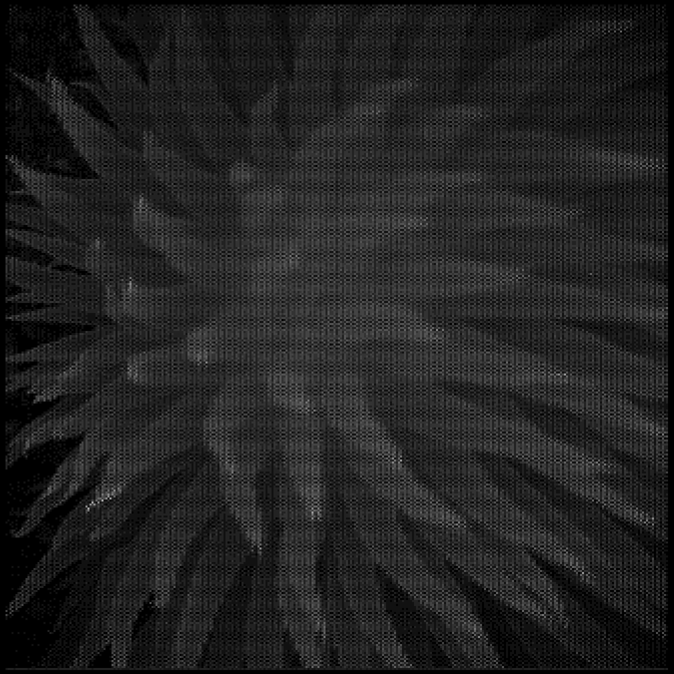
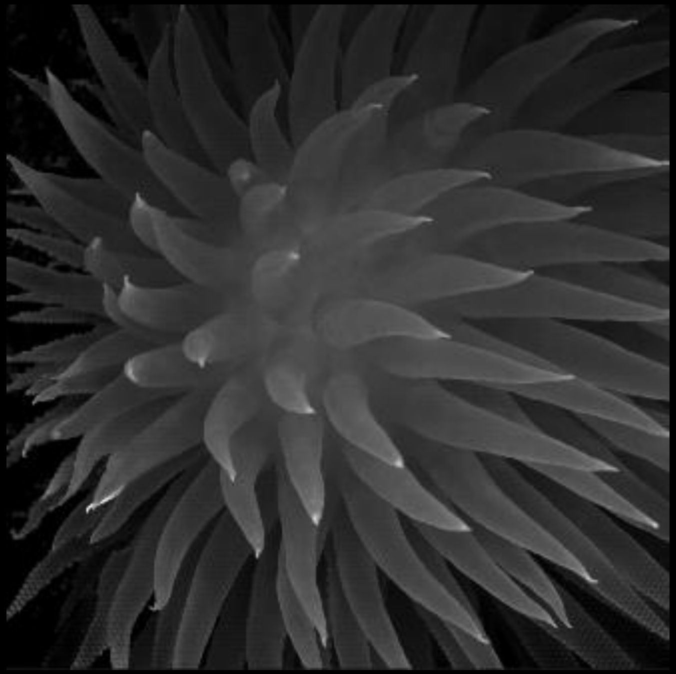
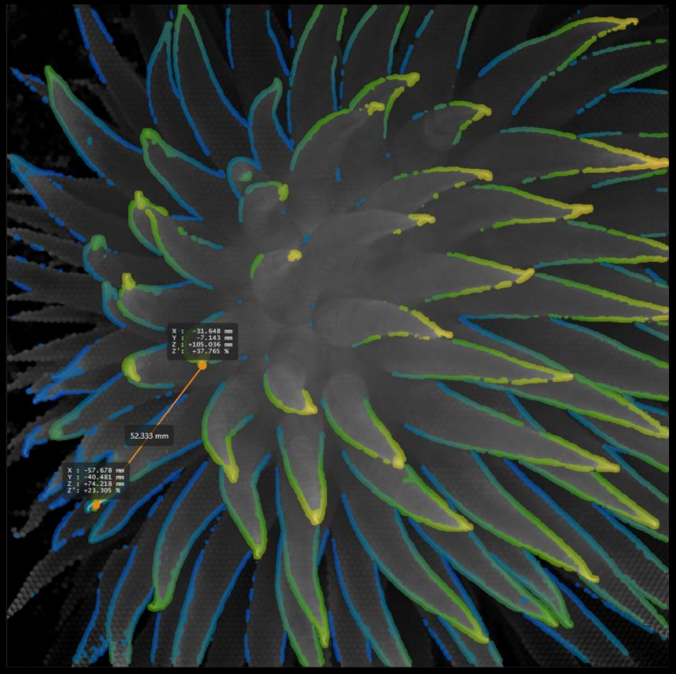
EyeRIS Remote Imaging System
Moore Foundation Grant 7583







Kakani Katija, Henry Ruhl, Alana Sherman, Paul L. D. Roberts, Denis Klimov, Jon Erickson, Rich Henthorn, Joost Daniels, Eric Orenstein, Kevin Barnard, Brett Hobson

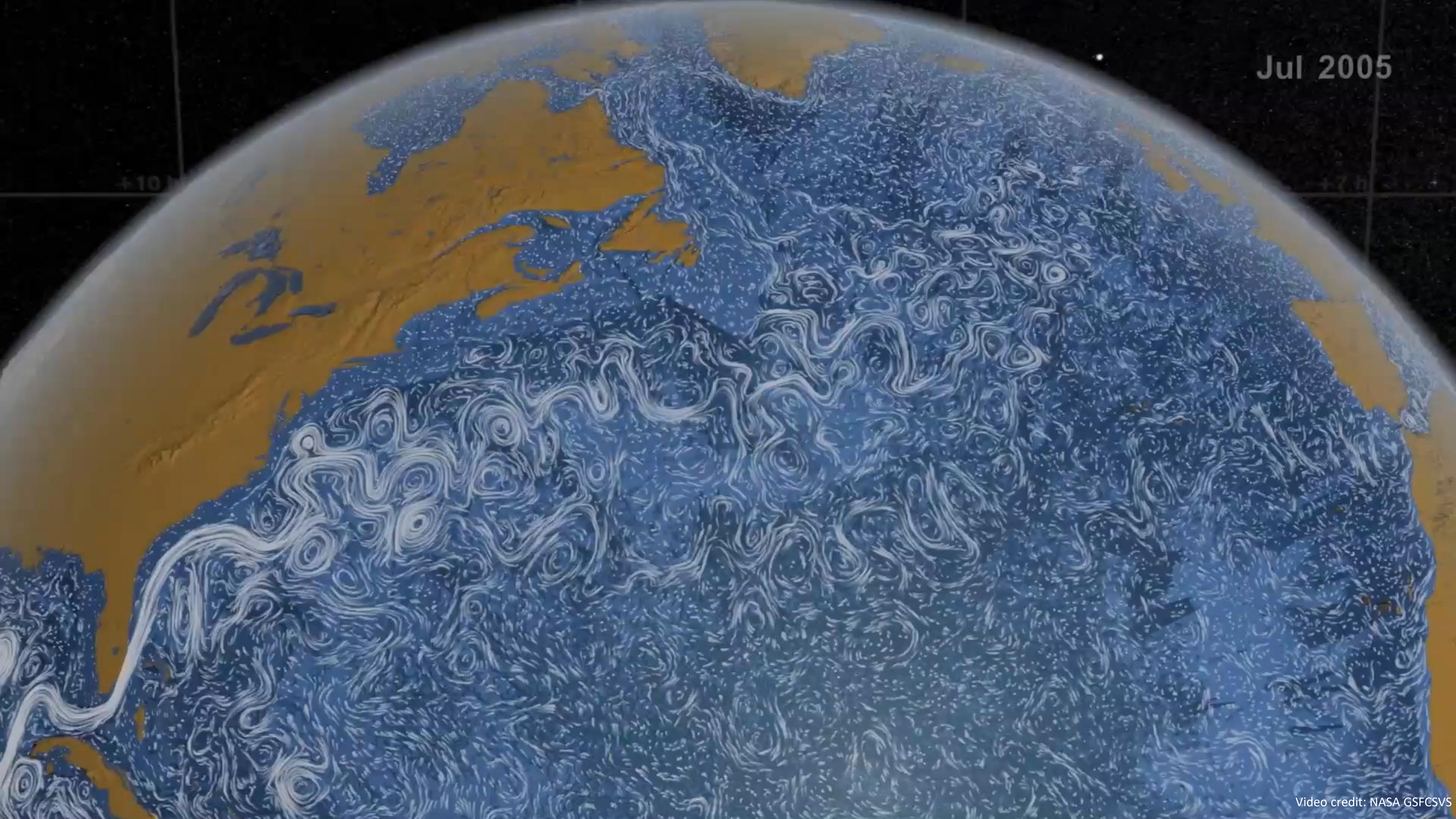
GORDON AND BETTY MOORE FOUNDATION
Grant #: **7583**

