

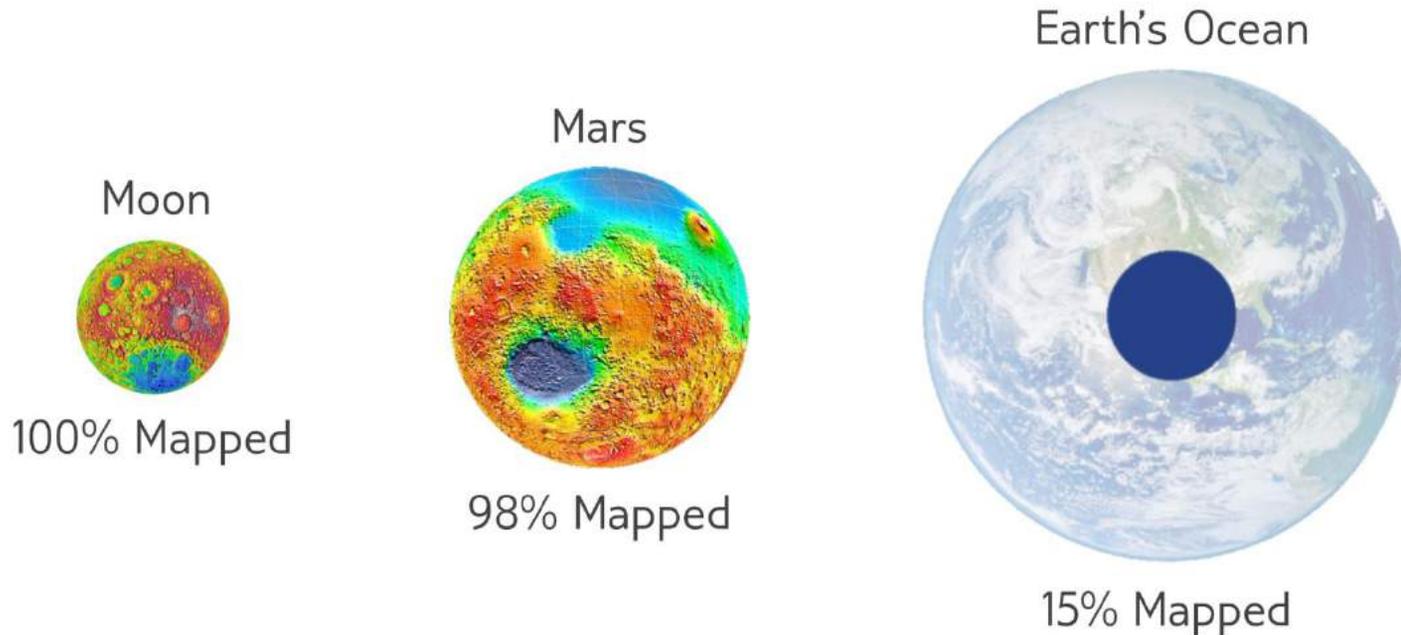
Ph.D. Thesis Defense:  
*Underwater & Out of Sight: Towards Ubiquity in Underwater Robotics*

Nicholas R. Rypkema  
June 14, 2019



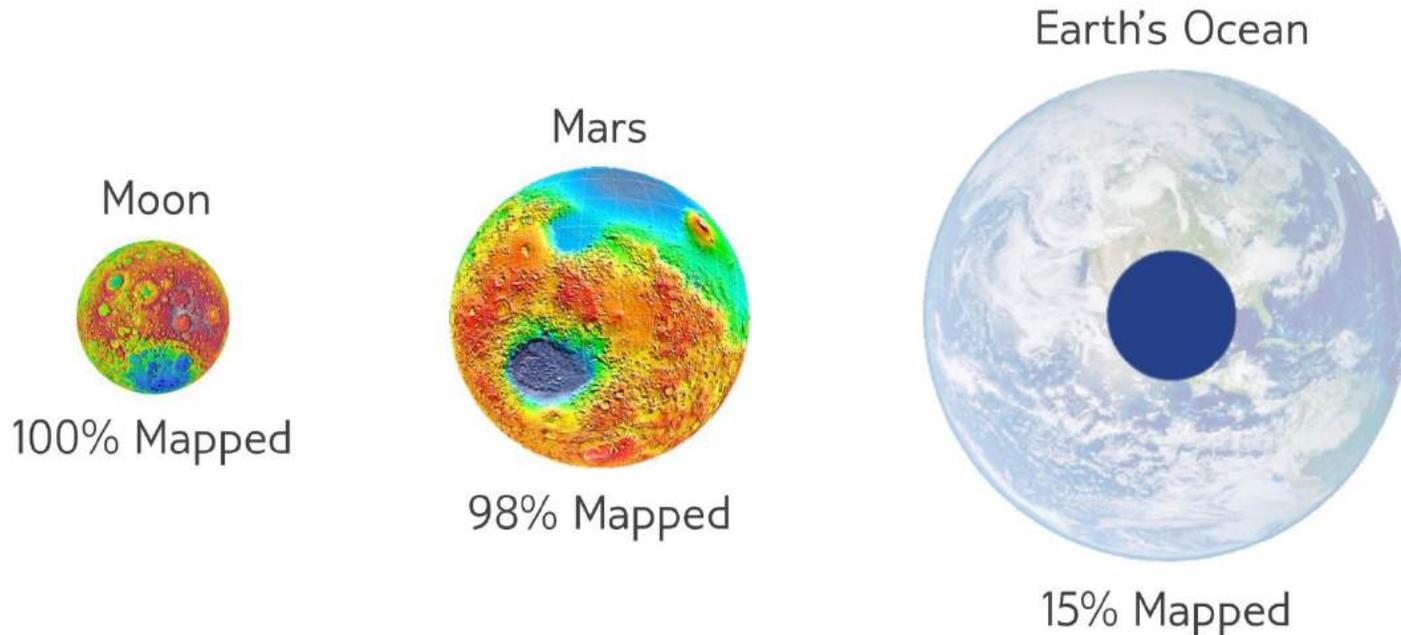
# Motivation

- 70% of the Earth is covered by ocean
- Less known about ocean floor than surface of Moon / Mars / Venus
- Moon / Mars / Venus: mapped to 100m resolution
- Ocean: 10-15% to 100m (100% to 5km)



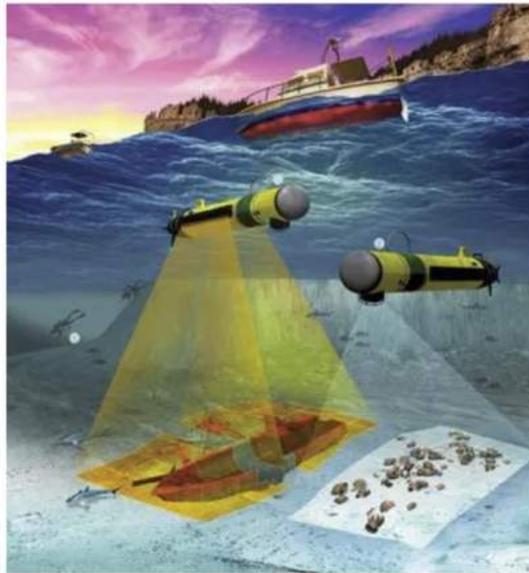
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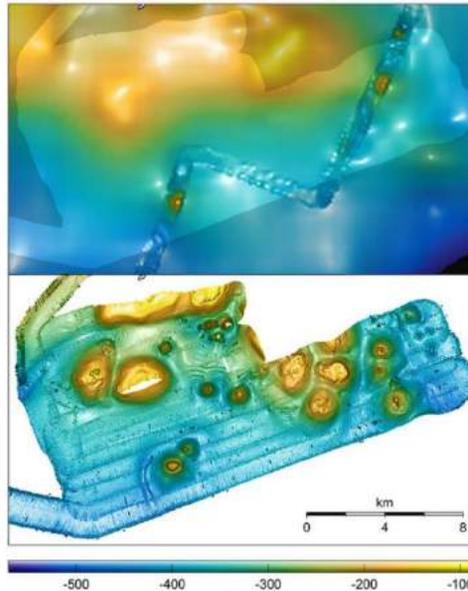


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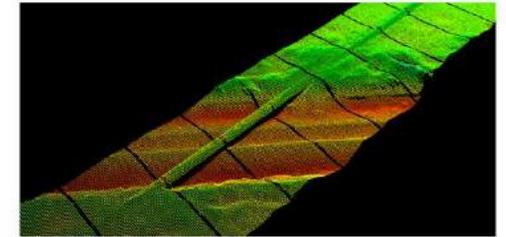
- Robots ideally suited for ocean exploration
- Ocean is vast, difficult, dangerous, dull for human exploration
- Autonomous Underwater Vehicles (AUVs) have come a long way – reliable tools for oceanography



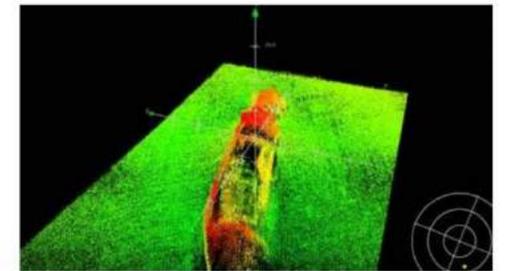
Kevin Hand, Popular Science



Adam Soule, WHOI



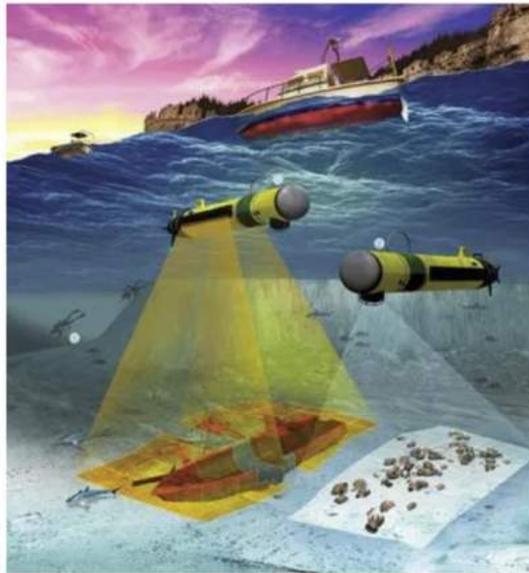
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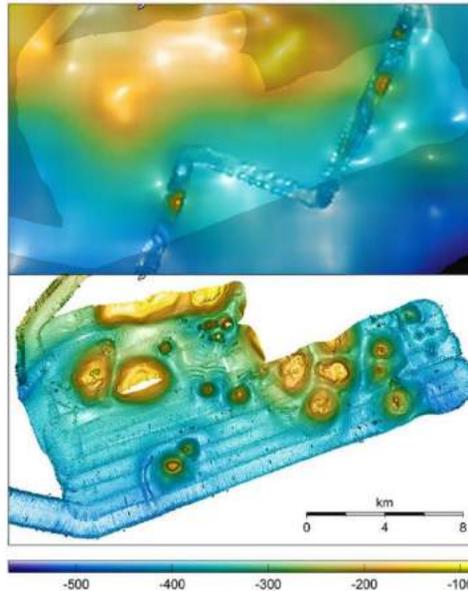
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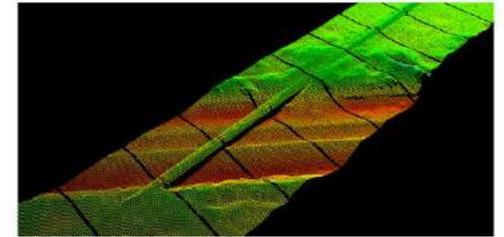
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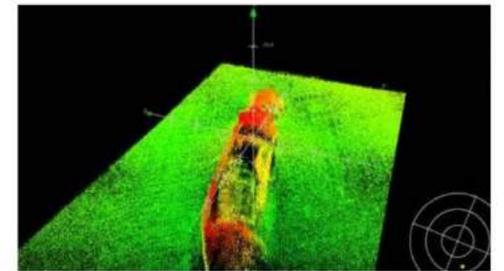
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# Motivation

- No GPS!!! (or EM-spectrum technologies)
- AUV development in the context of enabling key technologies
  - 1980s ADCP/DVL – measure water current velocities
  - 1950s/60s INS – ballistic guidance, Apollo
- Prevailing paradigm of AUV navigation – vehicles are large, expensive



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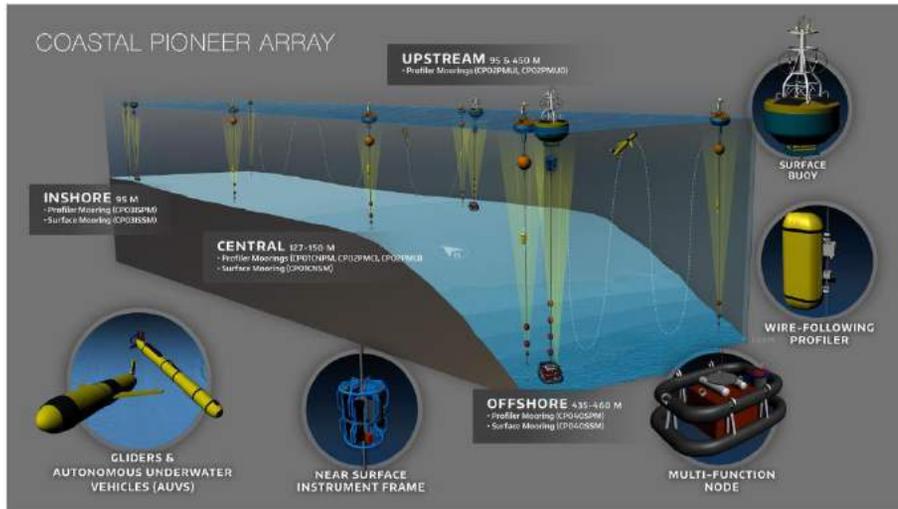
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# Motivation

- Ocean processes vary in *space and time* – multi-AUV sampling necessary to break spatiotemporal aliasing
- Multi-AUV deployments have been a dream for decades



Ocean Observatories Initiative: WHOI, UW, OSU



Phytoplankton bloom: NASA Earth Observatory

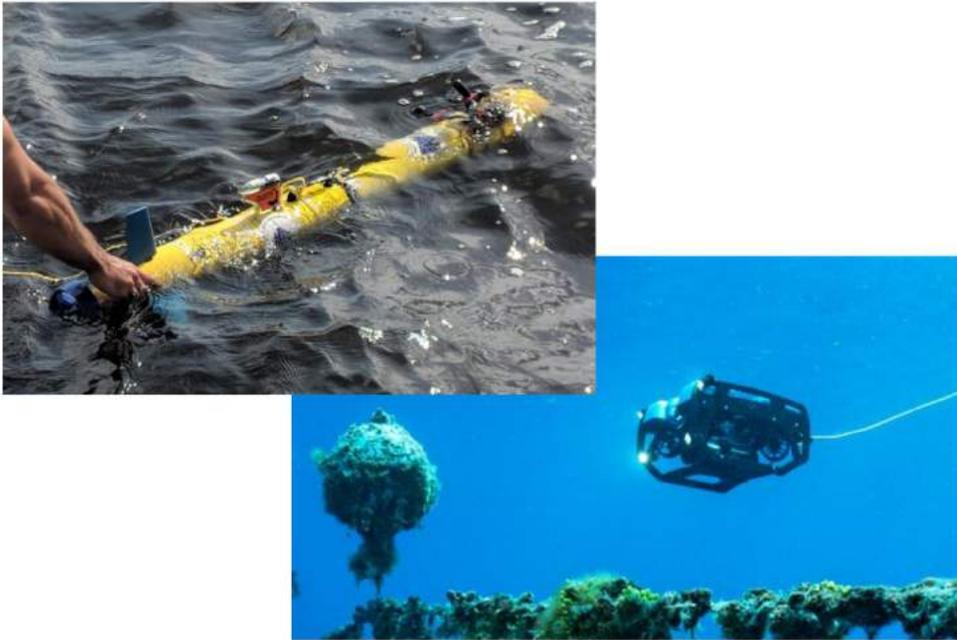
# Motivation

- End-point of conventional multi-AUV operations: Ocean Infinity (conservative cost: >\$100k/day, x8 \$5M HUGIN AUVs)



# Motivation

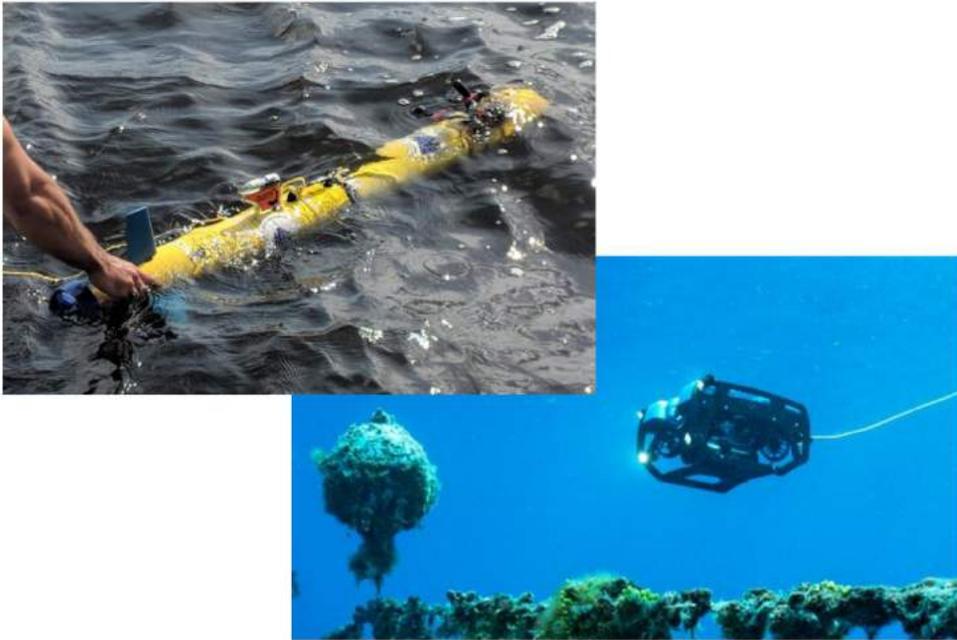
- Low-cost, miniature platforms have potential to democratize AUVs



BlueROV: Wired

# Motivation

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- Analogy of UAVs: Reaper -> drones everywhere!



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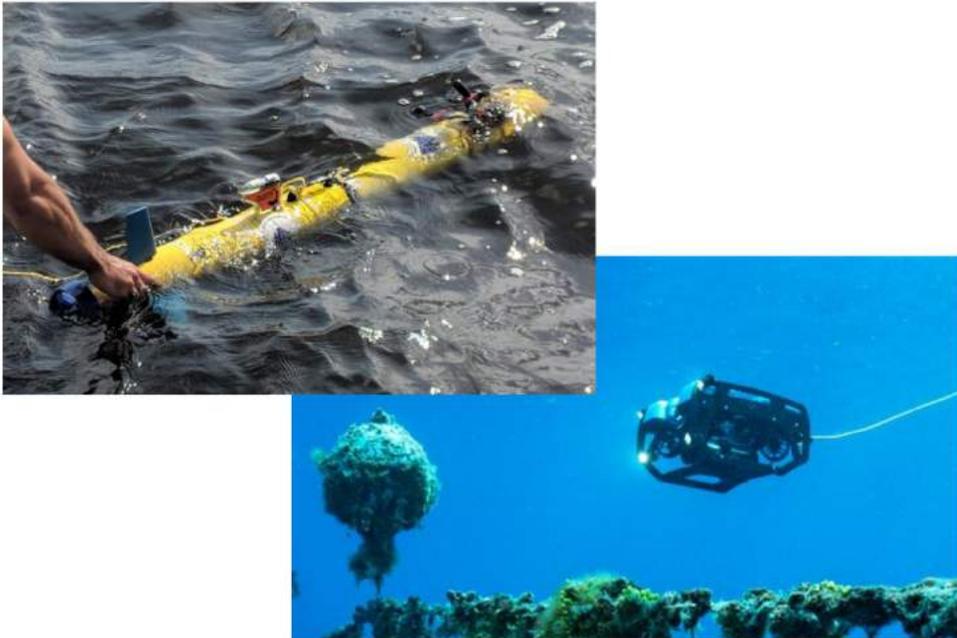
Foldable Drone: Zurich/EPFL



Skydio R1

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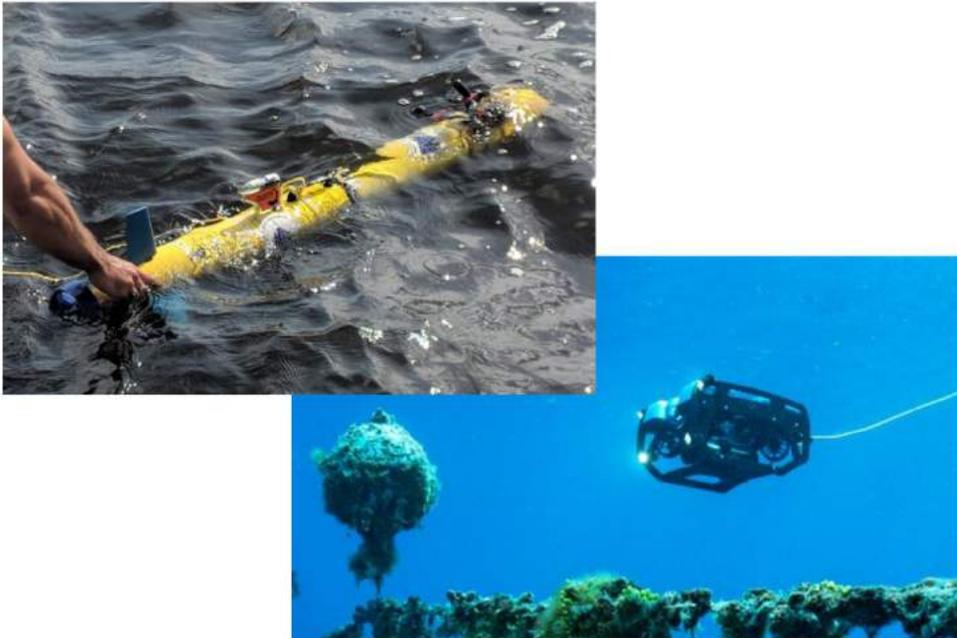
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- Low-cost, miniature platforms have potential to democratize AUVs
- Analogy of UAVs: Reaper -> drones everywhere!
- Ubiquity: accessibility of underwater robotics *and* multi-AUV
- Problem: we cannot use the conventional AUV navigation paradigm



BlueROV: Wired



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Skydio R1

# Problem

- Navigation is necessary for control, planning, mapping – utility!
- Can we design a navigation system to enable multi-AUV deployments?
- System goals:

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- System goals:
  - Scalable
  - Low-cost and low-power
  - Easy to deploy and operate
  - Robust



# Contributions

- Underwater acoustic navigation system that meets these goals



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- Multi-AUV operational paradigm that is user-friendly



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- Underwater acoustic navigation system that meets these goals
- Multi-AUV operational paradigm that is user-friendly
- Extensive experimental demonstrations of multi-AUV operations



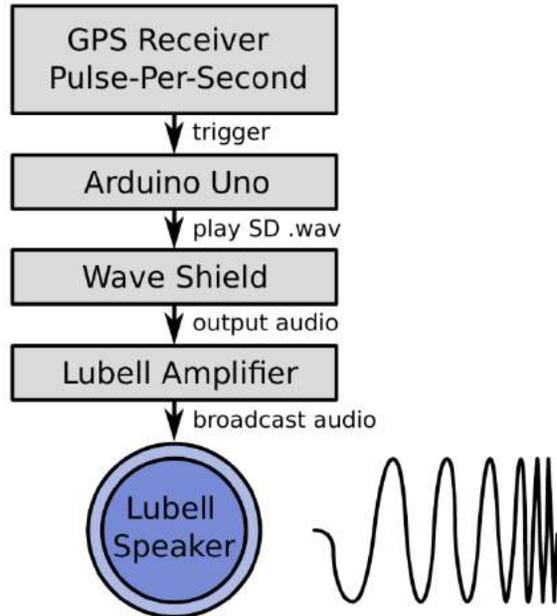
# Approach

- One-Way Travel-Time

## Inverted Ultra-Short Baseline

1,2

### Acoustic Beacon



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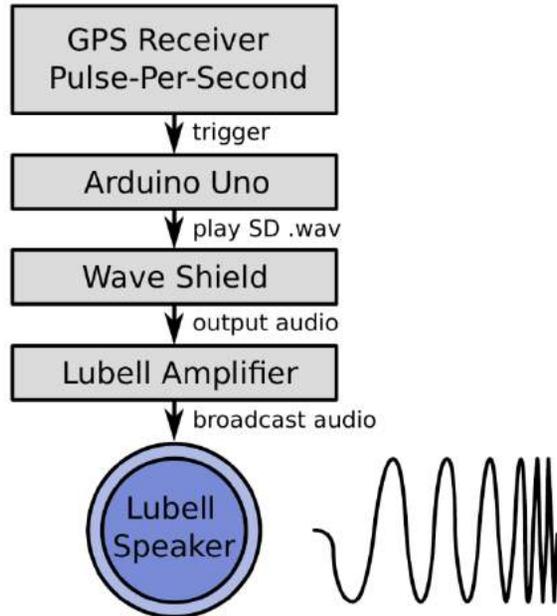
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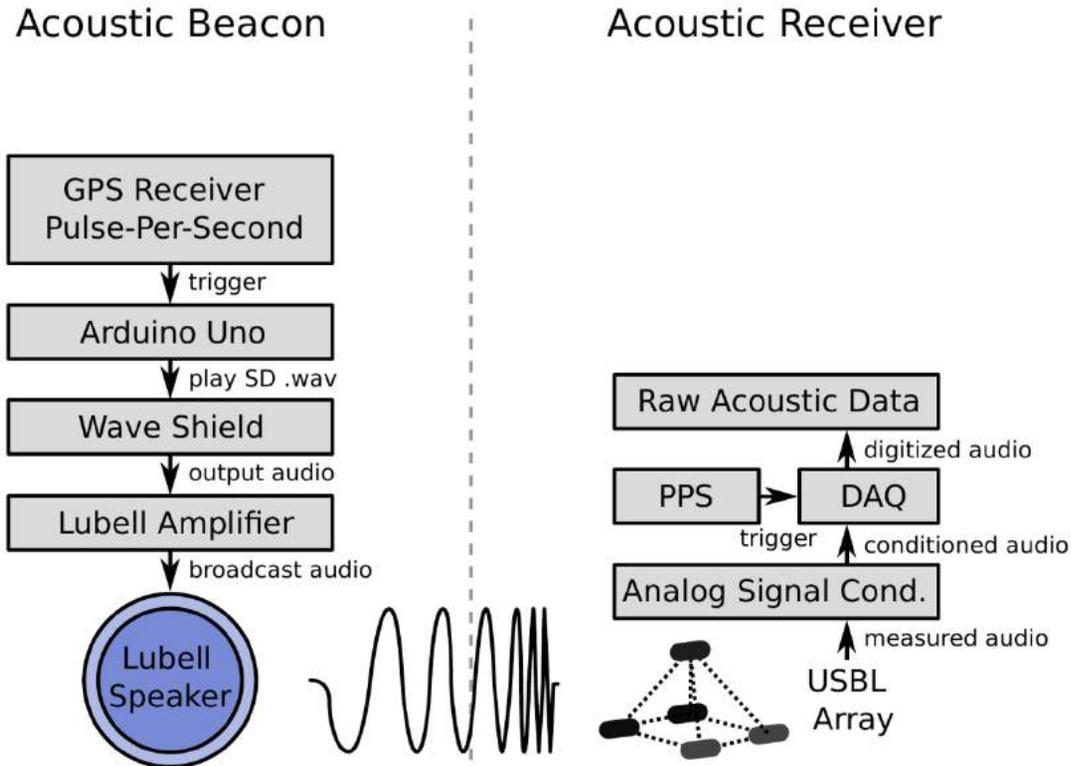
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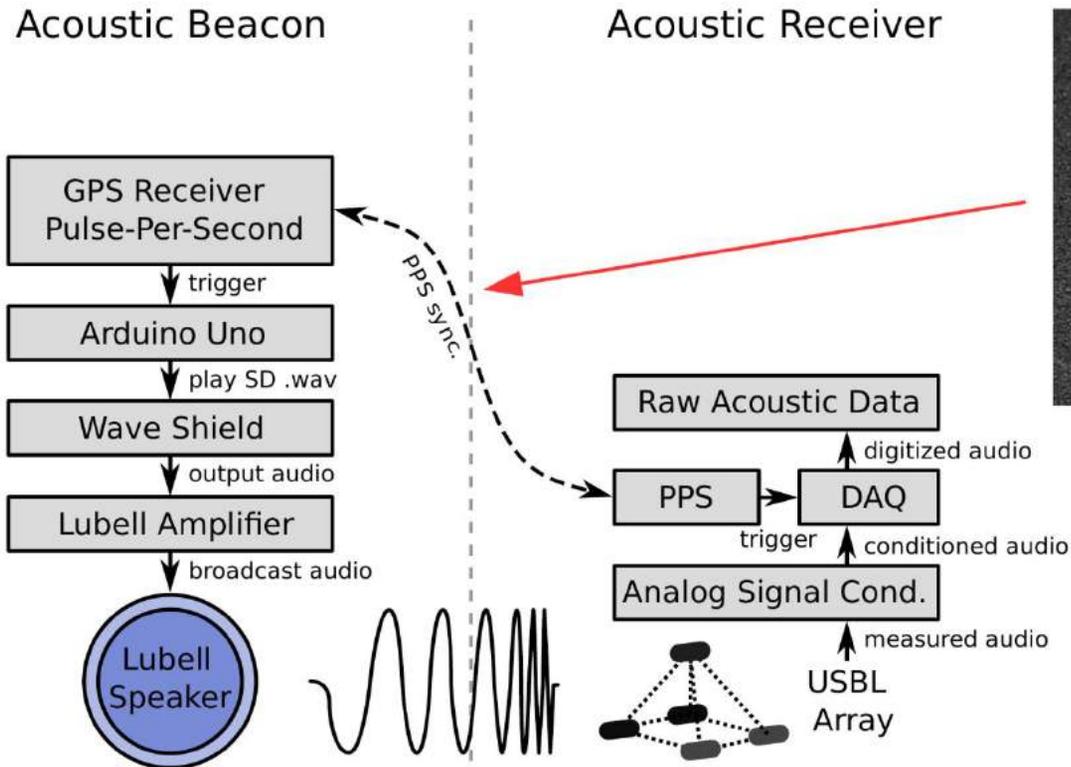
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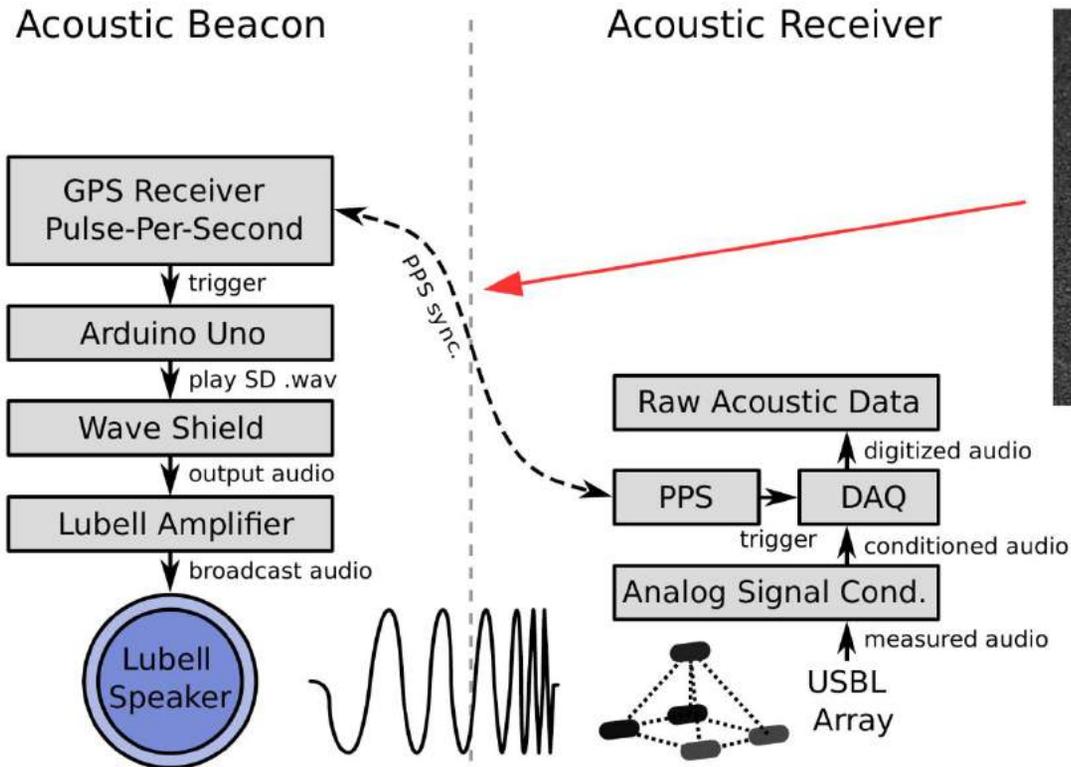


