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Next-Generation Acoustic Transmitter Development for Fish Passage Monitoring

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Pacific Northwest National Laboratory

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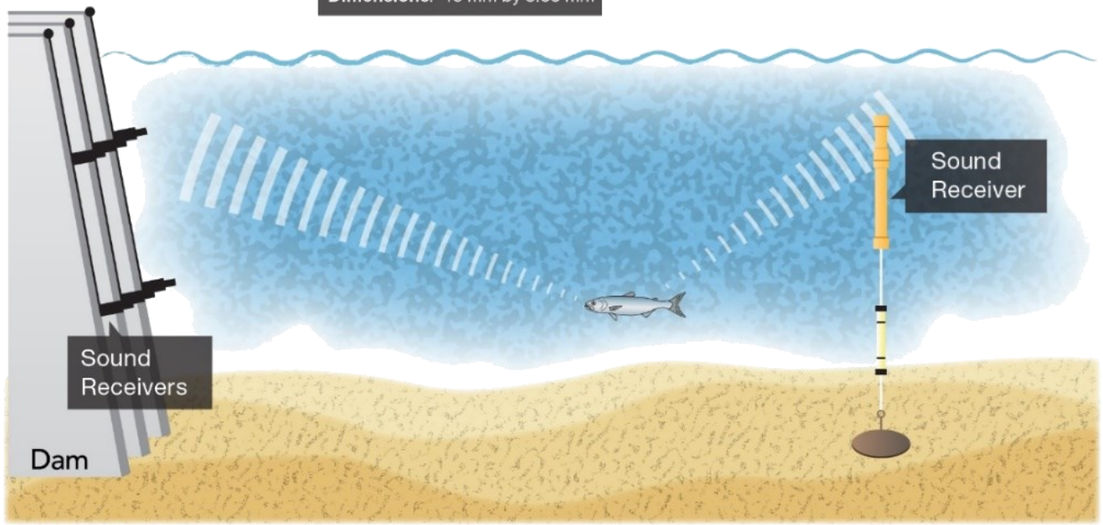
2023 Anadromous Fish Evaluation Program Annual Review

Acoustic Telemetry Technology for Studying Behavior and Survival of Aquatic Animals

- Sound source
- Receivers
- Encoding strategies
  - amplitude
  - frequency
  - phase of individual pulses
  - time between pulses
- Key Challenges
  - Nonlinear equations
  - ~100% detection efficiency
  - ~0% false positive rate
  - Complex environment



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$Time\ of\ Arrival$:

$$C \times t_i = [(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2]^{\frac{1}{2}}$$

$Time\ difference\ of\ arrival$:

$$C \times \Delta t_{ij} = [(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2]^{\frac{1}{2}} - [(x - x_j)^2 + (y - y_j)^2 + (z - z_j)^2]^{\frac{1}{2}}$$

$$i, j = 1, \ldots, N$$

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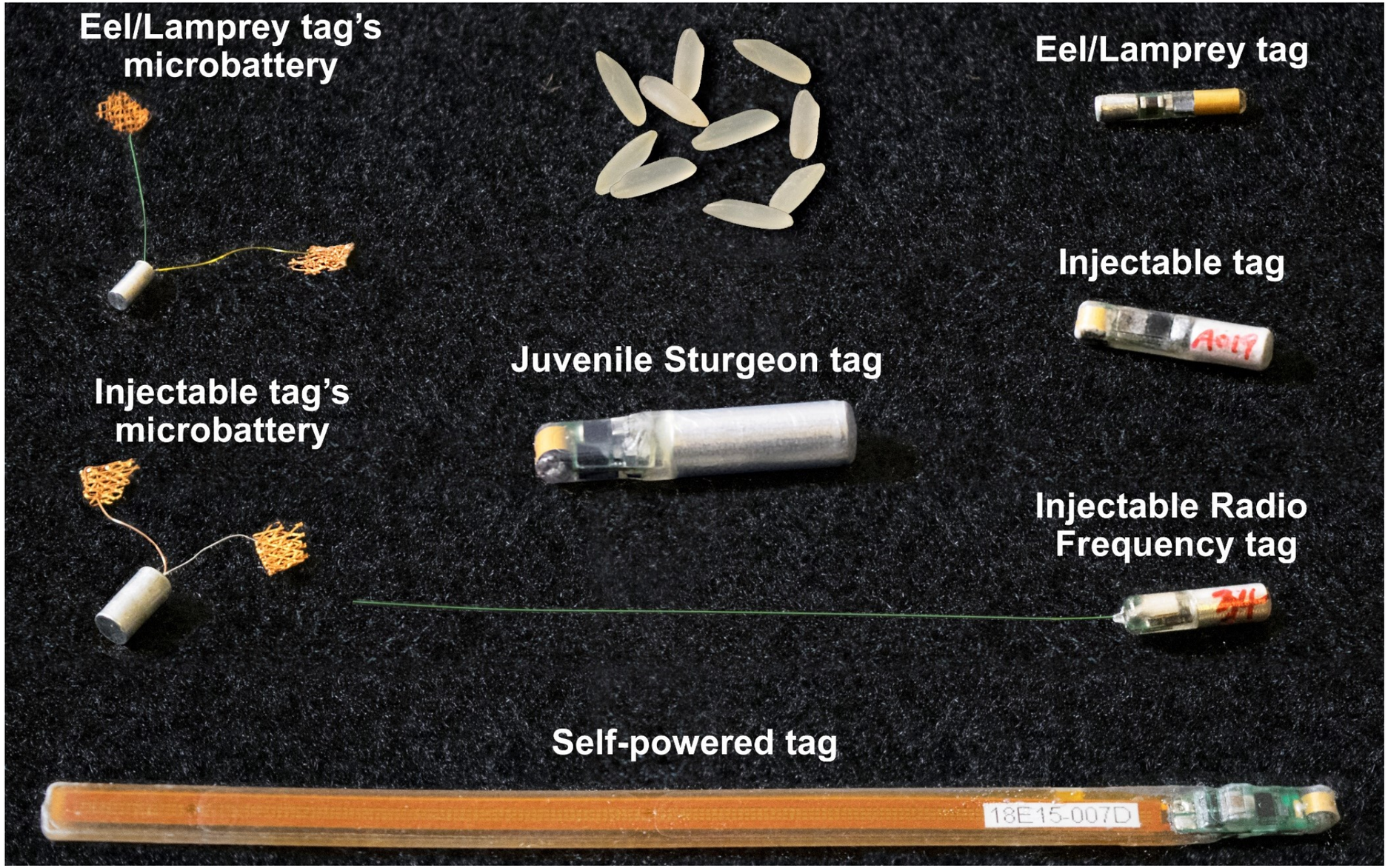
New Trends for Telemetry and Sensing