Monterey Bay Aquarium Research Institute

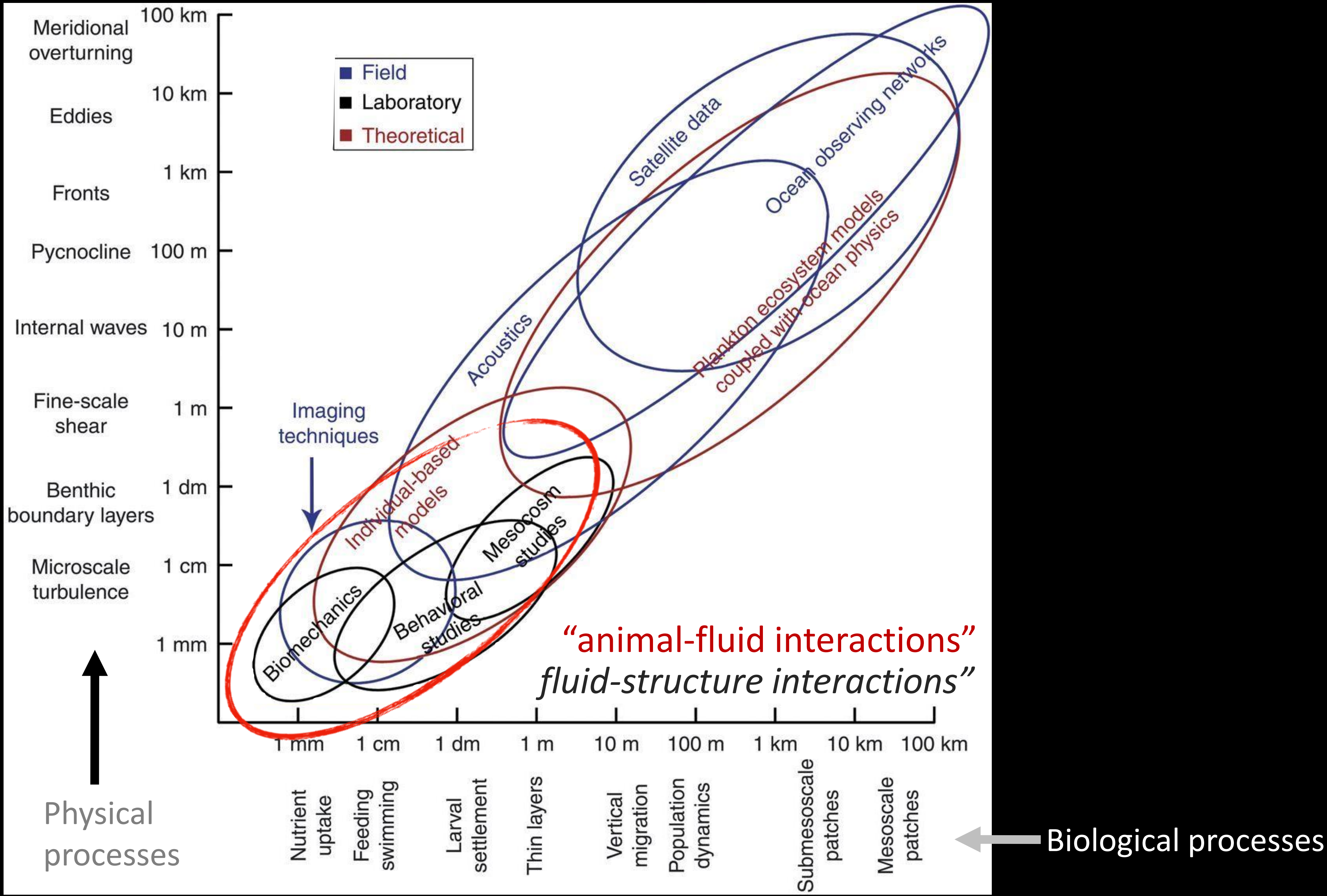
CENTRAL & NORTHERN CALIFORNIA OCEAN OBSERVING SYSTEM

Outline

- Motivation
- Timeline
- Cabled Instrument Design
- Cabled Instrument Data
- Autonomous Instrument Design
- Autonomous Instrument Data
- Future Work



Video credit: NASA GSFCSVS



Sutherland, et al. (2012)

Potential Science Applications

Midwater animal ecomechanics

Quantify feeding and predation interactions

Estimate energy expenditure and carbon flux

Health of deep sea benthic communities (coral and sponges)

Quantify boundary layer flow

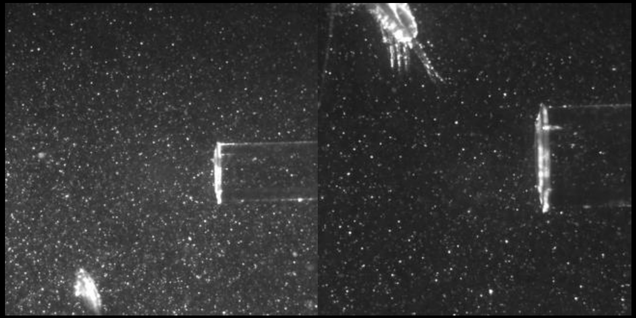
Estimate filtration rates and nutrient/carbon flux