CSAC: 1us/day drift = < 15cm/day  
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## Passive Inverted Ultra-Short Baseline (piUSBL)<sup>1,2</sup>



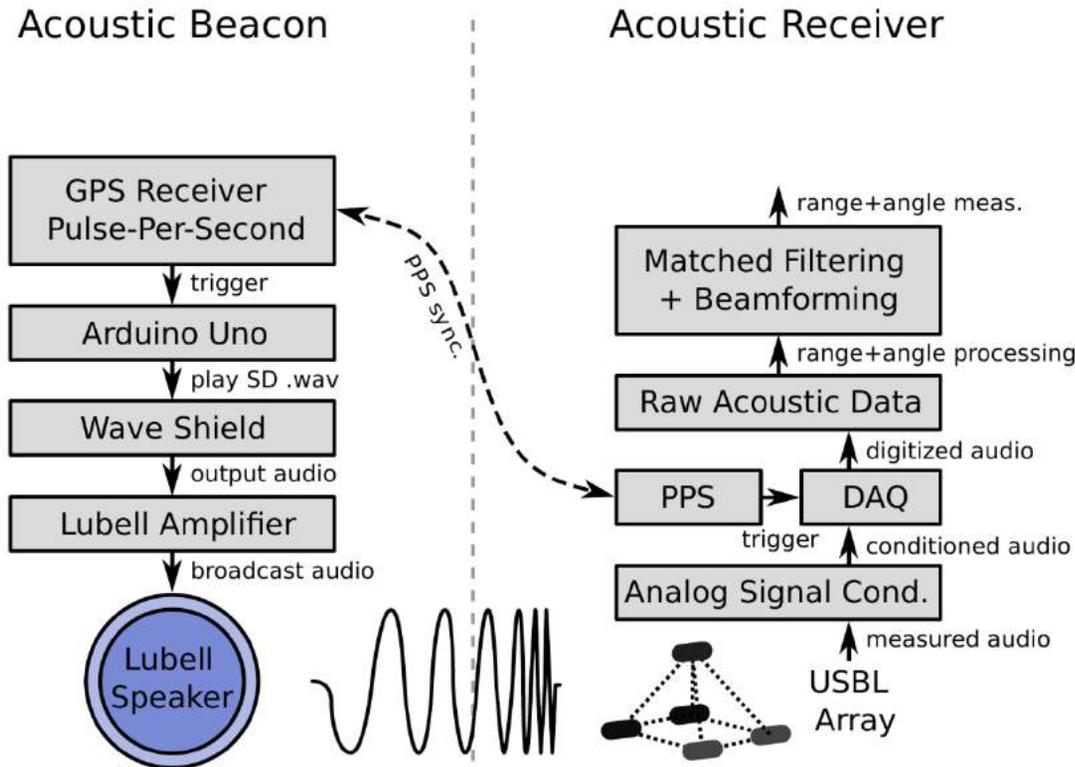
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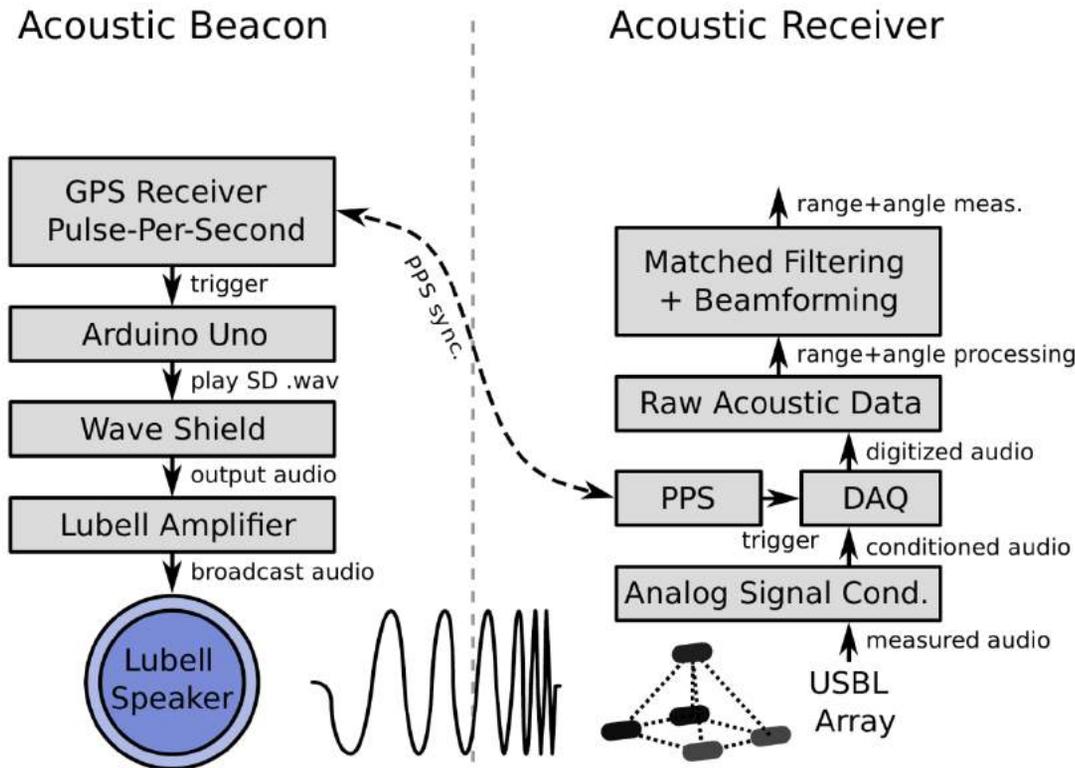


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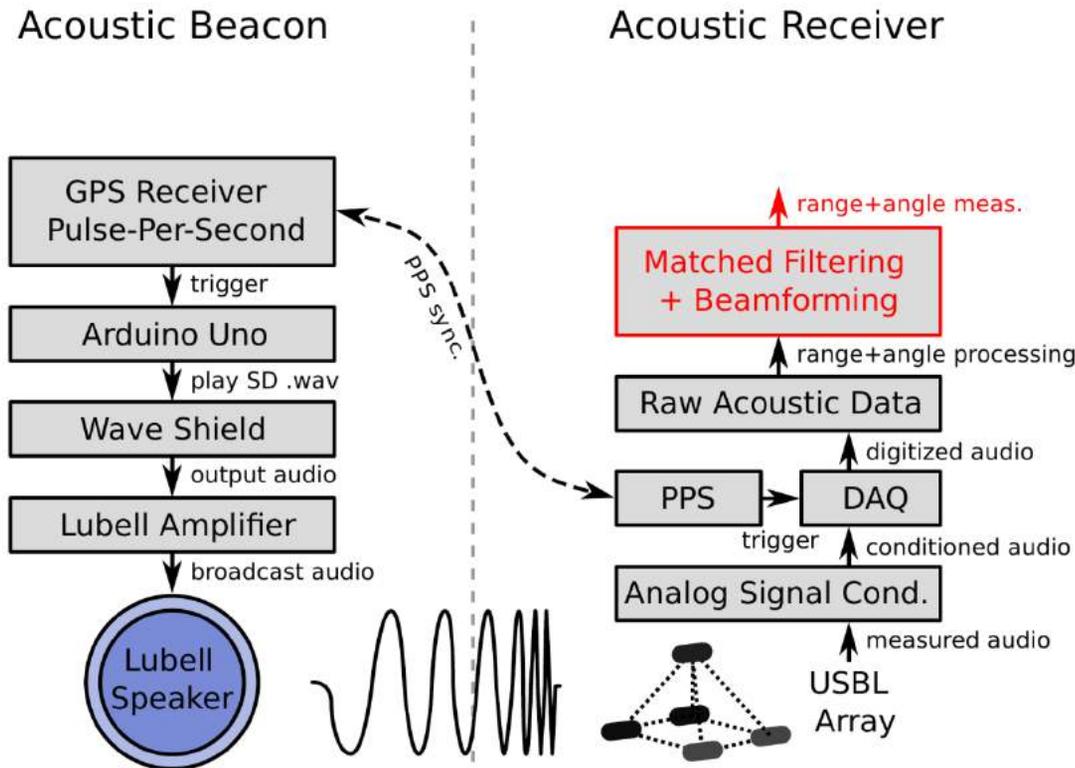


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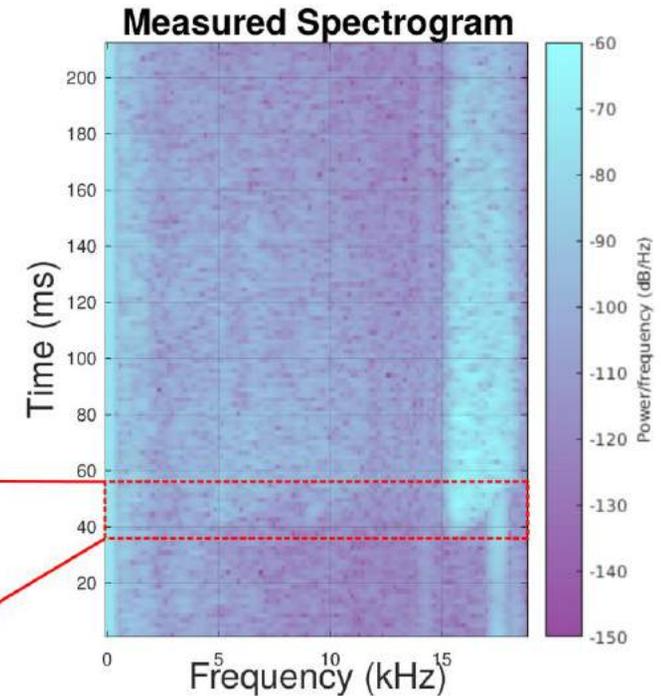
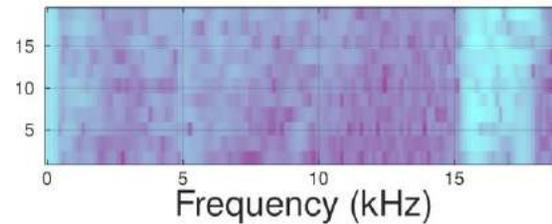
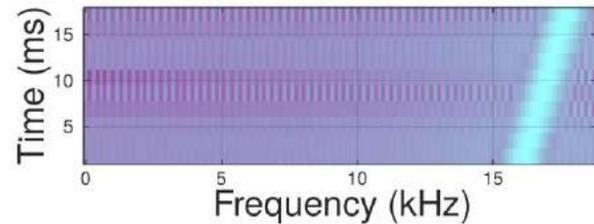
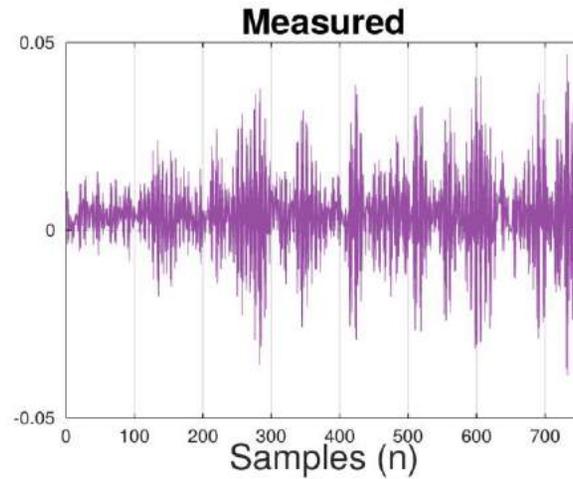
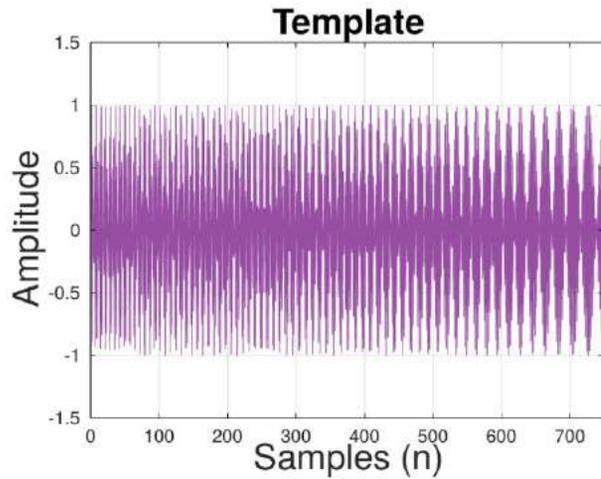
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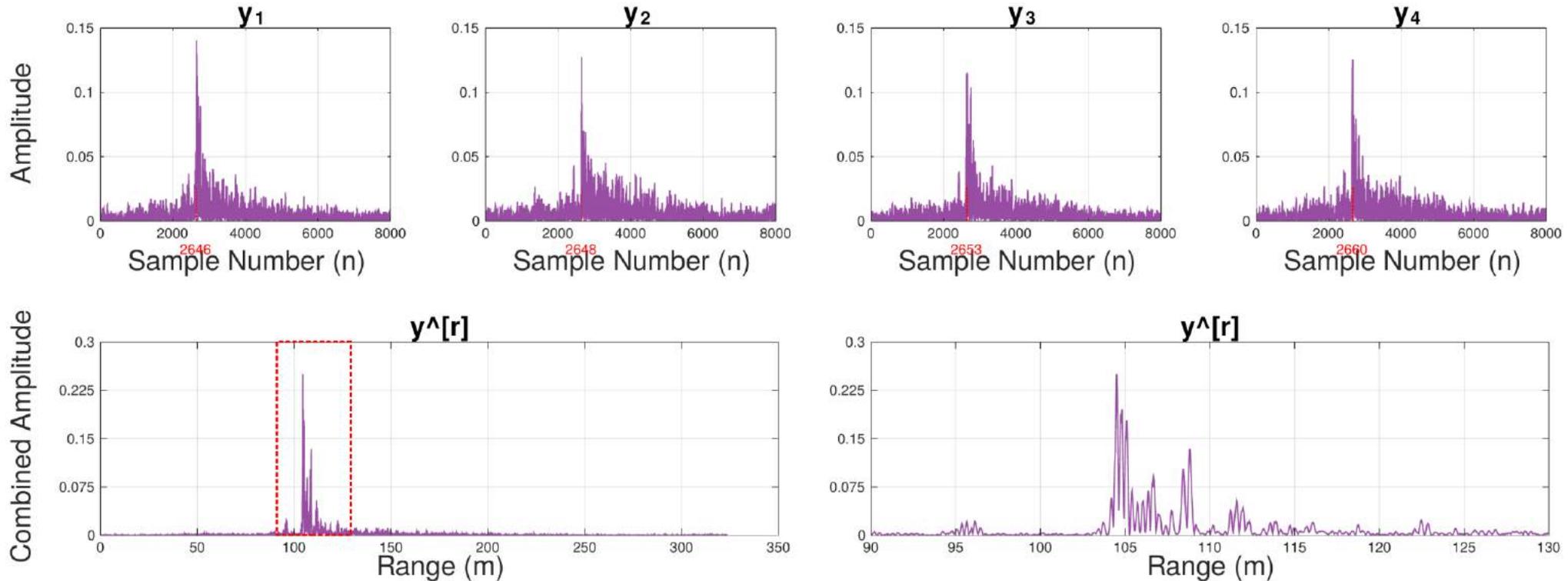
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- Correlate (convolve) received signals with template of broadcast



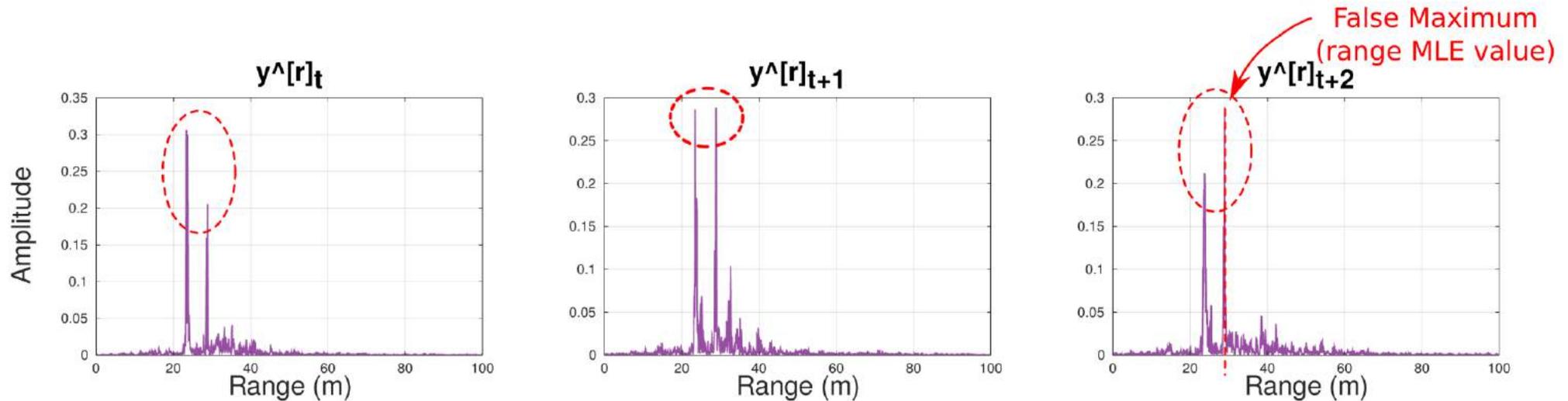
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- Correlate (convolve) received signals with template of broadcast
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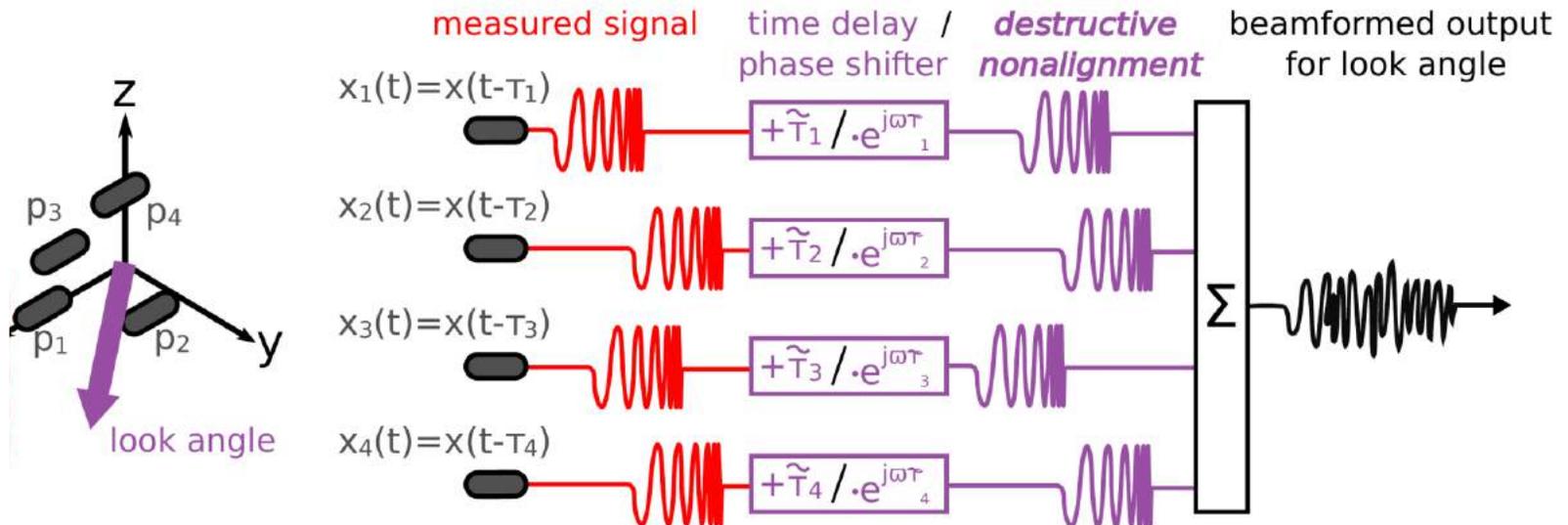
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- Correlate (convolve) received signals with template of broadcast
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- Range measurement (pseudo) distributions exhibit *multi-modality*



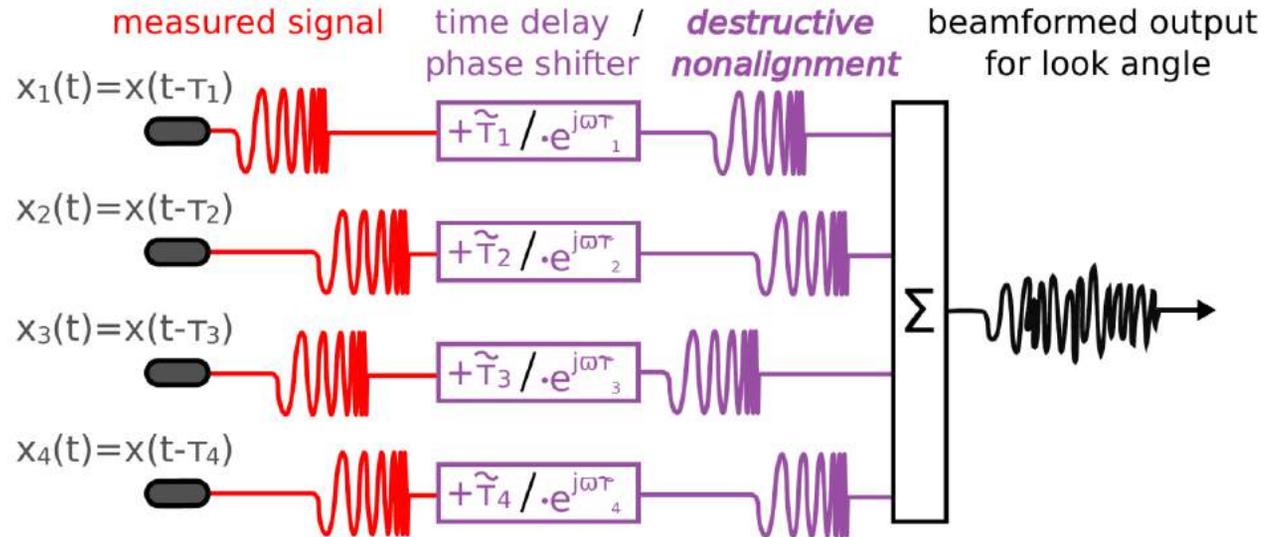
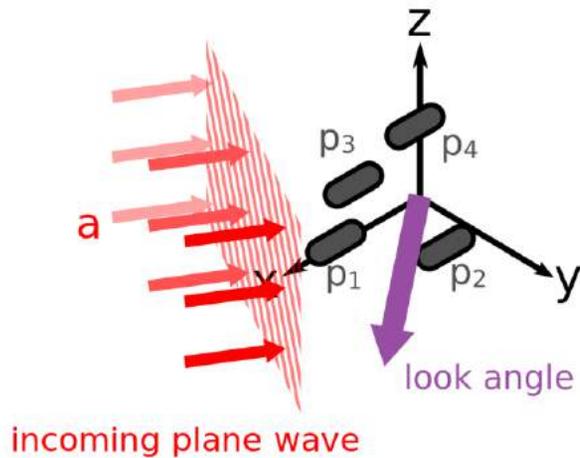
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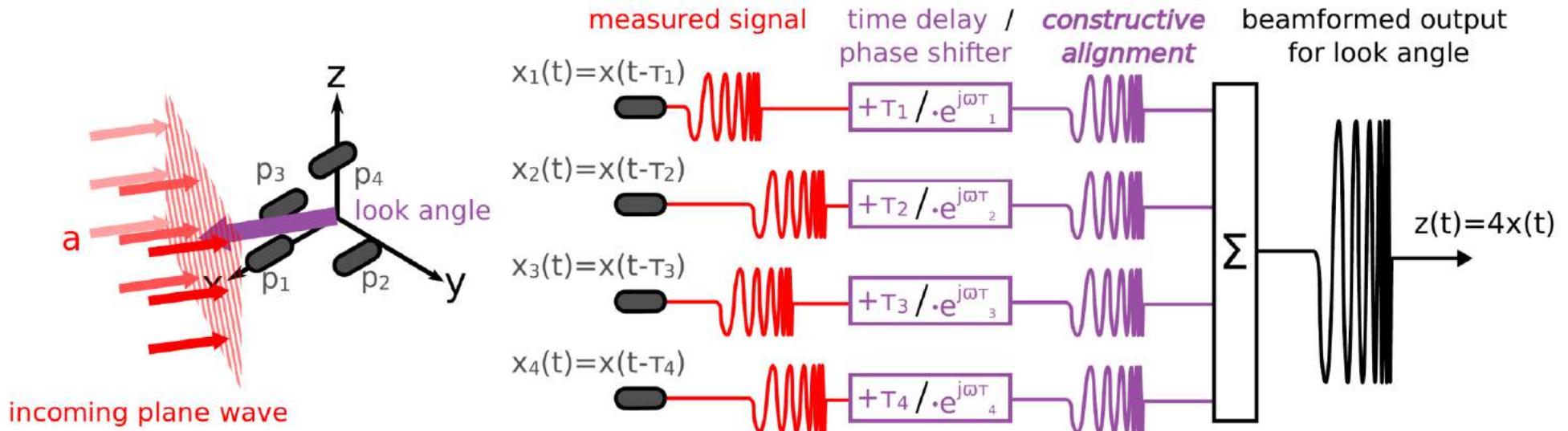
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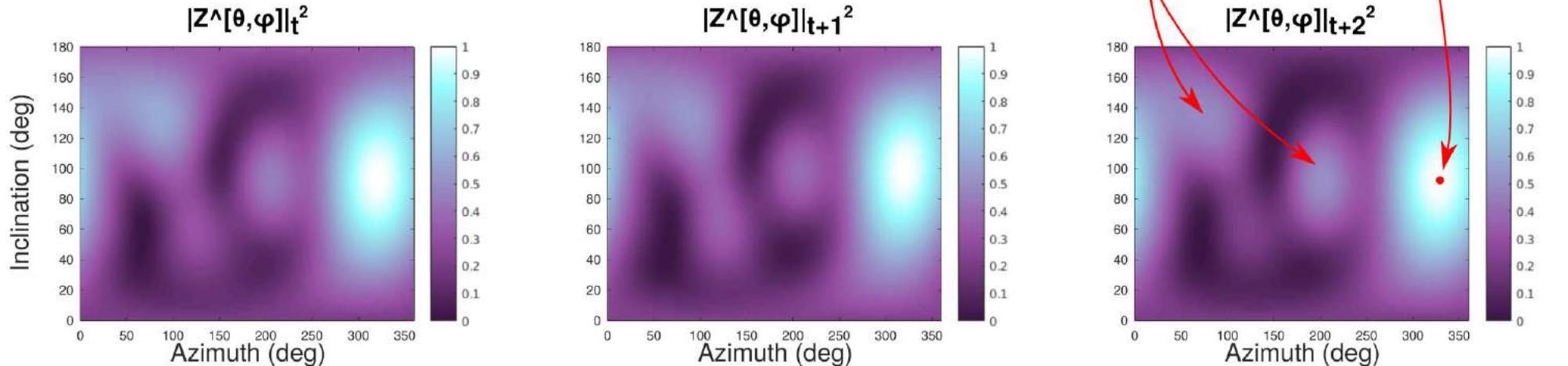
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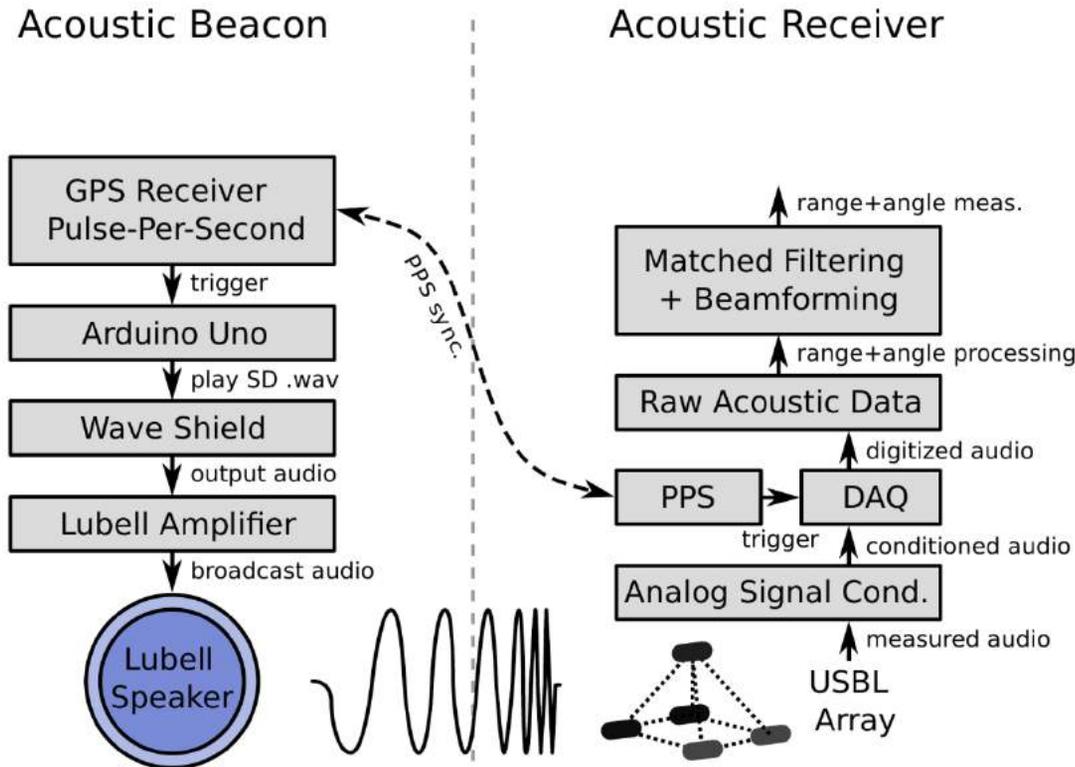
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# Approach