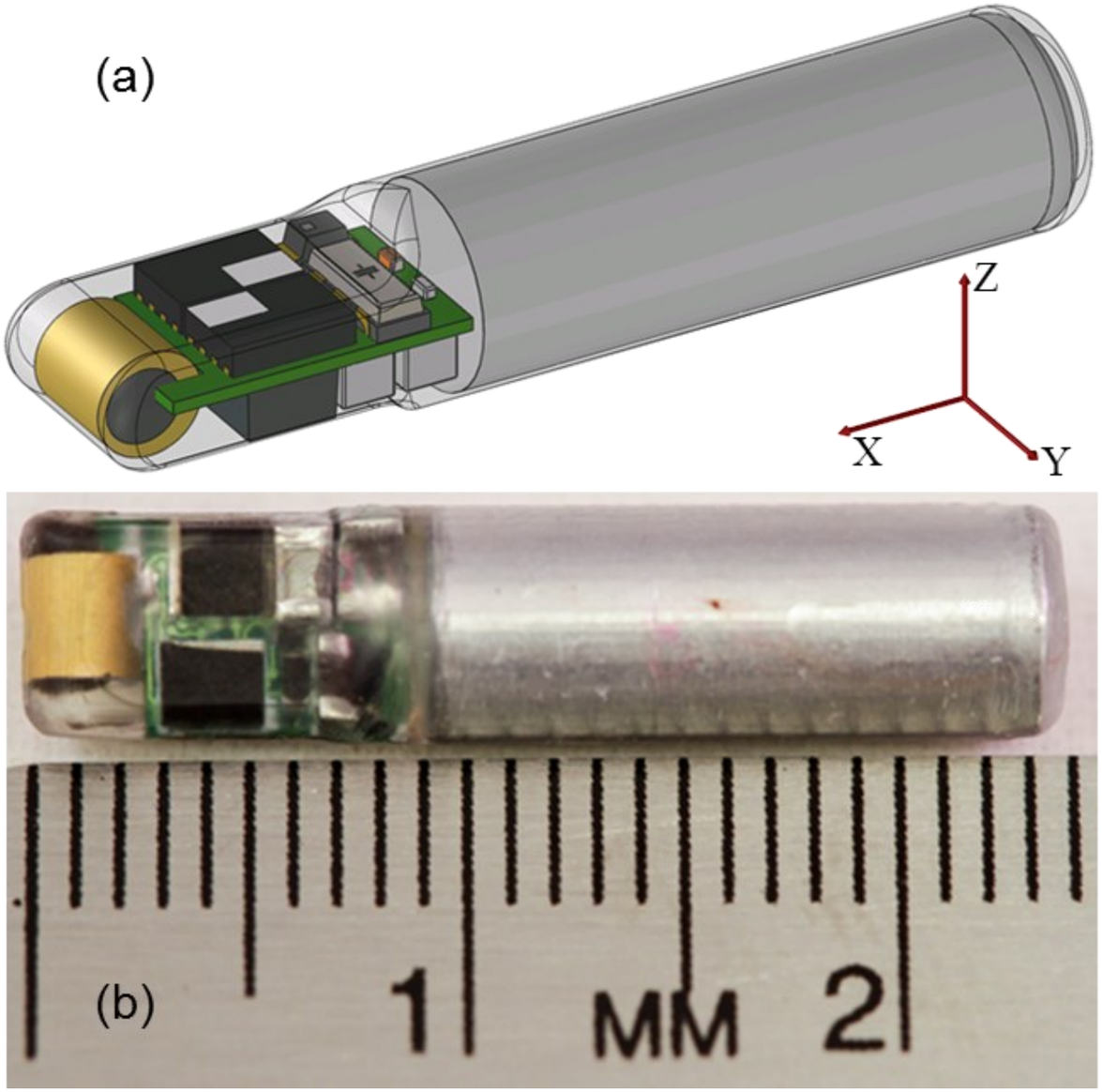
- Smaller and lighter transmitter
- More powerful transmitter in detection range
- Long-lasting transmitter including energy-harvesting sensing platform
- Multi-parameter (environmental, physiological, and location) sensing including bio-logging
- Flexible or stretchable: Emerging flexible and stretchable electronics will accelerate the development of novel flexible or stretchable sensors for bio-integrated applications
- Cloud-based and real-time system to estimate behavior or survival of aquatic animals
- Machine learning to improve 3D tracking accuracy and large data processing
- Sensing in extreme/challenging environments

Suite of Acoustic and Radio-Frequency Transmitters



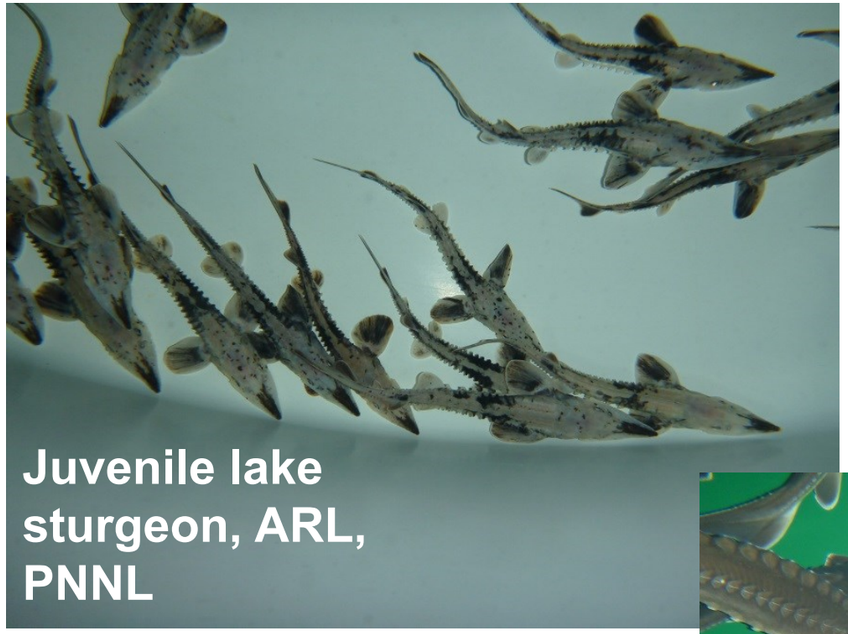
Long-term Juvenile Sturgeon Tag Specifications

- Dimension: 24.2 mm x 5.0 mm
- Dry Mass: 0.7 g
- Wet Mass: 0.2 g
- Source Level:
  - 161 or 163 dB at zero deg
- Configurable pulse rate interval & tag code
- Optional temperature, alternating tag code, and hibernation mode
- Tag Life: 365 days at 161 dB and 15-s pulse rate interval



Sturgeon Tag Applications

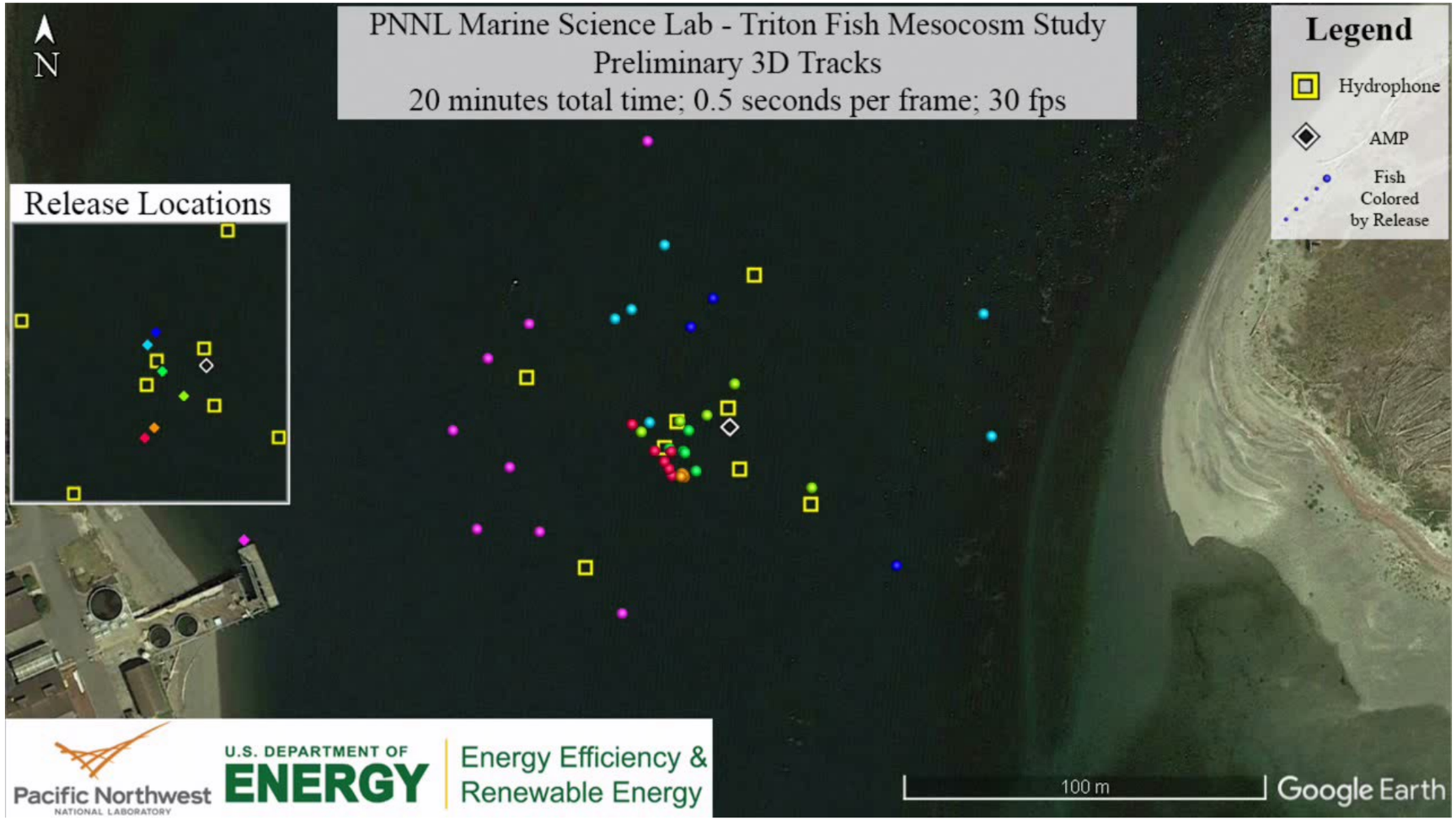
- Small juvenile (< 1 year old) sturgeon
- Long term monitoring for adult fish such as adult eel and lamprey
- Noisy environment such as immediate tailrace due to higher source level
- Mobile tracking due to longer detection range
- Marine environment



