comms, Networking and Autonomy



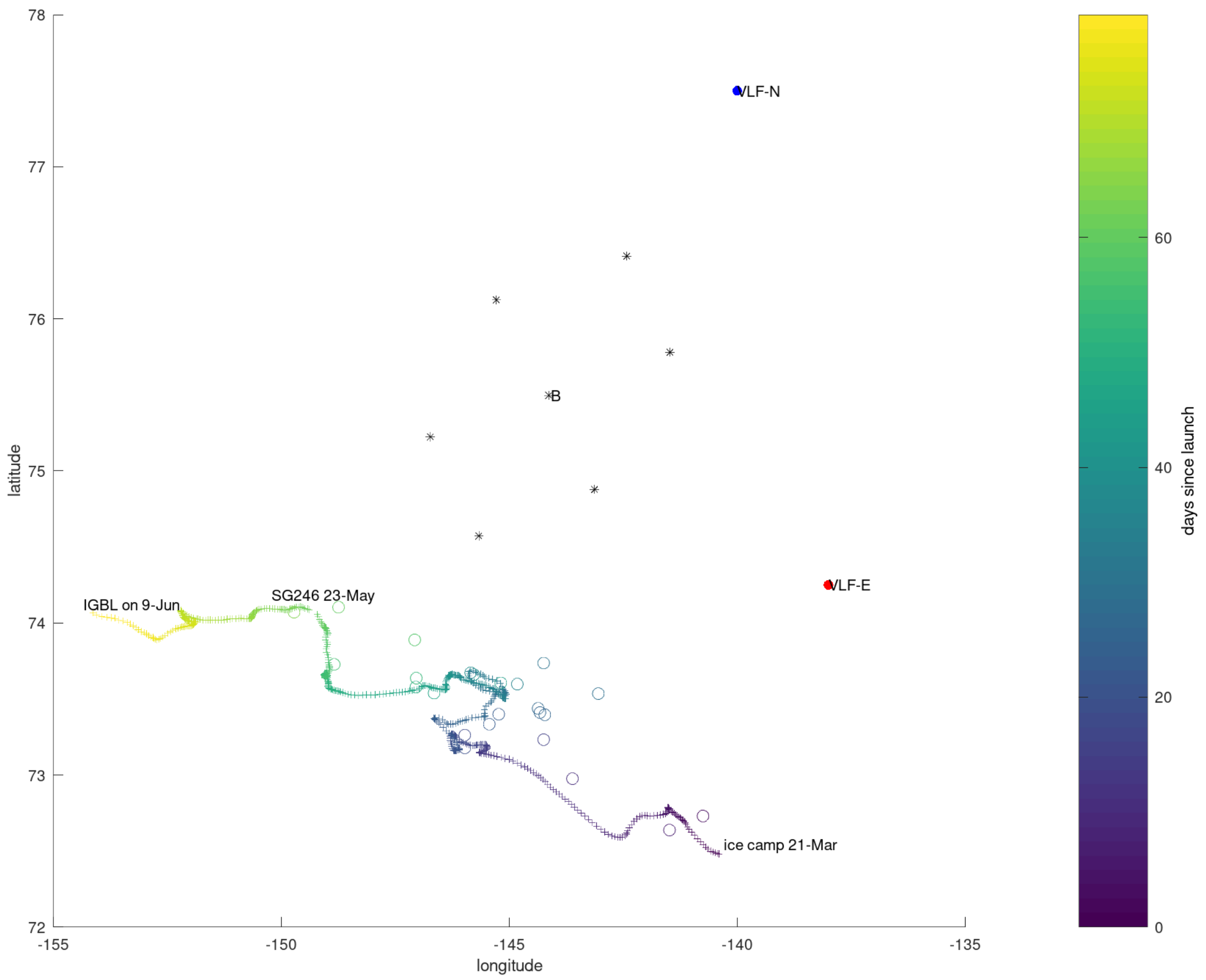
SGX Gliders Tracking, Following, Reacquiring IGB-H





- Gliders deployed through ice, fully autonomous operation under continuous ice cover.
- Two SGX gliders rendezvous with IGB-H and follow for roughly one month.
- Gliders reacquire IGB-H after loosing comms.
- SG245: 29 comm sessions, 36 dives transmitted.
- SG244: 27 comm sessions, 27 dives transmitted.