## Passive Inverted Ultra-Short Baseline (piUSBL)<sup>1,2</sup>

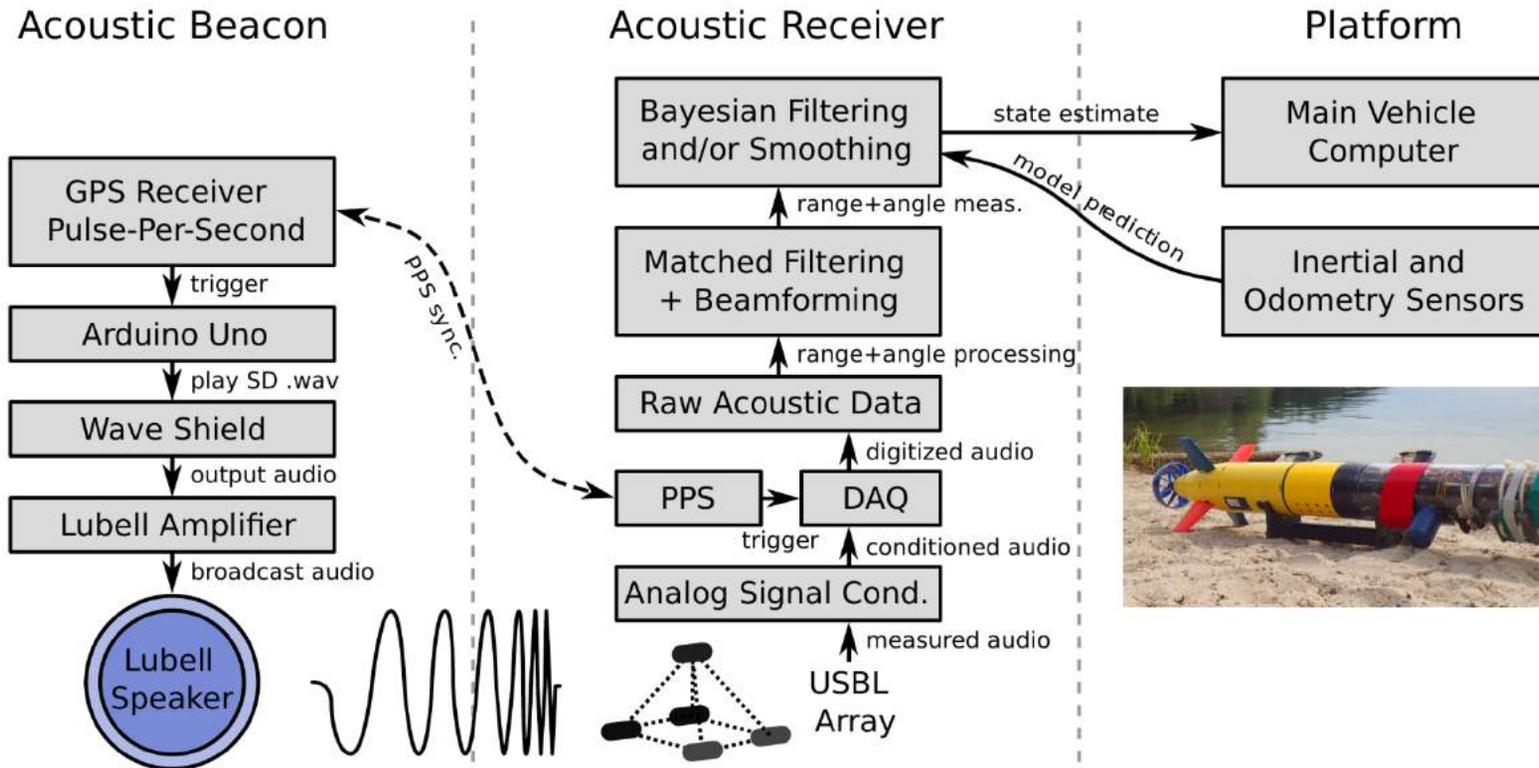


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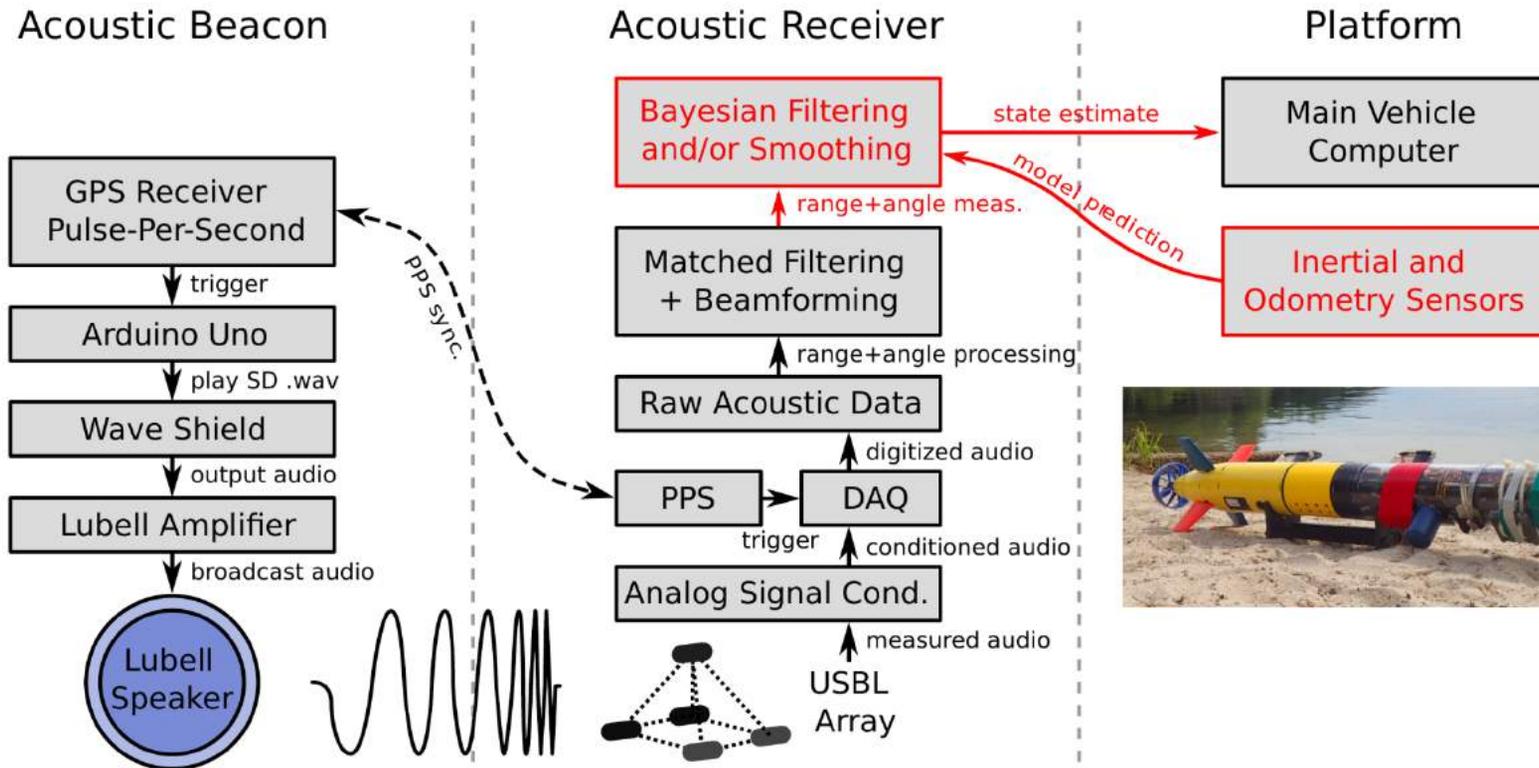
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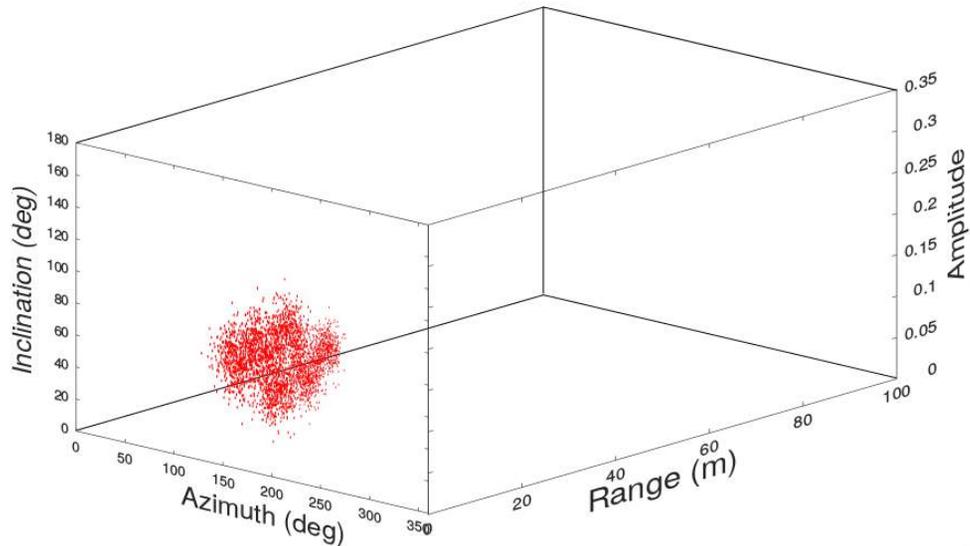
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# Particle Filter

- Fuse acoustic range and angle measurement (pseudo) distributions with platform attitude and speed measurements
- Generates a *temporally consistent* position estimate

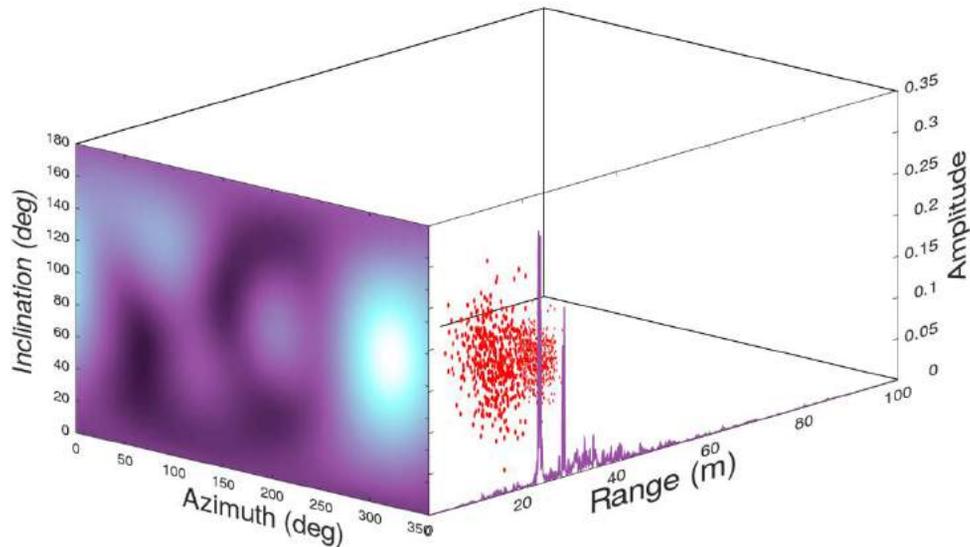
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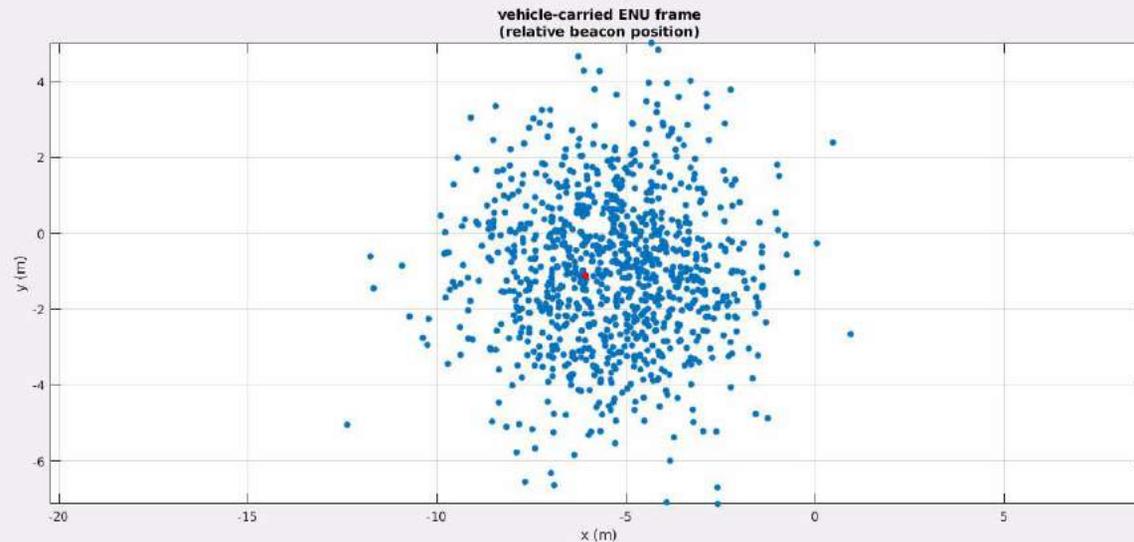
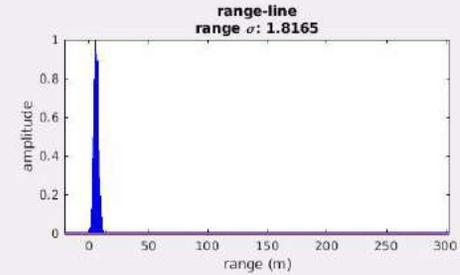
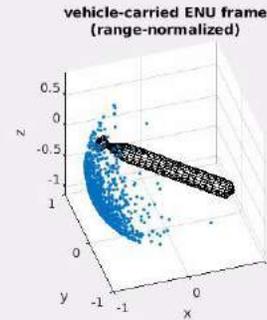
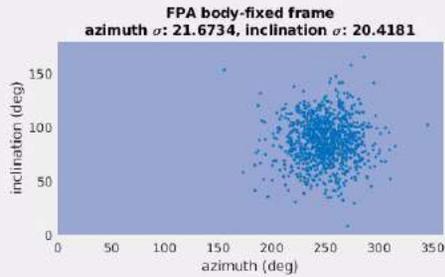
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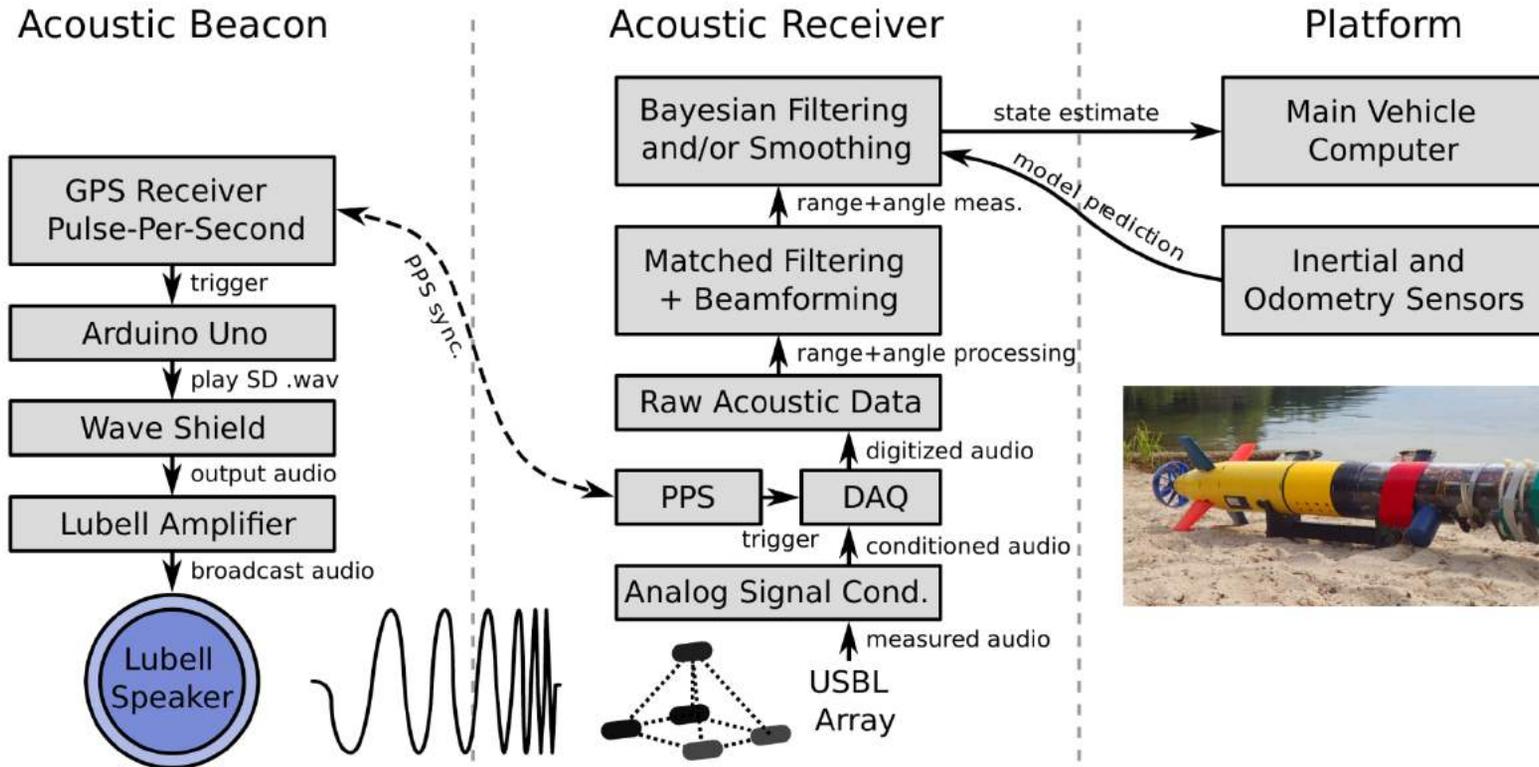
# Particle Filter

- Preserves dynamic range, not strictly correct but works well



# Approach

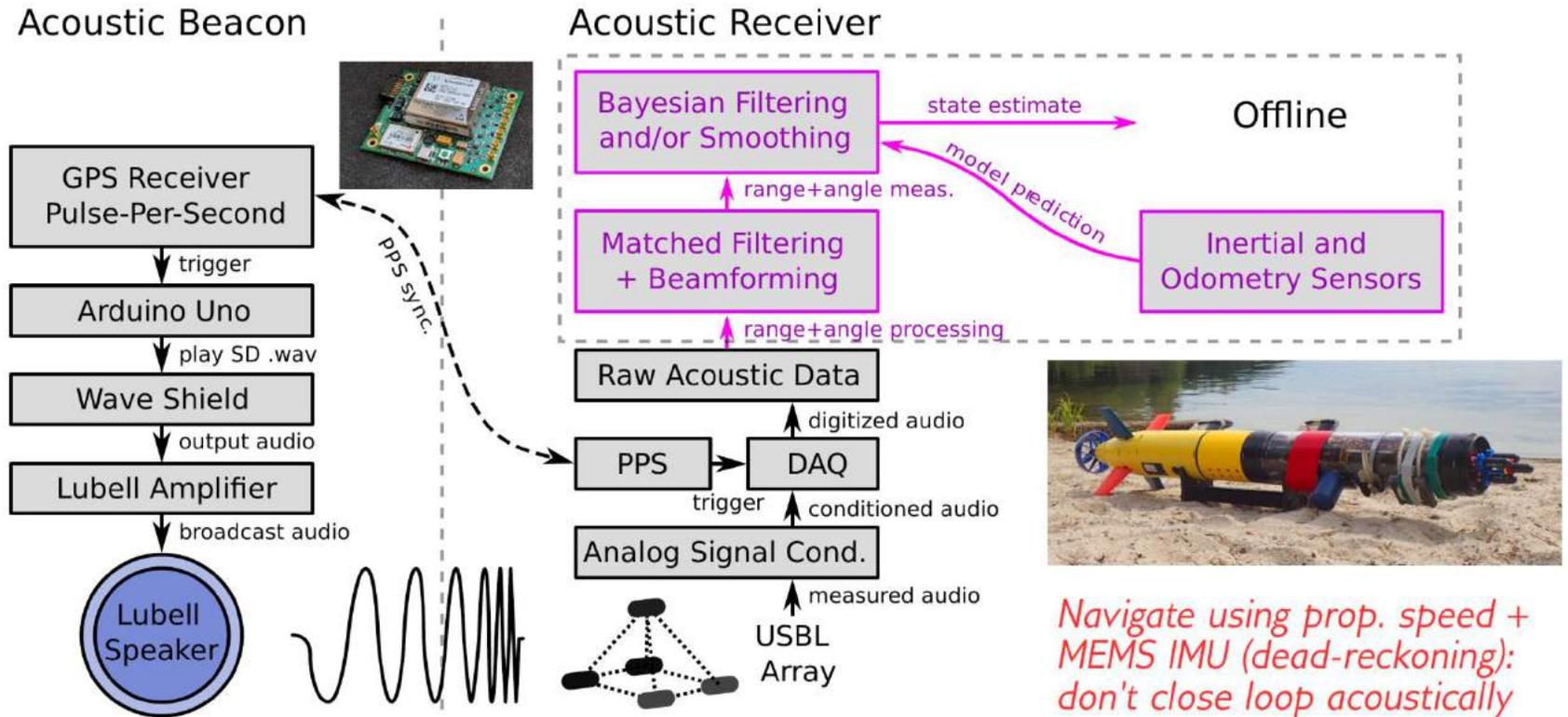
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# Prototype Implementation

- Demonstration of feasibility on prototype SandShark AUV<sup>2</sup>



# Prototype Results

- The processing stack works!!! Offline...

# Prototype Lessons Learned

- Computational bottleneck of CBF + particle filtering prevents closed-loop performance

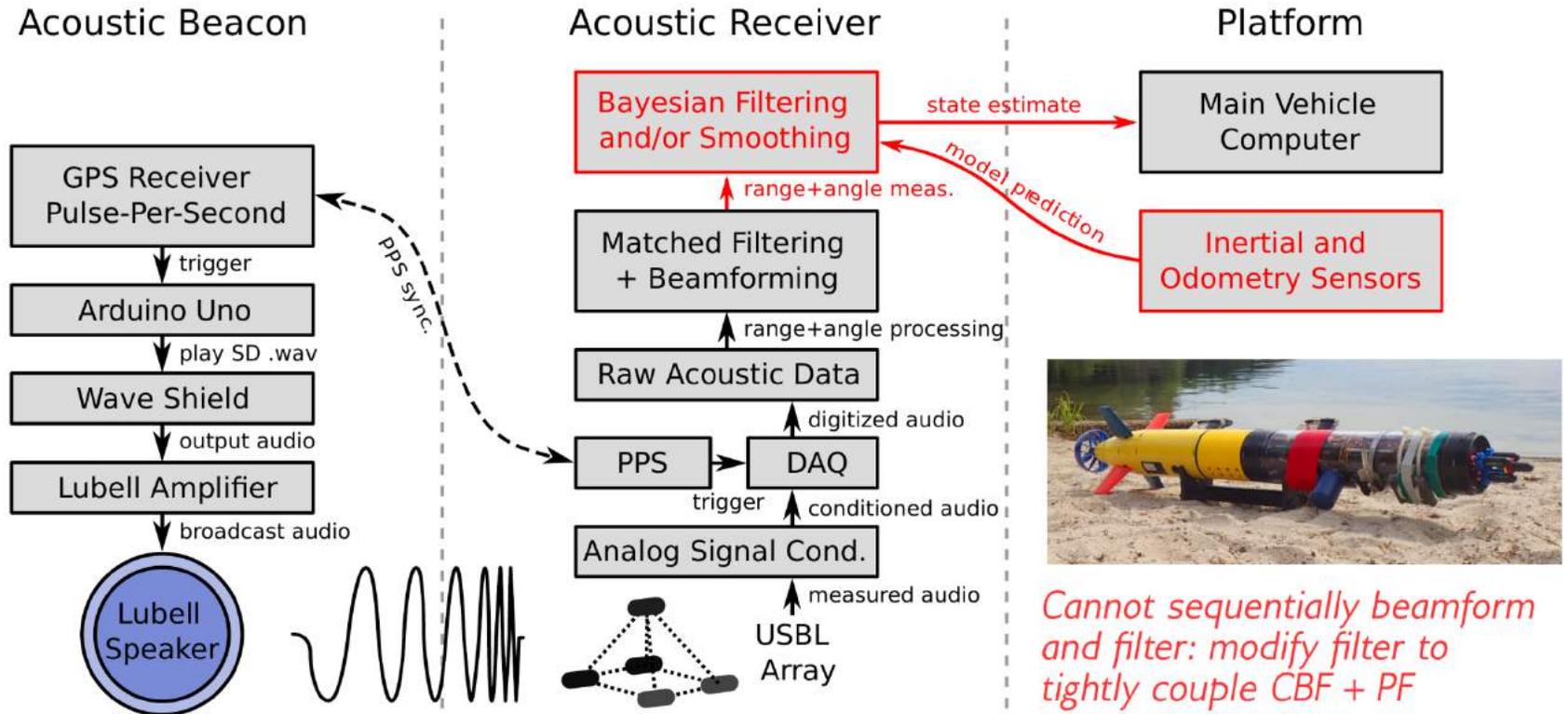
# Prototype Lessons Learned

- Computational bottleneck of CBF + particle filtering prevents closed-loop performance
- CBF on Raspberry Pi 3 @ resolution of 4050 look-angles:
  - 270 azimuth divisions
  - 15 inclination divisions
  - $\sim 1.25$  Hz



# Improvement 1 – Closing the Loop

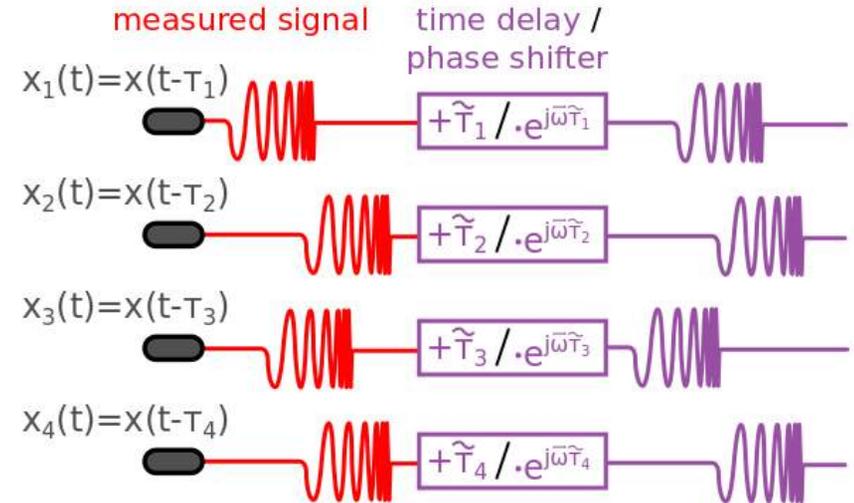
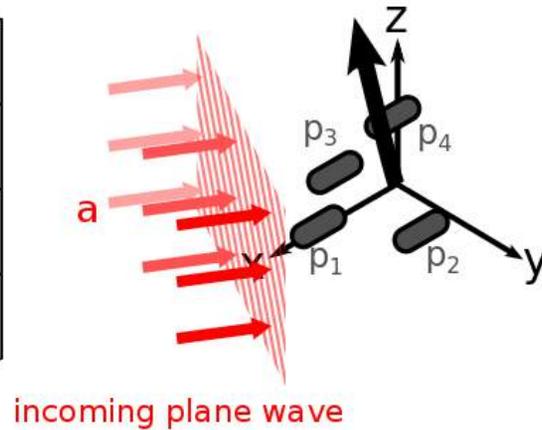
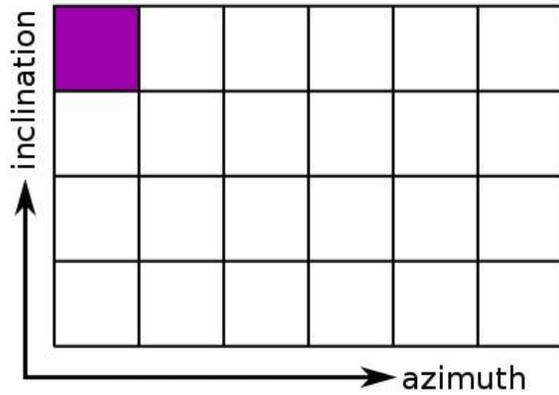
- How do we get real-time 100% on-board performance?<sup>1</sup>