Juvenile lake sturgeon, ARL, PNNL

Juvenile white sturgeon, ARL, PNNL

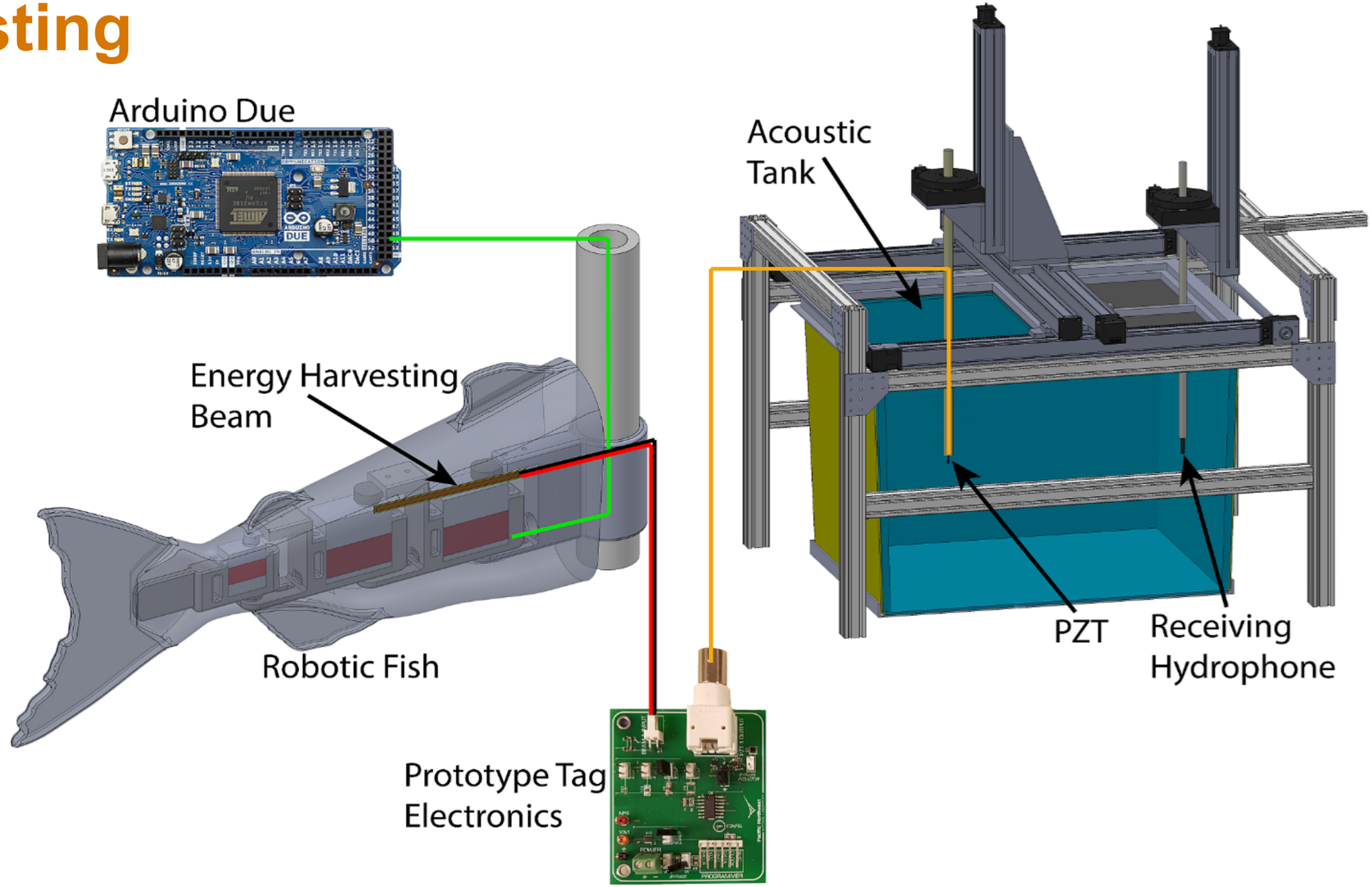
Application of Sturgeon Tag: Triton Fish Mesocosm Study in Sequim Bay*



Animation also available at: https://youtu.be/gQ4ydPwhY0g

*Staines et al. 2019. "Using acoustic telemetry for high resolution sablefish movement informing potential interactions with a tidal turbine." In Proceedings of OCEANS 2019 Seattle.

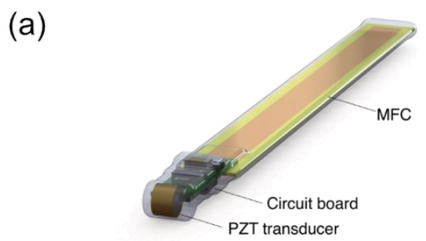
Self-powered Acoustic Transmitter: Benchtop Testing

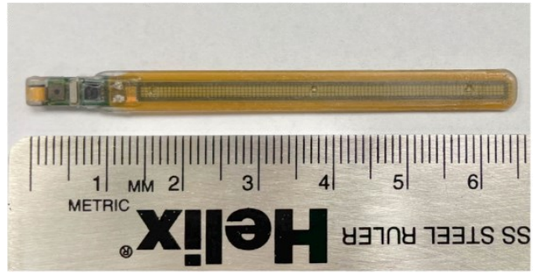


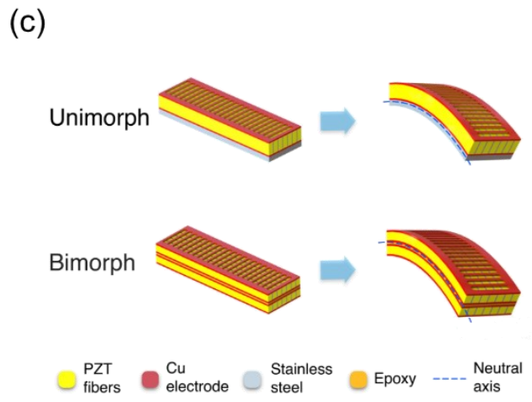
- Li H, C Tian, and ZD Deng*. 2014. "Energy Harvesting From Low Frequency Applications Using Piezoelectric Materials." Applied Physics Reviews 1(4):041301.
- Li H., J. Lu, M.J. Myjak, S.A. Liss, R.S. Brown, C. Tian, and Z. Deng*. 2022. "An Implantable Biomechanical Energy Harvester for Animal Monitoring Devices". Nano Energy. 98:107290