SGX Deployed at ICEX24, Follow IGB-L

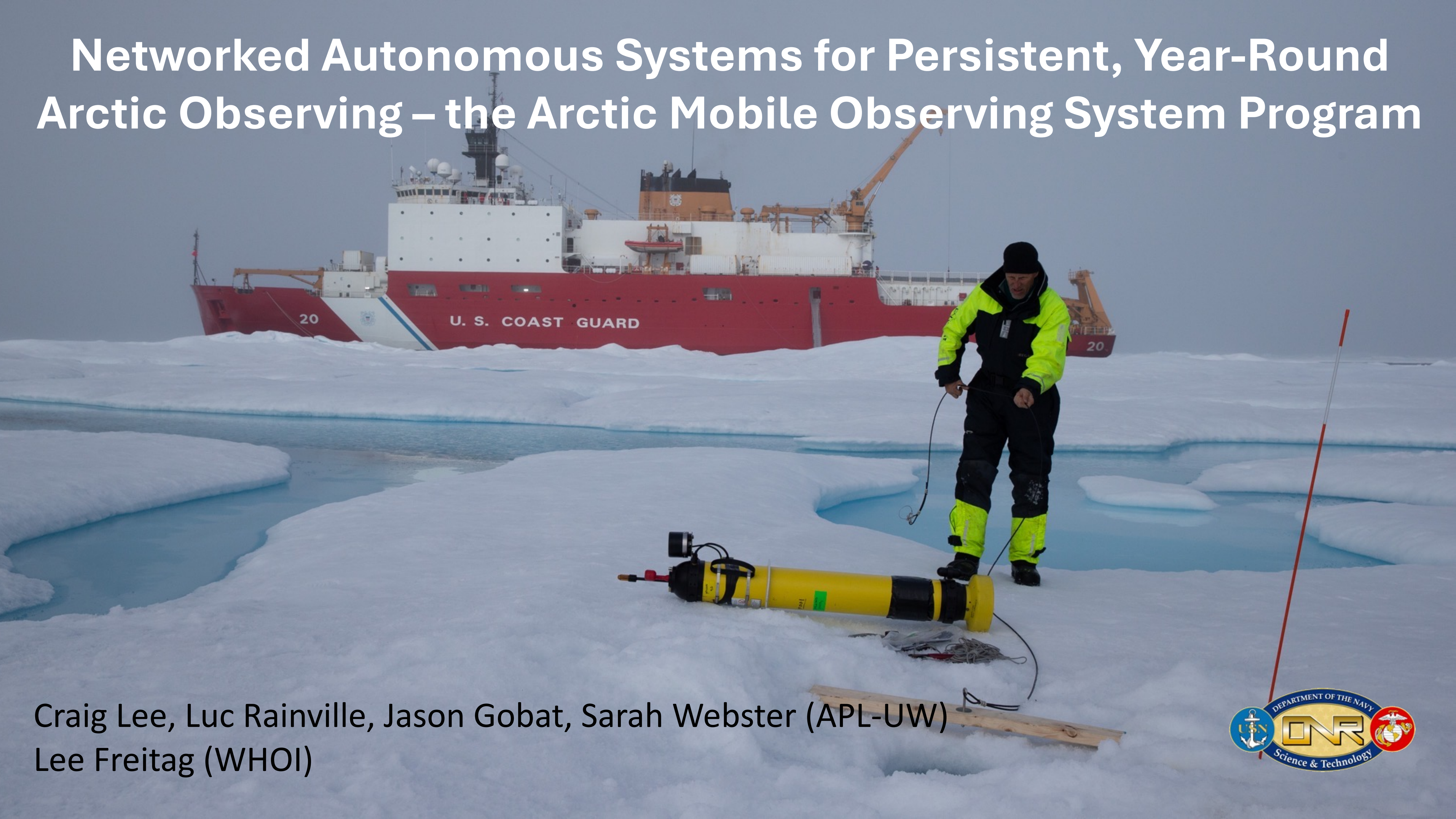


- Gliders deployed through ice at ice camp
- Autonomous ops, continuous ice cover.
- SGX glider tracks and follows IGB-L for 2+ months.
- Data transfers through gateway buoy.

Some Additional Thoughts

- Lightweight, flexible logistics valuable – expanded range of conops.
- Value in year-on-year, constant tempo experimentation.
  - Long development arc constrained by opportunities for in situ experimentation.
  - Understand/develop effective conops – as important as the technologies themselves.
- Operating at scale (redundancy) can be more tractable path to resilience than hardening of complex systems.
- Aim for lightweight, inexpensive, simple, flexible and many.

Networked Autonomous Systems for Persistent, Year-Round Arctic Observing – the Arctic Mobile Observing System Program



Craig Lee, Luc Rainville, Jason Gobat, Sarah Webster (APL-UW)
Lee Freitag (WHOI)

DEPARTMENT OF THE NAVY
ONR
Science & Technology

Multi-Scale Autonomous Observing

Climate

Planning & support

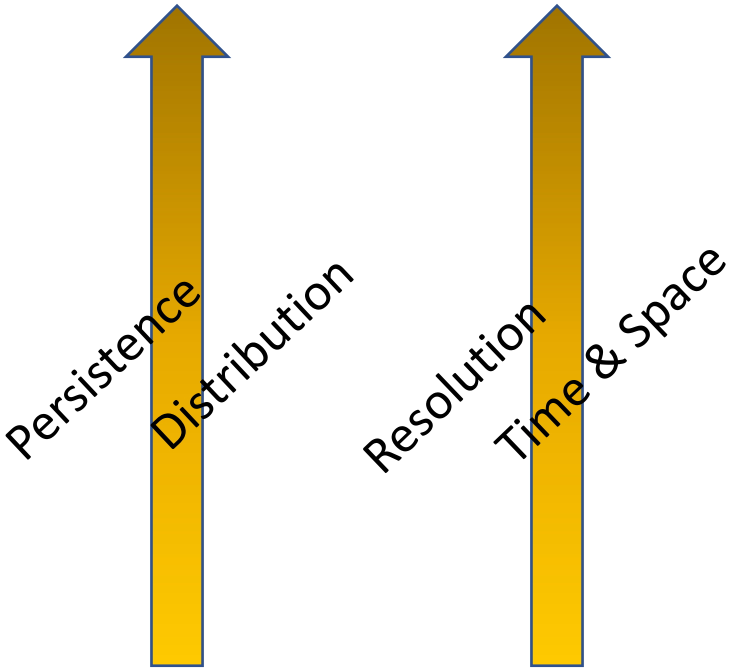
Constrain models

Improve forecasts

Situational awareness

Decades
Pan-Arctic

Months
O(100 km)



Weeks-Months
Regional

Hours-Days
Kilometers

Delayed Data

Policy
Inform long-term decision making

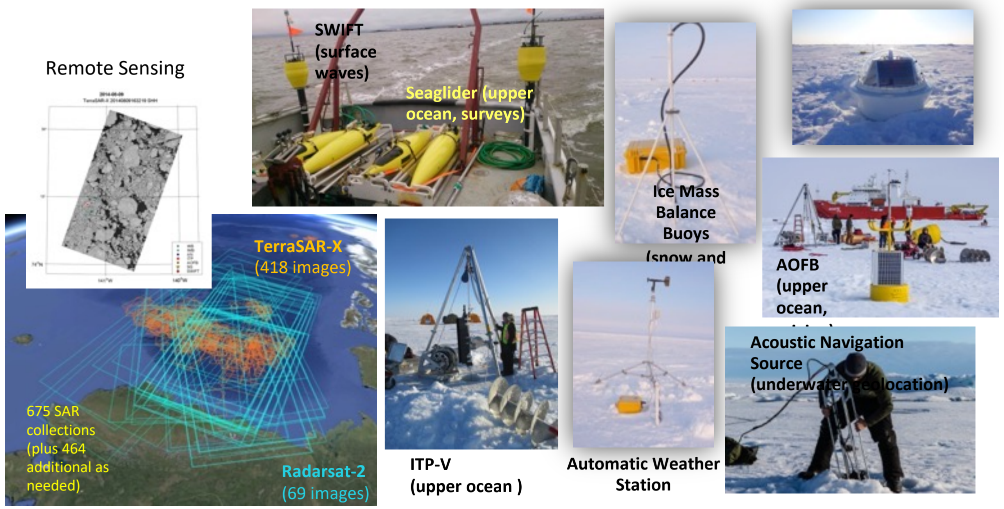
Strategy
Planning for high-risk activity