Identify passive mechanisms for feeding in high flows

Linking food webs to mechanosensing

Quantify hydromechanical signals

Understand role hydrodynamics plays in predation and ecology of marine organisms

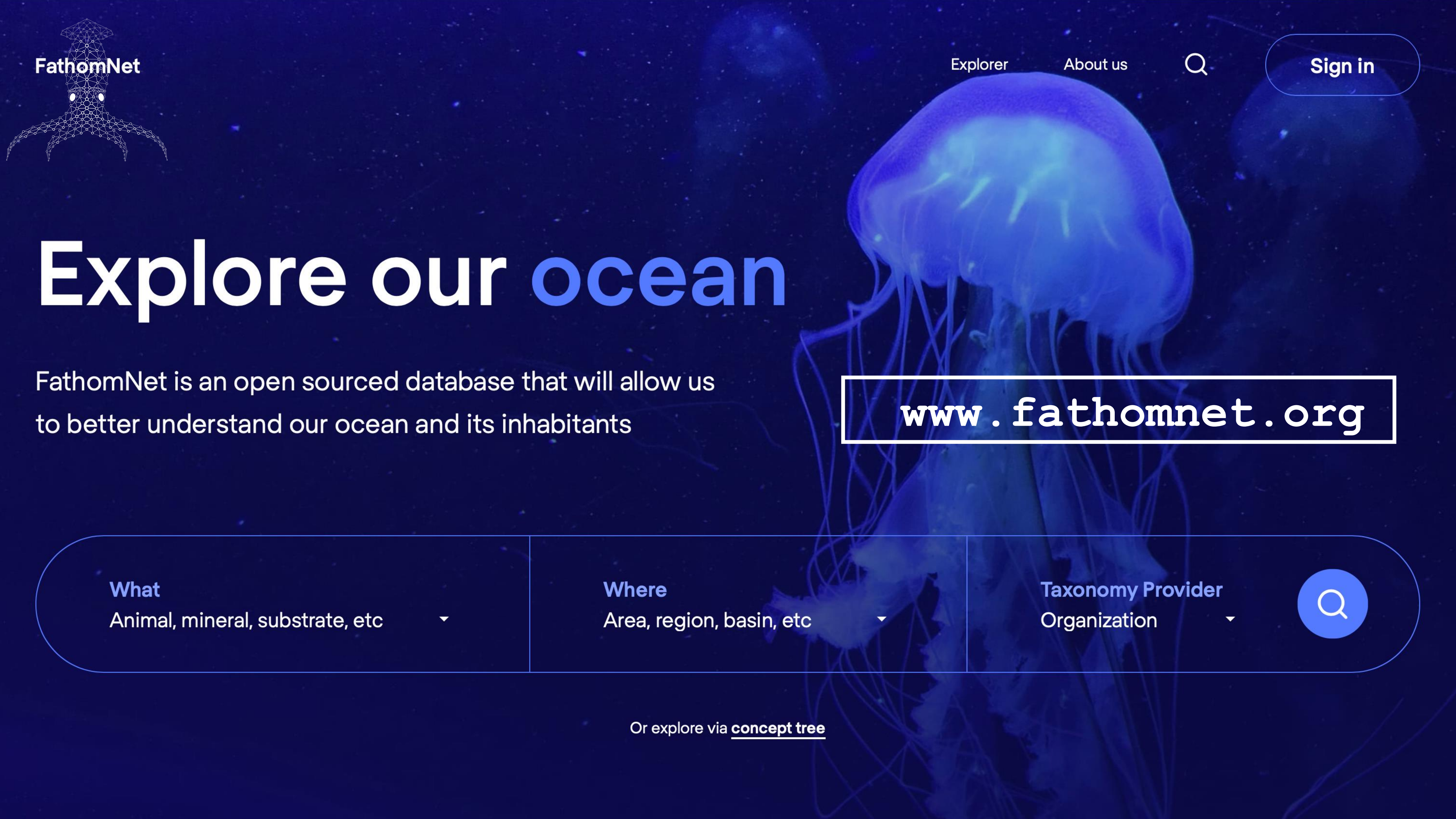


Fundamental Problem

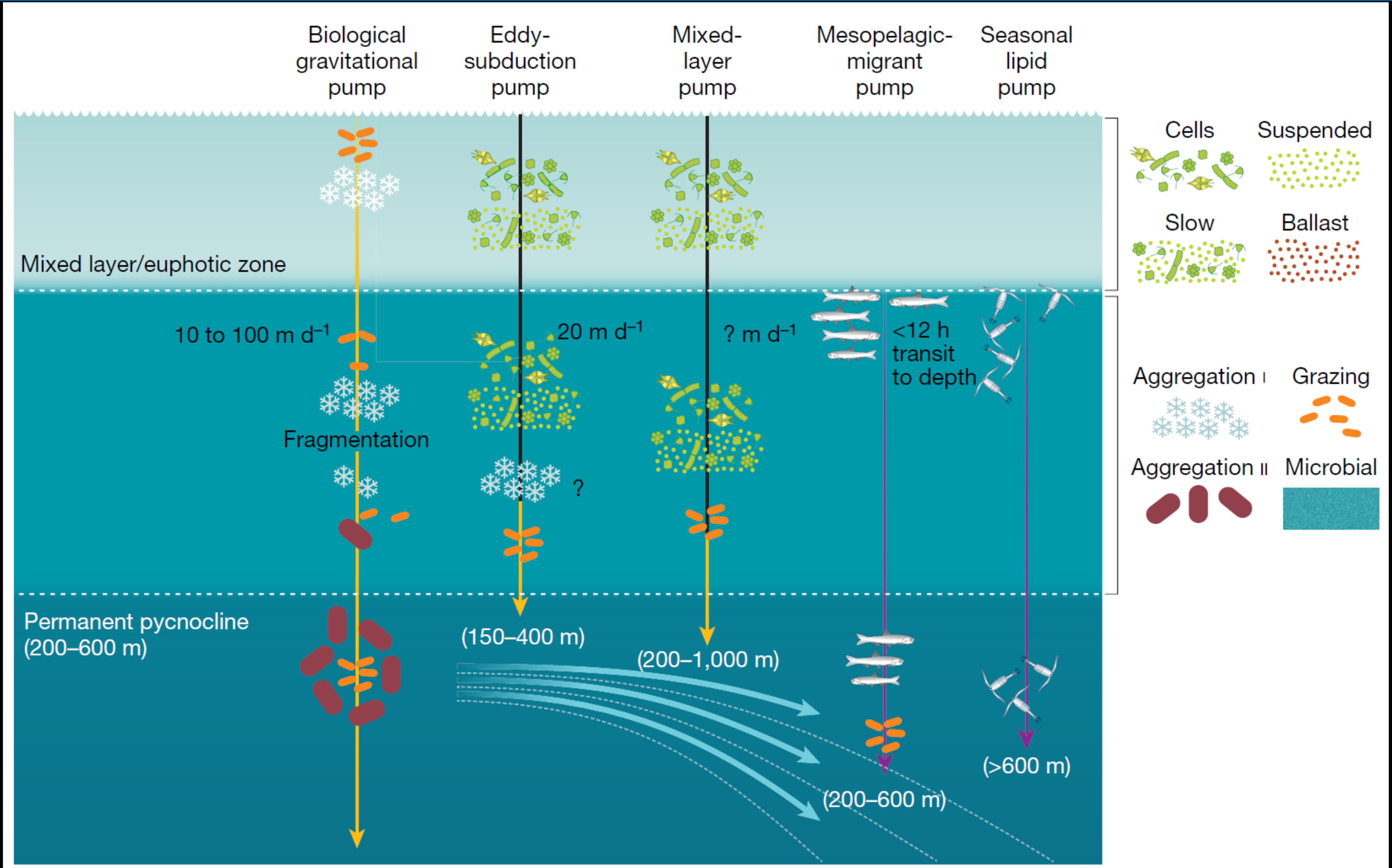
To robustly inform *fluid-structure interactions* in the ocean:

1. Measure 3D particle distributions
2. Measure 3D surfaces
3. Achieve (1) and (2) *simultaneously*

temporally varying targets


FathomNet
Explorer
About us
Sign in
Explore our ocean
FathomNet is an open sourced database that will allow us to better understand our ocean and its inhabitants
www.fathomnet.org
What
Animal, mineral, substrate, etc
Where
Area, region, basin, etc
Taxonomy Provider
Organization
Or explore via concept tree

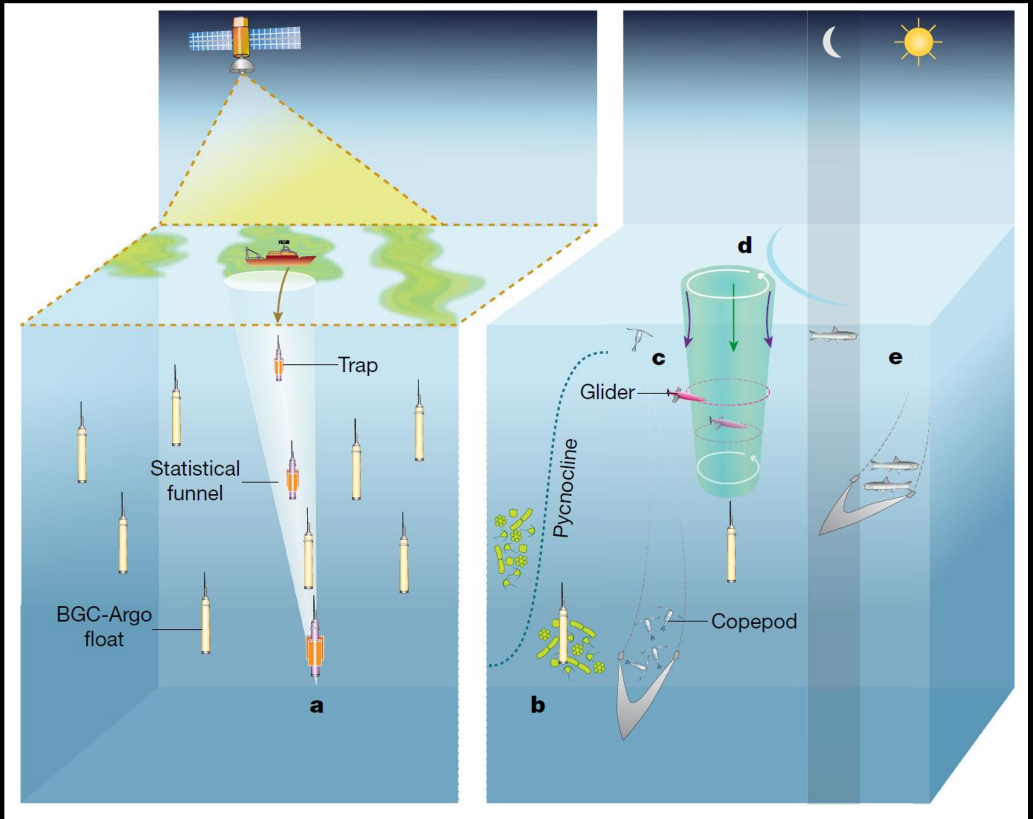
Biological Carbon Pump – Lots of Theories



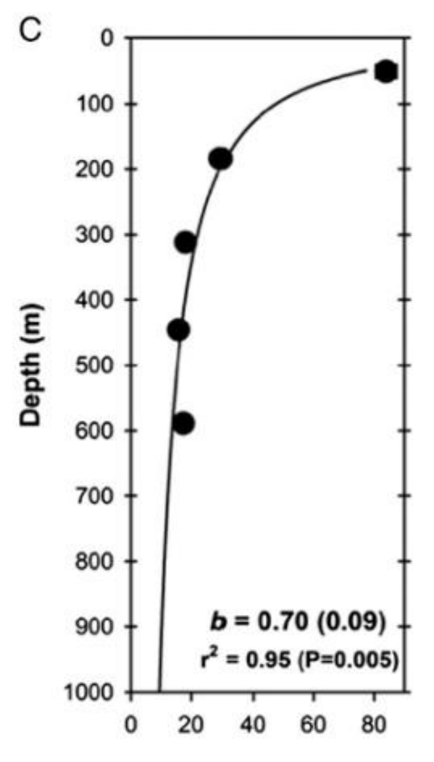
Boyd et al. Nature 2019, https://www.nature.com/articles/s41586-019-1098-2

Biological Carbon Pump – Now Lots of Tools

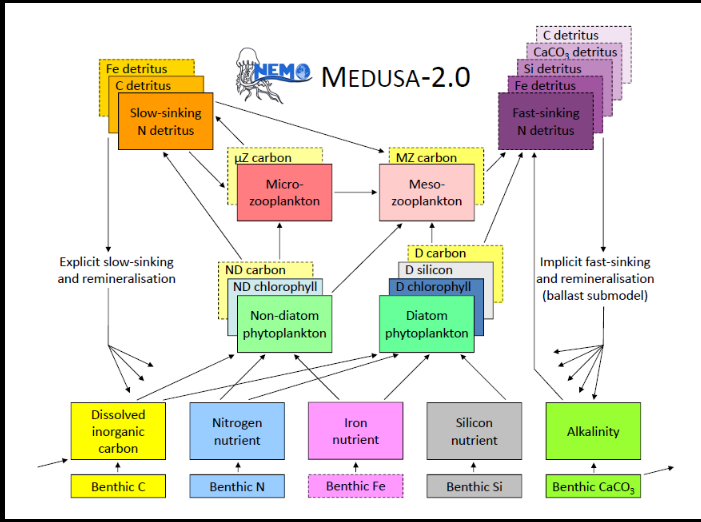
…But, a still not approaches that sufficiently bridge the object sizes and time scales needed to disentangle factors in a way that can are improving modelling of particles (*b* and RLS)



Boyd et al. 2019, Nature



Marsay et al. 2015, PNAS

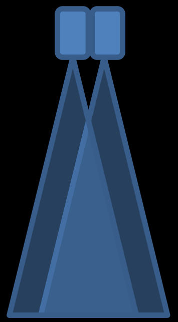


Yool et al. 2013, Geosci. Mod. Dev.