1. N.R. Rypkema, et al., "Closed-loop single-beacon passive acoustic navigation for low-cost AUVs", IEEE/RSJ IROS 2018

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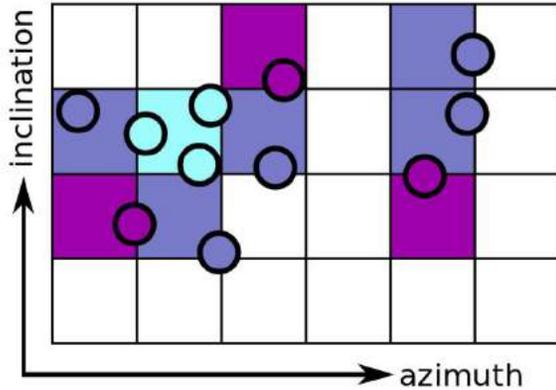
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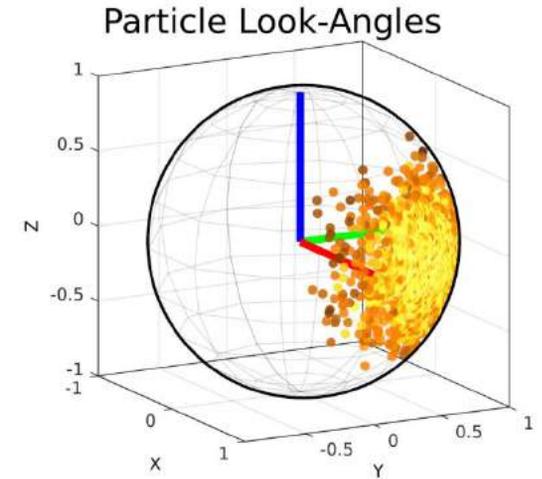
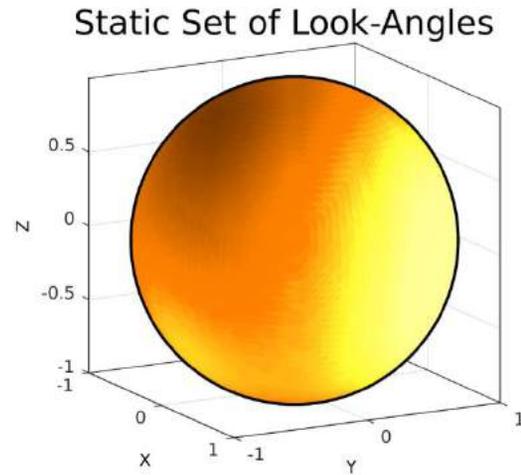
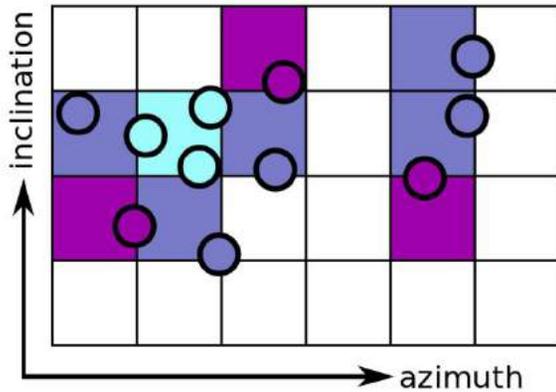
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- Insight: *Particles represent look-angles* in CBF space
- Solution: Beamform only at particle look-angles (coupled CBF + PF)



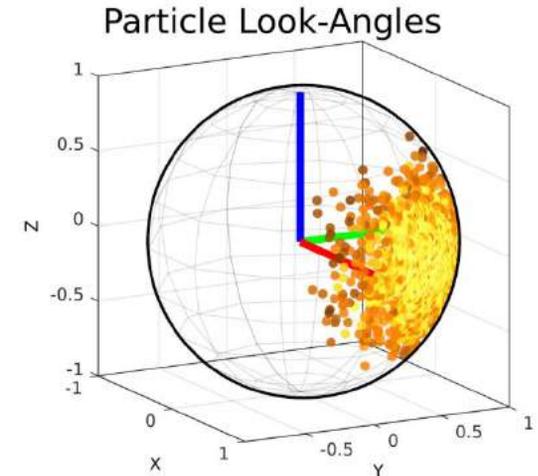
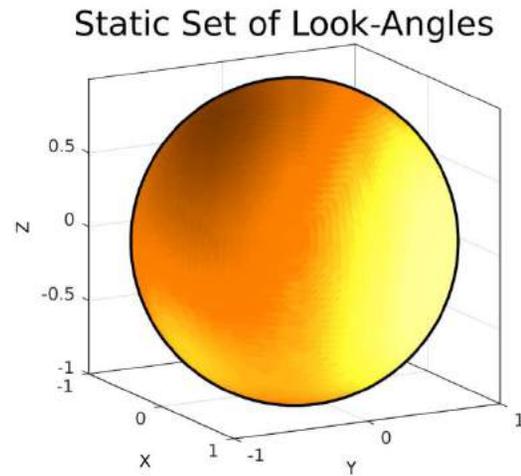
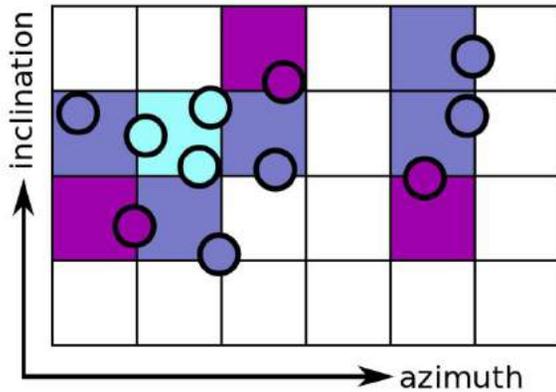
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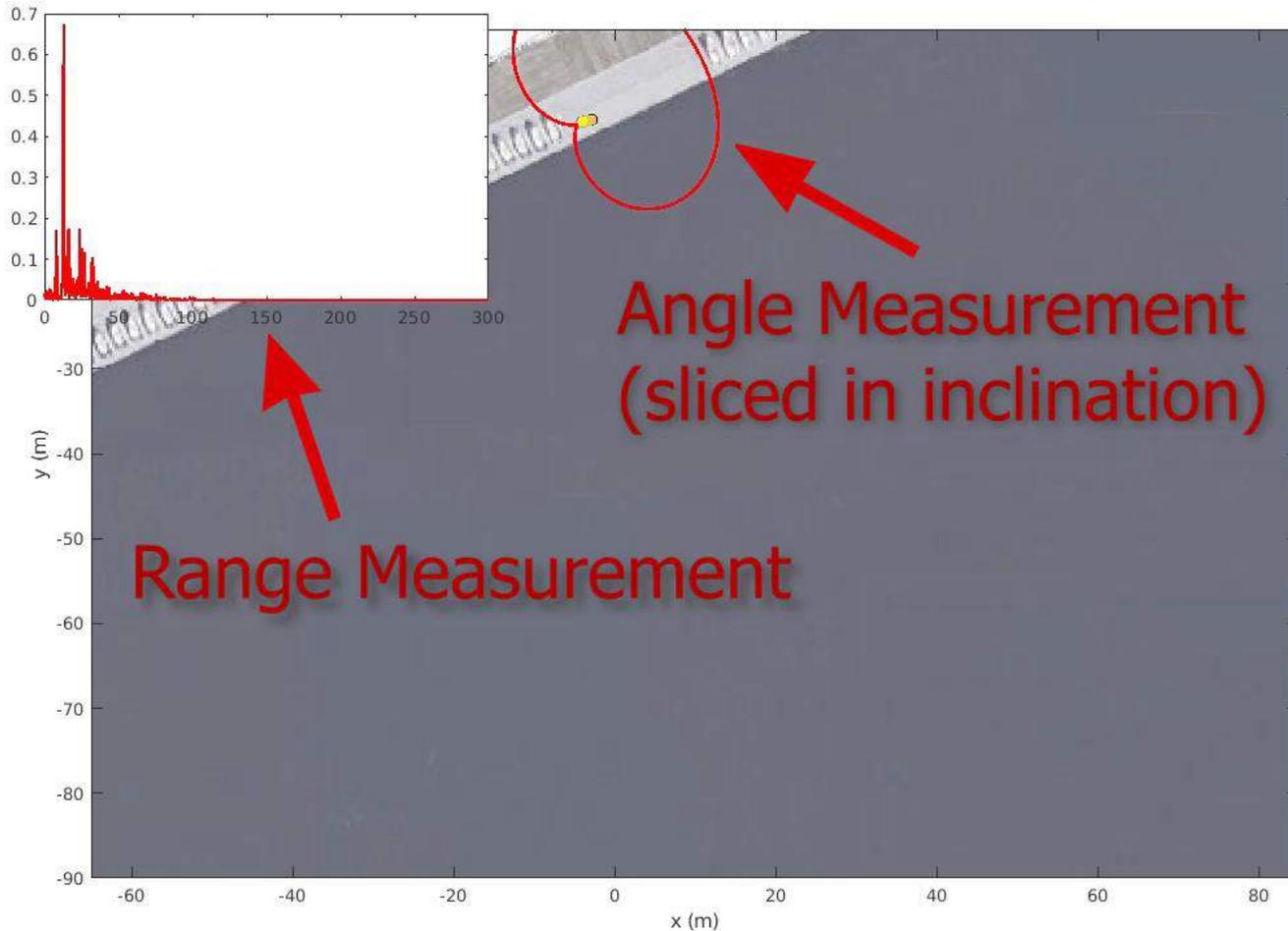
# Improvement 1 – Closing the Loop

- Beamforming followed by sampling by particle filter is slow
- Insight: *Particles represent look-angles* in CBF space
- Solution: Beamform only at particle look-angles (coupled CBF + PF)
- Simple but effective – accuracy and speed tied to no. of particles



# Closed-Loop Results

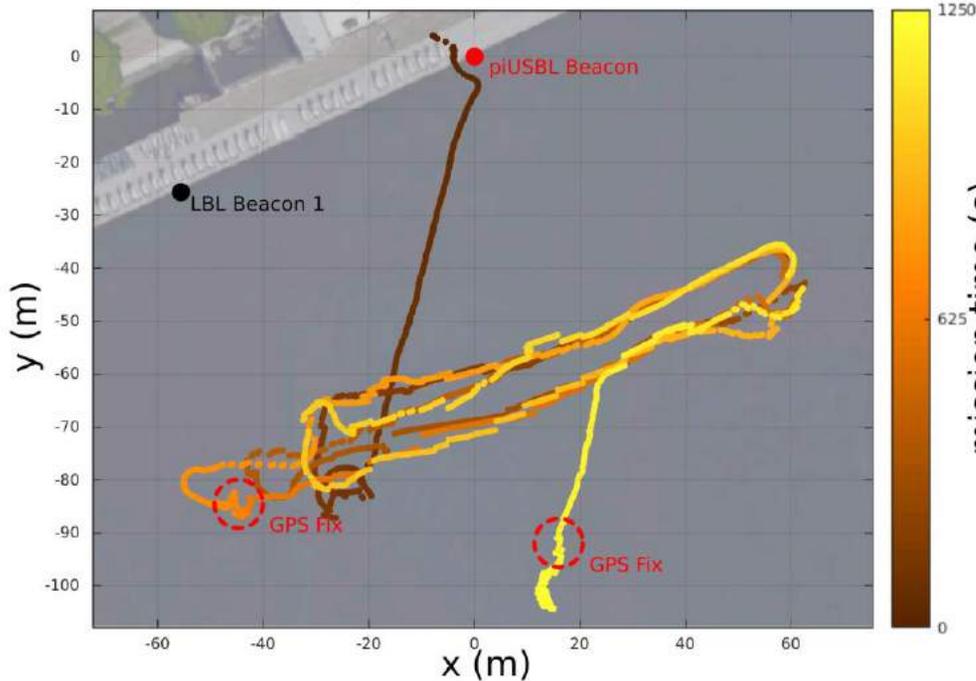
- 100% on-board processing – Prototype SandShark AUV



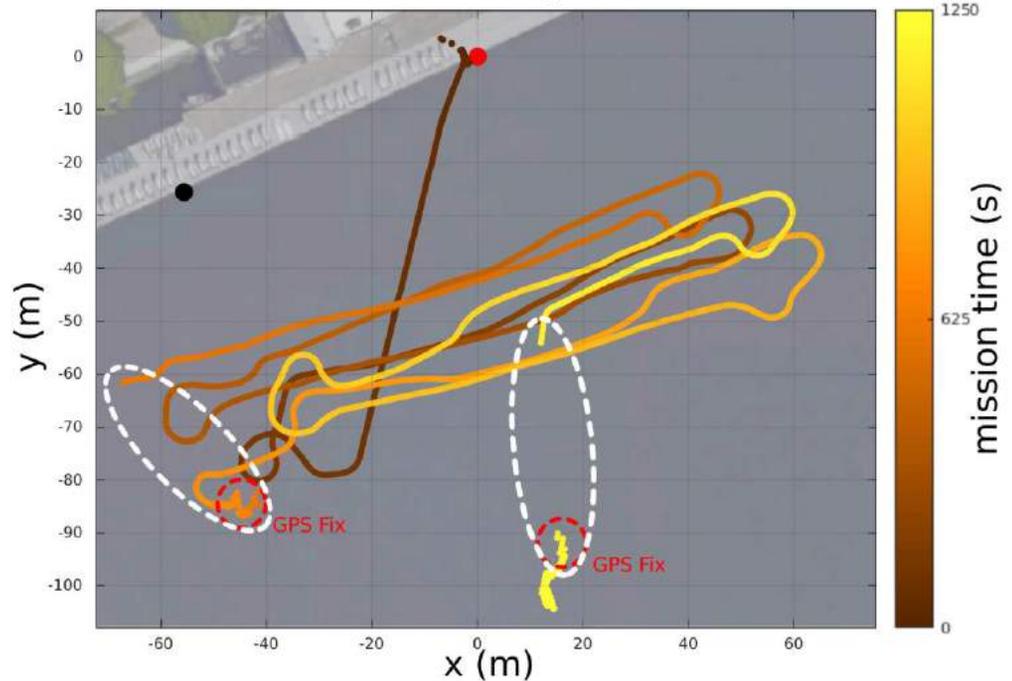
# Closed-Loop Results

- 100% on-board processing – Prototype SandShark AUV
- Charles River Spring 2017 – 2 runs, 2m depth, surfacing 2 times

piUSBL (Run 2)

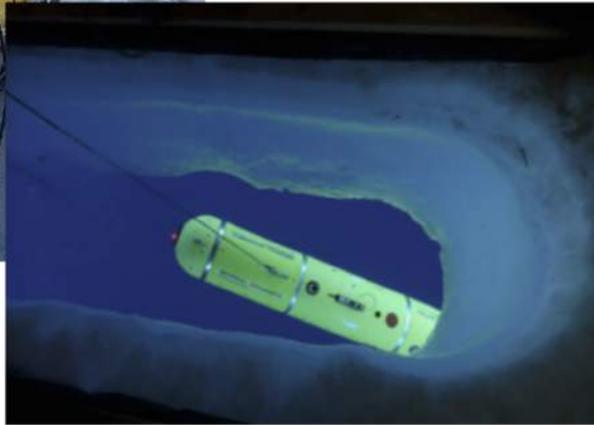


Dead-Reckoning (Run 2)



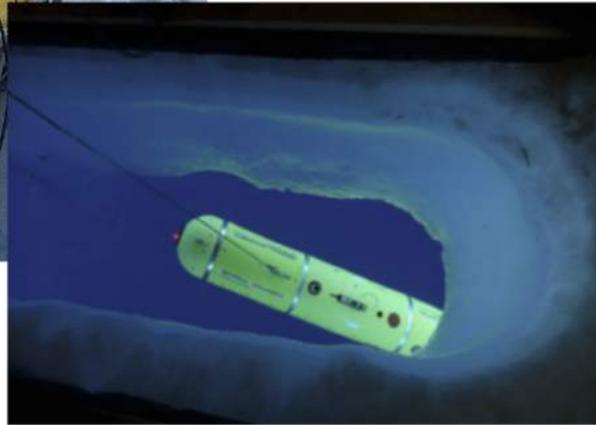
# Closed-Loop Results

- 100% on-board processing – Bluefin-21 AUV



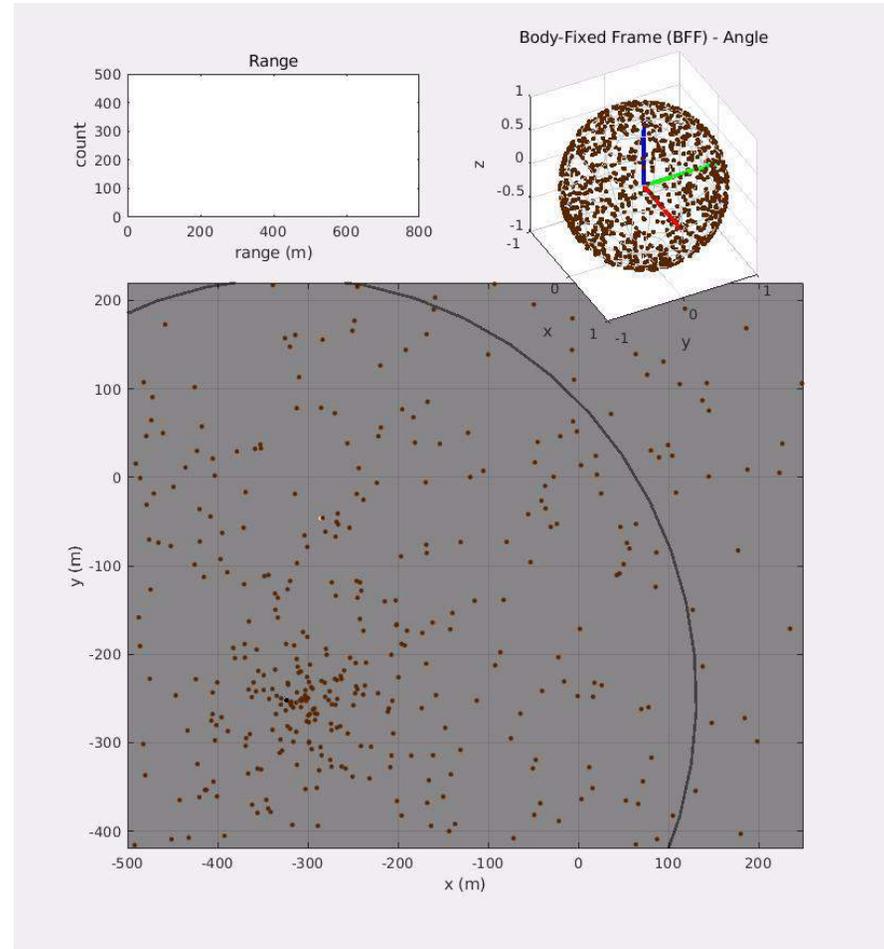
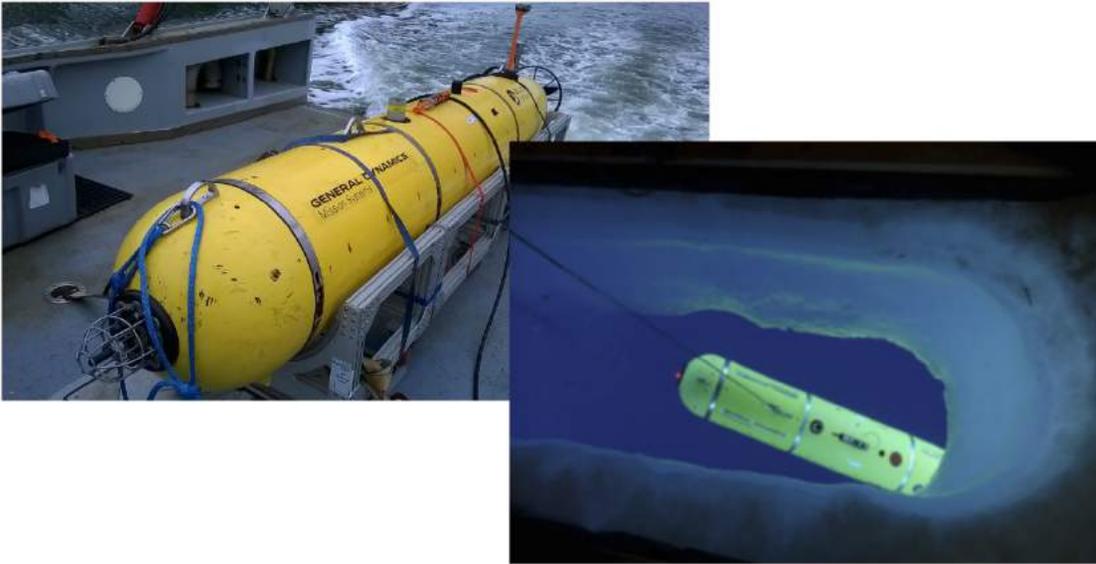
# Closed-Loop Results

- 100% on-board processing – Bluefin-21 AUV
- Massachusetts Bay 2017 – *“Relative Navigation”* (homing), 5m depth
- Offset relative filter estimate by boat GPS position in post-processing



# Closed-Loop Results

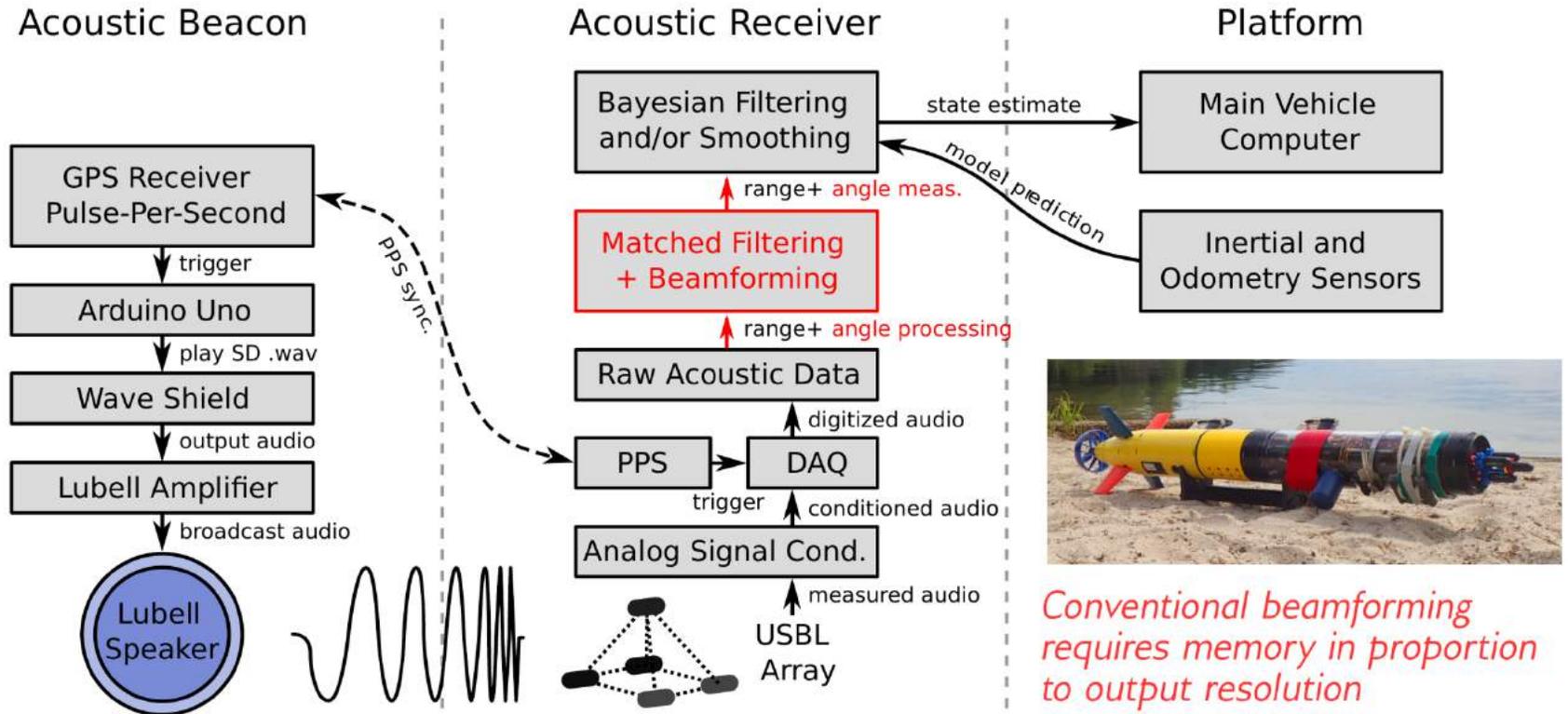
- 100% on-board processing – Bluefin-21 AUV
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# Improvement 2 – Memory Efficient Beamforming

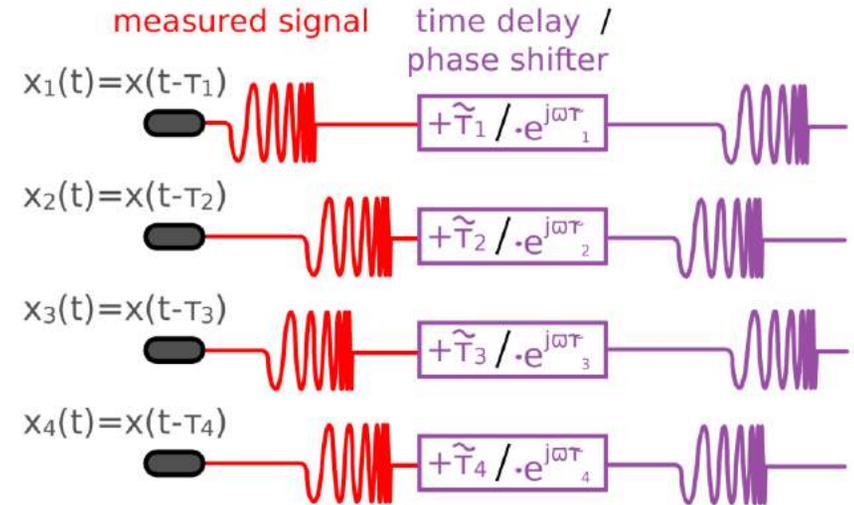
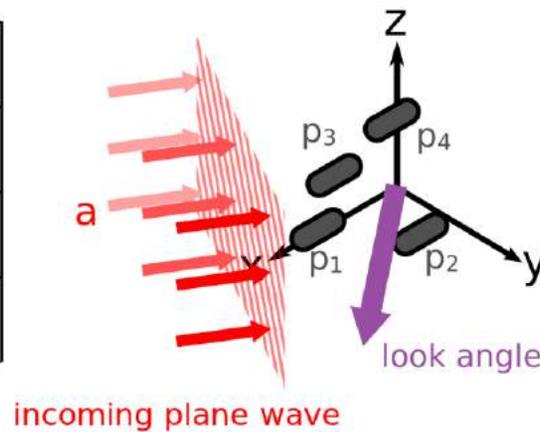
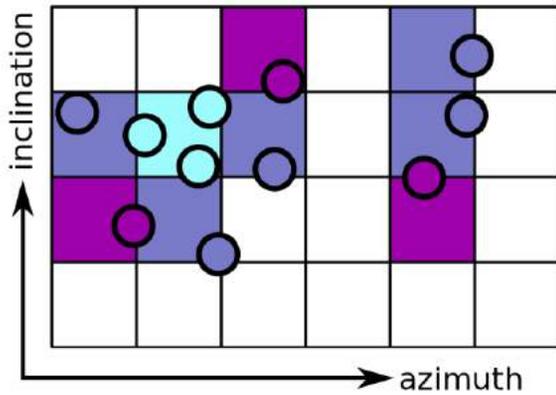
- How to break the memory-computation trade-off of CBF?<sup>1</sup>



1. N.R. Rypkema, et al., "Element Pair Decomposition Beamforming", In Preparation

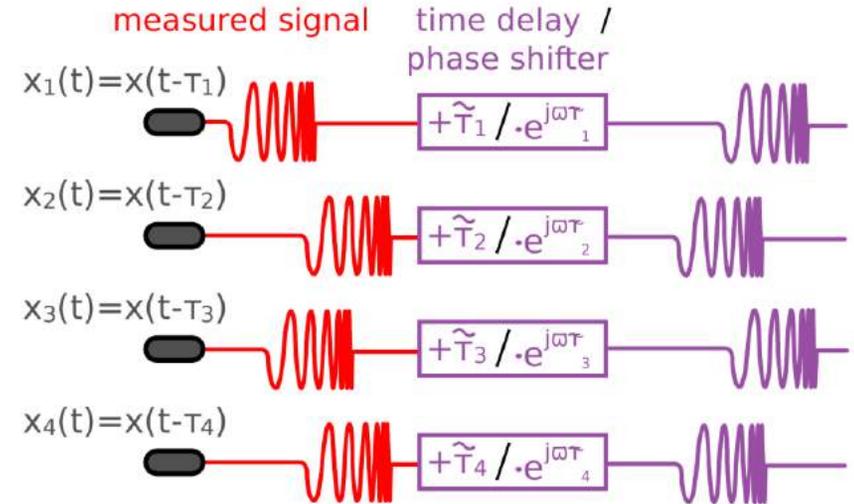
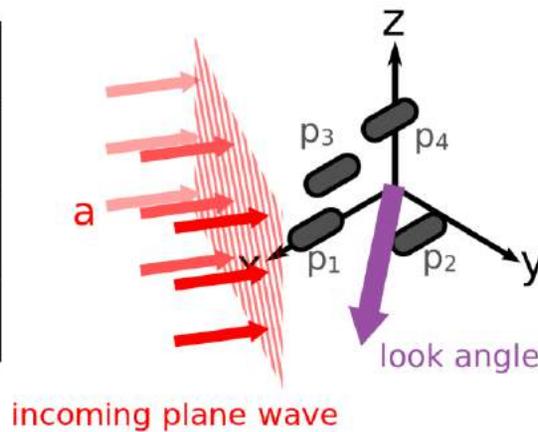
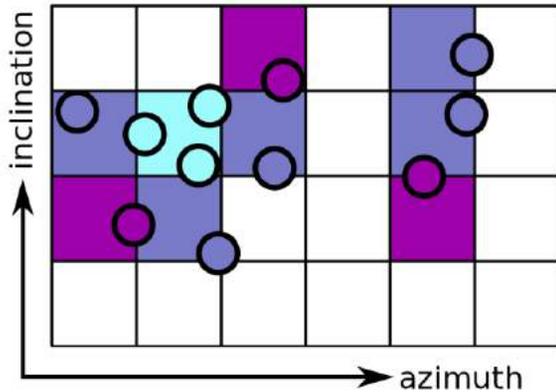
# Improvement 2 – Memory Efficient Beamforming

- We precompute phase-shifts (time-delays) for each look-angle
- Memory requirement grows with resolution ( $O(N^2)$  for grid)



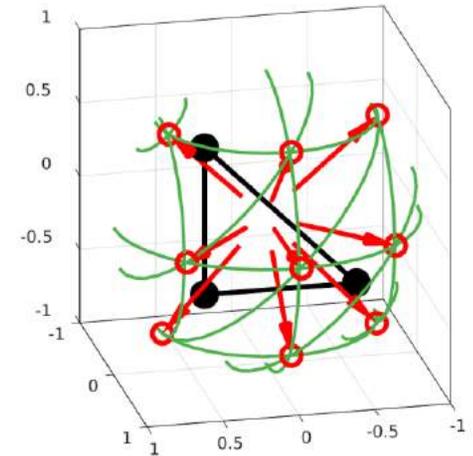
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- $N_{\text{azim.}} \times N_{\text{incl.}} \times \text{NFFT} \times N_{\text{elem}}$ 
  - e.g.  $15 \times 270 \times 1024 \times 4 \times 16$  bytes = 265MB – RasPi 3 has 1GB!