Tactics
Local support for day-to-day operations

Real-time Data

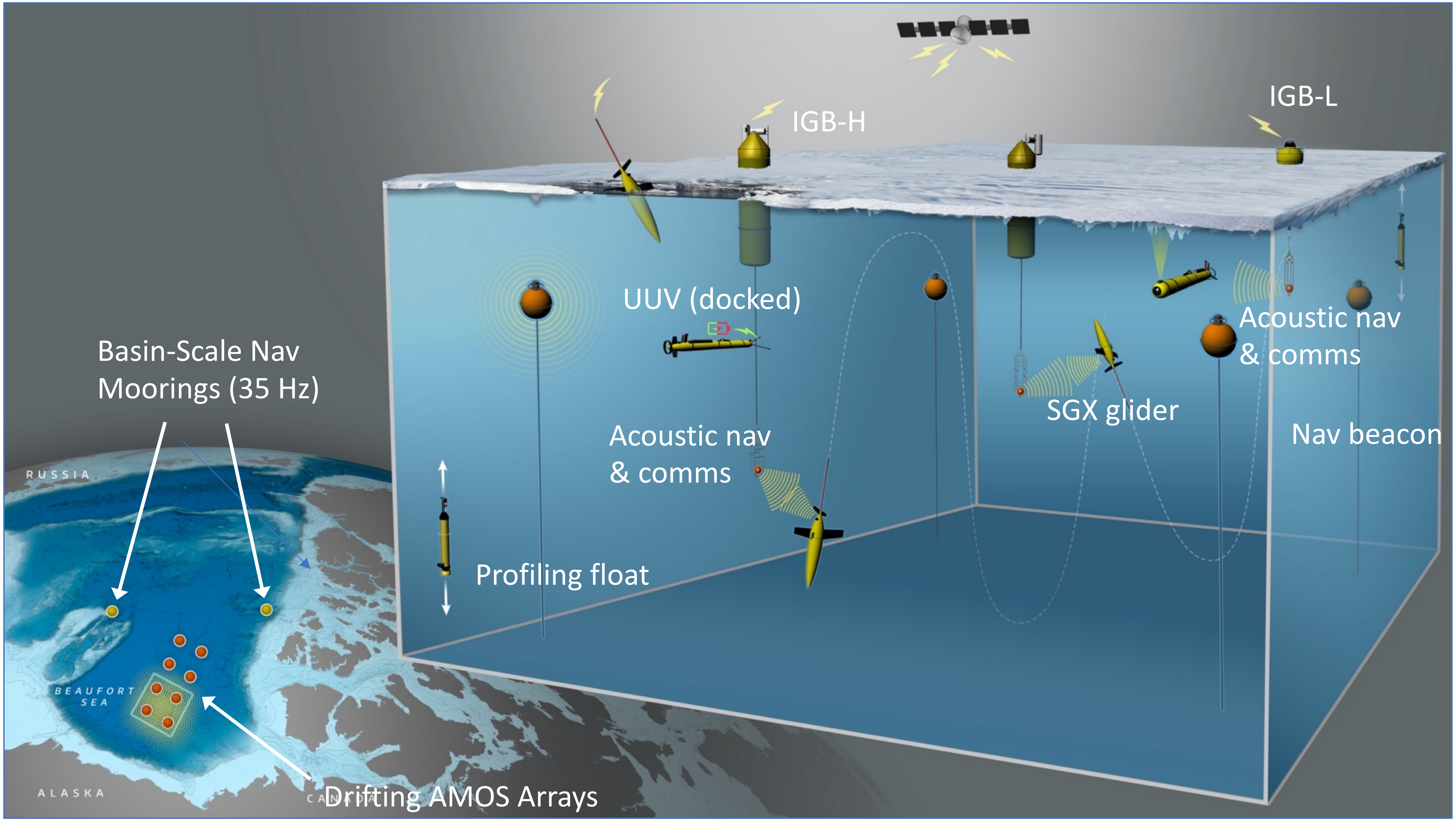
Nonlinear physics… interactions between scales are important.

Robotic Instruments Meet the Challenge



- Persistent – year-round presence on & under ice
- Scalable – inexpensive, flexible logistics, distributed
- Nimble – adaptive sampling, change with evolving needs
- Sustainable – operate for years, decades
- Networked – timely exfil of data, adaptive ops

Arctic Mobile Observing System (AMOS)



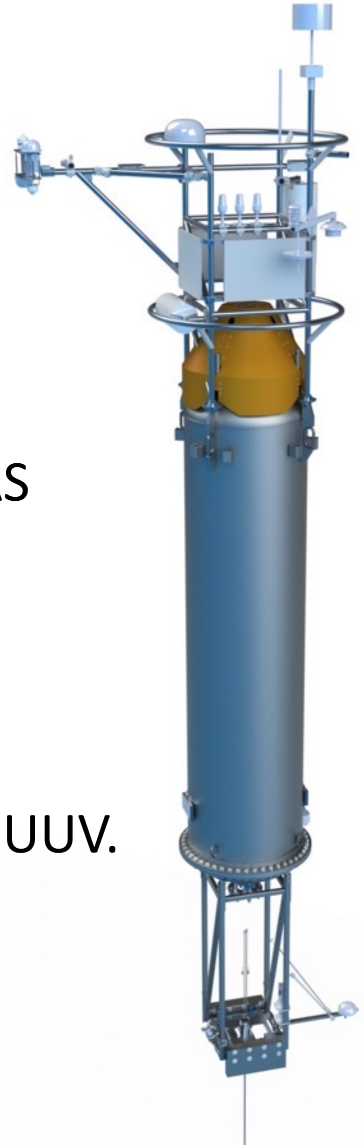
Heavyweight Ice Gateway Buoy (IGB-H)