Informing United Nations (UN) – Intergovernmental Panel on Climate Change (IPCC)

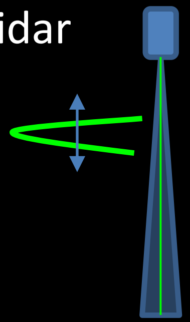
In Situ 3D Imaging methods

Stereo Cameras



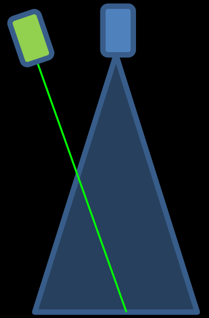
WHOI / MBARI : Mesobot

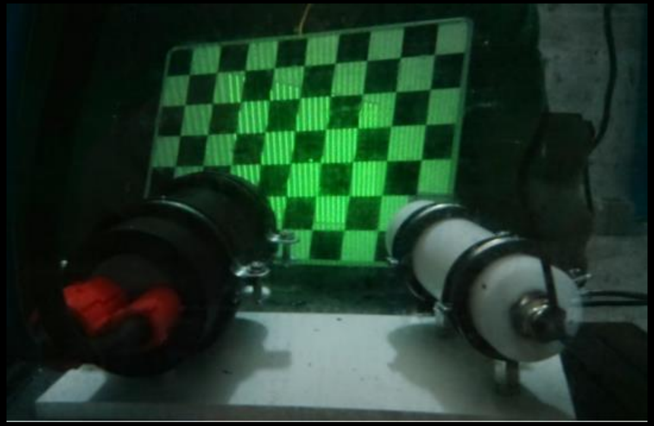
Time of Flight / Lidar



SIO: Laser Line Scan Lidar System

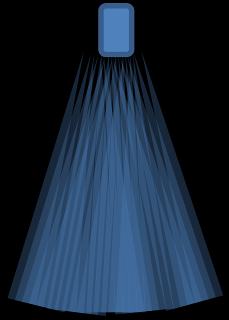
Structured Light





Massot-Campos et. al 2014

Lightfield

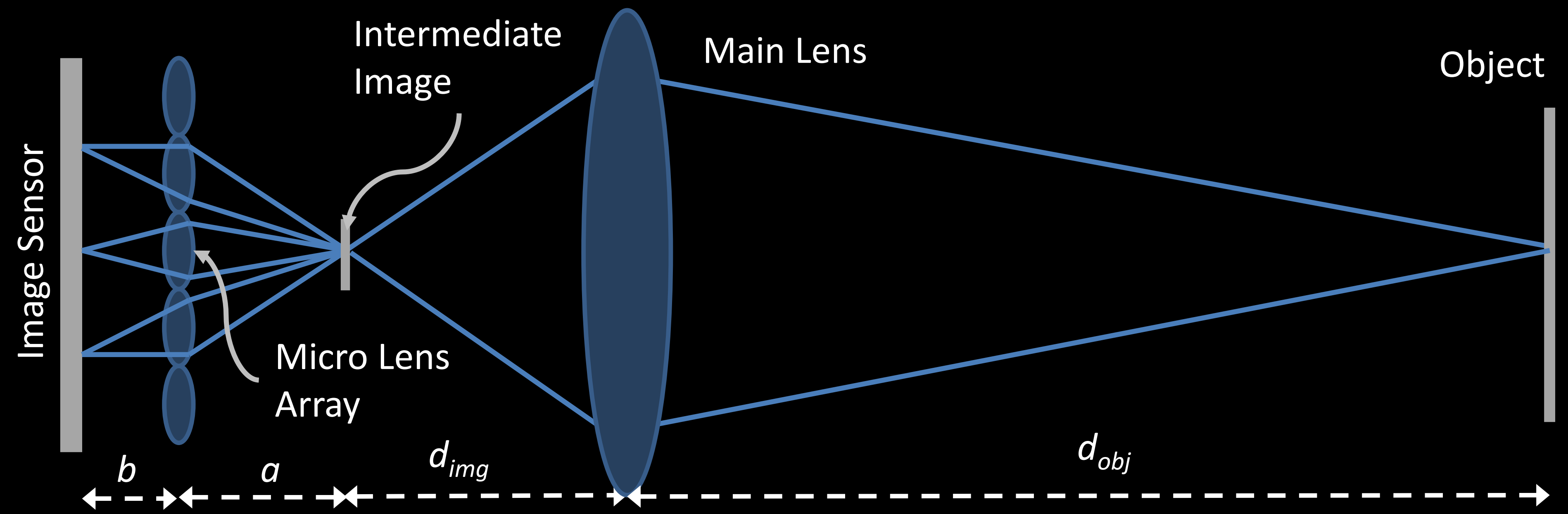


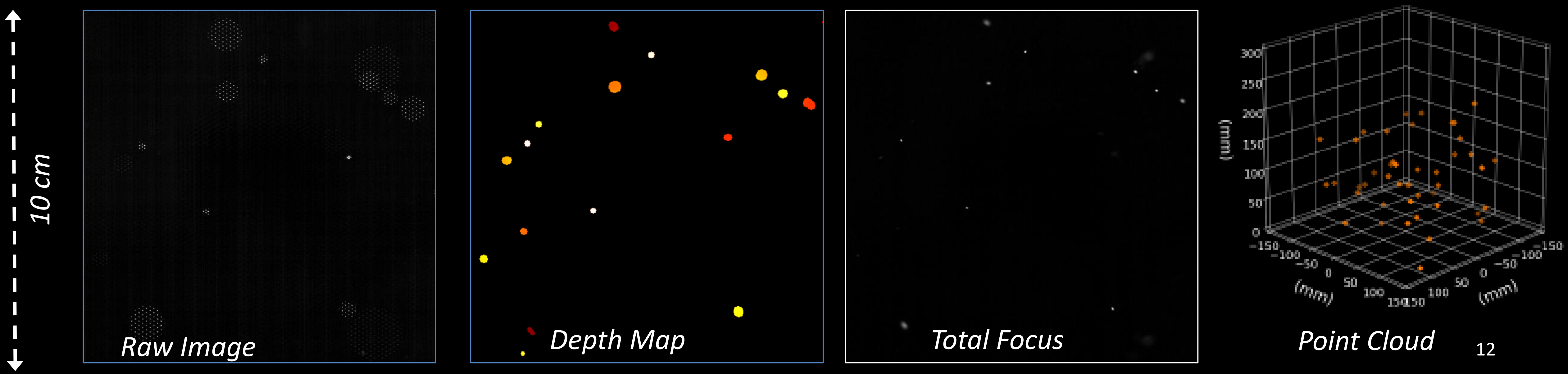
NOAA / Ocean Innovations / Guatek

Proposed Solution: Lightfield Imaging

- Greatly simplified automated correspondence matching and real-time depth estimation
- Depth maps can achieve resolution on the order of camera pixel resolution
- Extensive work in industrial applications have resulted in robust hardware/software solutions for real-time visualization

Lightfield Imaging





Project Summary

Outcome 1:

With a new underwater imaging system, scientists can directly observe and quantify fluid motion, particles, and living organisms in three dimensions

Output 1

Acquisition and testing of new imaging hardware in the laboratory

Output 2

Packaging of instrument hardware suitable for deploying the imaging device to 4000m depth on a cabled platform

Output 3

Demonstration of the instrument's functionality on a cabled, remotely operated vehicle platform

Output 4

Packaging of instrument hardware suitable for deploying the imaging device to 4000m depth on an autonomous platform.

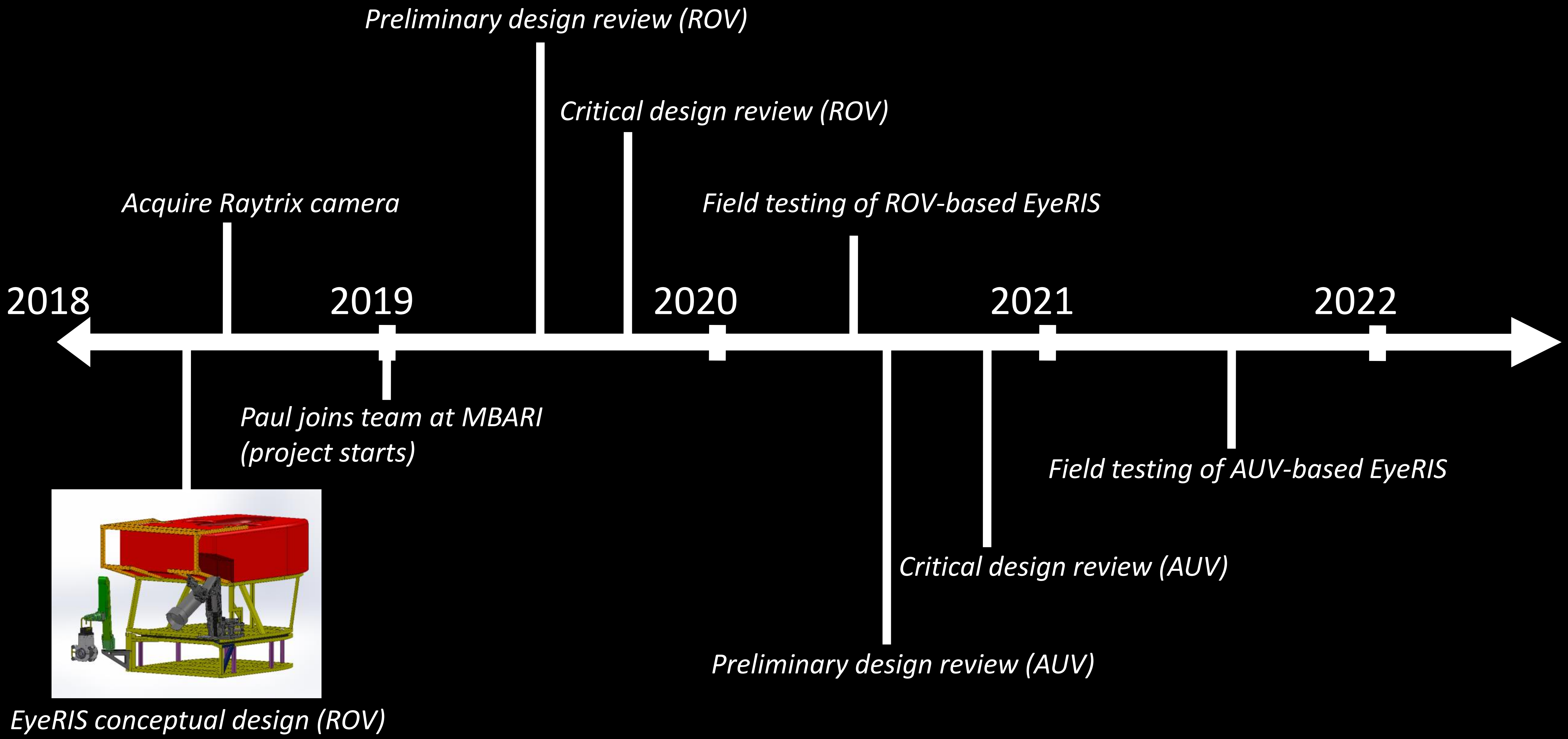
Output 5

Deployment of instrument hardware on a long-range autonomous underwater vehicle.