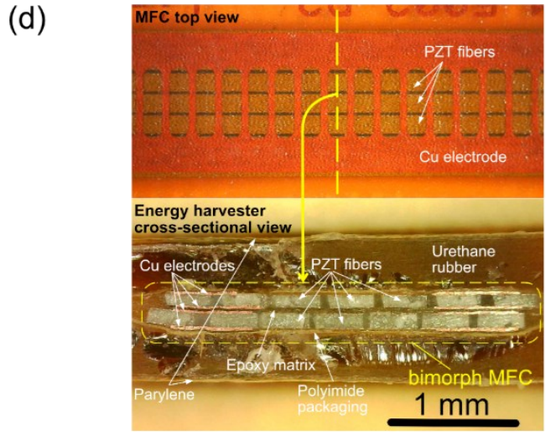
Self-powered Acoustic Transmitter

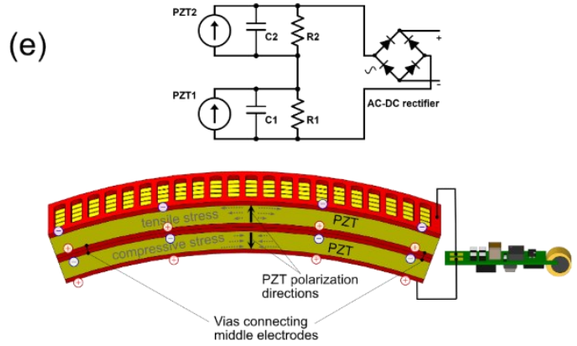
- Design 1: Without battery, 0.80 g,
- Design 2: With battery, 0.85 g
- Transmitter lengths can be customized based on power requirements and fish characteristics of specific applications.

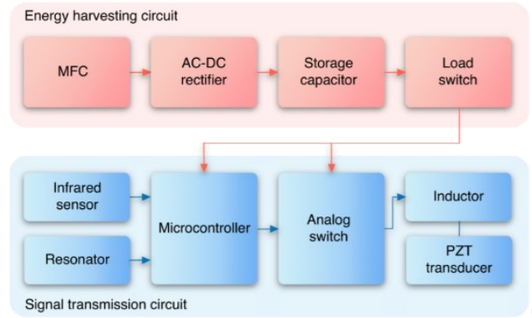








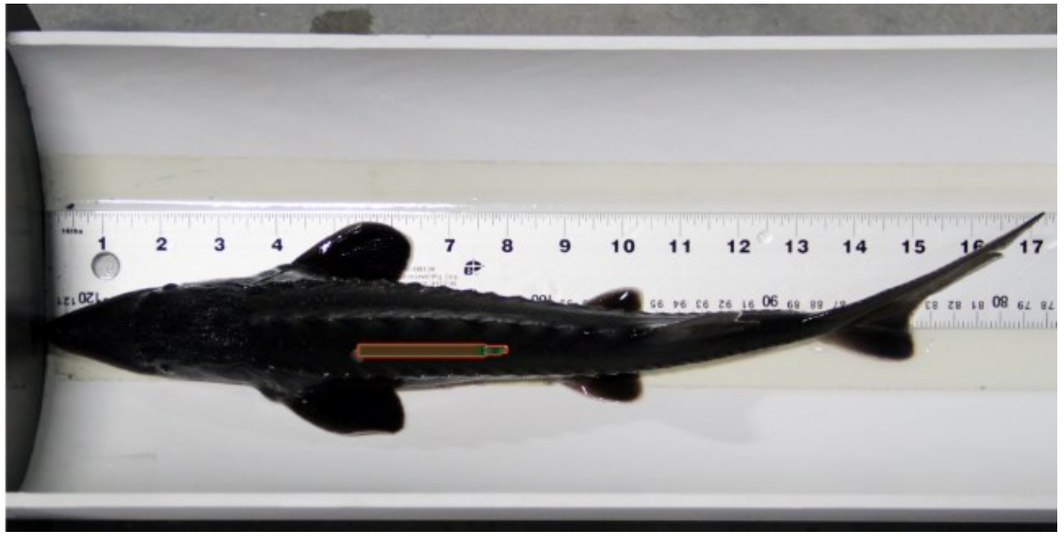




An Implantable Biomechanical Energy Harvester for Animal Monitoring Devices. Nano Energy. 2022. 98:107290

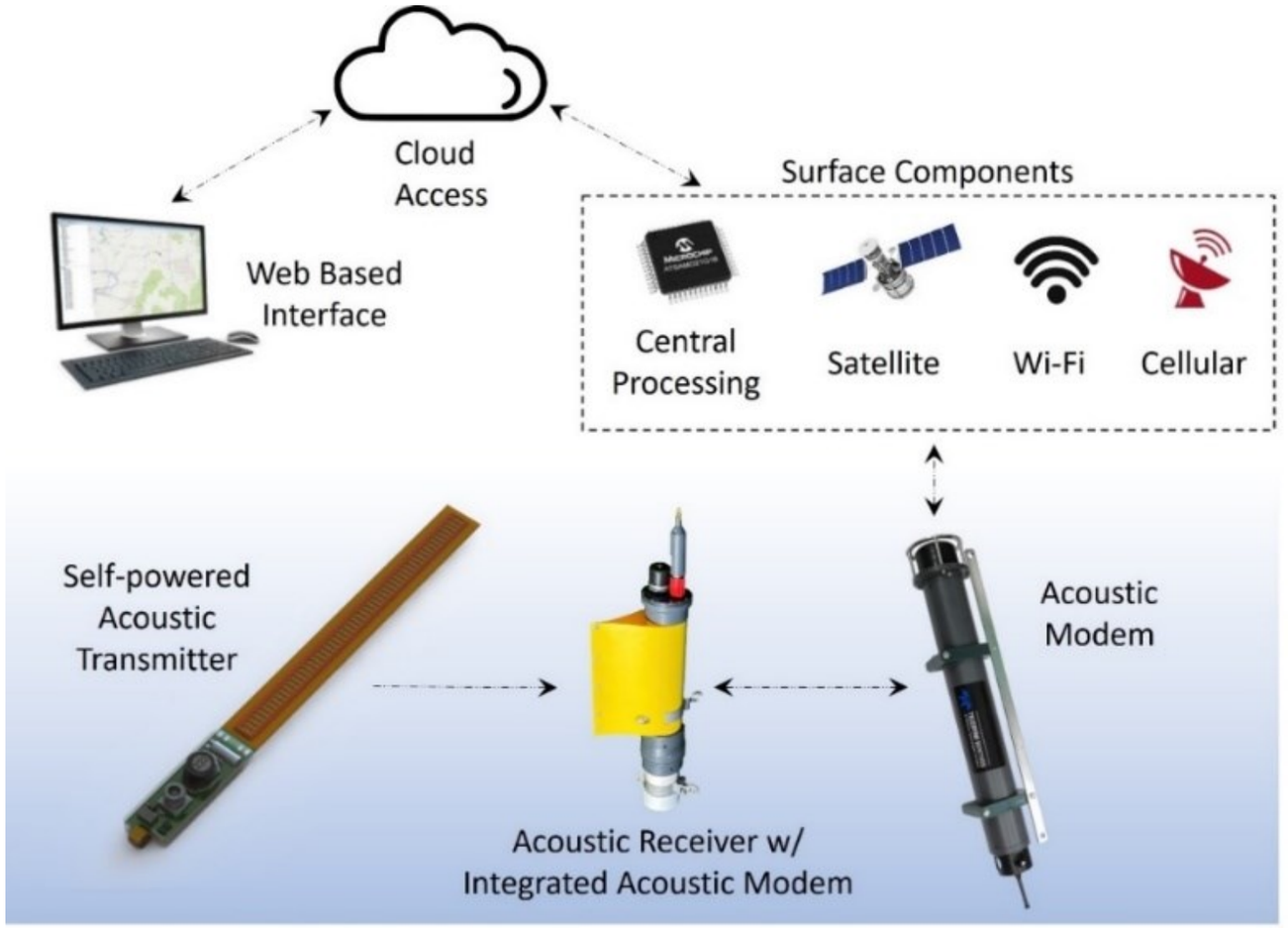
Self-powered Acoustic Transmitter: Live Fish Experiments