Sarah Webster, Lee Freitag (WHOI), Chris Cox (NOAA), Tim Stanton (NPS), Jeremy Wilkerson (BAS), Thomas Handley (JHU-APL)

Current Capabilities

- Surface and Subsea cameras
- High bandwidth Iridium
- Subsea acoustic comms, WHOI
- Solar recharging
- Host of MET sensors, NPS/NOAA/BAS
- Radar phenomenology, JHU-APL
- UUV docking, WHOI
- Can host 500+ lb wet payload

Deployed 2023-2024 with docked REMUS UUV.
Larger-diameter hull for future missions.



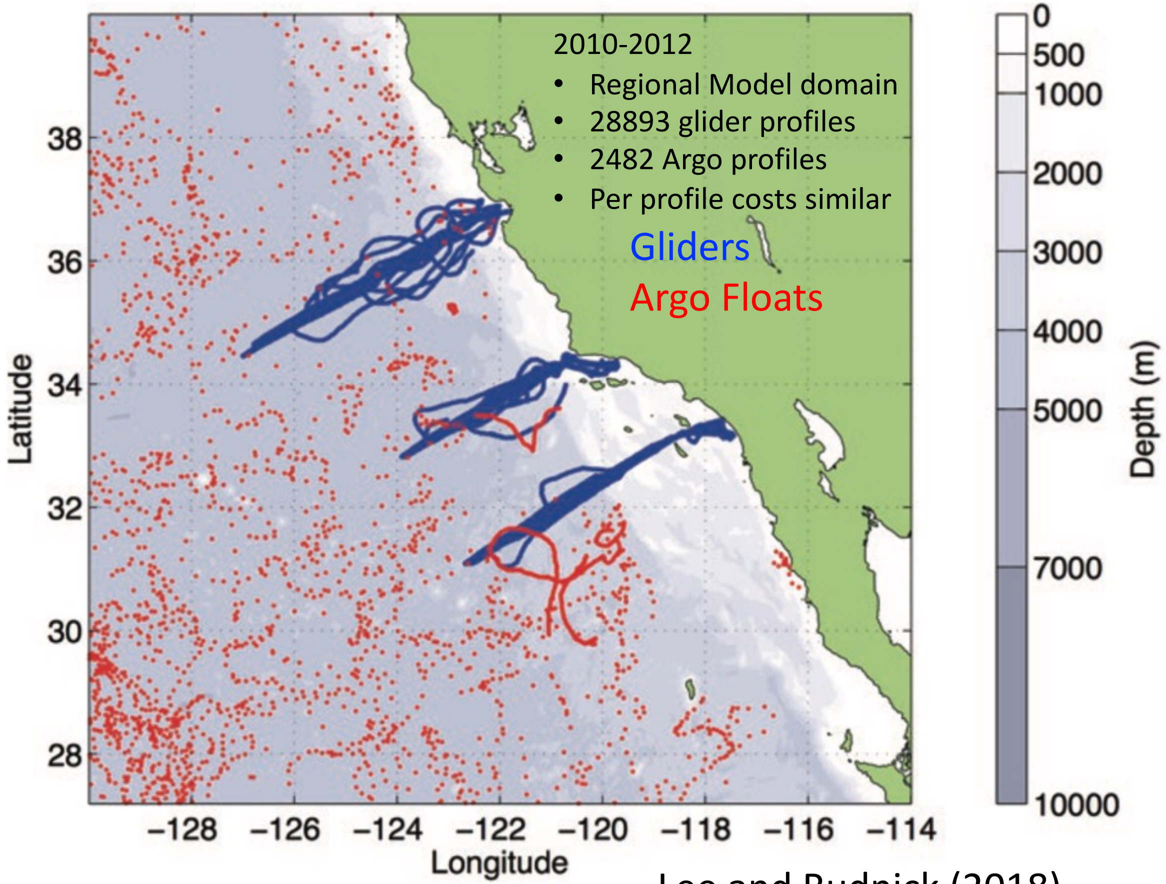
- 8450 lbs in air
- 33.25’ LOA, 45” diameter
- 905 lbs Lithium batteries
  - 194 kWHr Lithium Thionyl Chloride
  - 33 kWHr Lithium-Ion Nickel Manganese Cobalt (Li-Ion NMC) rechargeable