Output 6

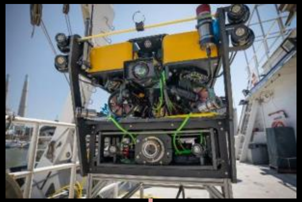
Synthesis of results

The Proposed Timeline (Dec 2018)

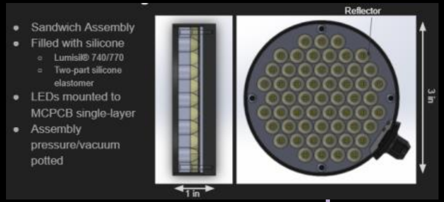


Summary Timeline

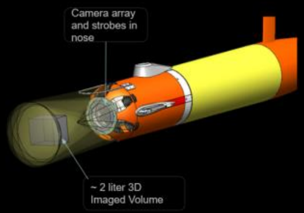
Deployment on MiniROV / WF



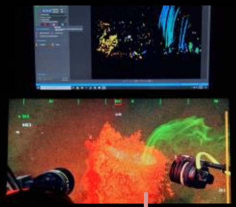
Strobe Concept Review



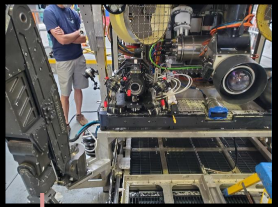
LRAUV Integration
Preliminary Design Review



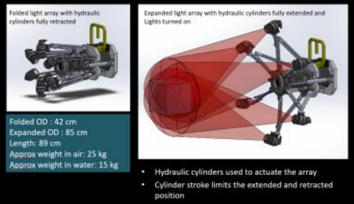
Deployment on ROV
Doc Ricketts / WF



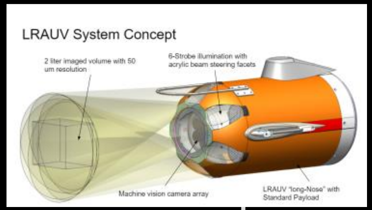
Deployment on ROV
Doc Ricketts / WF



Cabled Instrument
Preliminary Design Review



Concept for AUV system



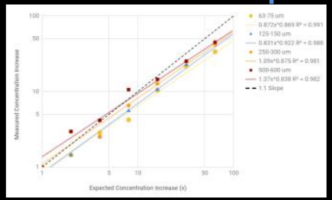
Deployment on
ROV Doc Ricketts / WF

LRAUV Payload
Completed Drawings

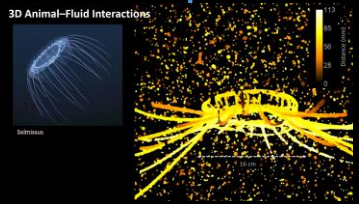
Deployment on LRAUV

Jun 2019 | Nov 2019 | Feb 2020 | Jun 2020 | Jan 2021 | May 2021 | Aug 2021

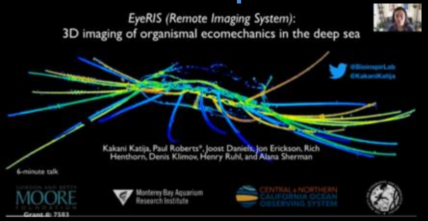
Apr 2019 | Aug 2019 | Jan 2020 | Apr 2020 | Aug 2020 | Oct 2020 | Mar 2021 | July 2021 | Oct 2021 | Nov 2021



Marine Imaging Workshop 2019
3D particle counting lab studies

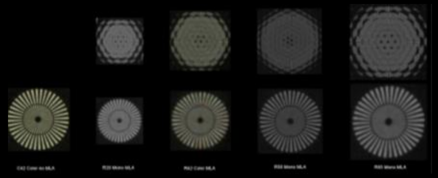


Ocean Sciences 2020

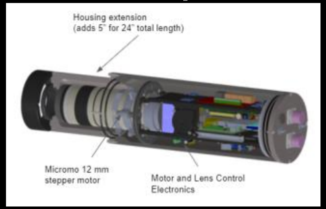


SICB 2021

Deployment on ROV SuBastian / FK



Visit to Raytrix, Camera Selection

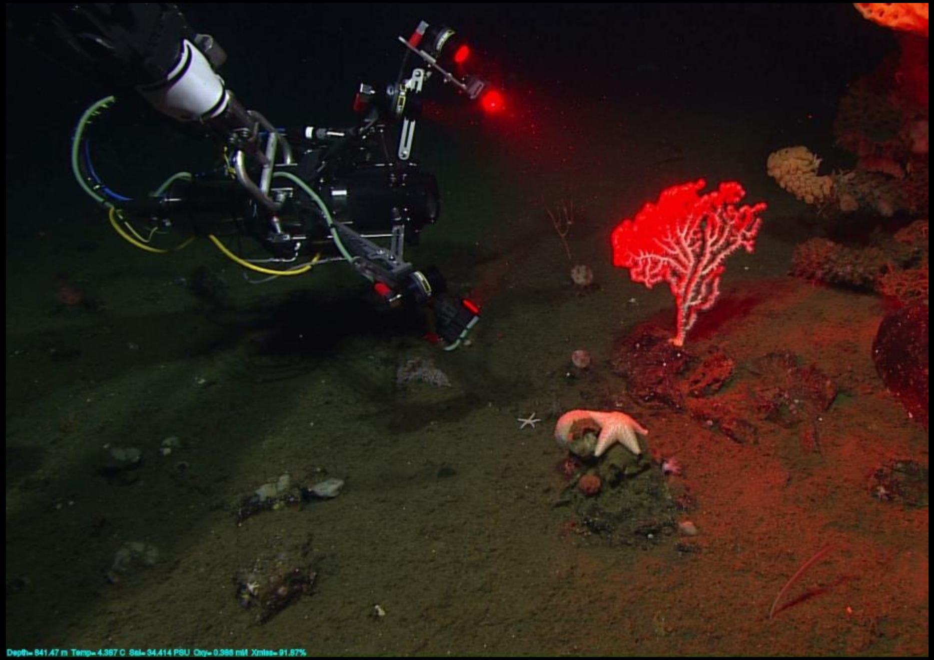


Zoom Lens Addition

Deployment on ROV Ventana / RC

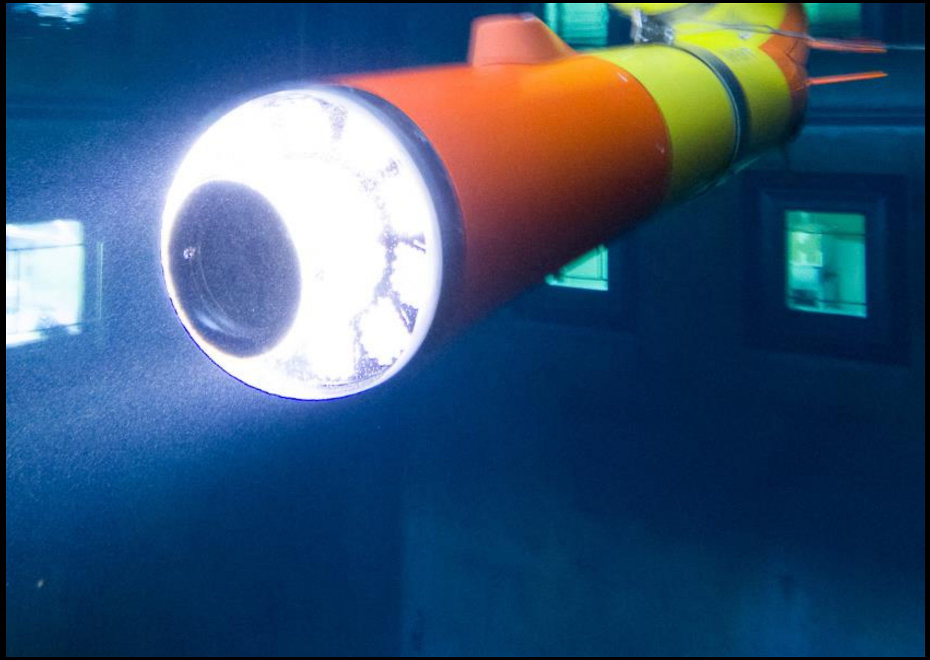
- Design Review
- Field Deployment
- Synthesis and Dissemination