- A 100-mm tag was used for 53-cm-long rainbow trout
- A 77-mm tag was used 38-cm-long juvenile white sturgeon
- Implanted on the back of the fish near the dorsal fin
- 6-mm incision was first made with a scalpel that only cut barely beneath the skin
- The implantation process took ~75 seconds



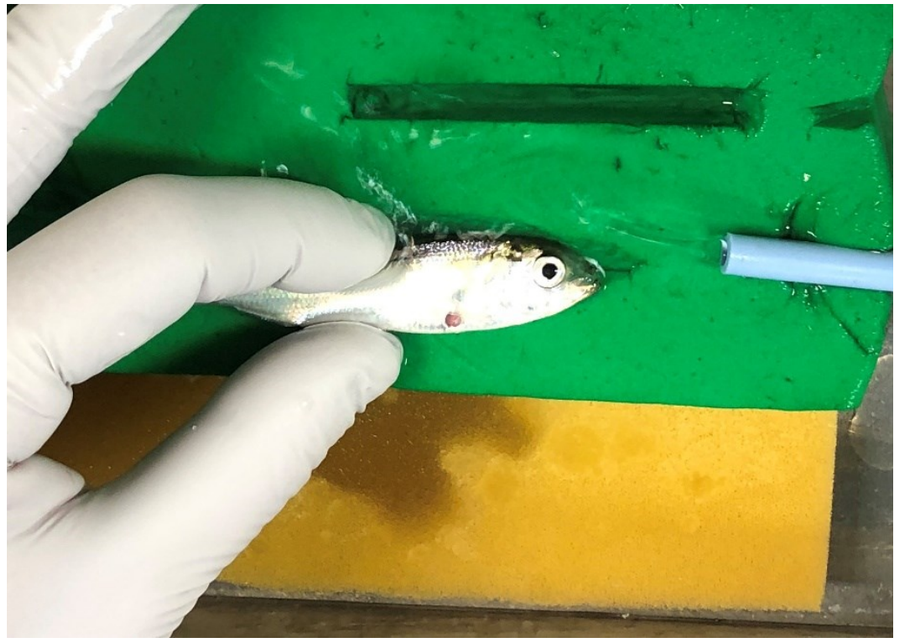
New Project Objectives

- Develop a self-powered, modular acoustic telemetry system, consisting of an energy harvesting unit, an acoustic transmitter, a sensing unit with edge computing, an energy storage solution (a rechargeable microbattery or a super capacitor), a receiving unit, and a cloud-based control and data visualization interface, for long-term monitoring of long-living species over long range and duration.
- Initial target species: American eel and white sturgeon



American Shad Acoustic Transmitter

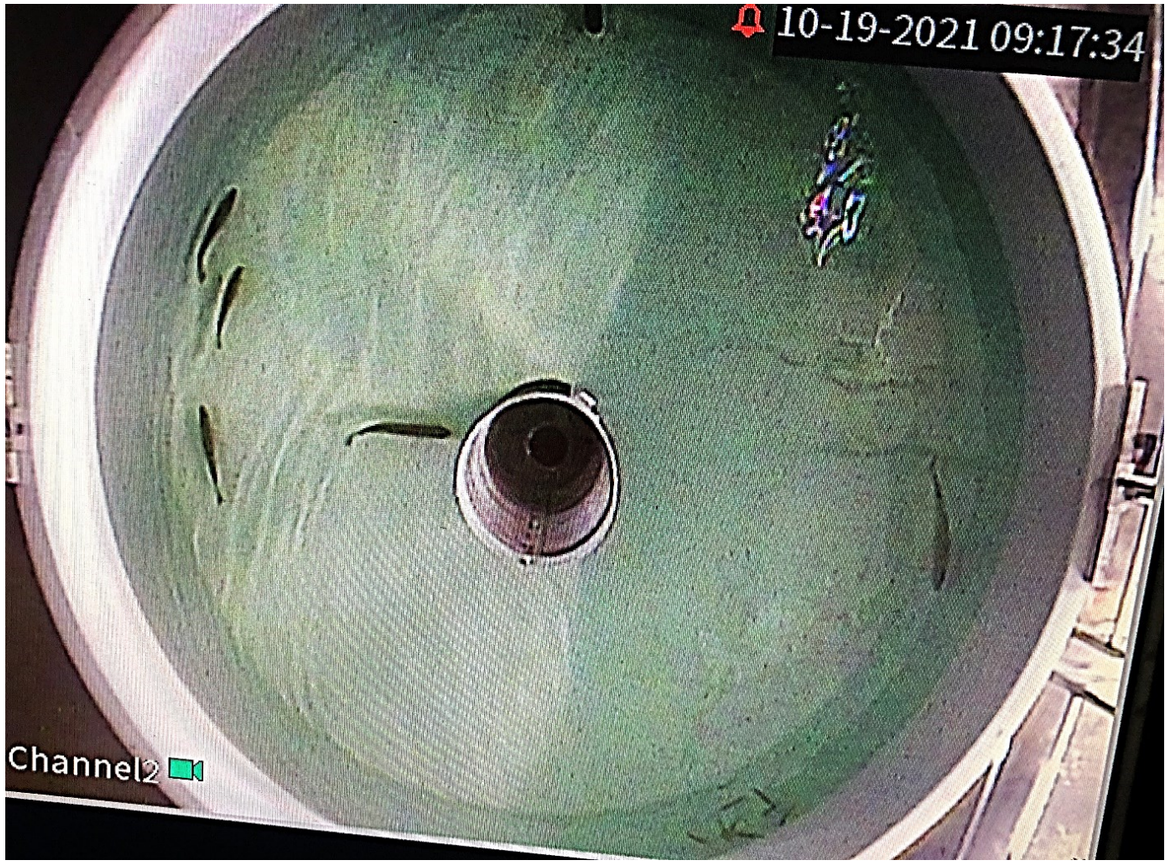
- Dimension: 7.6 mm x 2.0 mm
- Mass: 0.05 g
- Source Level: 144 dB
- Configurable pulse rate interval & tag code
- Optional temperature, alternating code, and hibernation mode
- Tag life: 30 days at 5-s pulse rate interval
- Demonstrated feasibility in lab



American Shad Acoustic Transmitter: Predator Testing – Fall 2021

- Largemouth Bass - 10 per tank (~21cm long)
- Shad - 10 control + 10 tagged
- Goal - end at ~50% consumption
- Survival = Not eaten + not wounded

- 9 trials
  - Tagged 55-100mm (avg 80mm)
  - Control 56-97mm (avg 79mm)
  - Trial duration 3min – 2hr 6min (median 7min 39s)
  - 171 shad tested – 114 eaten, 11 wounded, 3 killed, 43 survived.
  - 23 controls and 20 tagged survived