Ready for launch on the USCGC Healy, Oct 2022

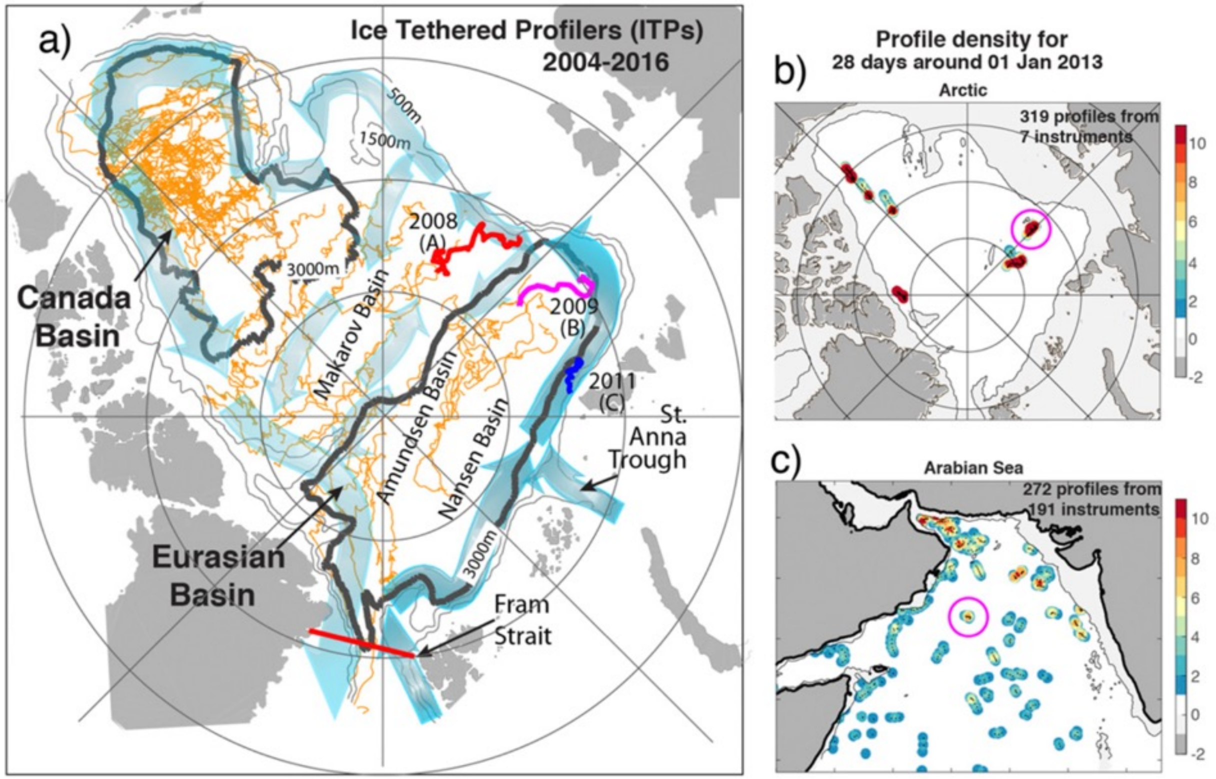
Arctic Argo Pilot

Craig Lee, Jason Gobat, Luc Rainville (Applied Physics Laboratory, UW)
Lee Freitag (Woods Hole Oceanographic Institution)
Dan Rudnick, Jeff Sherman (Scripps Institution of Oceanography, UCSD)

Why Profiling Floats in the Arctic?



Lee and Rudnick (2018)



Nguyen et al (2020)

- Gliders provide high-resolution sampling
- Floats provide distributed profiles

- Ice-based instruments provide sampling similar to gliders (but with real-time data return).

AMOS Navigation, Communication and Networking

Geopositioning

- Moored and drifting (IGB-H, IGB-L) LF (900 Hz) provide regional coverage.
- Moored VLF (35 Hz) provide basin-scale coverage.

Communication

- IGB-H, IGB-L, REMUS, moorings carry LF (900 Hz) to provide low-bandwidth, two-way acomms at 100s of km.
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- Potential expansion of 10 kHz to include moored data depots.

Extensive network and autonomy allow platforms to interact, exchange data.

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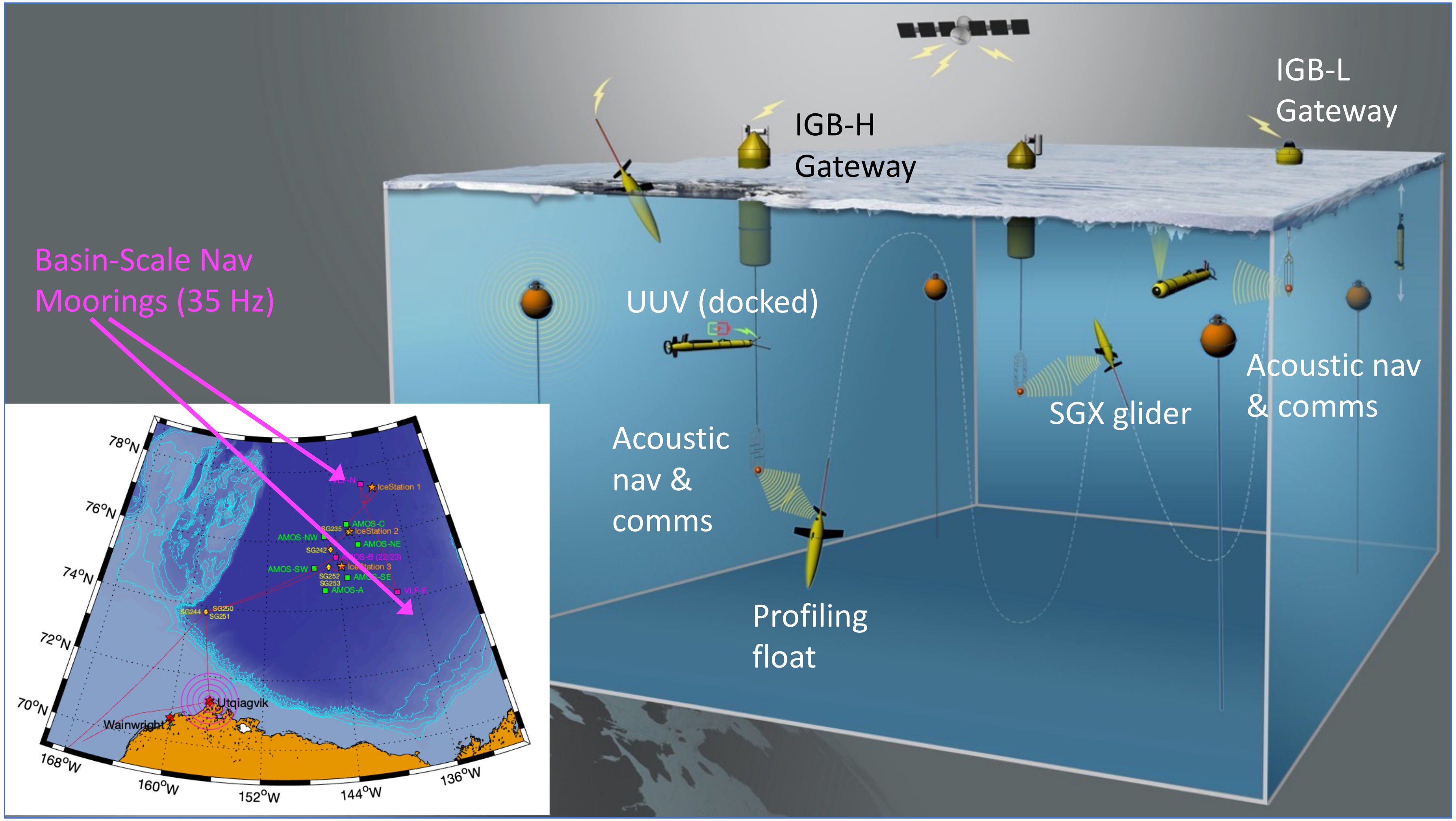
- Basin-scale acoustic geolocation.