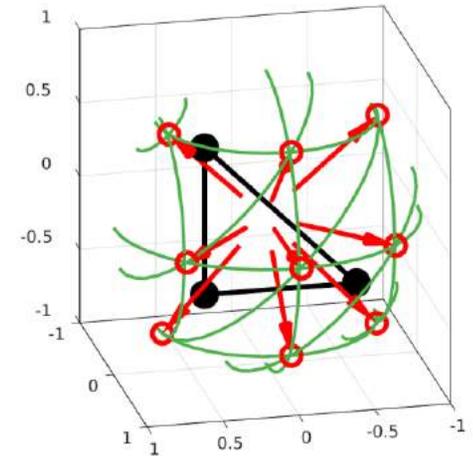
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- Key Insight: Full spherical output can be estimated using intersection of '*coning angles*' from pairs of array elements



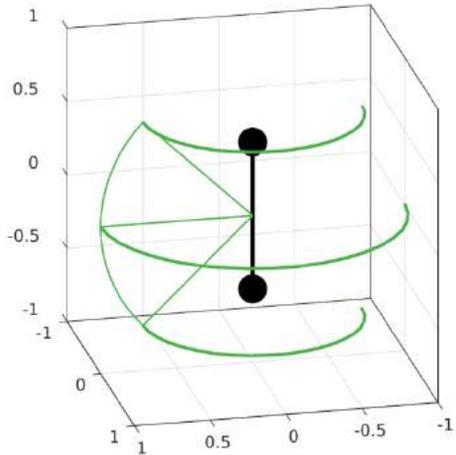
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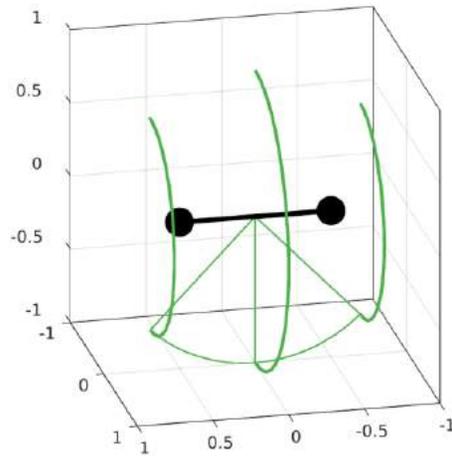
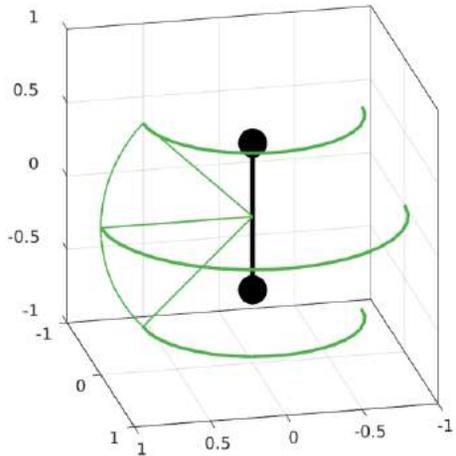
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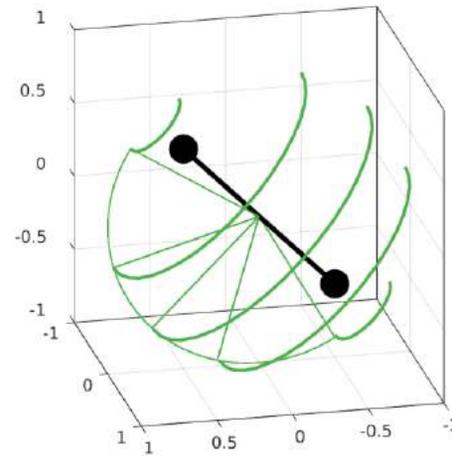
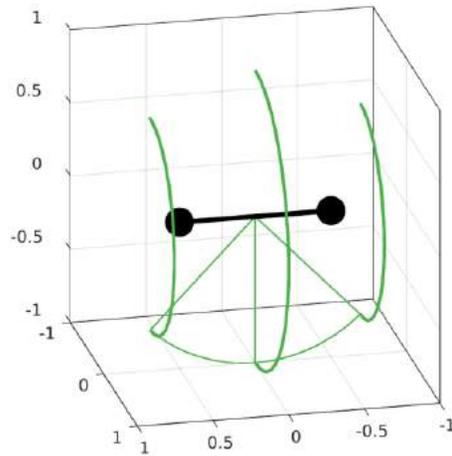
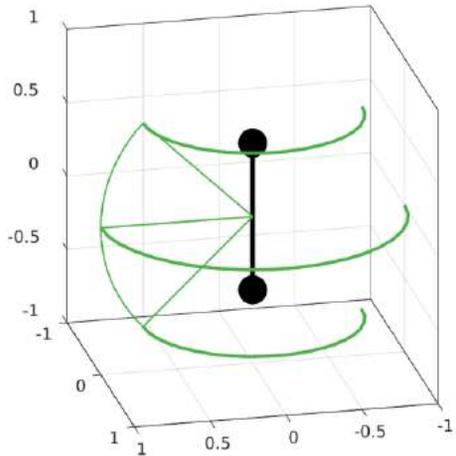
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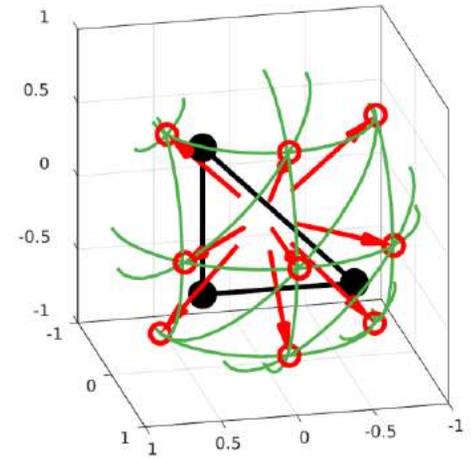
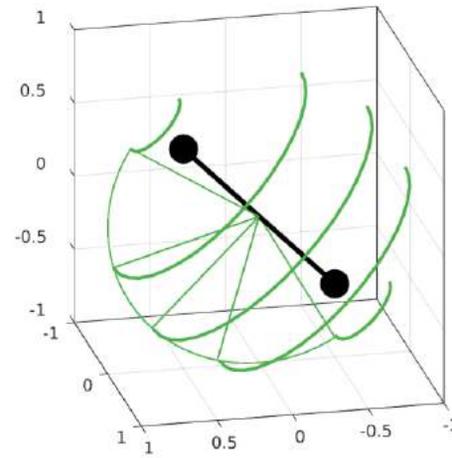
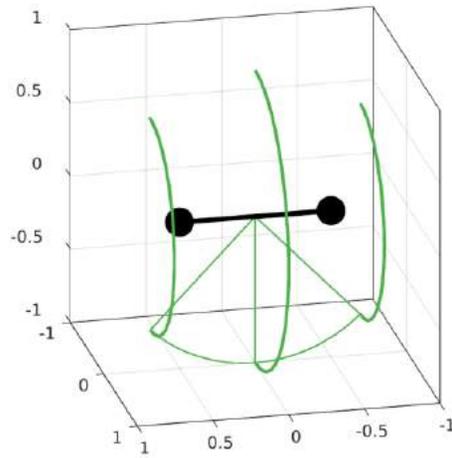
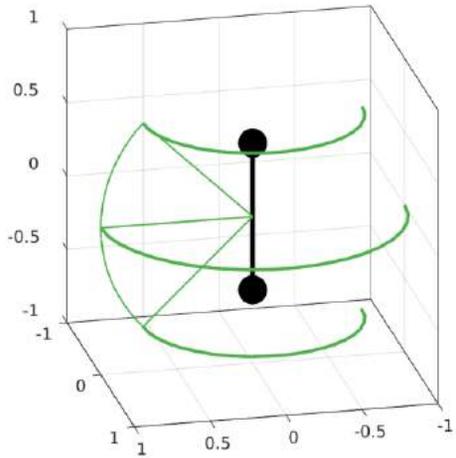
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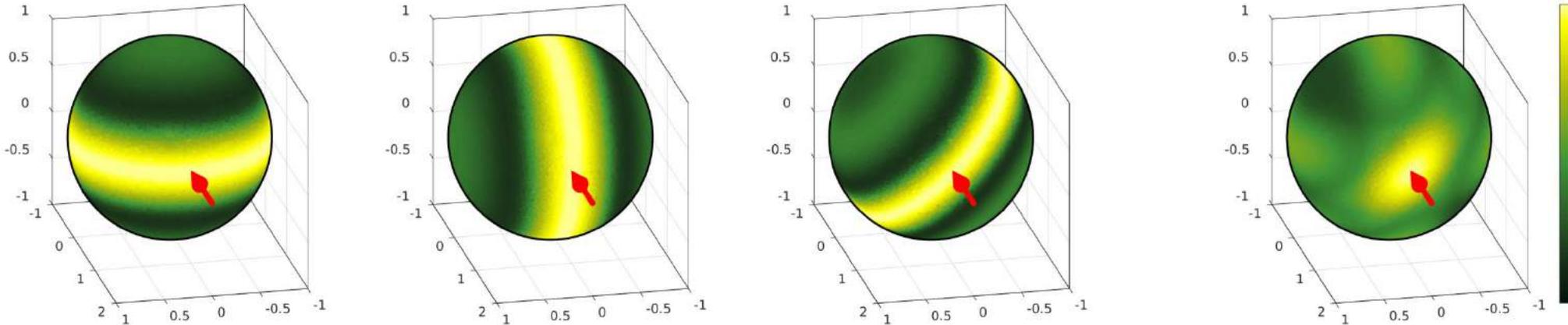
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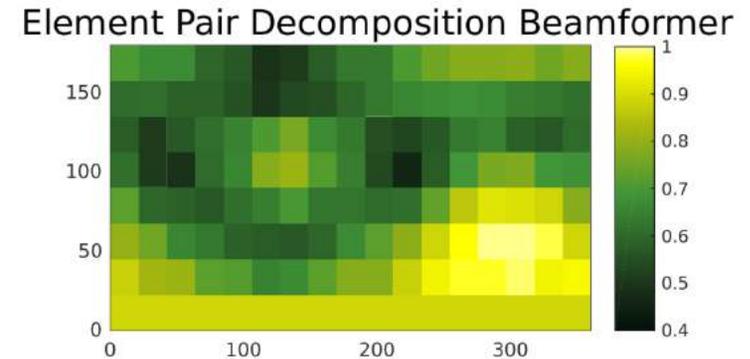
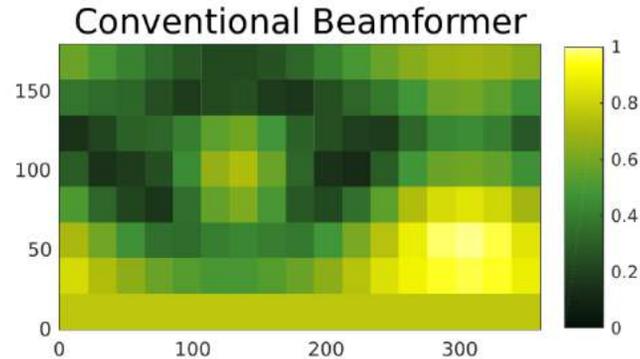
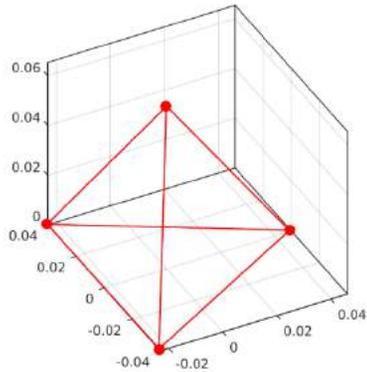
# Improvement 2 – Memory Efficient Beamforming

- Replace CBF with novel beamformer: *Element Pair Decomposition BF*
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- Pair beamformed output 'interfere' destructively/constructively



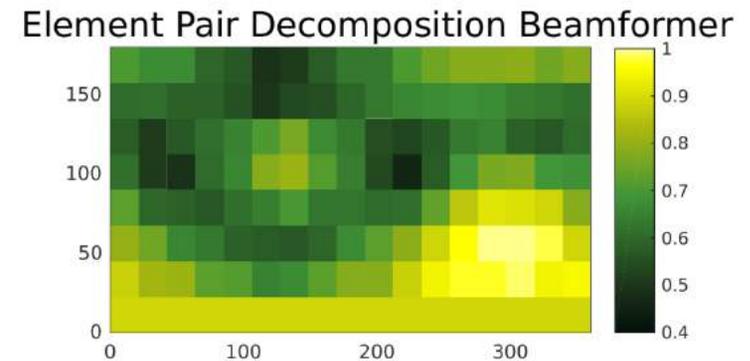
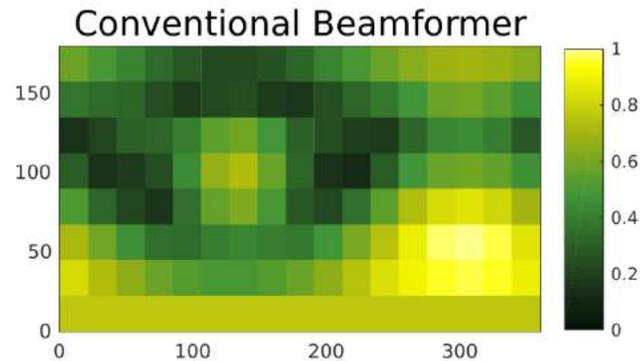
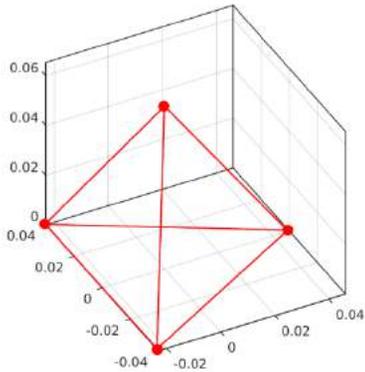
# Improvement 2 – Memory Efficient Beamforming

- Example: regular tetrahedron (all pairs equidistant)
- CBF:  $18 \times 9 = 162$  look-angles (*162 evals., ~10MB*)
- EPD BF: 18 coning angles, 6 pairs =  $18 \times 6 = 108$  look-angles (*108 evals., ~2MB...*)



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# Memory Efficient Beamforming Results

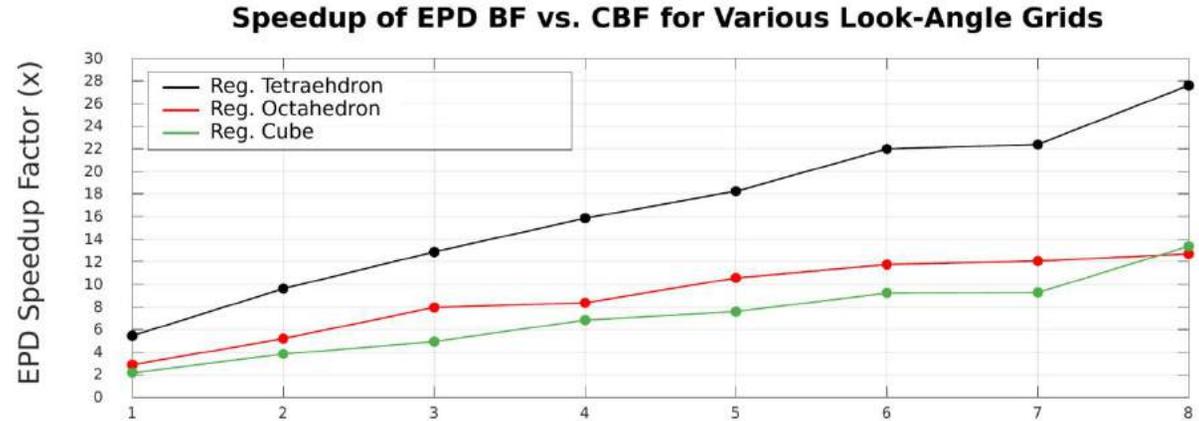
- Without loss of accuracy, *look-angle grid* speedup, memory saved

config	$S_{\text{angles}} (N_{\theta} \times N_{\phi})$	$S_{\text{coning}} (N_{\phi})$
1	$23 \times 45 = 1035$ look-angles	45 coning angles
2	$45 \times 90 = 4050$ look-angles	90 coning angles
3	$68 \times 135 = 9180$ look-angles	135 coning angles
4	$90 \times 180 = 16200$ look-angles	180 coning angles
5	$113 \times 225 = 25425$ look-angles	225 coning angles
6	$135 \times 270 = 36450$ look-angles	270 coning angles
7	$158 \times 315 = 49770$ look-angles	315 coning angles
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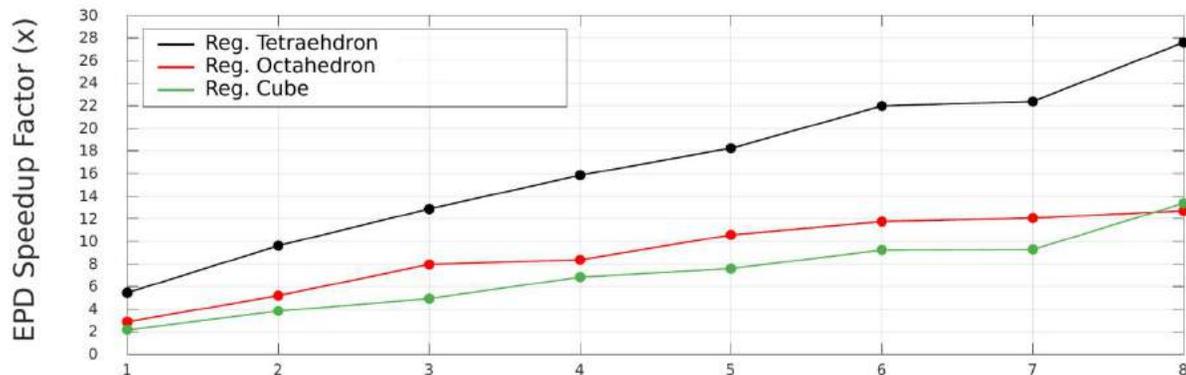


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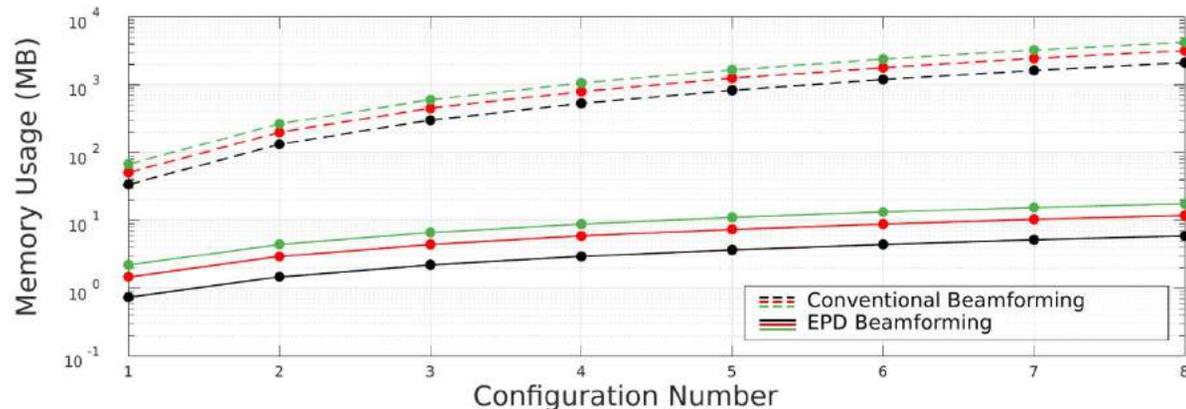
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Speedup of EPD BF vs. CBF for Various Look-Angle Grids

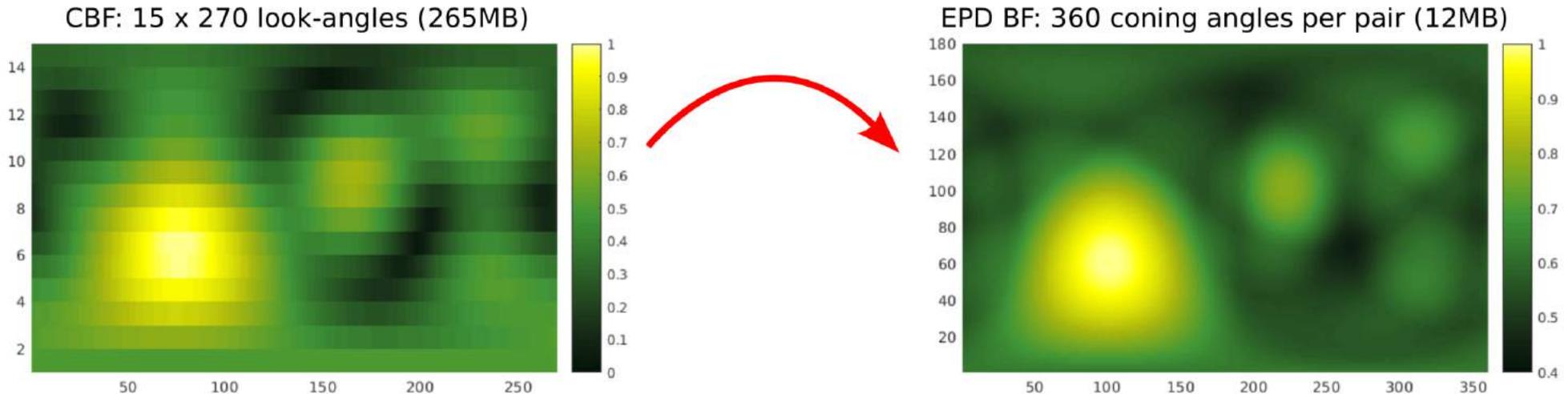


Memory Usage of EPD BF and CBF for Various Look-Angle Grids



# Memory Efficient Beamforming Results

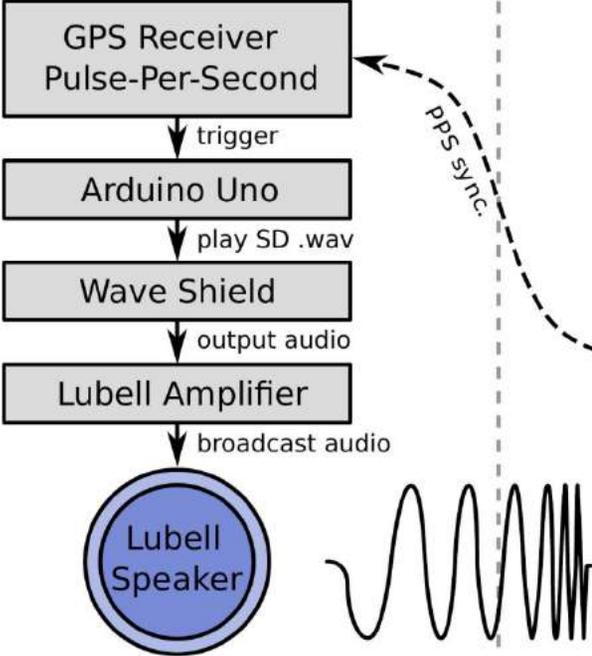
- Without loss of accuracy, *look-angle grid* speedup, memory saved
- Precomputation of phase-shifts necessary for real-time CBF
- RasPi 3 memory (1GB) severely limits resolution when using CBF
- Enormous memory savings allow a huge improvement in resolution of angle measurement (pseudo) distribution!!!



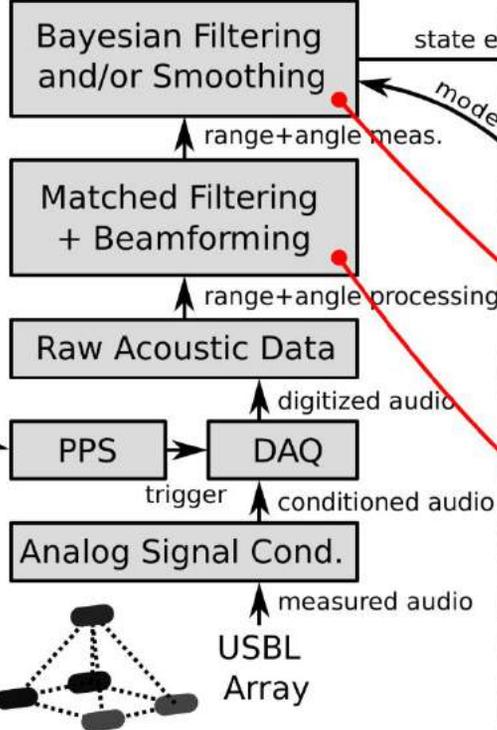


# Final System

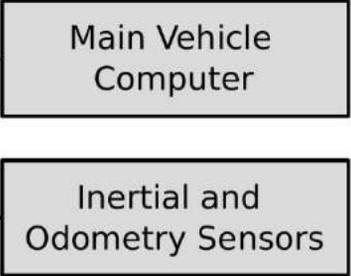
## Acoustic Beacon



## Acoustic Receiver



## Platform



Closely-coupled beamforming and particle filtering (enables closed-loop rates)

Memory efficient EPD beamforming (enables high-res. angle measurement dist.)

state estimate

model prediction

range+angle meas.

range+angle processing

digitized audio

trigger

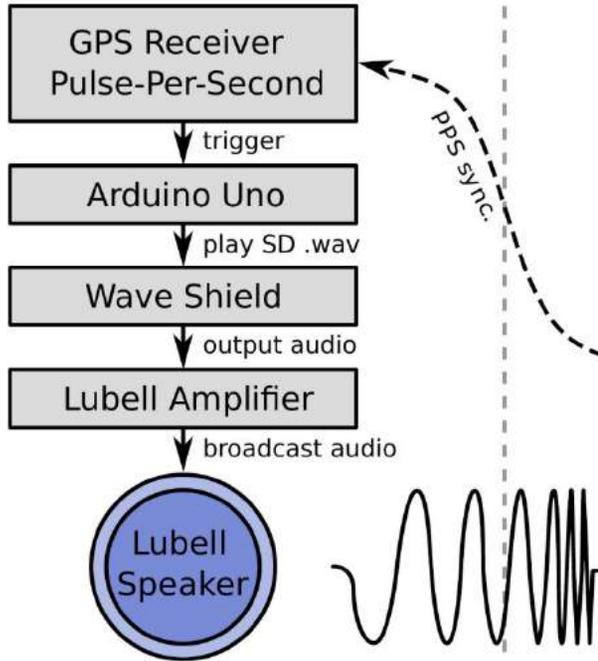
conditioned audio

measured audio

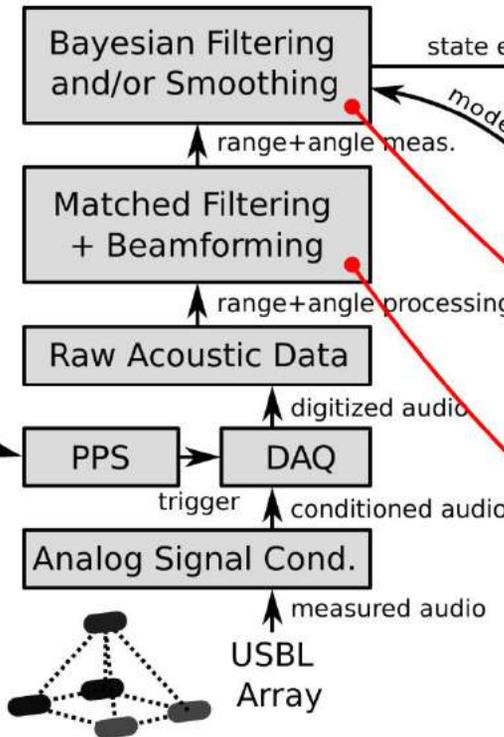
USB Array

# Final System

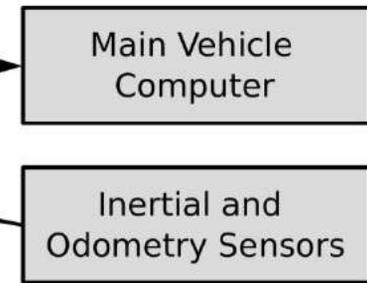
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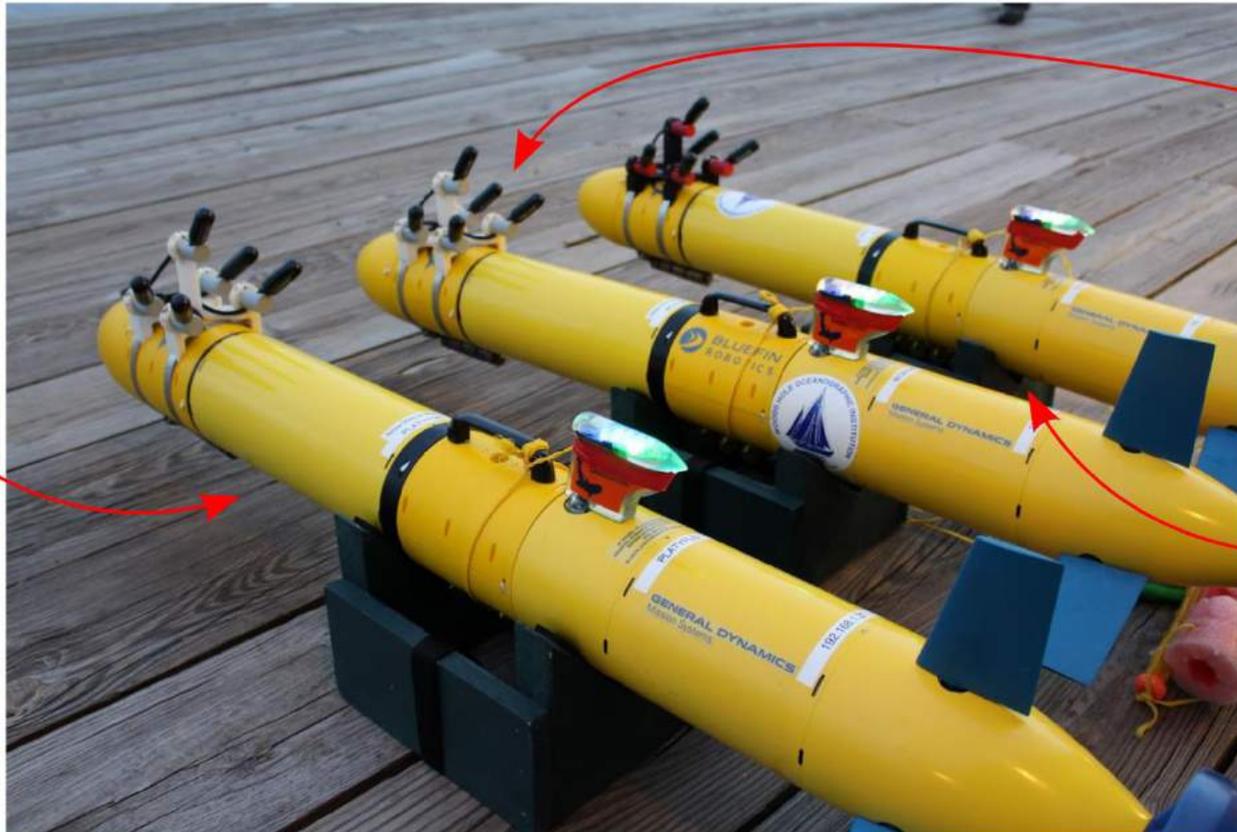


# Multi-AUV Implementation

- Final system implemented on fleet of 3 commercial SandShark AUVs
- Integration, ballasting, PID tuning, mag. calibration, etc.