***No difference in survival by treatment

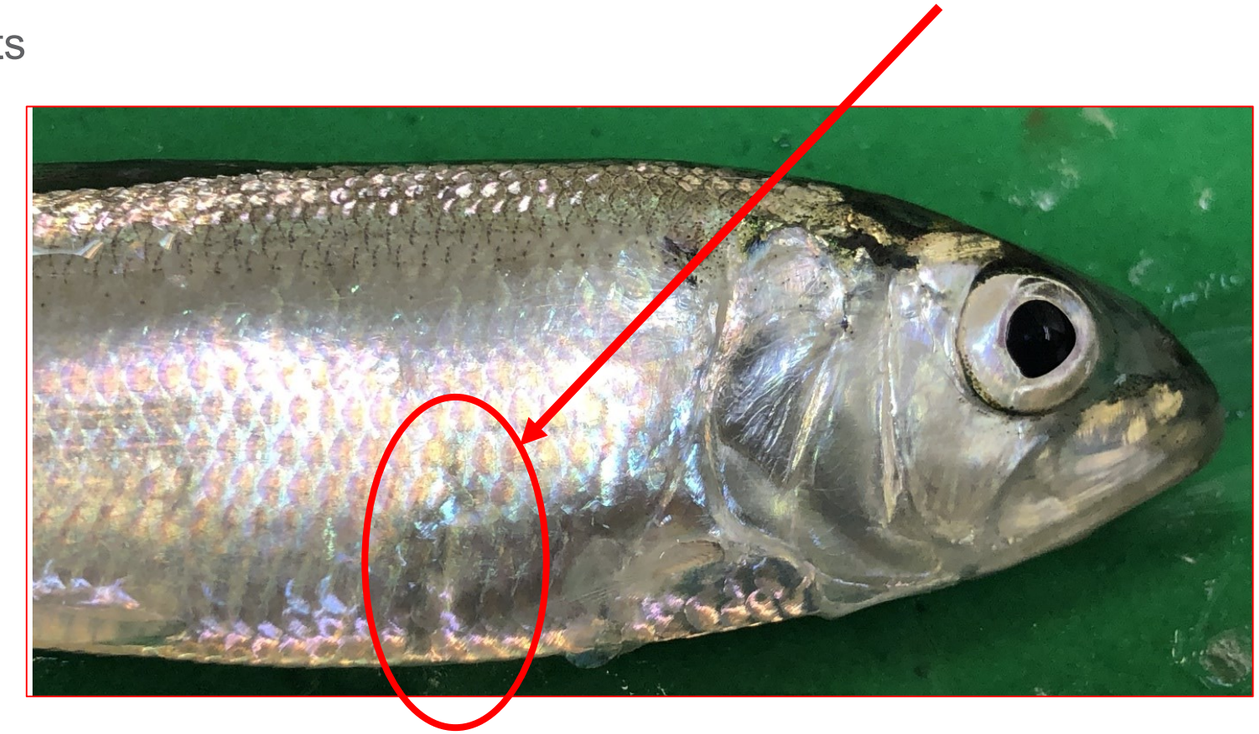
***Larger fish were more susceptible to predation

American Shad Acoustic Transmitter: 60d Holding - 2022

- Jan 2022 – used remaining shad (transported Sept 2021)
  - 54 tagged – 69-105mm (avg 89mm)
  - 19 control – 82-100mm (avg 91mm)
    - ✓ 2 tanks; controls help identify tank effects

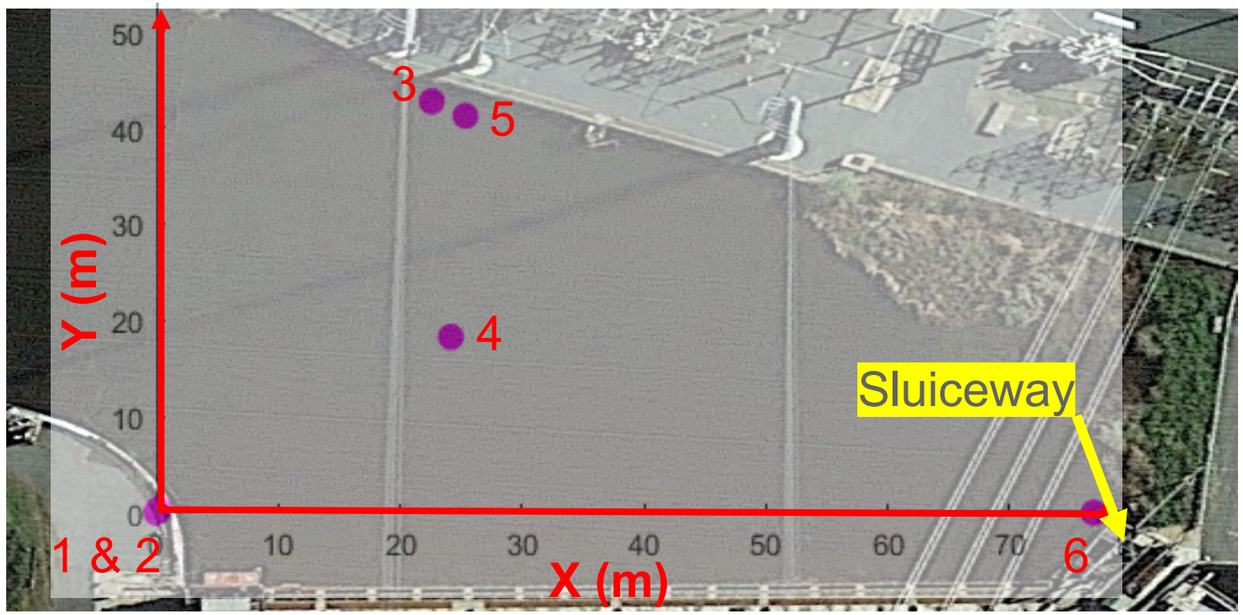
- Tank effect
  - 20% mortality by day 6 for Tank A
  - 20% mortality by day 34 for Tank B

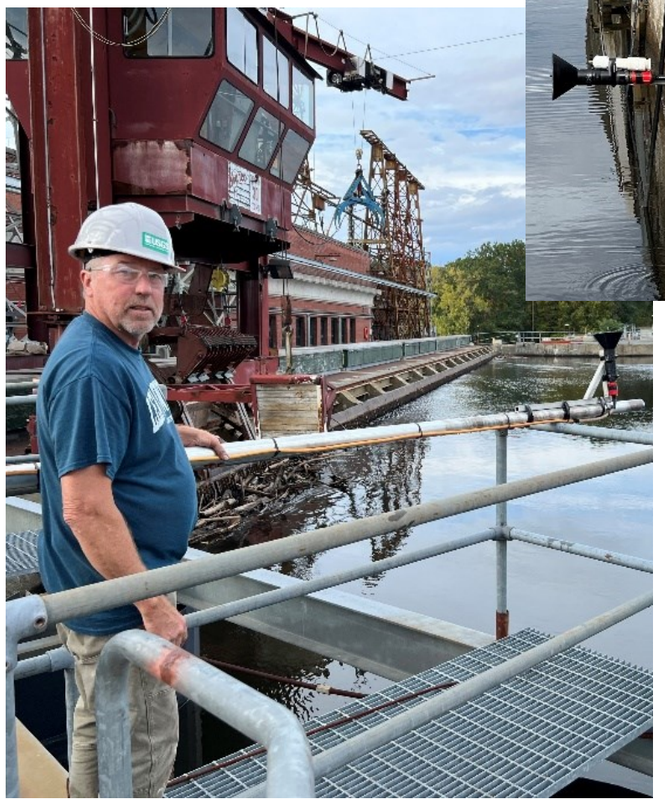
- Tank B 60d survival
  - 81.5% tagged (avg. growth 10mm)
  - 70% control