Float Position Error and Reporting Interval Estimated using ASTE

Nguyen et al (2020)

Questions:

How far would floats drift?

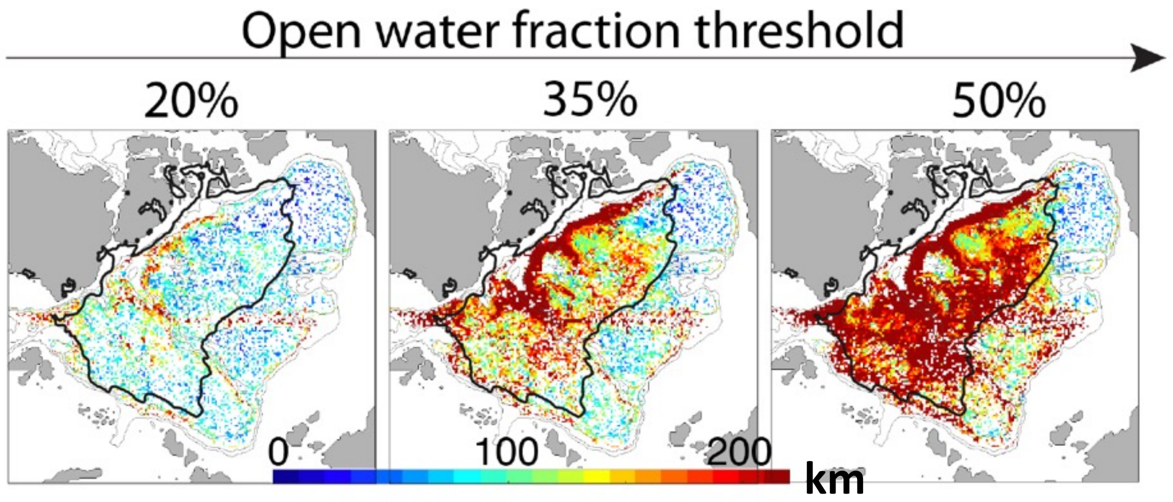
What would the resulting errors be in estimated profile positions between surfacings?

How often would floats surface (and thus exfiltrate data)?

Would the resulting data, with position errors, be useful for improving the state estimate?

Ability to surface in partial ice cover valuable.

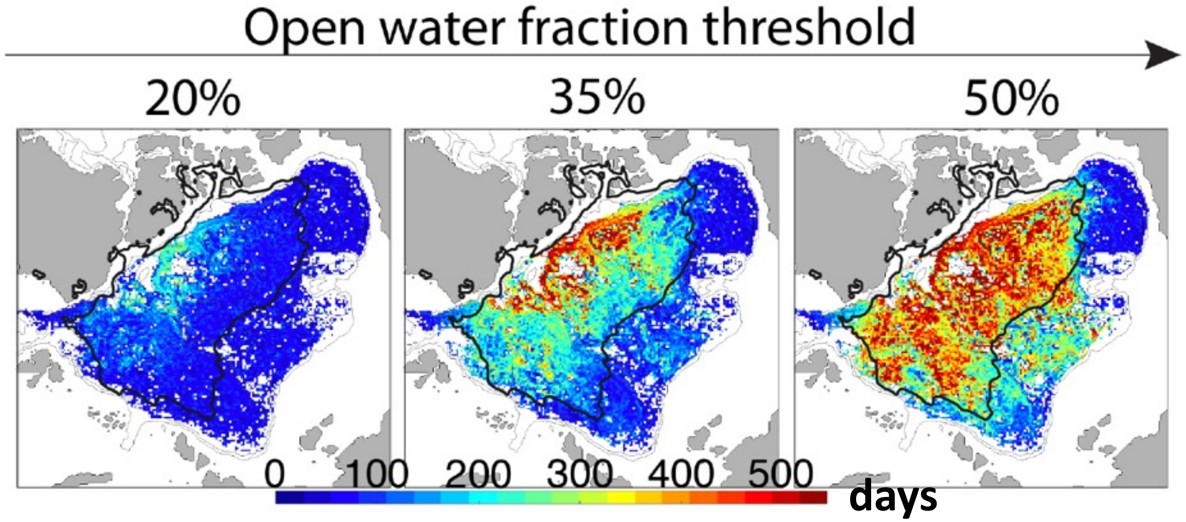
Mean Separation Distance (true vs. simulated, 100 samples)



Large uncertainties:

- Heavy ice cover (long drift intervals).
- Energetic currents

Time Between Surfacing



- High probability of surfacing multiple times per year.
- In regions of multi-year ice, floats may drift for years, until they move to area of seasonal ice cover.