Instruments Developed



EyeRIS Cabled Instrument

- Raytrix R26 lightfield camera, 25 megapixel, 60 fps, 2 GB/s data rate
- 6, DSPL 660 nm spot lights
- Real-time depth, surface mesh, and measurement through topside-interface
- Deployed on all three MBARI ROVs and Schmidt Ocean SuBastion
- 4000 m depth rating

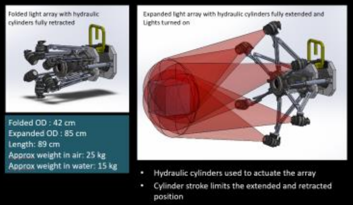


AyeRIS Autonomous Instrument

- 7, Sony IMX183, 20 megapixel sensors in hexagonal array,
- 10, 33,000 lumen strobes in a ring around the cameras
- Real-time particle detection and size spectra estimation
- Deployed on MBARI’s Long-Range AUV
- 300 m depth rating version completed and demonstrated
- 1500m and 6000m versions designed and ready for fabrication

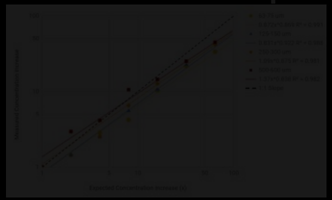
Cabled Instrument Timeline

Cabled Instrument
Preliminary Design Review



Apr
2019

Marine Imaging Workshop 2019
3D particle counting lab studies

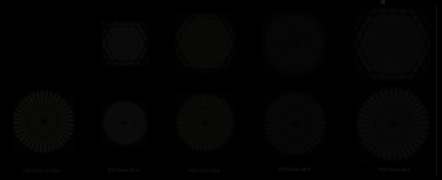


Jun
2019

Deployment on
MiniROV / WF

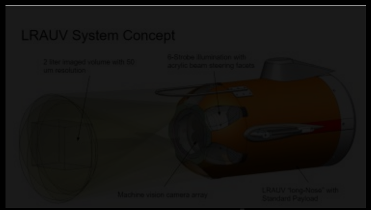
Aug
2019

Visit to Raytrix, Camera Selection



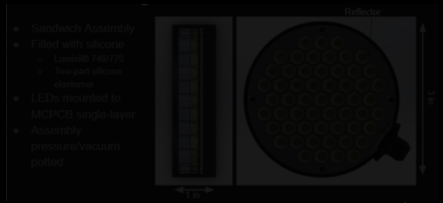
Nov
2019

Concept for AUV system



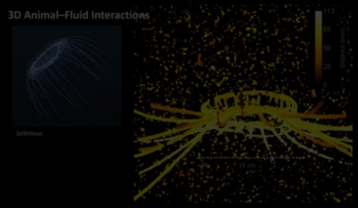
Jan
2020

Strobe Concept Review



Feb
2020

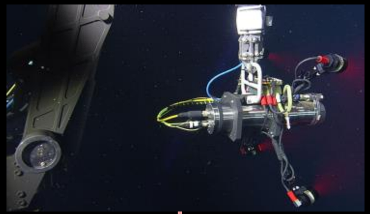
Apr
2020



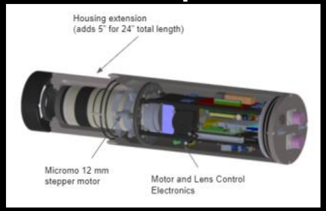
Ocean Sciences 2020

Jun
2020

Deployment on
ROV Doc Ricketts / WF

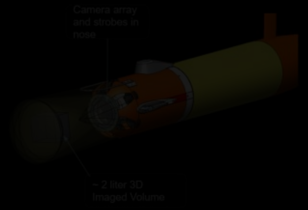


Zoom Lens Addition

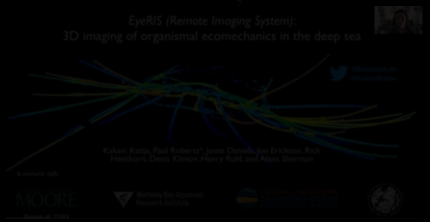


Aug
2020

LRAUV Integration



Oct
2020



SICB 2021

Jan
2021

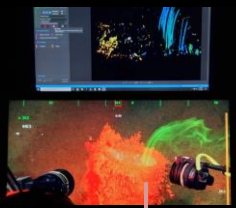
LRAUV Payload
Completed Drawings

Mar
2021

Deployment on ROV Ventana / RC

May
2021

Deployment on ROV
Doc Ricketts / WF

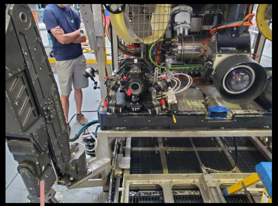


July
2021

Deployment on ROV SuBastian / FK

Aug
2021

Deployment on ROV
Doc Ricketts / WF



Oct
2021

Deployment on LRAUV

Nov
2021

- Design Review
- Field Deployment
- Synthesis and Dissemination

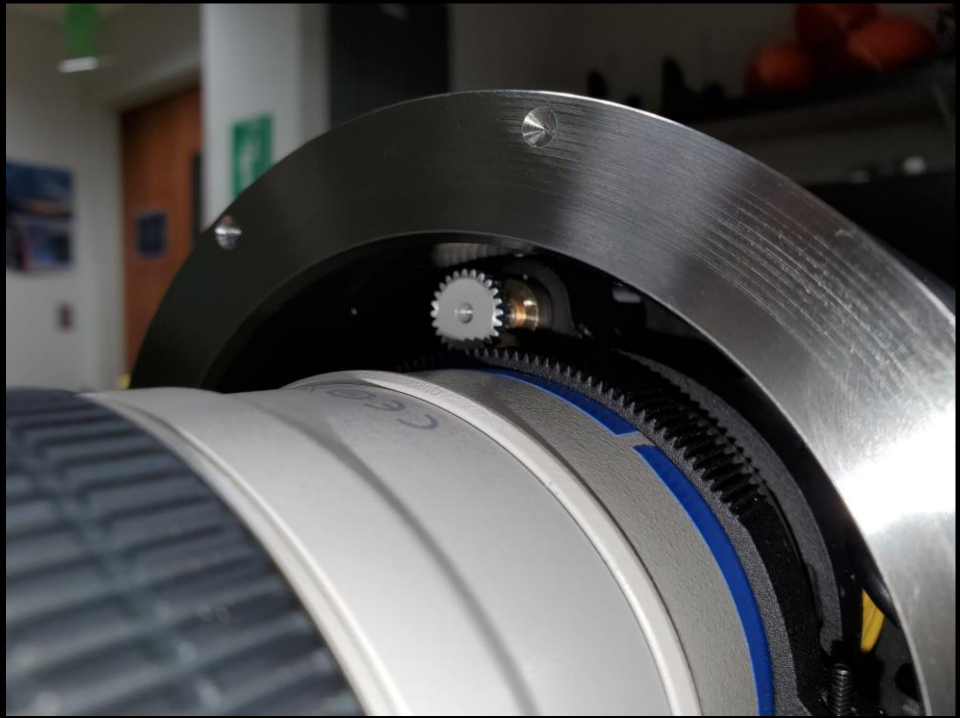
Cabled Instrument: Design

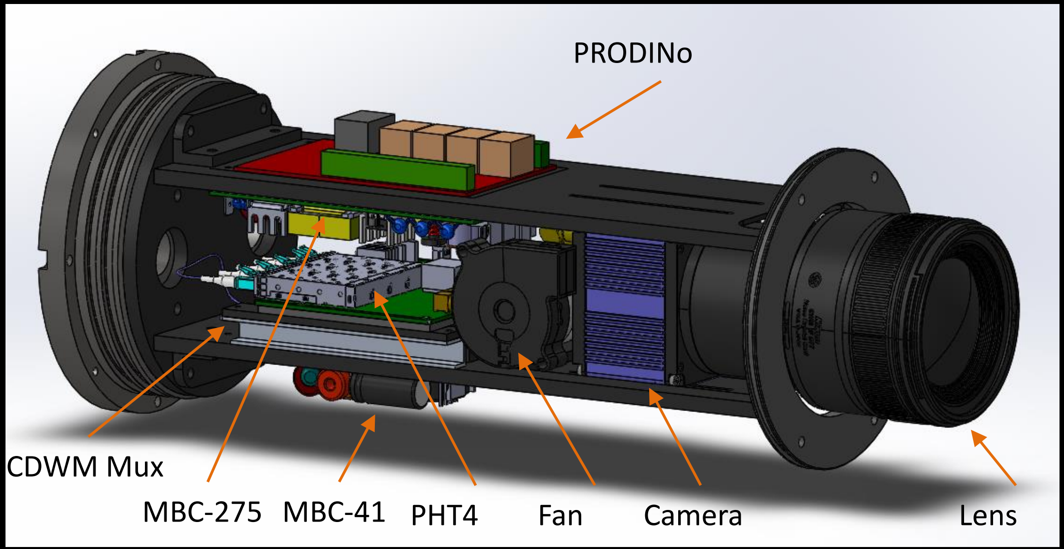
- Key requirements
  - Self-contained and able to interface with vehicle through existing infrastructure
  - 3D data available in real-time to inform science mission and aid pilot
  - Deployable on manipulator arm or tool sled
- Key challenges
  - Very high data rate ~ 2 GB/s
  - Available hardware for camera interface
  - Limited space and weight