Platypus



Wombat

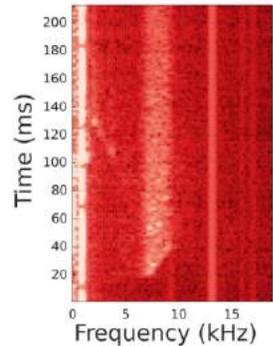
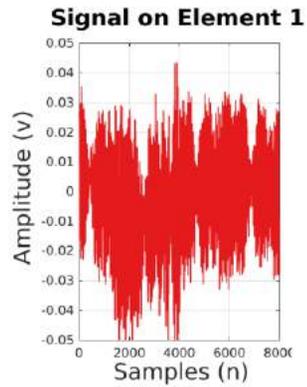


Quokka



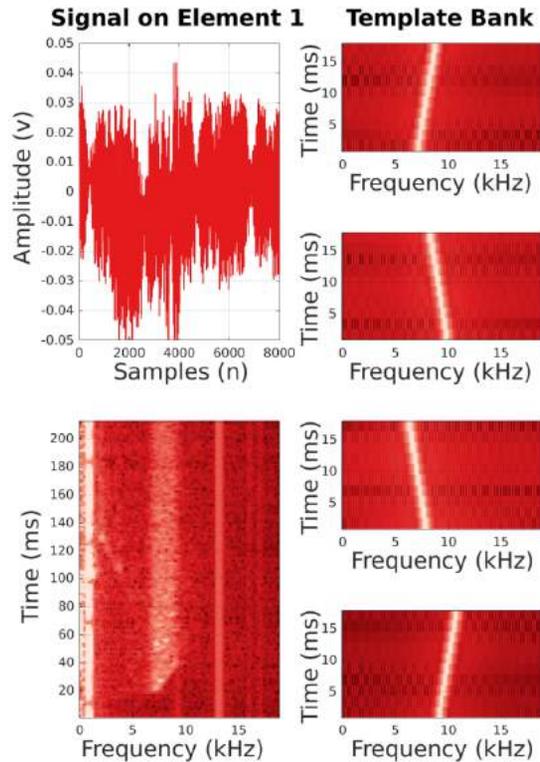
# Multi-AUV Relative Navigation

- Fleet-wide command enabled by memory efficient beamforming



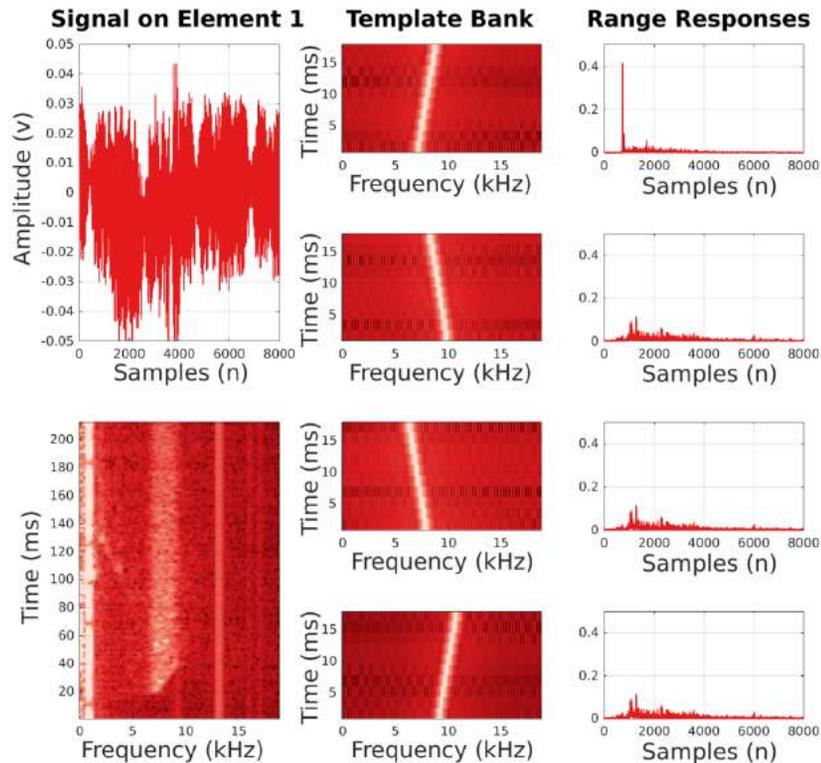
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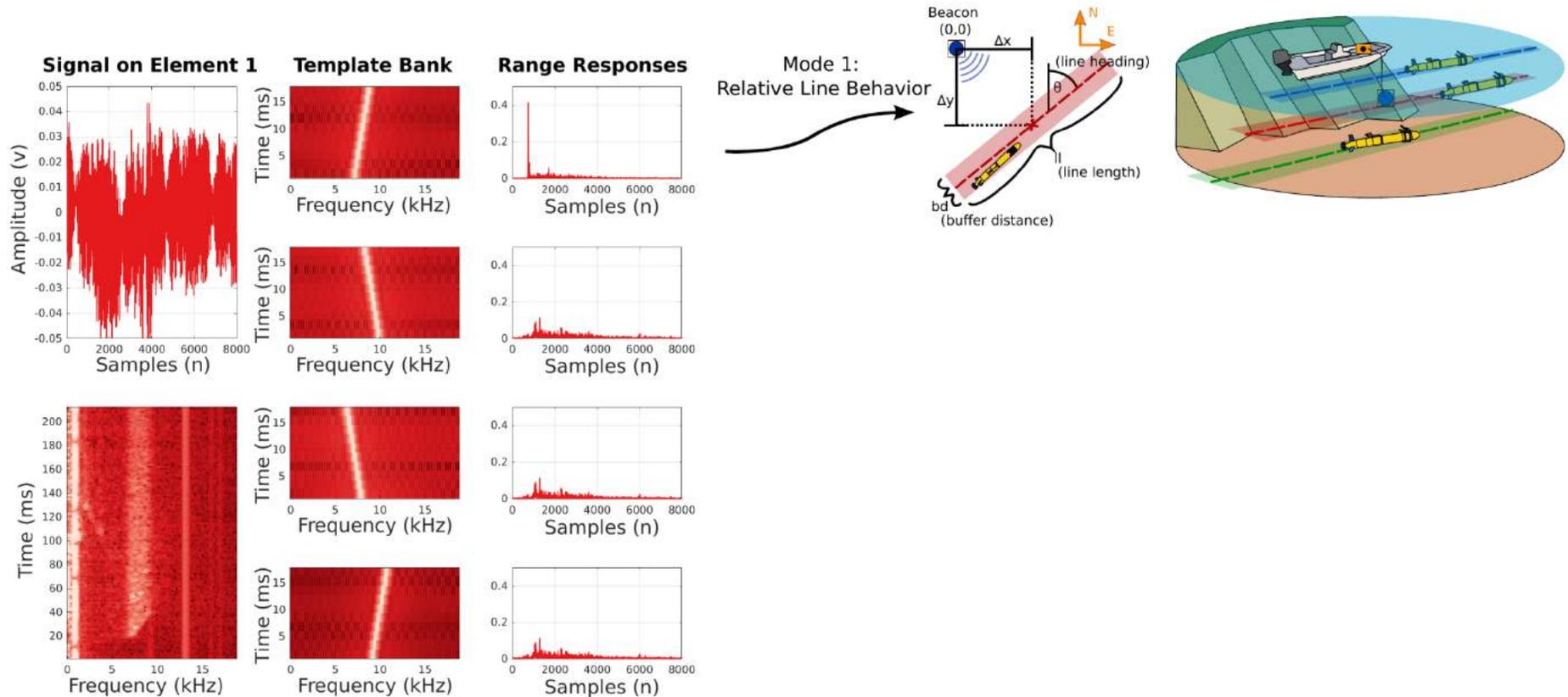
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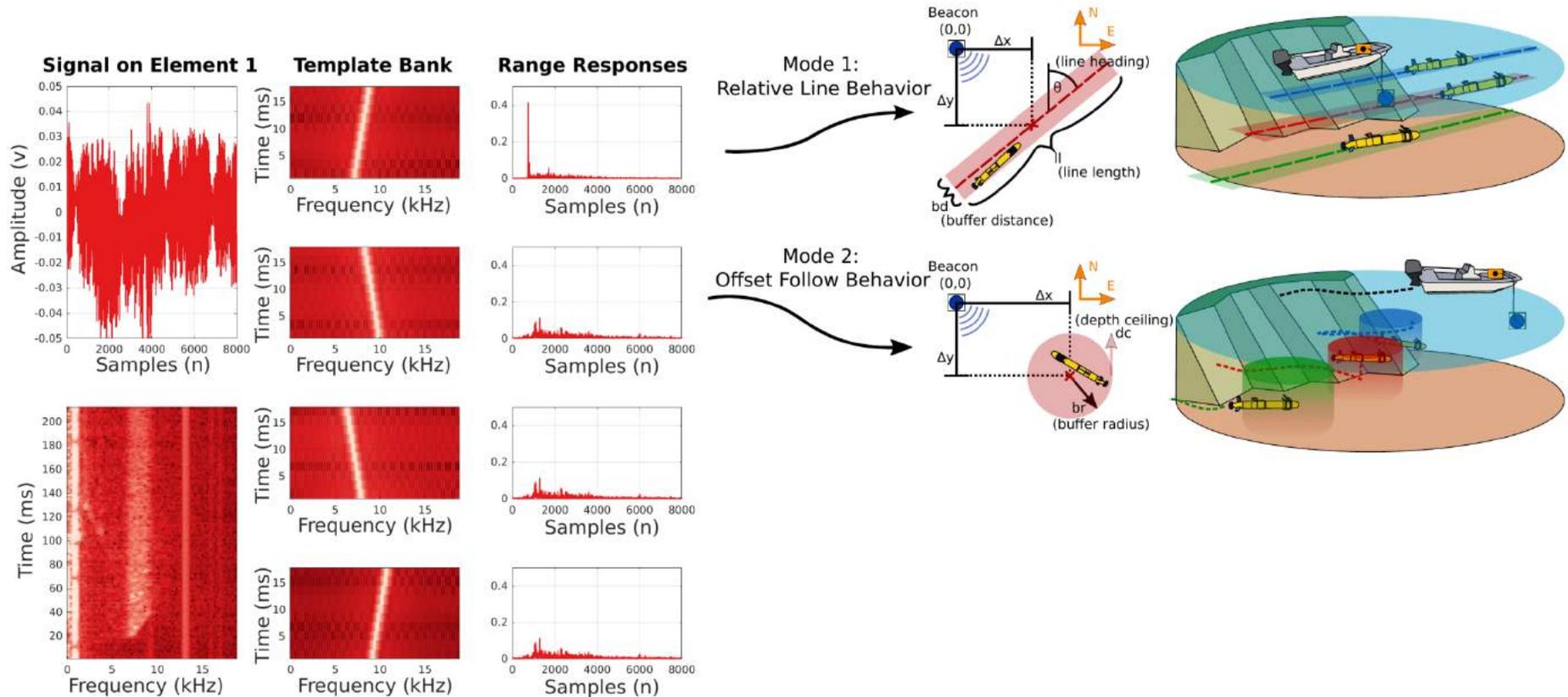
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- *Different broadcast signals* command different relative behaviors



# Multi-AUV Relative Navigation

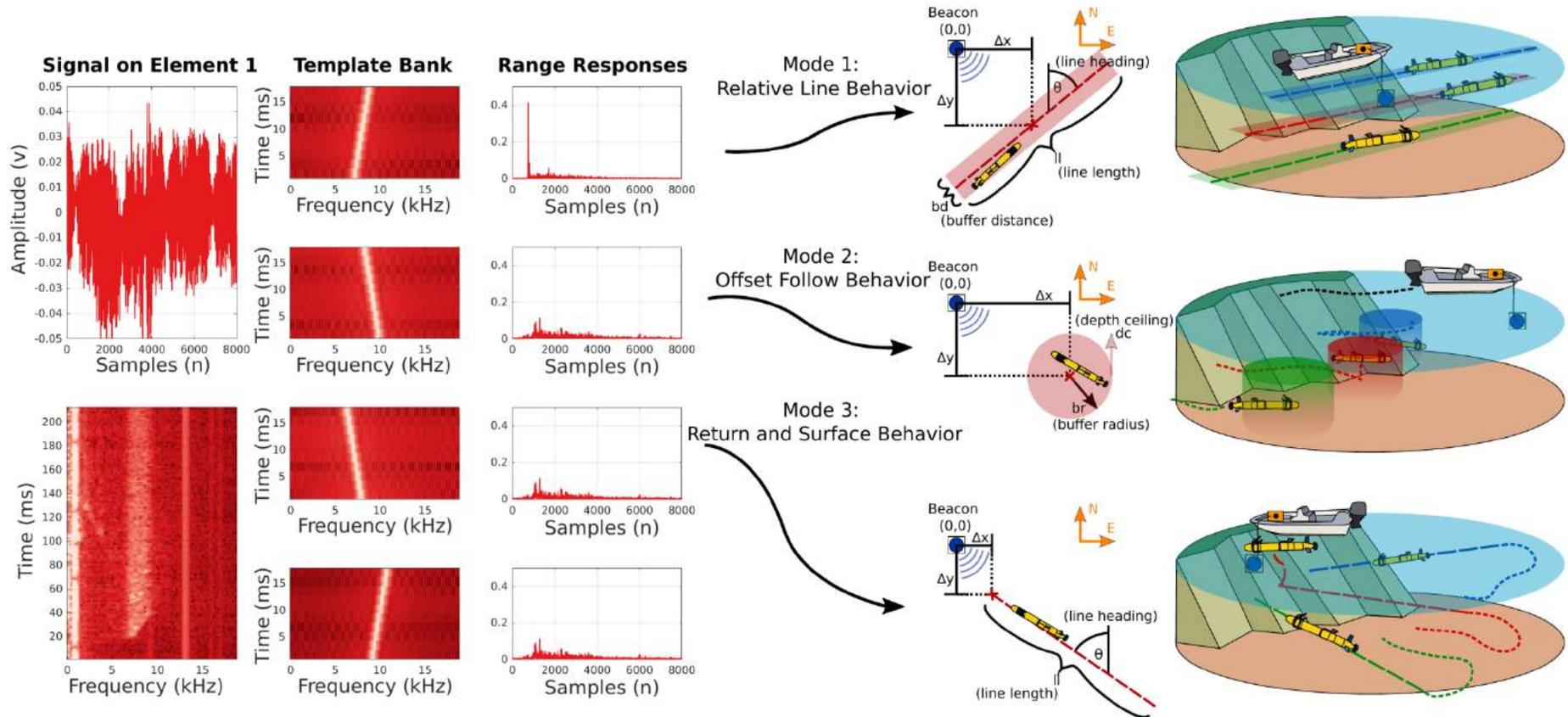
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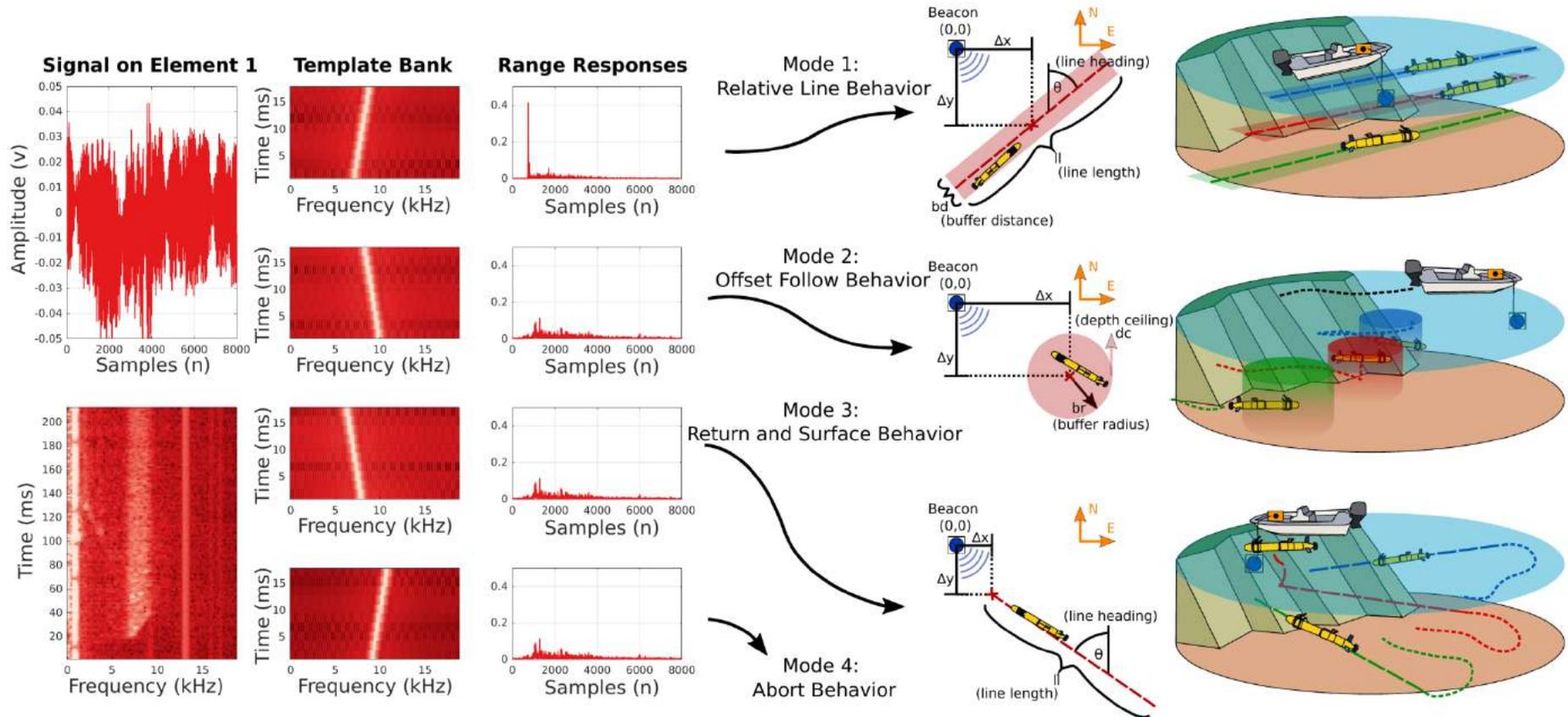
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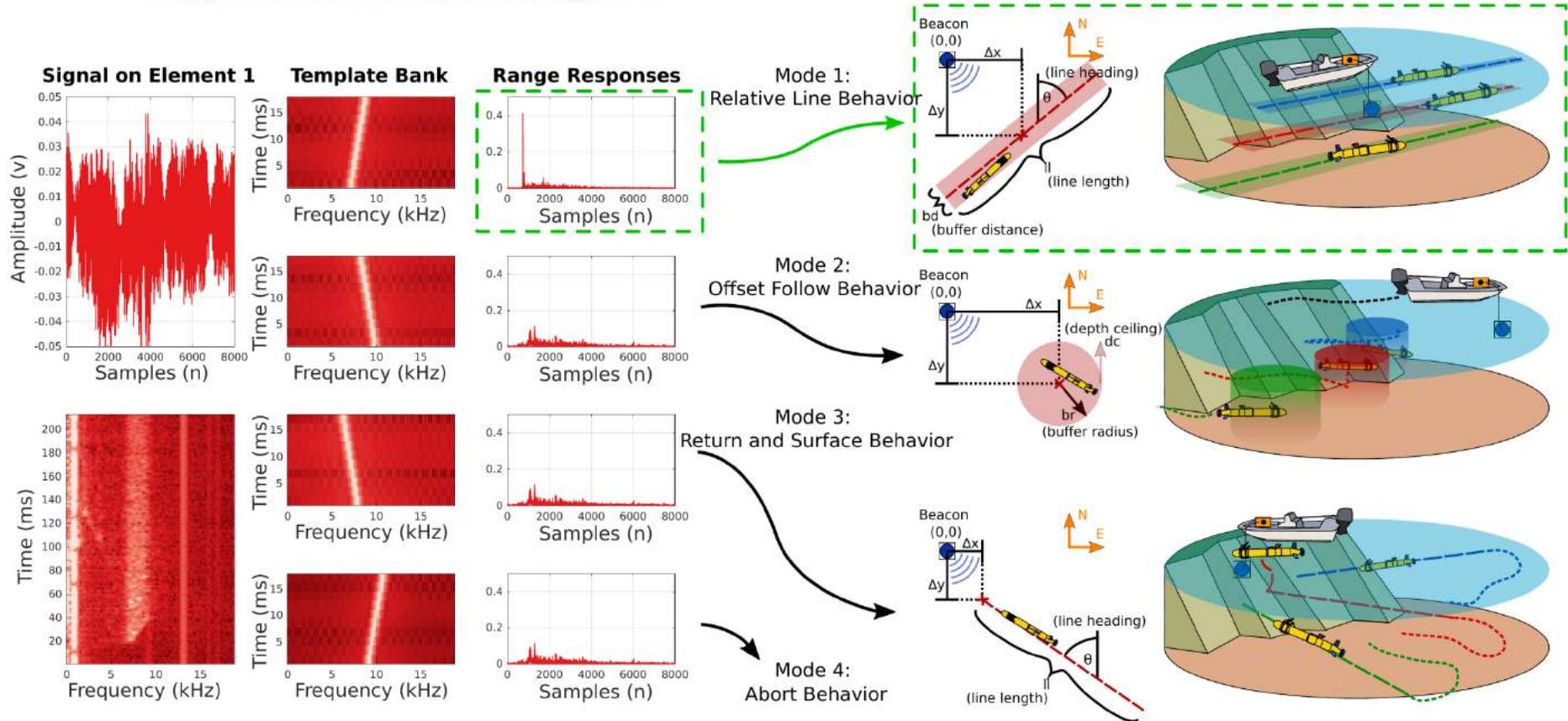
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# Multi-AUV Relative Navigation

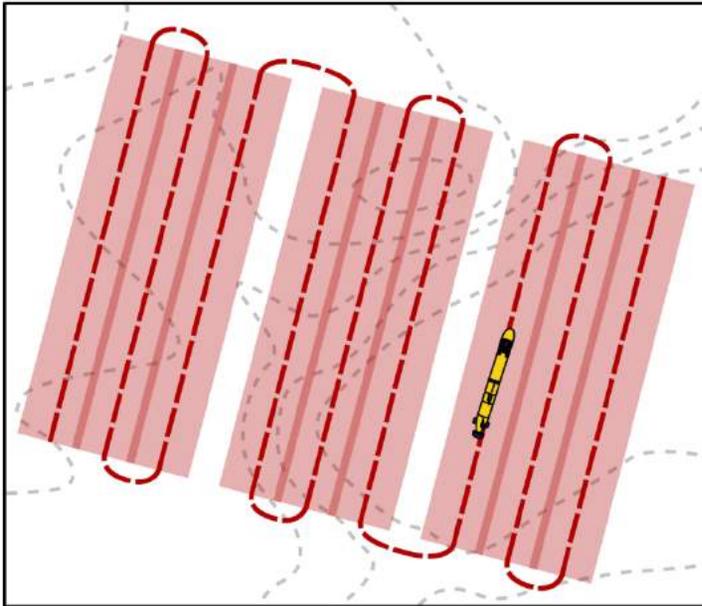
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# Multi-AUV Relative Navigation

- Fleet-wide command enabled by memory efficient beamforming
  - *Different broadcast signals* command different relative behaviors
- Fleet-wide control enabled by *beacon movement*

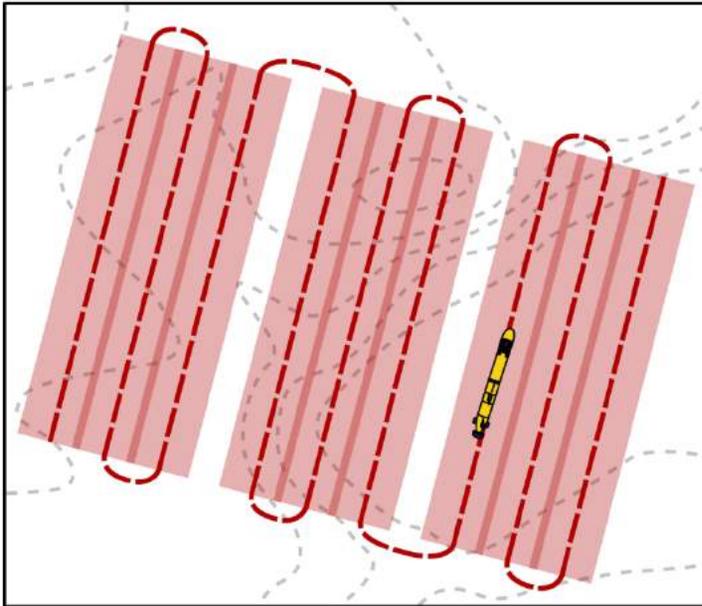
Conventional Operating Paradigm  
(Absolute Racetrack)



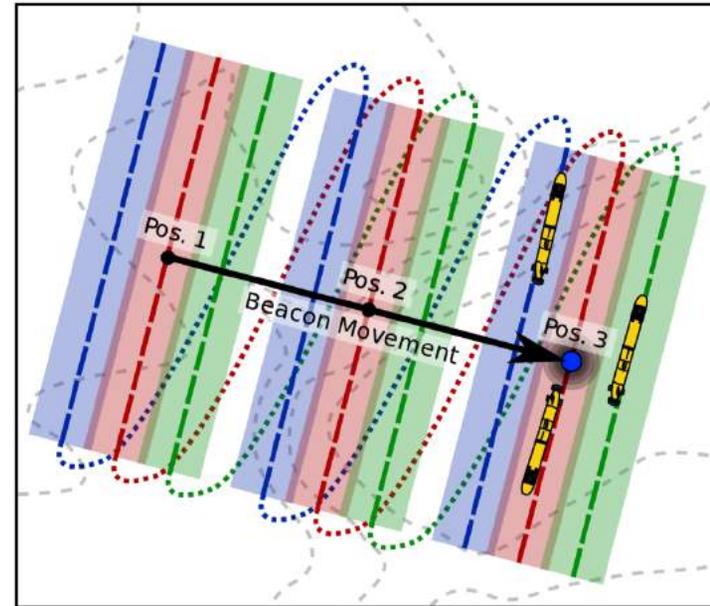
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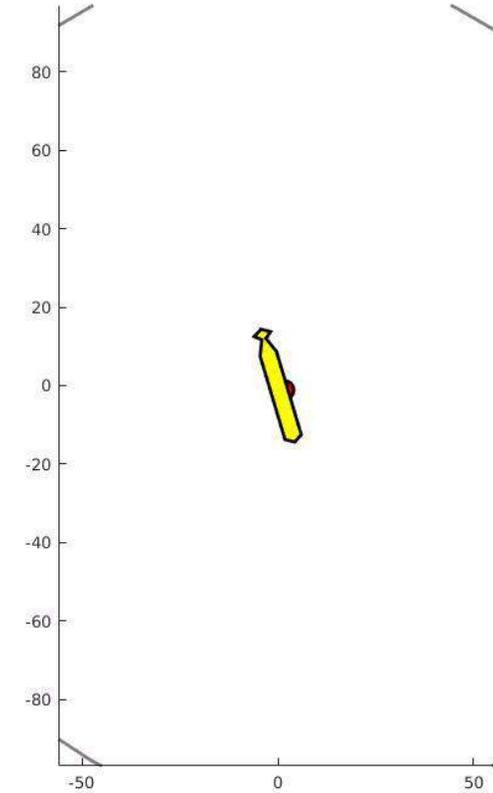
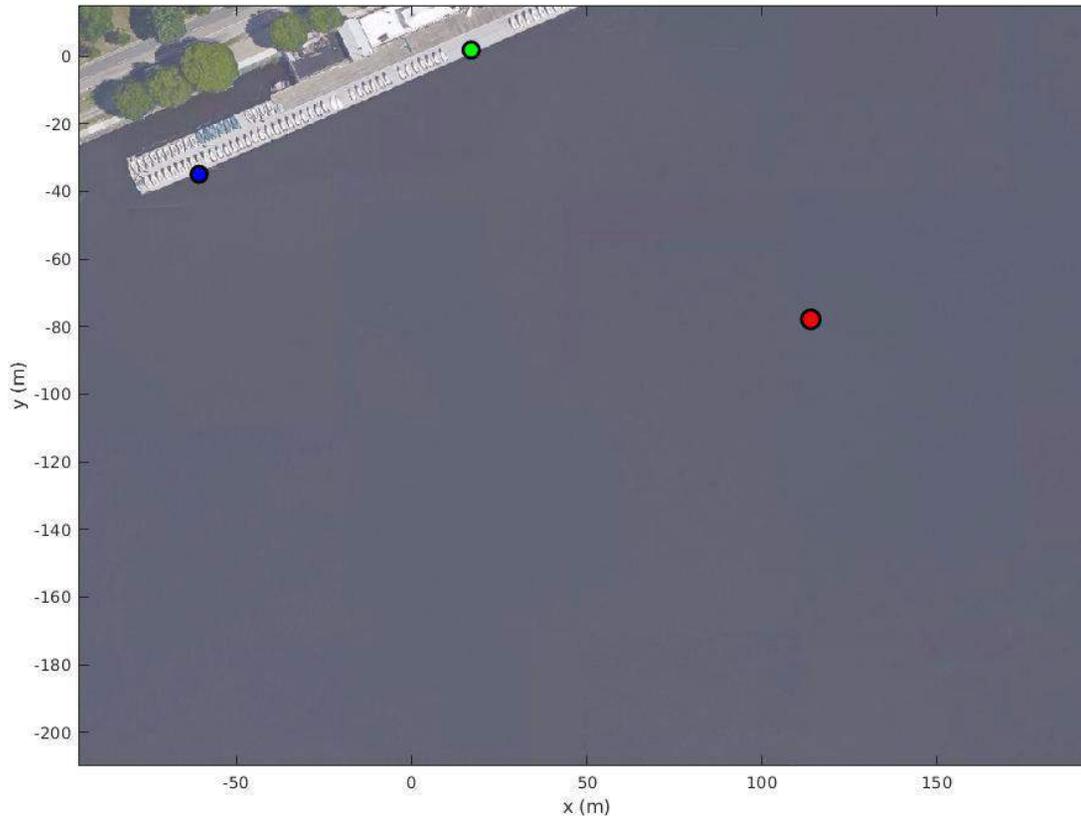


piUSBL Relative Navigation Paradigm  
(Relative Line with Moving Beacon)



# Multi-AUV Relative Navigation

- Relative navigation operational paradigm example
  - *2 extra piUSBL beacons for LBL* dockside