AMOS Teledyne APEX Float and Ice-Tethered 'Launcher'

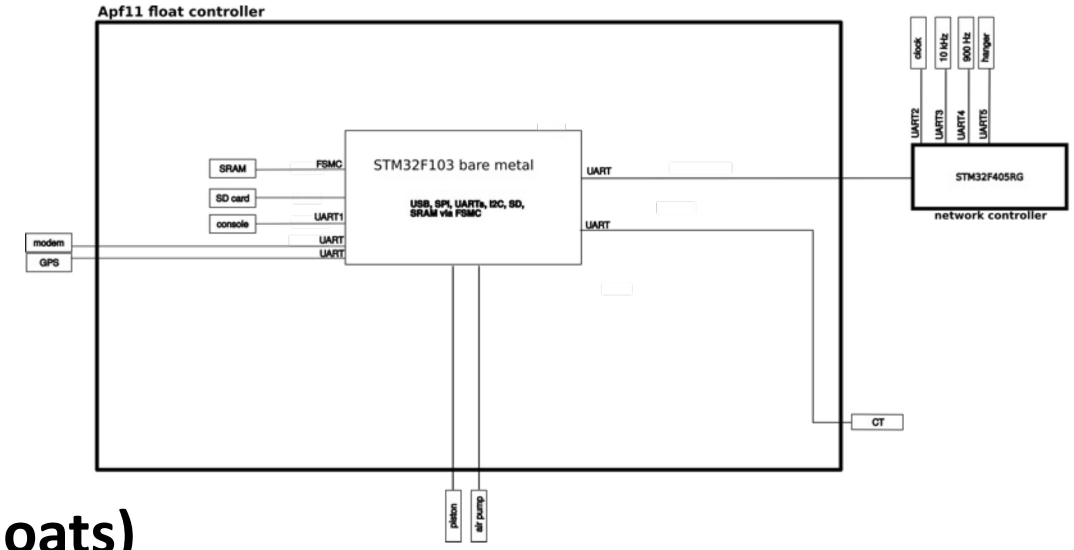
Jason Gobat, Craig Lee, Luc Rainville (APL-UW)


'Ice Guard'

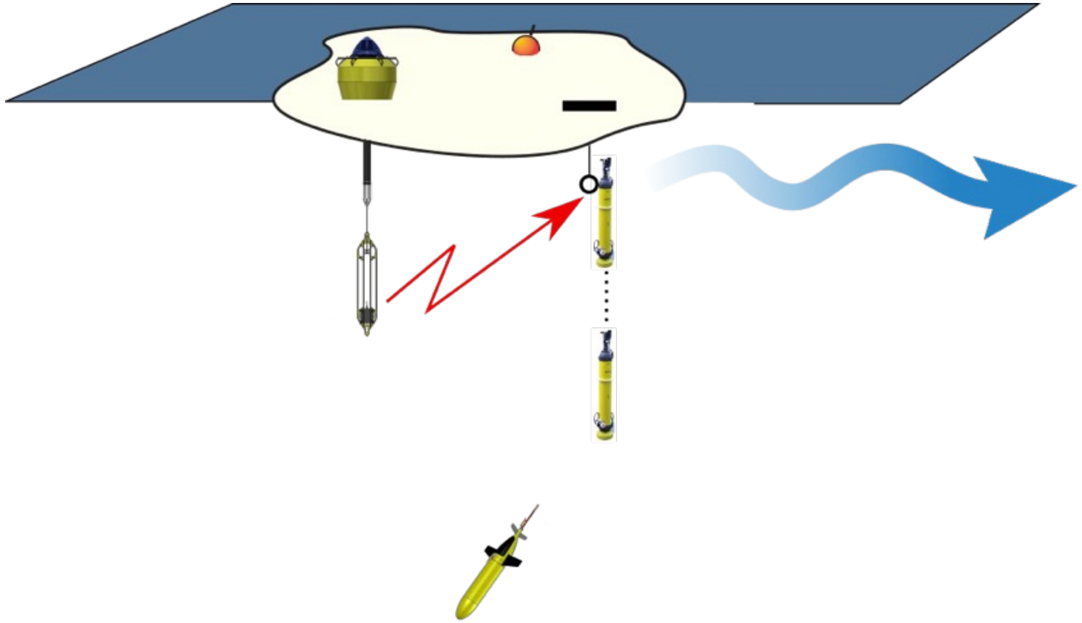
Independent Network Controller

- Acoustic modem/900 Hz nav (900 Hz carrier, 3-25 bps, Rx only)
- Acoustic modem/Nav source 2 (10 kHz carrier, 300-5000 bps)
- Clock
- Hanger release

Ice avoidance and backlog management



Successfully deployed summer, 2023 (3 floats)

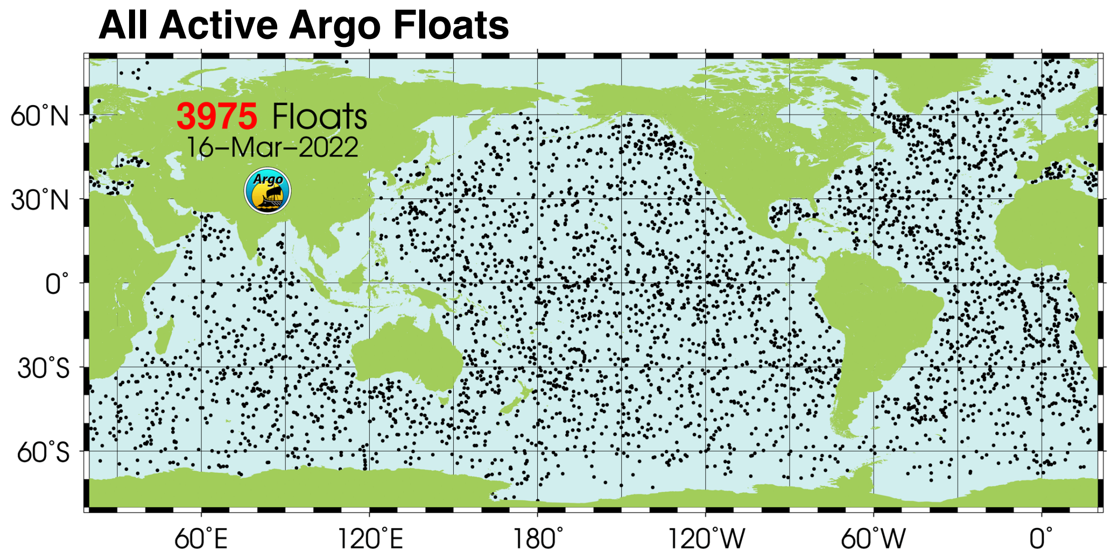


Ice-Based Float Hanger

- Exploit ice drift to distribute floats, release on command.
- Floats suspended from ice, attached via burn wire.
- Network controller listens for release signal (currently from independent, drifting 900 Hz acoustic source, but could transition to system integrated into Hanger).
- Float released on command to begin profiling mission.
- Design aims for simplicity, low cost.