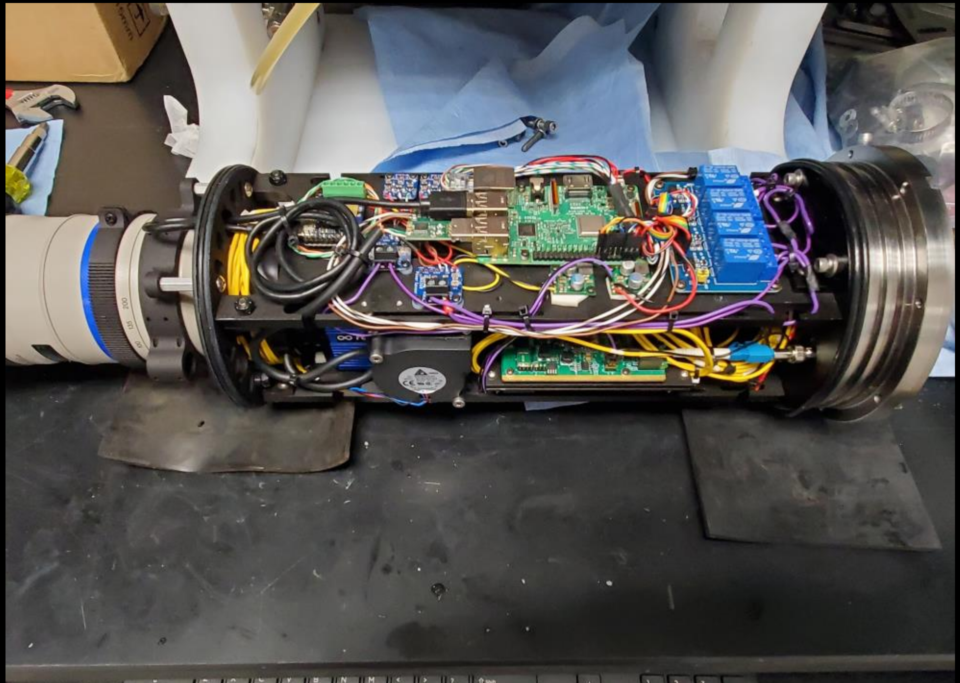
Optical Design: Raytrix R26 Camera

- 25 MP sensor
- 80 fps max rate
- ~ 2 GB/s data rate
- 4-channel CoaXPress-6 interface
- 4.5 um x 4.5 um pixels
- 23 mm x 23 mm sensor
- 12000 electron full well depth
- 41 dB peak SNR

Cabled Instrument: Internal Chassis

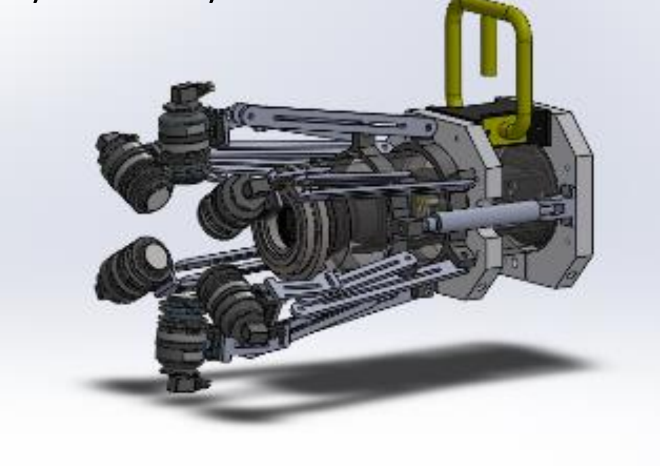






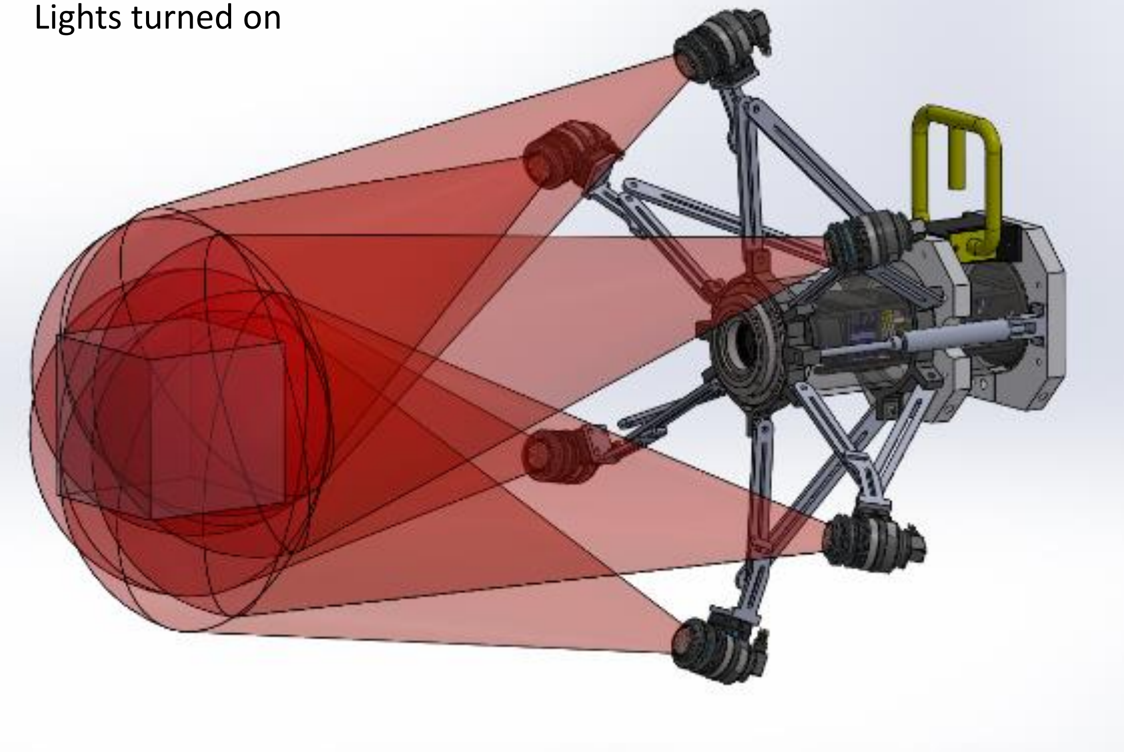
Cabled Instrument: External Assembly

Folded light array with hydraulic cylinders fully retracted



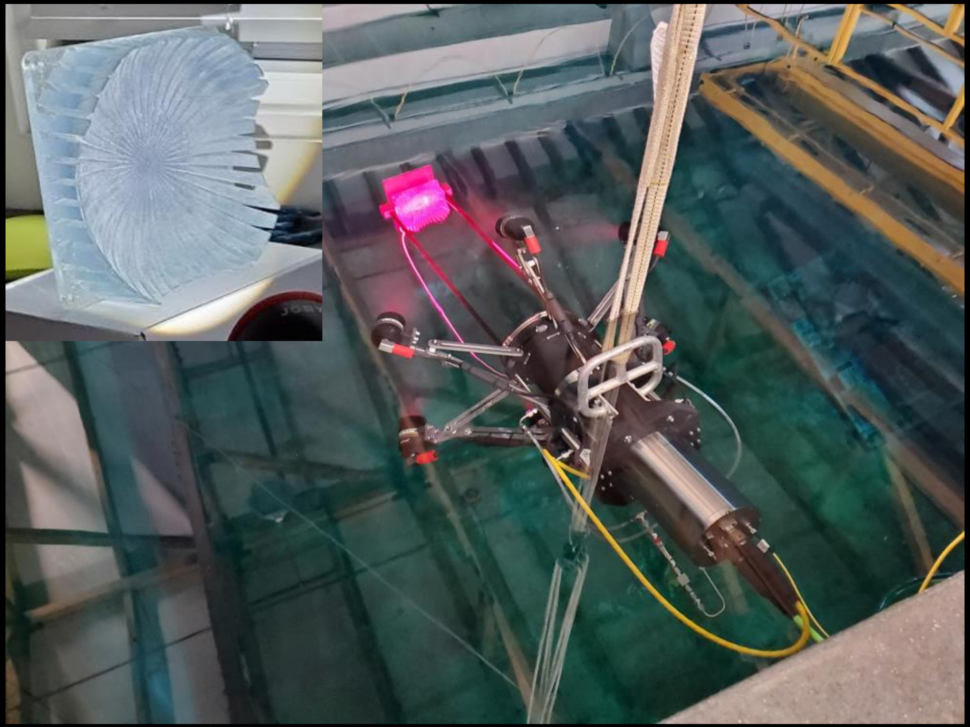
Folded OD : 42 cm
Expanded OD : 85 cm
Length: 89 cm
Approx weight in air: 25 kg
Approx weight in water: 15 kg

Expanded light array with hydraulic cylinders fully extended and Lights turned on