# Multi-AUV Experiments

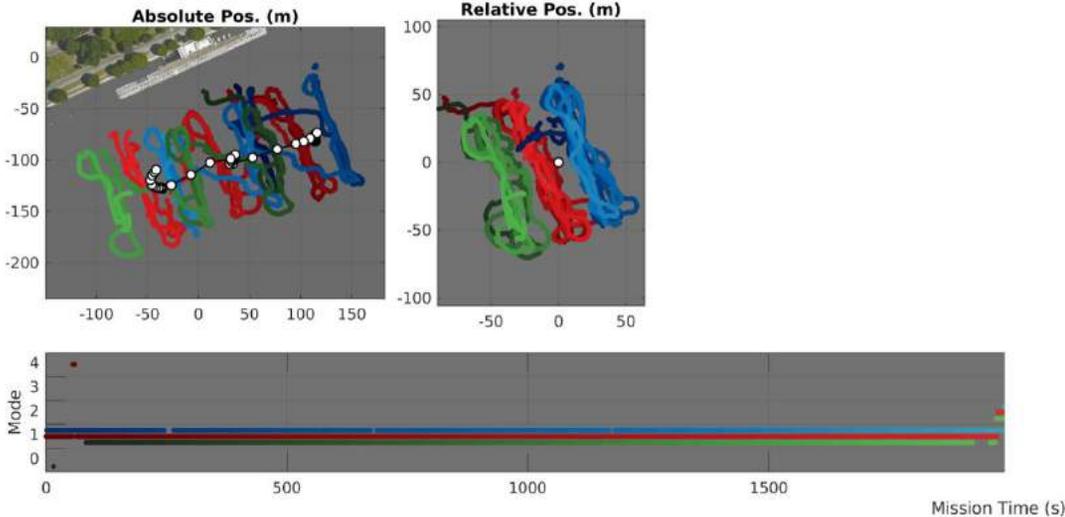
- Charles River Fall 2018 – *12 missions* over 1 month, *~36 hours*, 3 AUVs
- Closed-loop piUSBL – ~1 hour missions, 2.5m depth, no surfacing
- Validated using LBL, piUSBL solution offset by beacon GPS



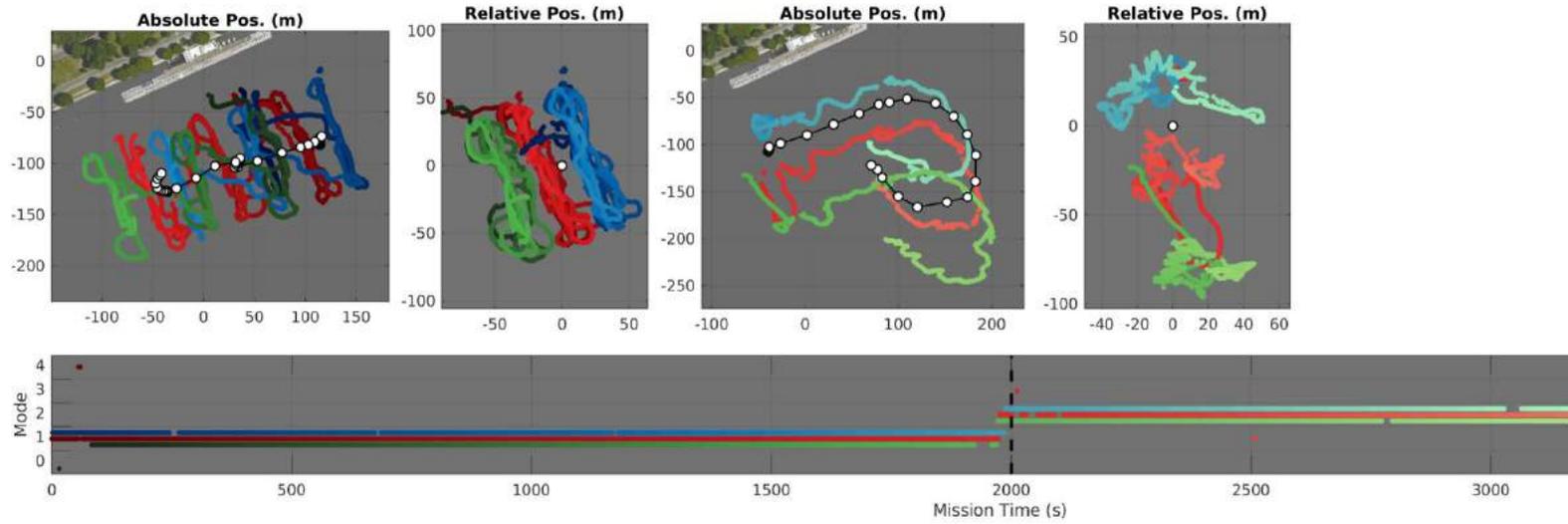




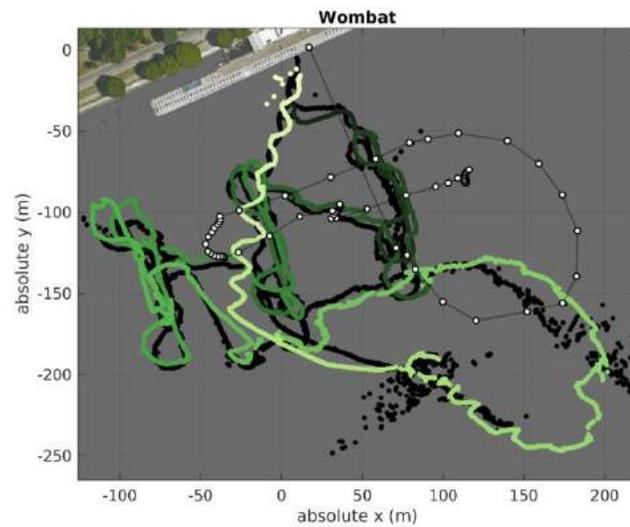
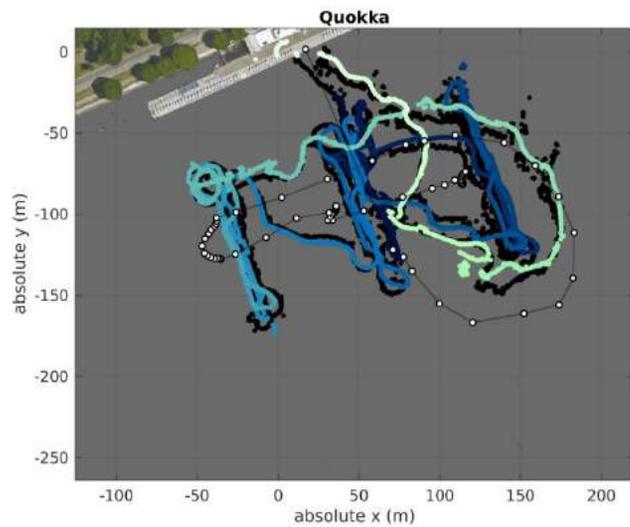
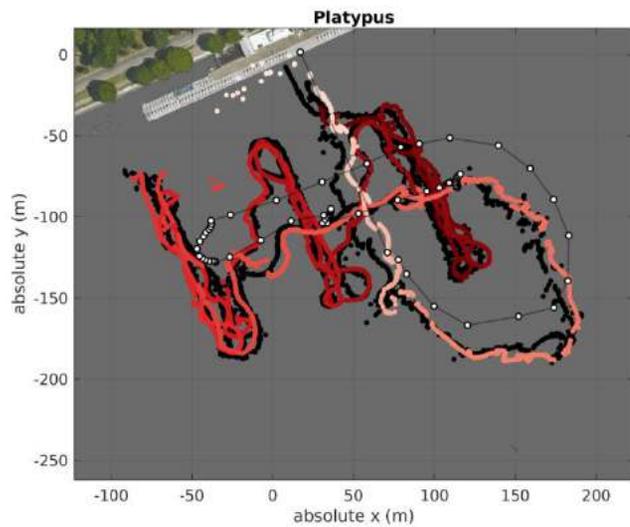
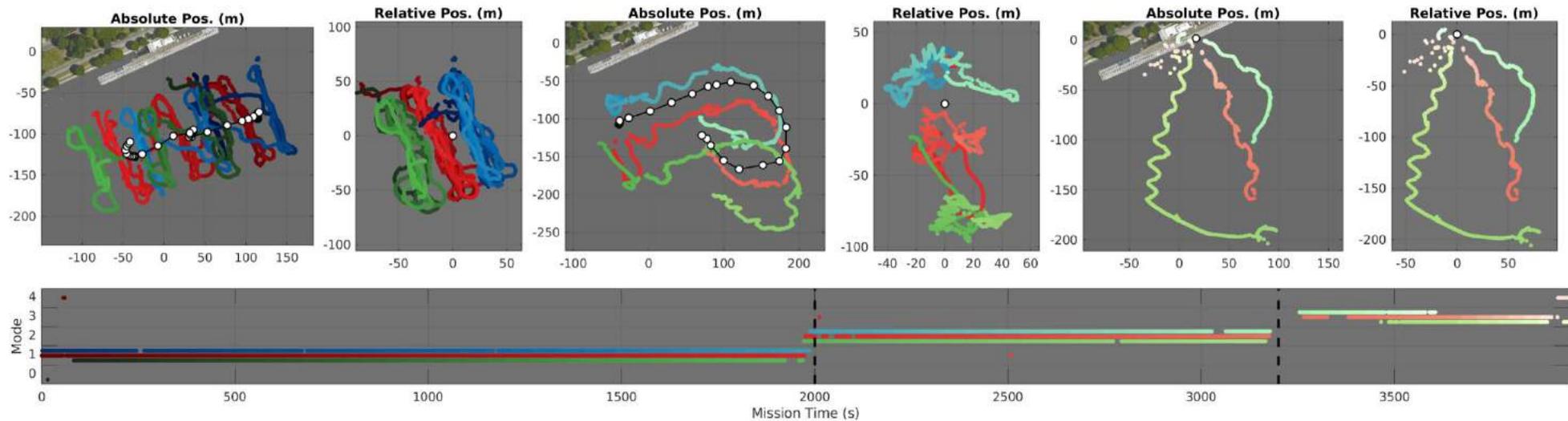
# Multi-AUV Experiments (Run 11)



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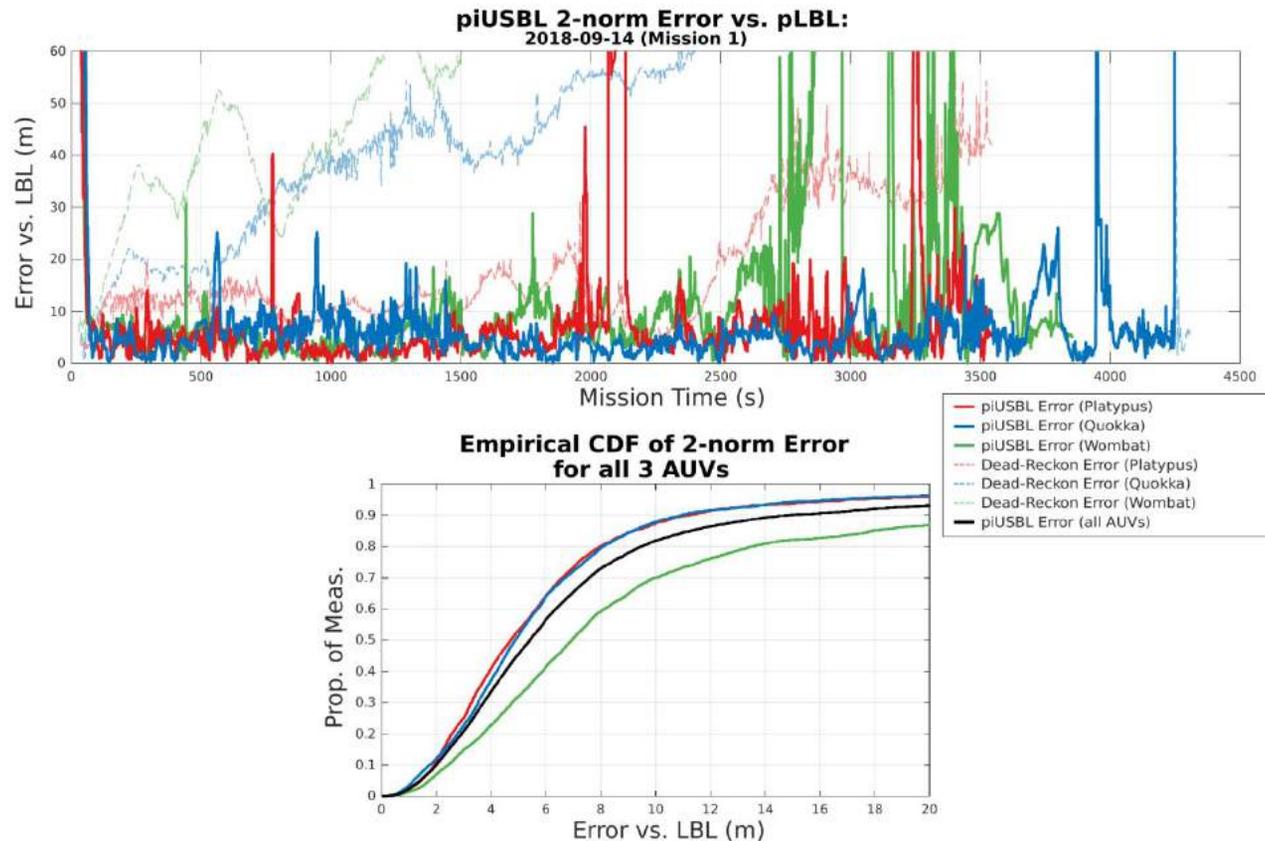


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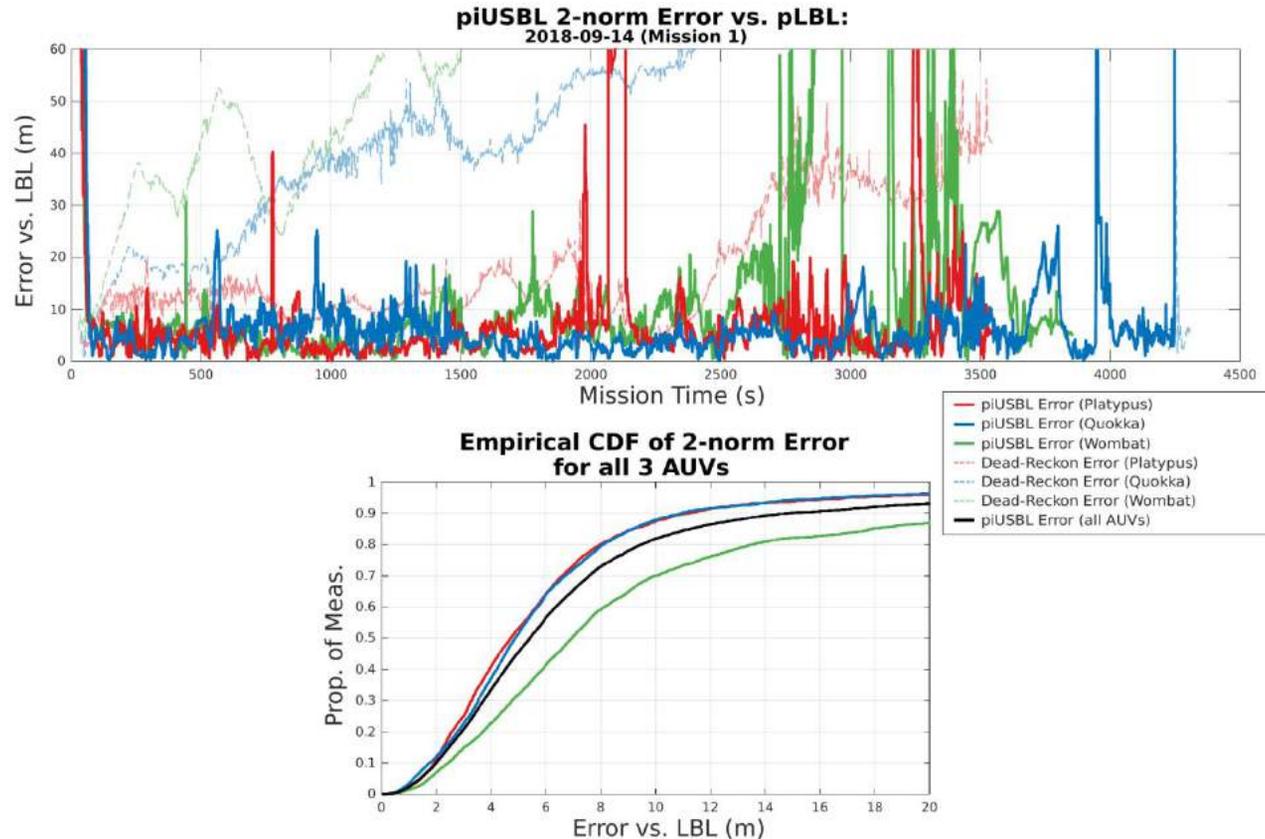
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- Comparison vs. LBL – not perfect, LBL has outliers!
- *68% error vs. LBL < 7.5m* and *68% error across all missions < 7.9m*



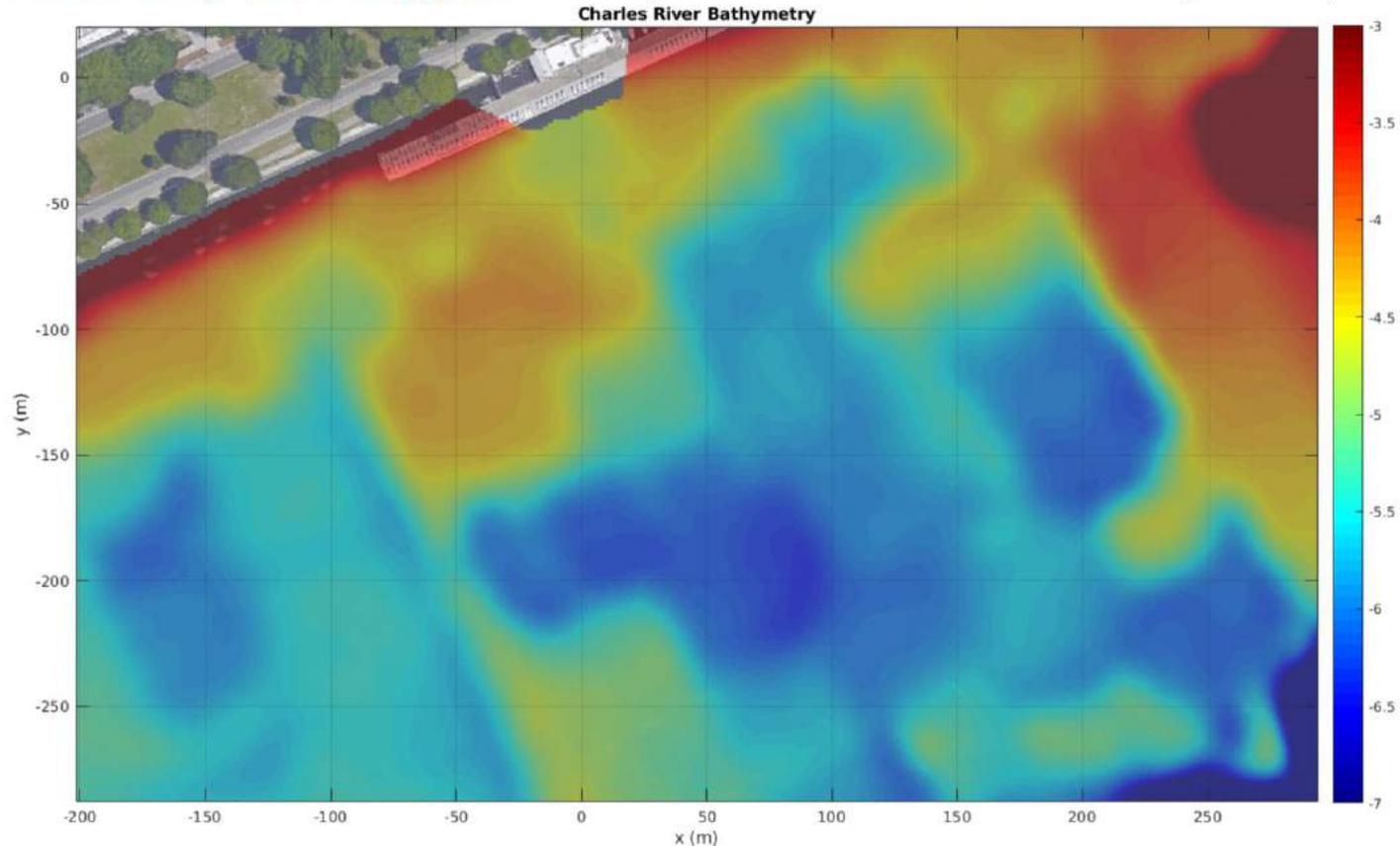
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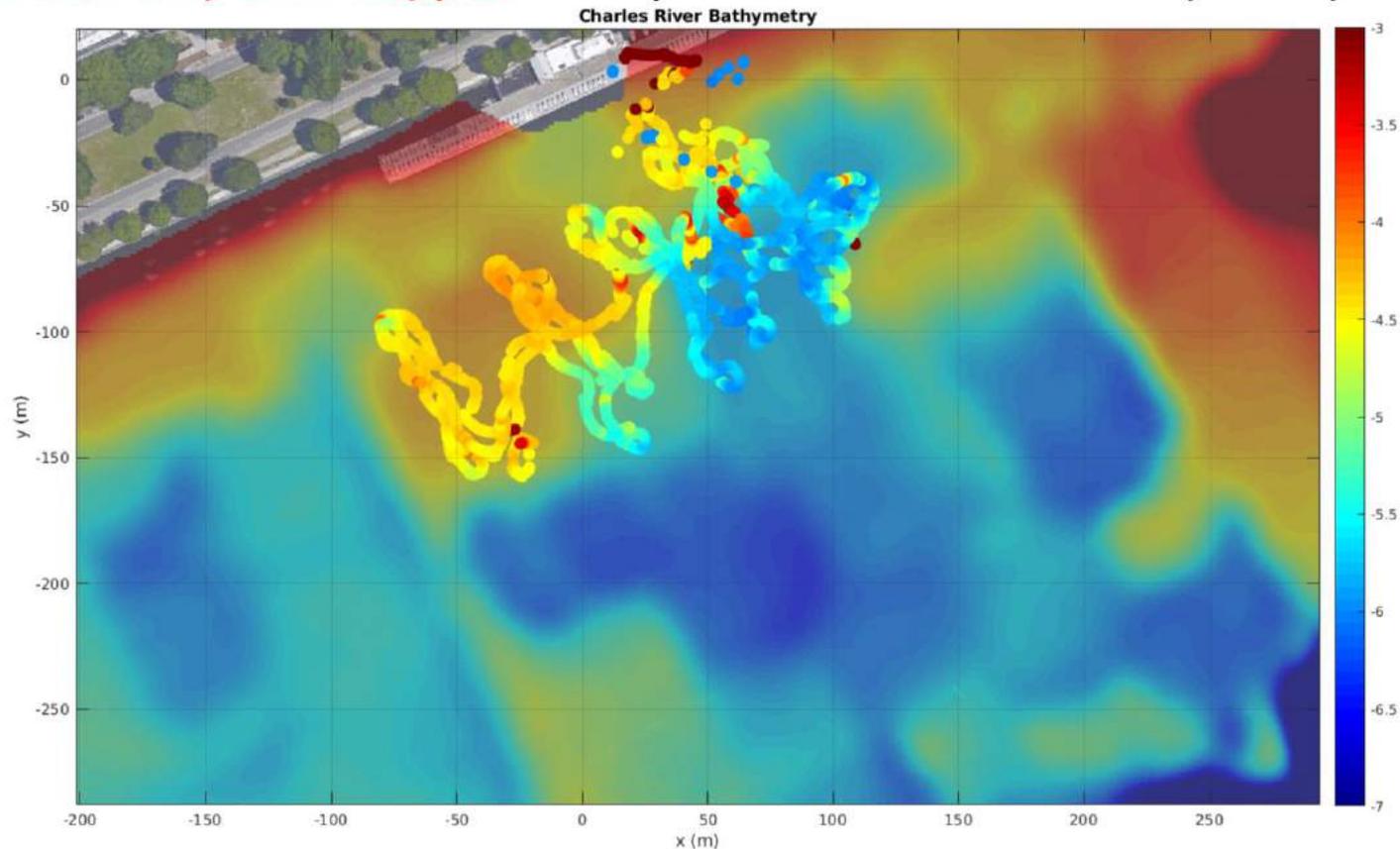
# Multi-AUV Proof-of-Concept Application

- As a *'proxy'* of spatiotemporal sampling (no CTD or other sensors)
- *Altimeter only on Platypus*, compare to SeaGrant Bathymetry