American Shad Acoustic Transmitter: Pilot Demonstration at Cabot Station

- Objective is for technology demonstration
- Collaborative effort
  - FirstLight Power Resources
  - Kleinschmidt Group
  - University of Connecticut
  - United States Geological Survey



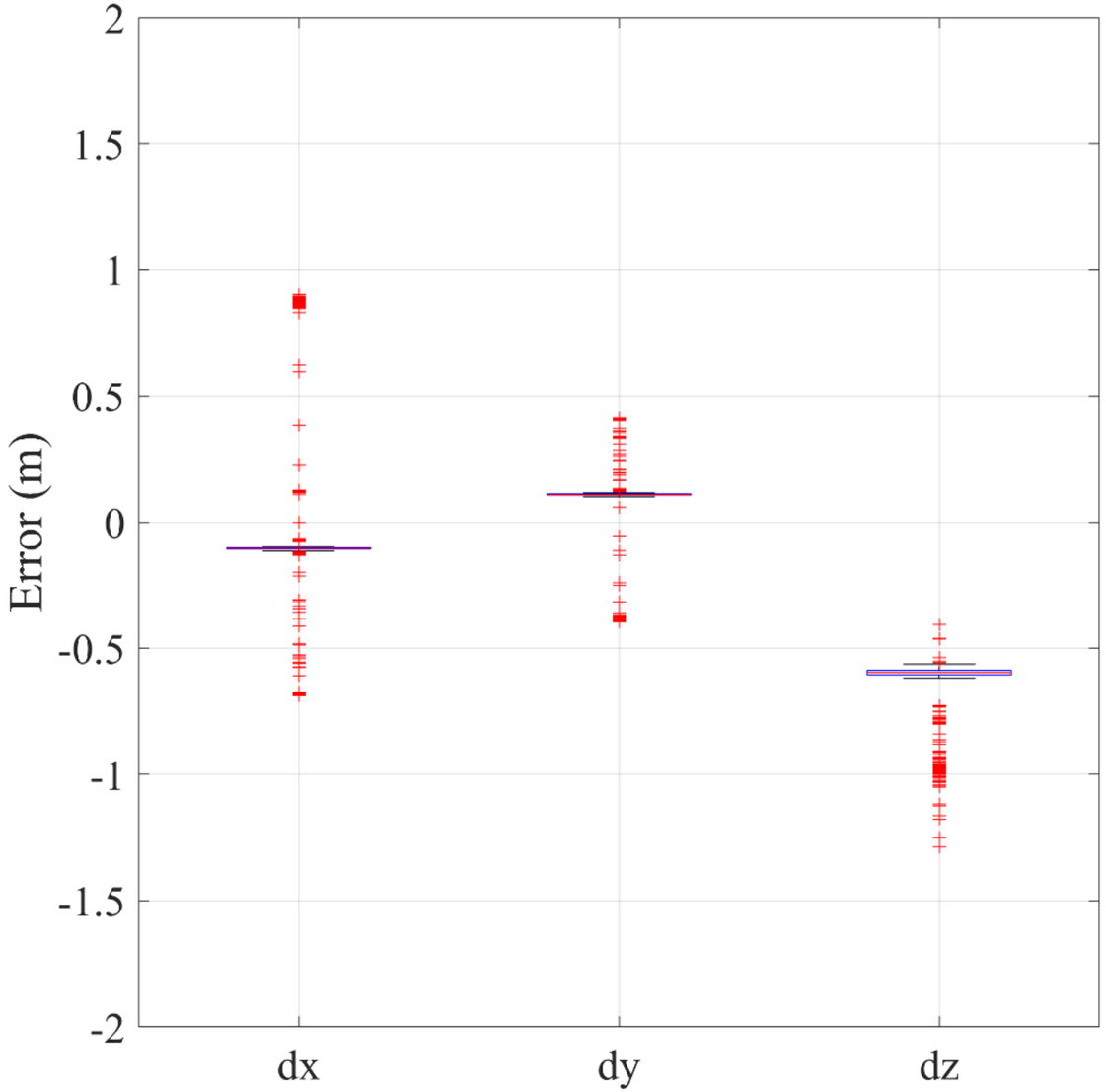


American Shad Acoustic Transmitter: Detection and 3D Tracking of Released Fish

- 100 fish tagged released
  - About 34M detections total.
    - ✓ Median is 150k
  - About 5.2M 3D tracked locations.
    - ✓ Median is 20k.

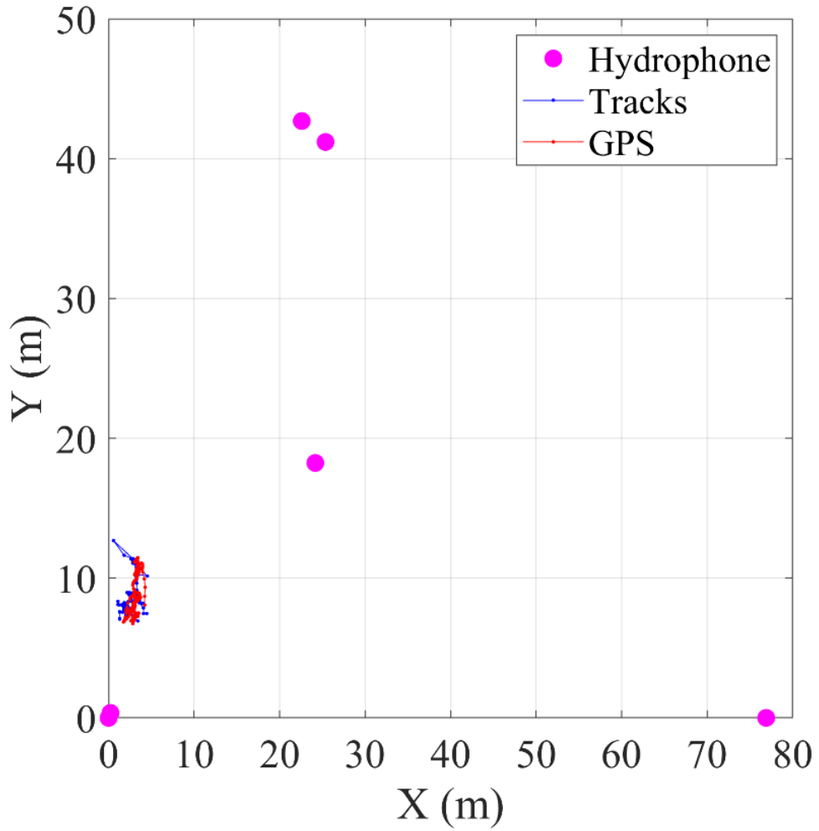
	# of Detected Fish	Mean # of Detections /Points	Median # of Detections /Points	Total # of Detecitons /Points
Autonomous Receiver	95	3,394	831	322,394
Cabled Detections	83	406,440	149,592	33,734,525
3D Tracking	82	63,688	19,802	5,222,438