Arctic Argo Pilot – Tech Development

Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Dan Rudnick, Jeff Sherman (SIO), Lee Freitag (WHOI)



SOLO-II Hardware changes

- Integrate 9523 modem for higher rate telemetry of backlog
- Hardened antenna
- Ice avoidance mast
- Hydrophone port

SOLO-II Software changes

- Interface with acoustic controller
- Backlog handling
- Integrate acoustic payload and configuration into telemetry stream

Electronics to support acoustic navigation (broad applicability)

- New low-power acoustic navigation receiver (LPD): 50 mW vs current 500 mW
- New low-power RTC (10-50 ppb) for navigation (LPRTC): 0.1 mW vs current 5 mW
- Modular acoustic controller isolates most mission specific software functionality

Arctic Argo Pilot – Operations

Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Dan Rudnick, Jeff Sherman (SIO), Lee Freitag (WHOI)

Acoustic Geopositioning in the Beaufort Sea

ONR Arctic Mobile Observing System (AMOS-INP)

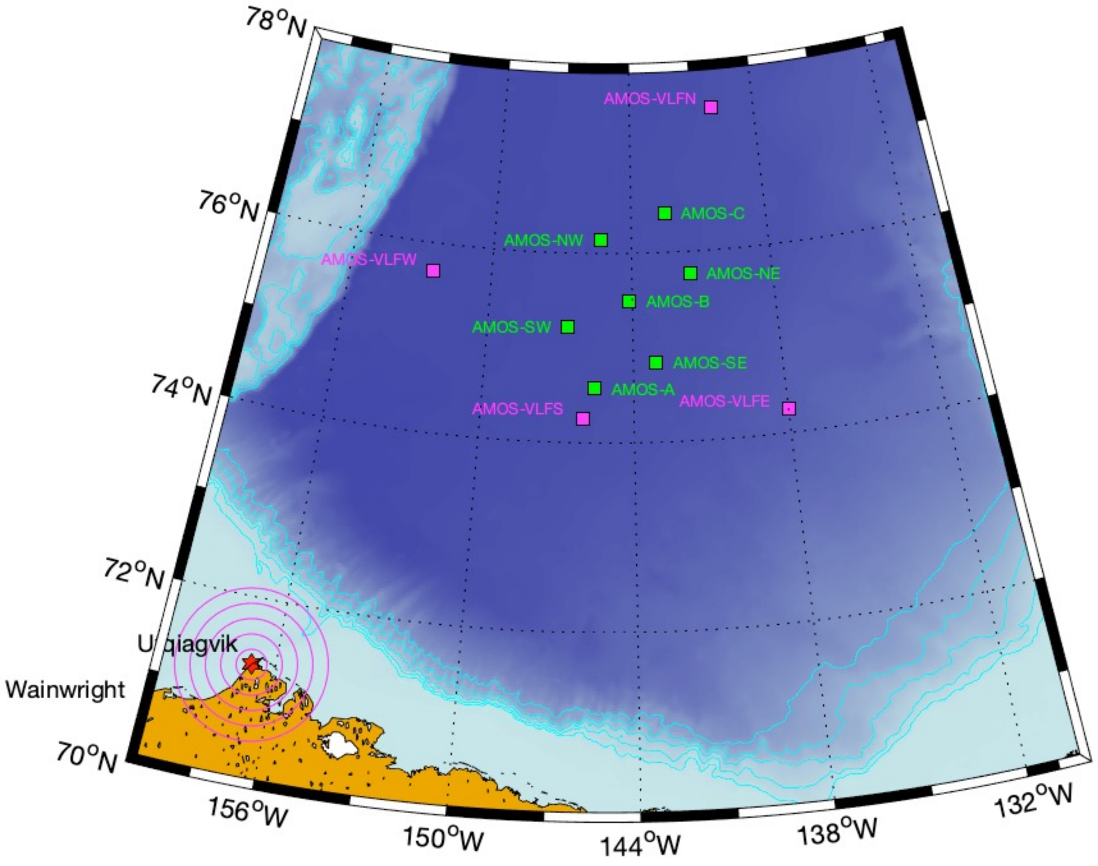
- 7-element 900 Hz array (2018-2024)
- 2/4-element 900 Hz array (2024-?)
- 2-element 35 Hz array (2023-2025?)

SOLO-II Pilot Deployments

- Fabricate 30 SOLO-II floats (10 per year beginning in 2024).
- Local testing in year 1.
- Arctic deployments begin in autumn 2024 (coincident with deployment VLF array).
- Data will flow to Argo DAC.

Logistics

- AMOS-INP cruises and/or ice camps.
- Collaboration with other Beaufort Sea programs.



Floats and Acoustic Receivers – Integration Status

- **Teledyne APEX** – MicroModem integrated and in use. LPD/LPRTC integration TBD (but straightforward).
- **Teledyne ALAMO** - LPD/LPRTC integration by MRV, driven by Steve Jayne (WHOI).
- **SOLO-2** - LPD/LPRTC integration as part of Arctic Argo pilot.
- IOP team working to package LPD/LPRTC as stand-along serial device with external hydrophone. Allow easy integration on any platform with connector and API for serial sensors (e.g. **NKE floats**). Easy on-ramp for using acoustic geolocation infrastructure.
- LPD/LCRTC for geopositioning. Micromodem for two-way acomms.

Autonomous Observing beneath the Dotson Ice Shelf

Craig Lee, Luc Rainville, Jason Gobat, James Girton (APL-UW), Pierre Dutrieux (BAS), Knut Christianson (ESS-UW), Tae-Wan Kim, Sang-Hoon Lee (KOPRI)

- **Acoustic Navigation:** (3) 780 Hz RAFOS sources moored off shelf edge provided reliable signals deep into cavity.
- **Floats (4):** Sampled circulation pathway through cavity before exiting to Amundsen Sea
- **Sealiders (3):** 14+ months continuous sampling w/ 33 sections of cavity interior and 35 sections across face.