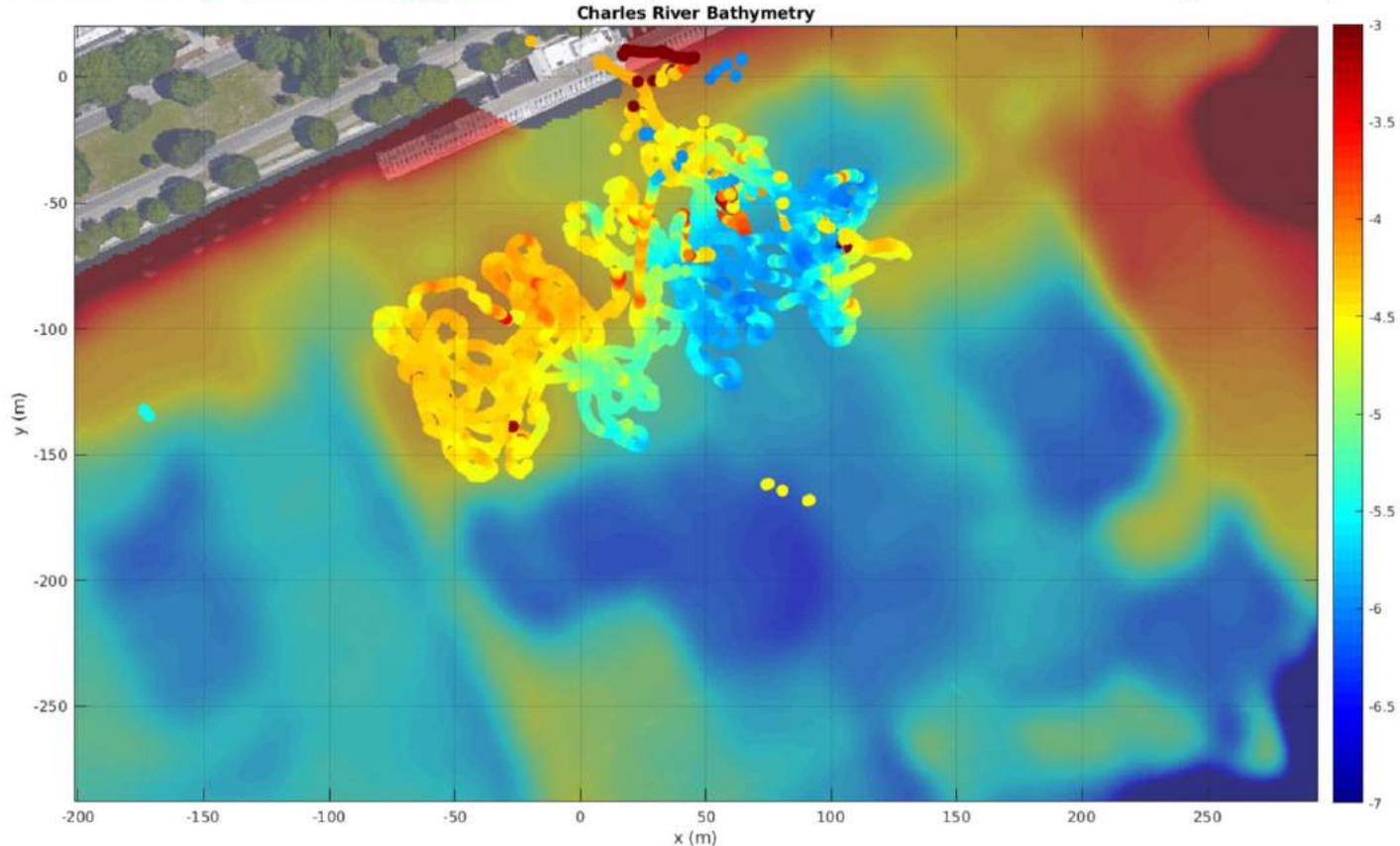
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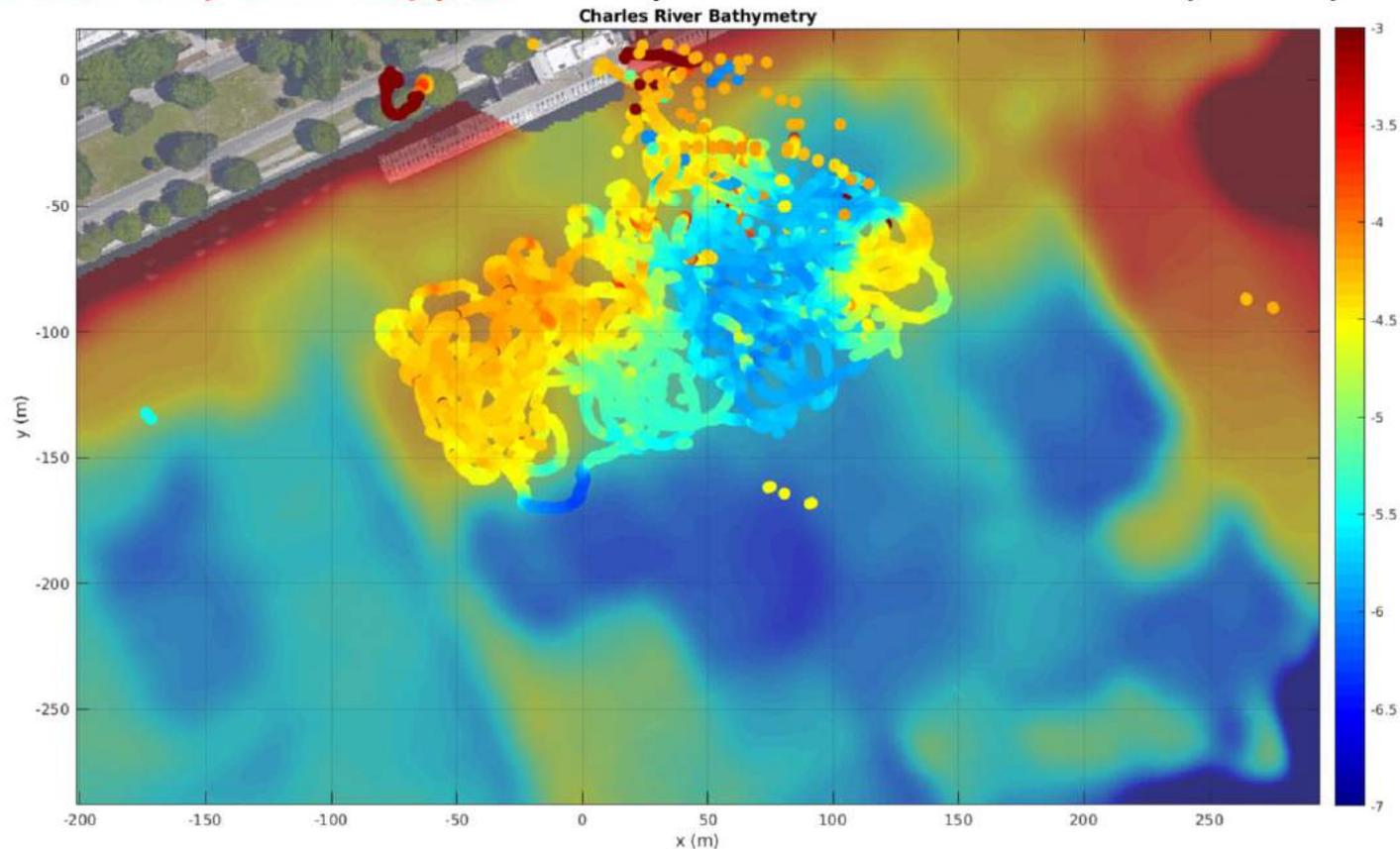
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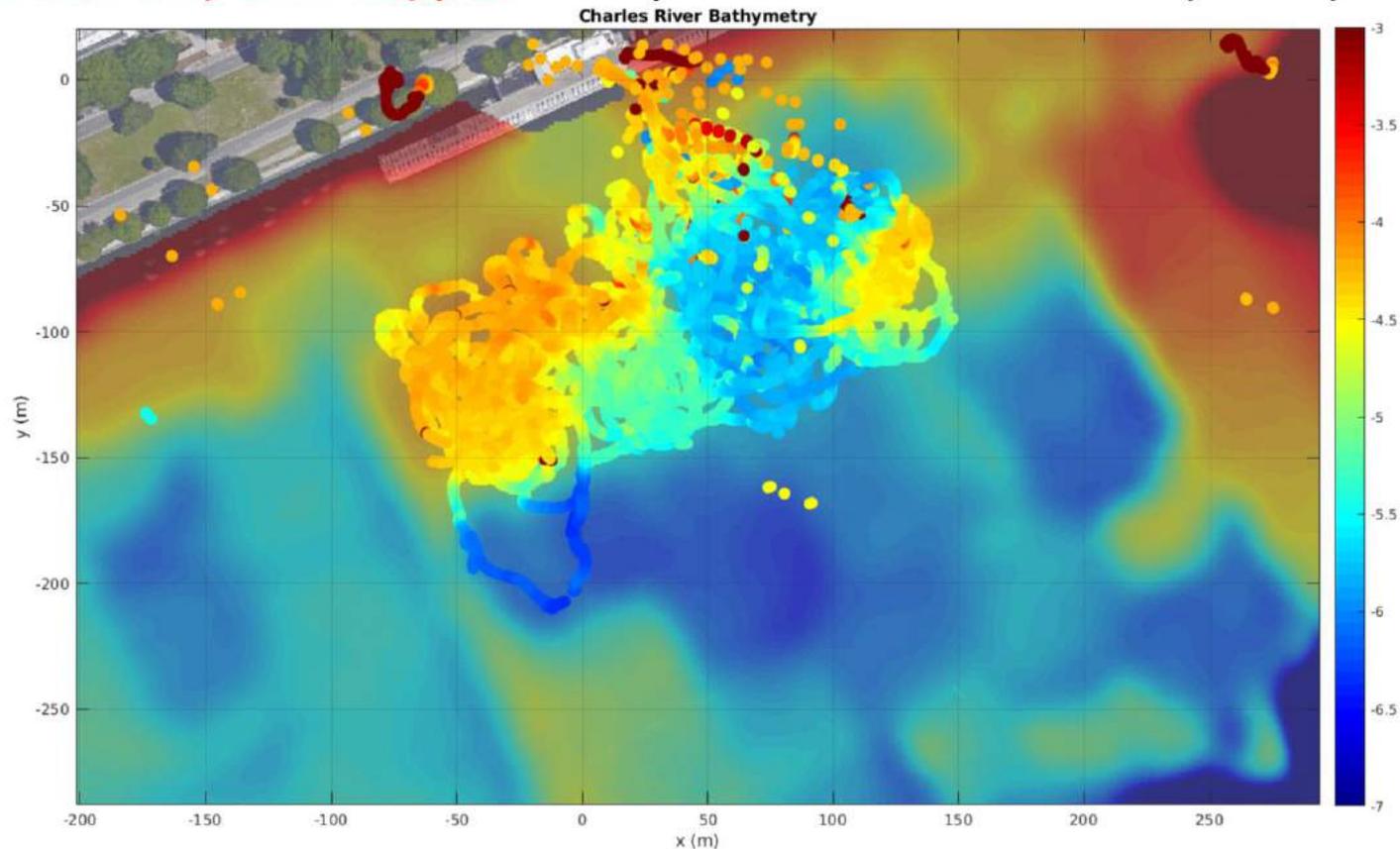
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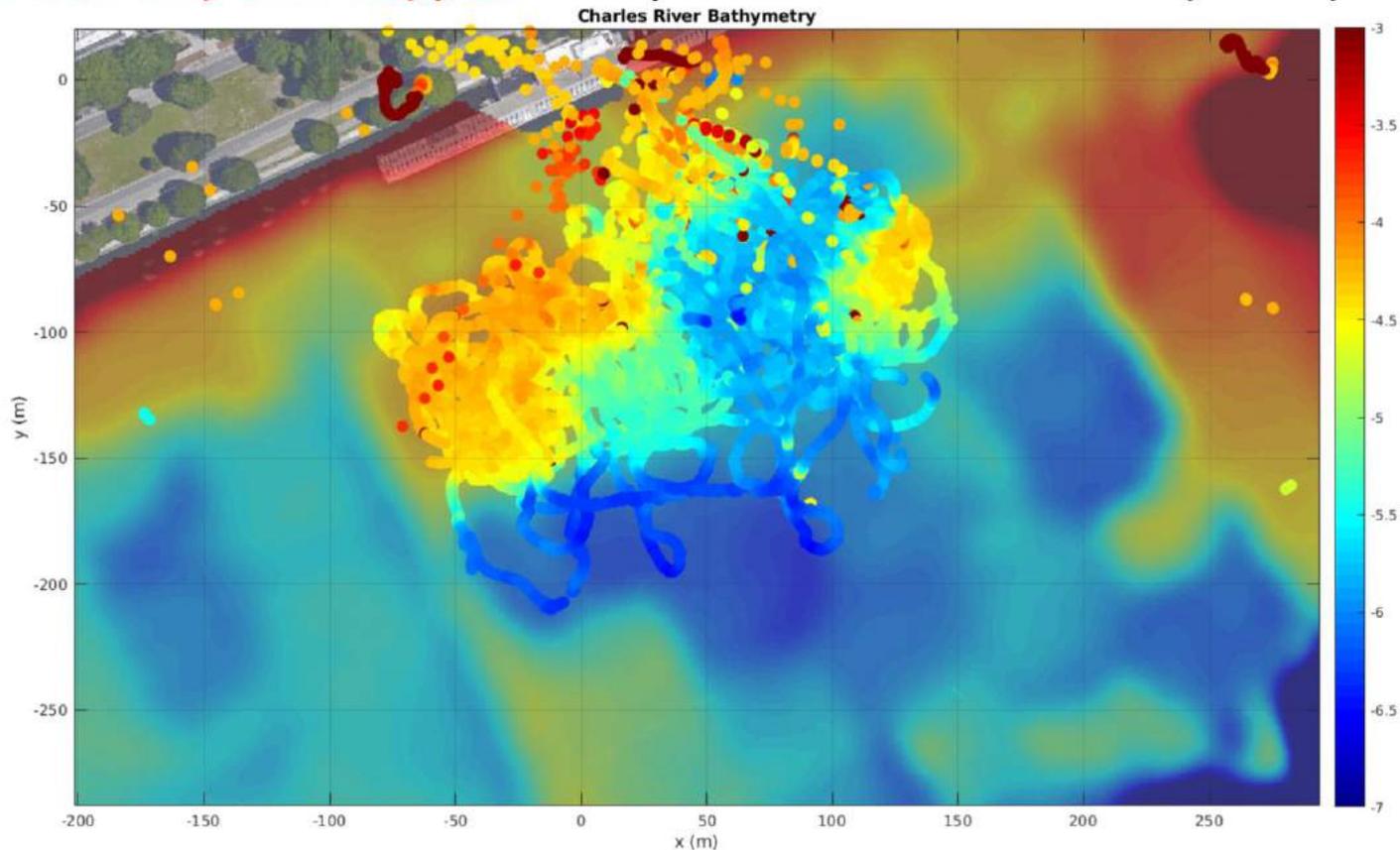
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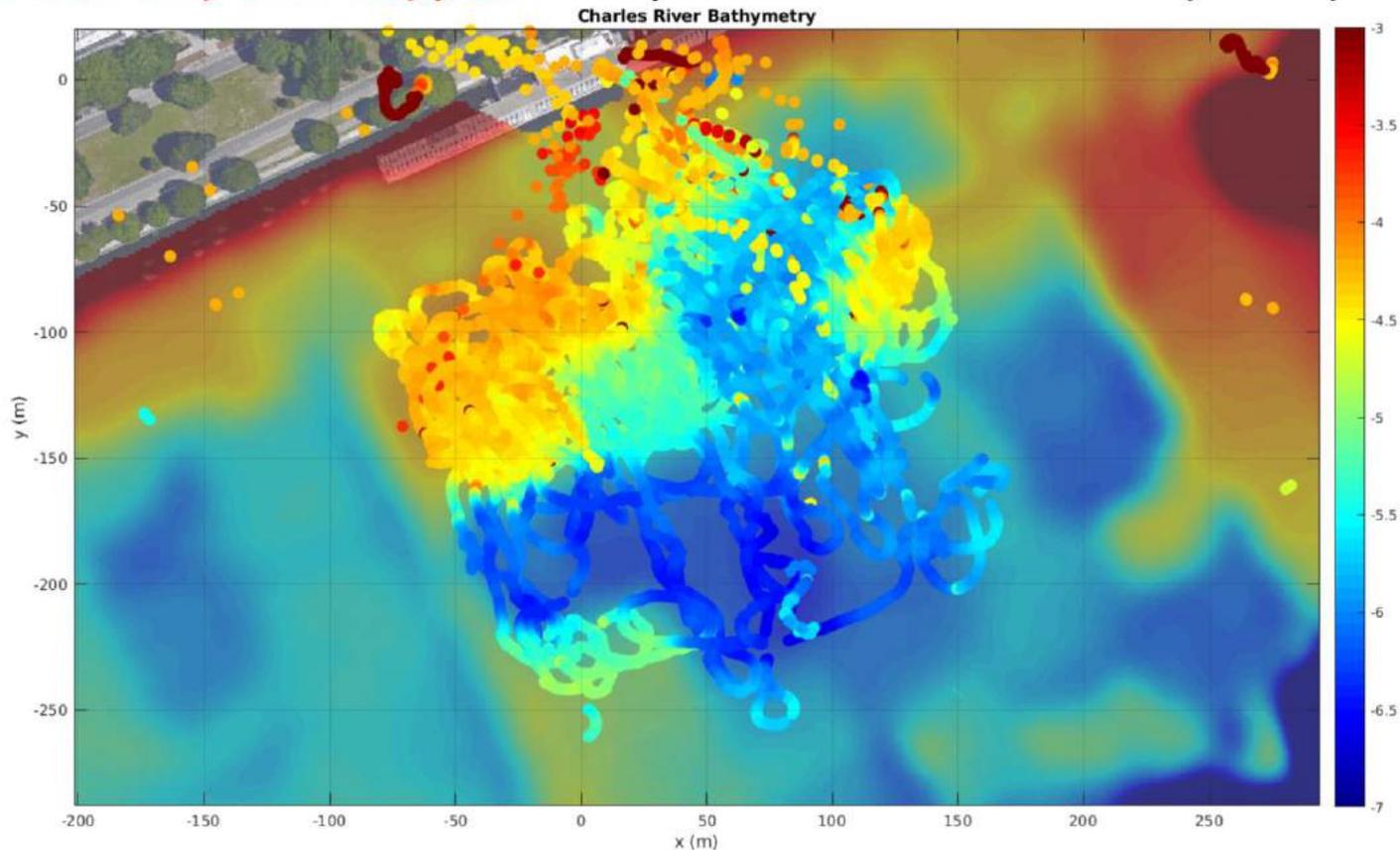
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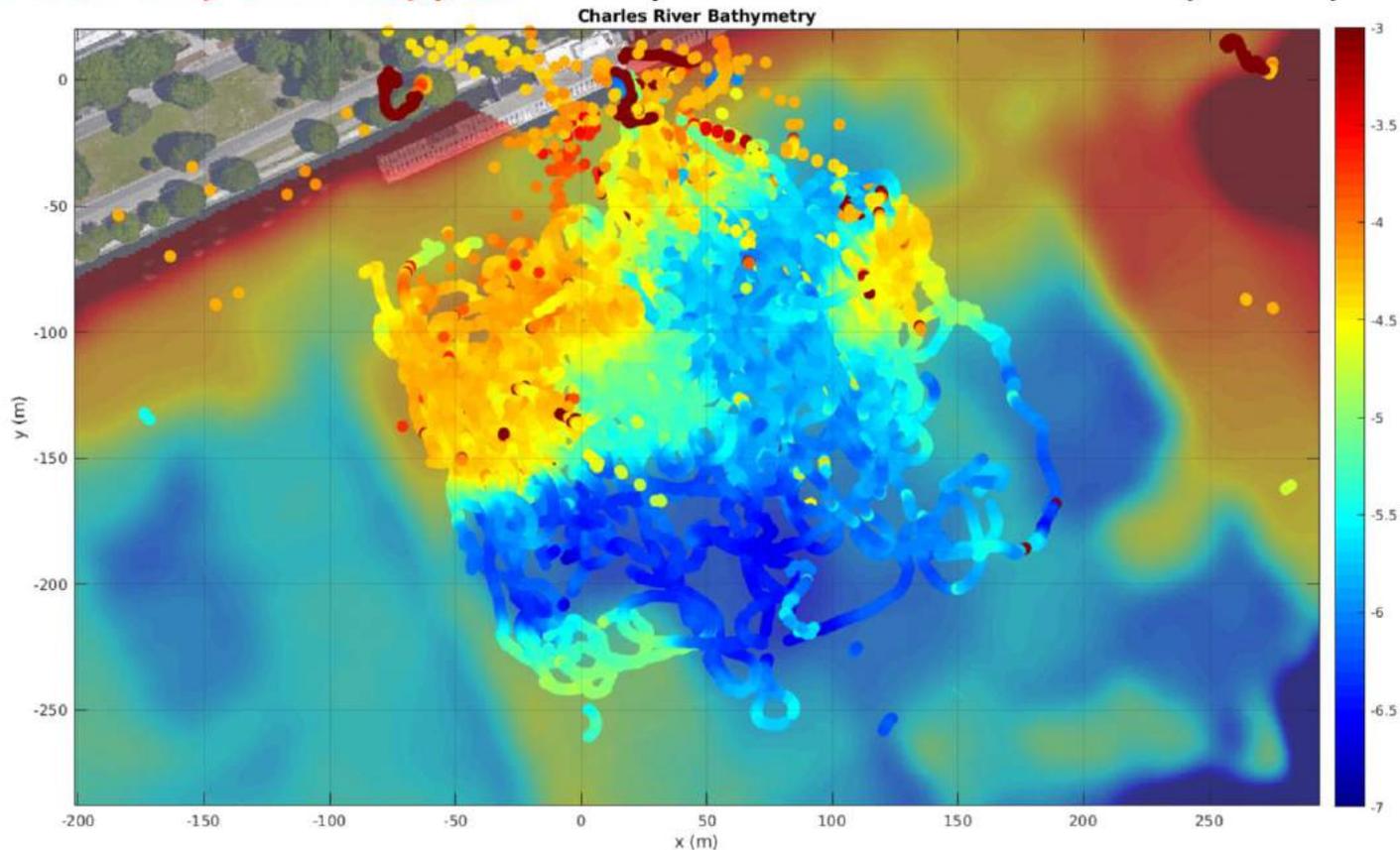
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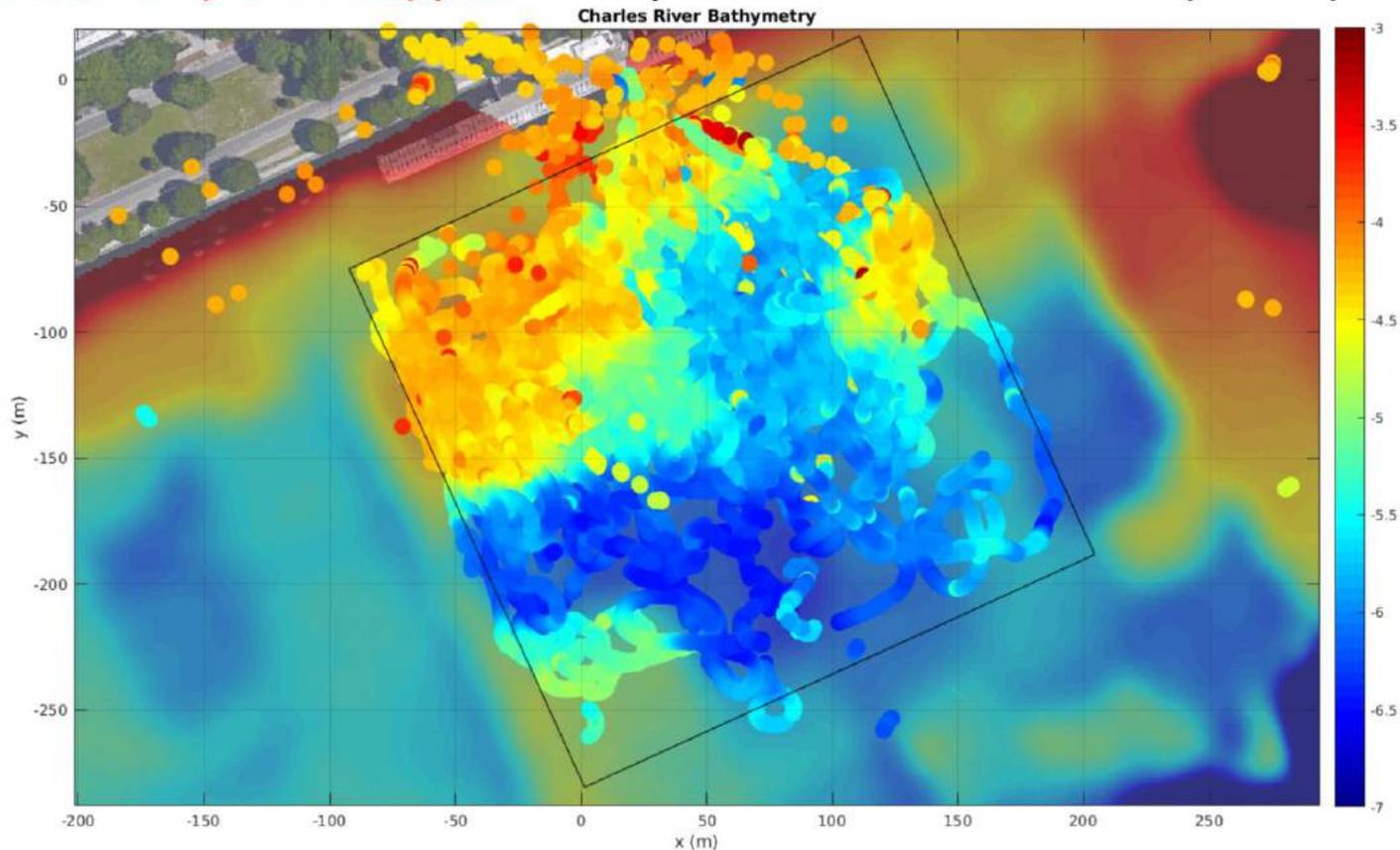
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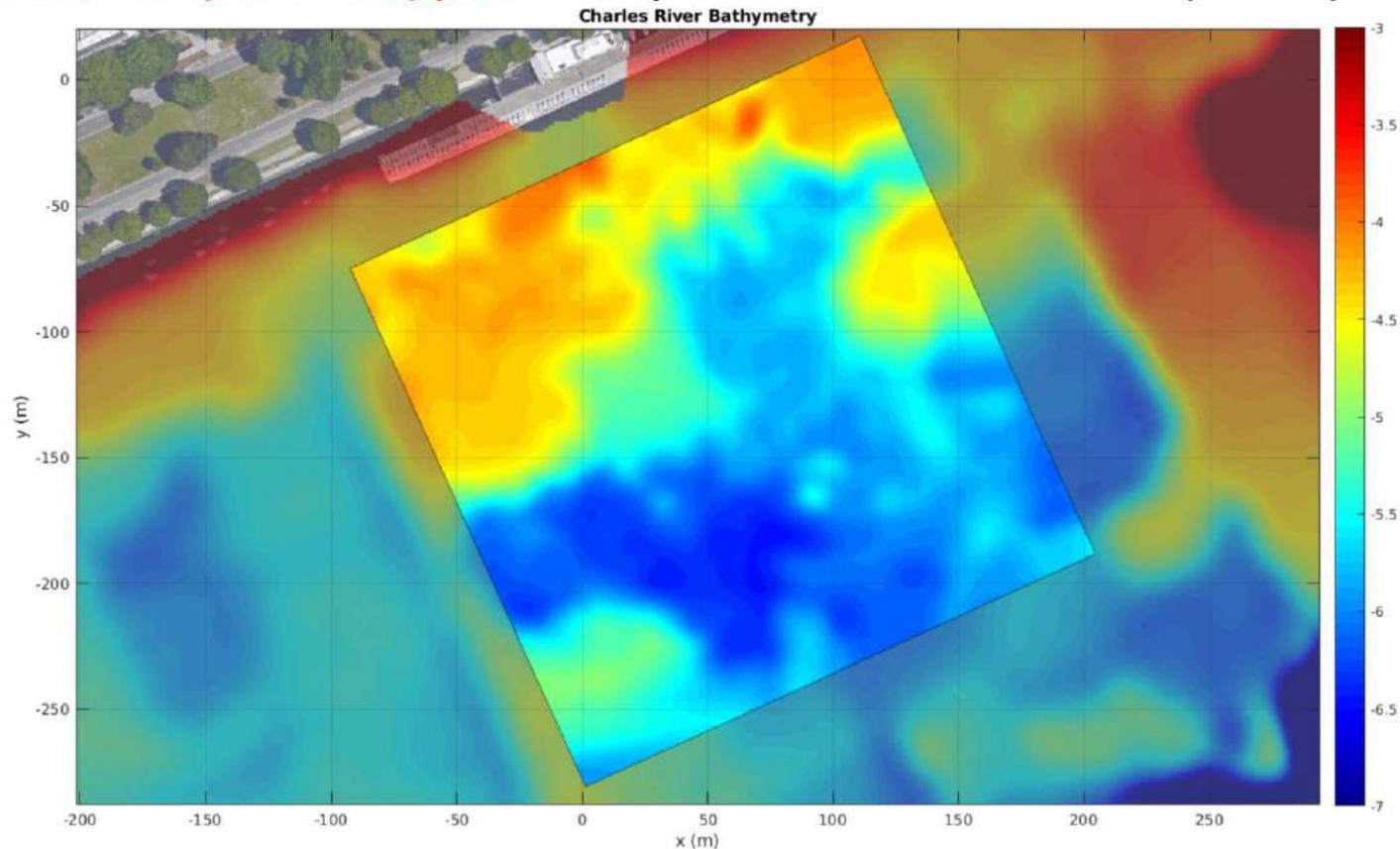
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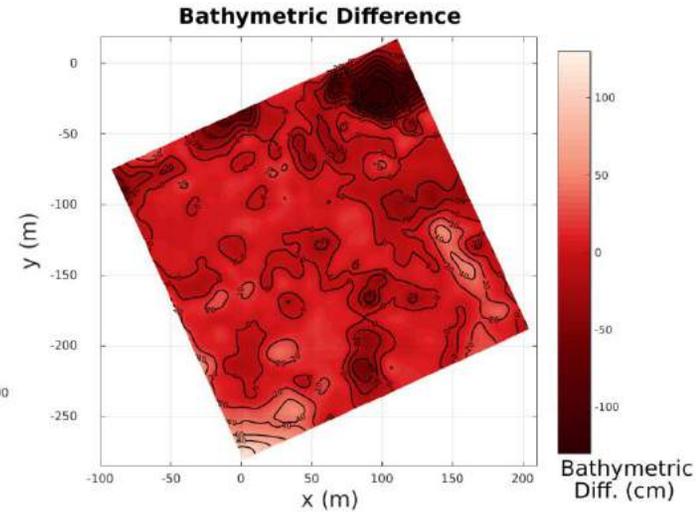
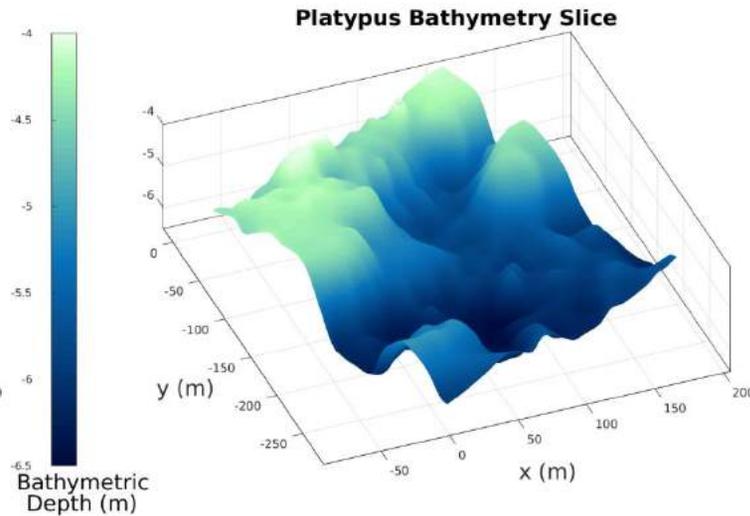
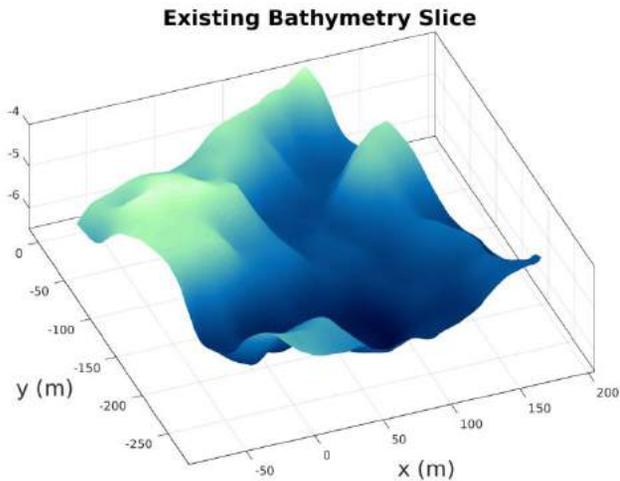
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# Multi-AUV Proof-of-Concept Application

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- *79% of bathymetric diff. < 20cm* and *95% of bathymetric diff. < 50cm*

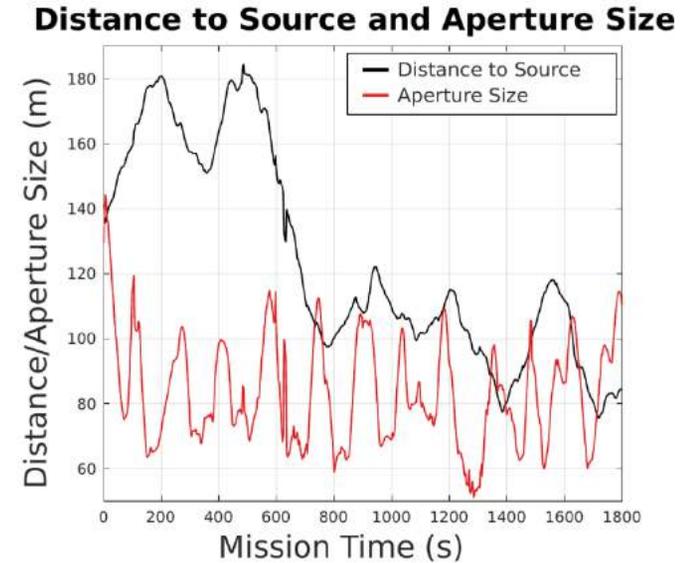
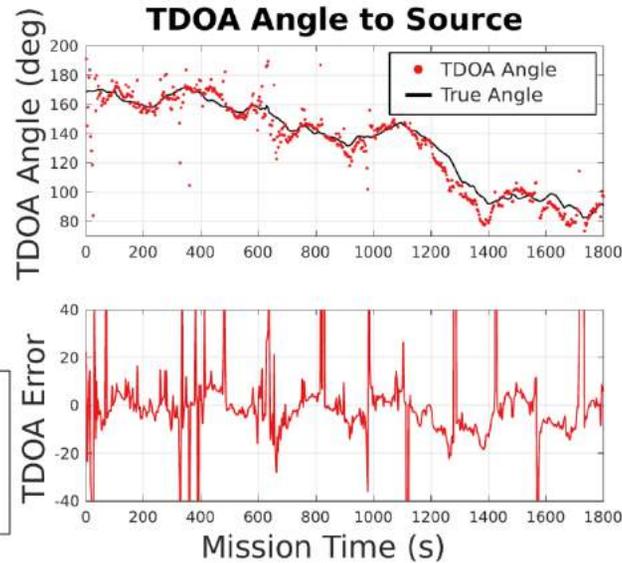
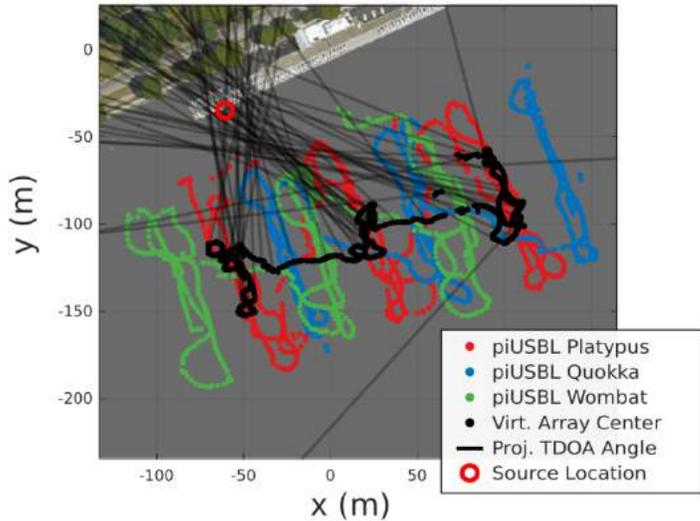




# Multi-AUV Proof-of-Concept Application

- Using three vehicles as *'virtual array'* to localize LBL beacon
- Coherent acoustic processing - TDOA angle estimation
- 'Array' geometry not ideal, *not in far-field*

### Coherent Fleet-Wide TDOA Source Localization



# Future Possibilities

- Fleet Tracking
  - Operator has no feedback on vehicle state
  - Vehicles must be trusted to operate correctly
  - Track vehicle fleet actively – array collocated with beacon

# Future Possibilities

- Fleet Use and Expansion
  - CTDs being integrated – measure spatiotemporal ocean phenomena
  - Formation control and 'virtual' acoustic arrays
  - Operational details – deployment, retrieval, data management
  - Using a 'leader' AUV as a beacon, or an ASV
  - Implementation on gliders, low-cost ROVs
  - Time synchronization without a CSAC – estimate drift
  - Post-processing of fleet trajectories using nonlinear optimization

# Contributions

- Acoustic navigation system suitable for low-cost underwater robots
- Multi-AUV operational paradigm that is user friendly
- Extensive experimental demonstrations of multi-AUV operations

Questions?