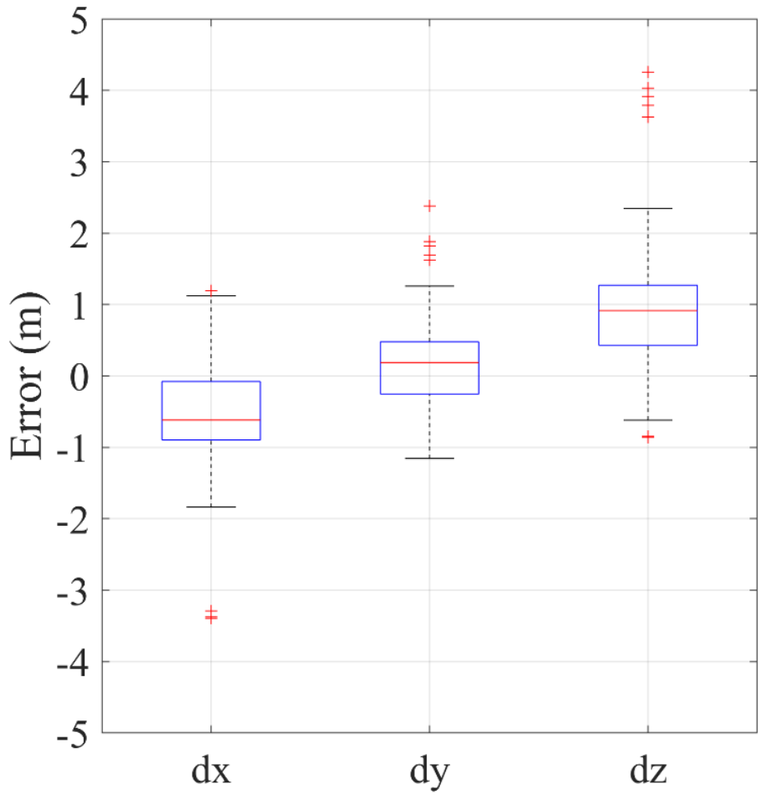
American Shad Acoustic Transmitter: Forebay Beacon #1 (attached to Hydrophone 4) 3D Tracking Error



Tracking Efficiency: 99.5%			
	X	Y	Z
Mean Absolute Error (m)	0.22	0.16	0.64
Median Absolute Error (m)	0.11	0.11	0.60
Root-Mean-Square Error (m)	0.34	0.18	0.66

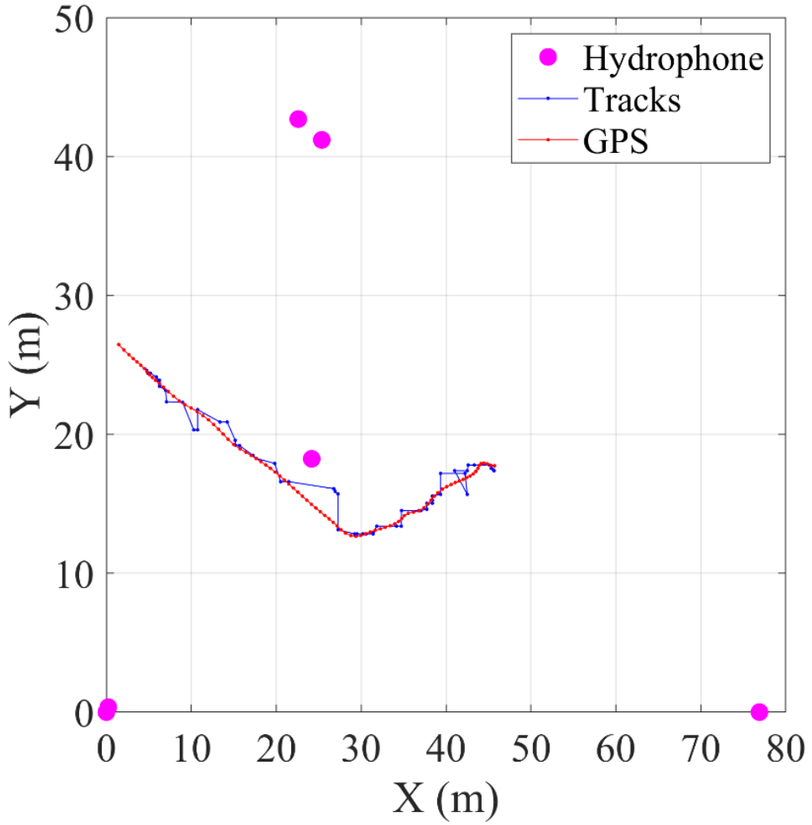
American Shad Acoustic Transmitter: Stationary Testing – Preliminary Results

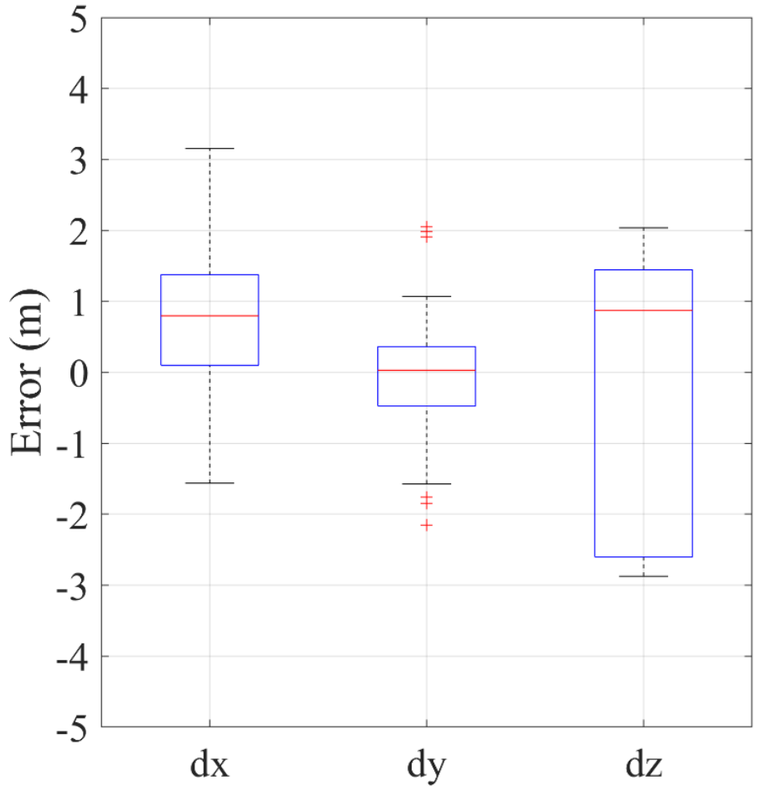




Tracking Efficiency: 96%			
	X	Y	Z
Mean Absolute Error (m)	0.71	0.48	1.30
Median Absolute Error (m)	0.69	0.42	0.92
Root-Mean-Square Error (m)	0.88	0.61	1.88

American Shad Acoustic Transmitter: Drifting Testing – Preliminary Results





Tracking Efficiency: 86%			
	X	Y	Z
Mean Absolute Error (m)	0.99	0.57	1.74
Median Absolute Error (m)	0.98	0.39	1.81
Root-Mean-Square Error (m)	1.20	0.77	1.92

American Shad Acoustic Transmitter: Summary and Future Testing Ideas

- Improved methods for transporting shad
  - Improved 1d survival from 50% to 99%.
- Successfully tagged shad (50-105mm) with new acoustic transmitter (7.6mm x 2.0mm; 0.05g).
  - All pectoral incision locations tested had >90% survival by day 7.
  - Tagged fish performed as well or better than controls.
    - ✓ 60d survival was 81.5% for tagged fish.
    - ✓ Tagged fish were able to avoid predators as well as control fish.
- Successfully demonstrated its performance at Cabot Station, MA
  - High accuracy
  - High efficiency
- Future studies:
  - Conduct pilot field demonstration at York Haven Dam, PA.
  - Actively looking for partners for demonstration of this technology.

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Next Frontiers in Acoustic Telemetry

- Smaller, lighter, more powerful transmitter
- Long-lasting transmitter: self-powered platform
- Bio-logging sensors
- Flexible or stretchable sensors
- Cloud-based and real-time system to estimate behavior or survival of tagged aquatic animals using edge-computing
- Machine learning / deep learning for fish passage and operations of waterpower systems
- Sensing and data telemetry in extreme/challenging environments
- Only way to achieve these goals is multi-disciplinary approach and close collaboration between stakeholders nationally and internationally

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Acknowledgements

- US DOE Water Power Technologies Office
- US Army Corps of Engineers
- Electric Power Research Institute
- Idaho Power Company
- United States Geological Survey
- FirstLight Power Resources
- Kleinschmidt Group
- University of Connecticut
- PNNL LDRD Program

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Thank you

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