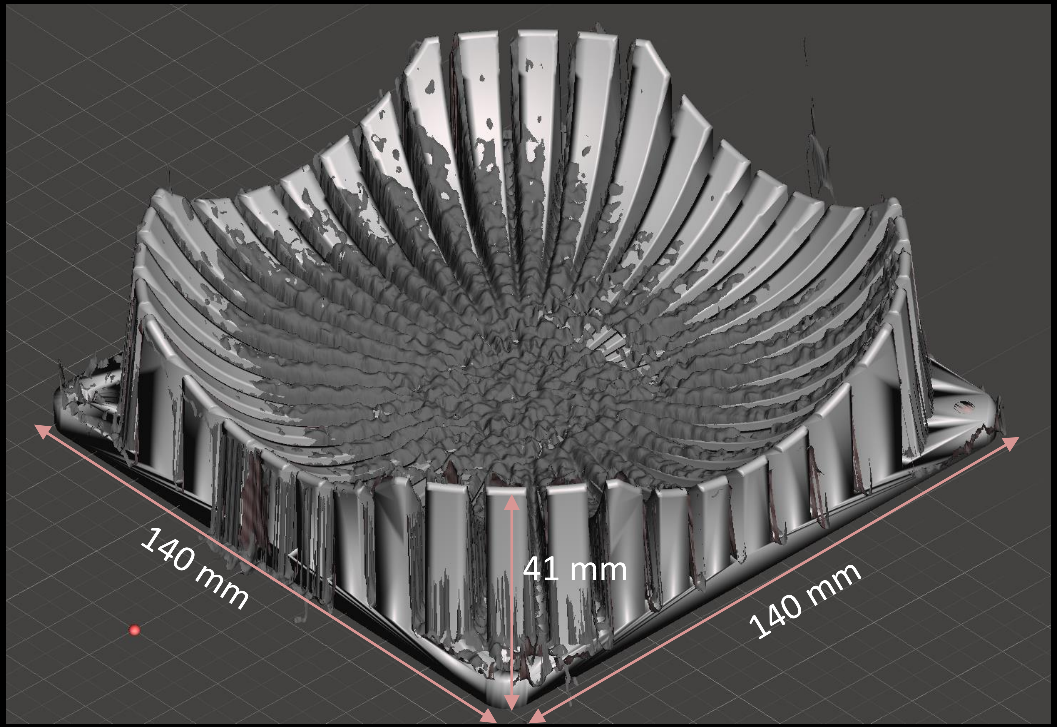


- Hydraulic cylinders used to actuate the array
- Cylinder stroke limits the extended and retracted position

In Situ Measurement Fidelity



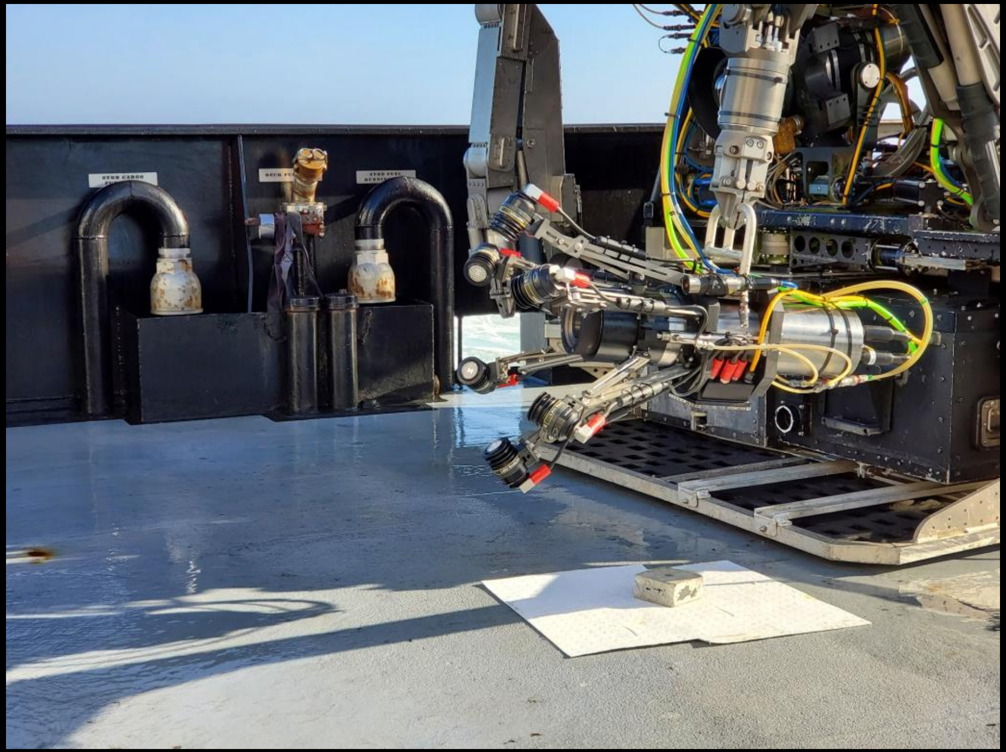
Imaging the 3D printed start target in the test tank

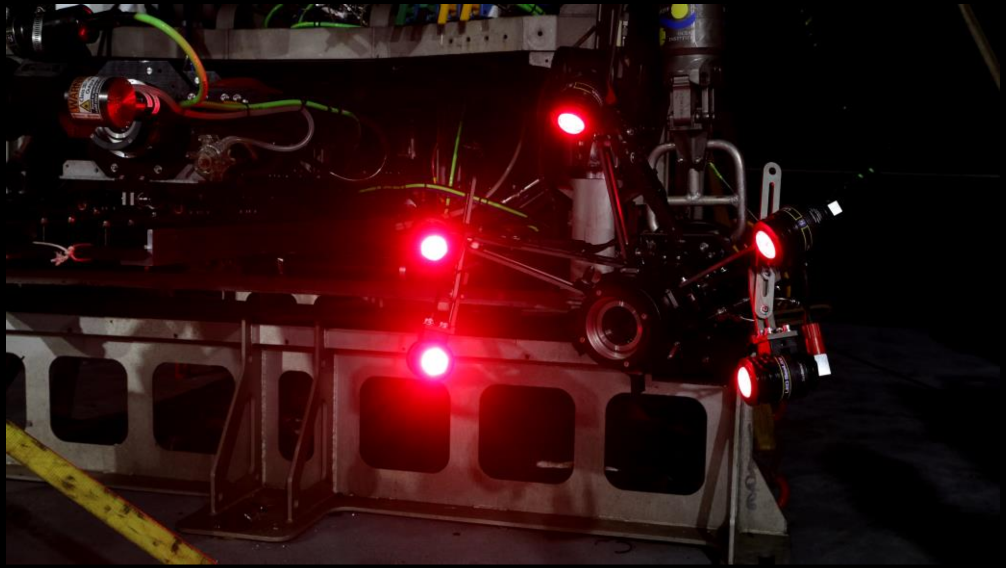


The 3D model from Solidworks (dark gray) with the measured 3D mesh from EyeRIS (light gray) overlayed and aligned ***without any scaling***.

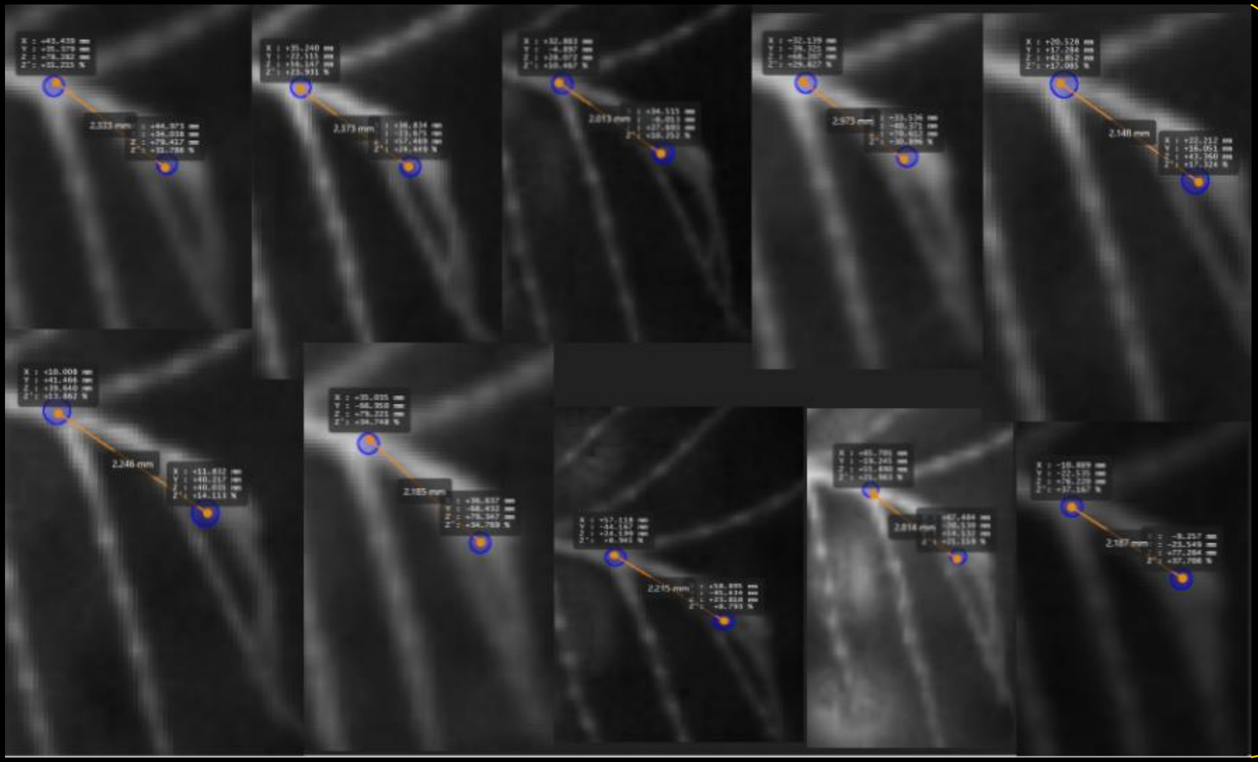
Current Instrument Configuration

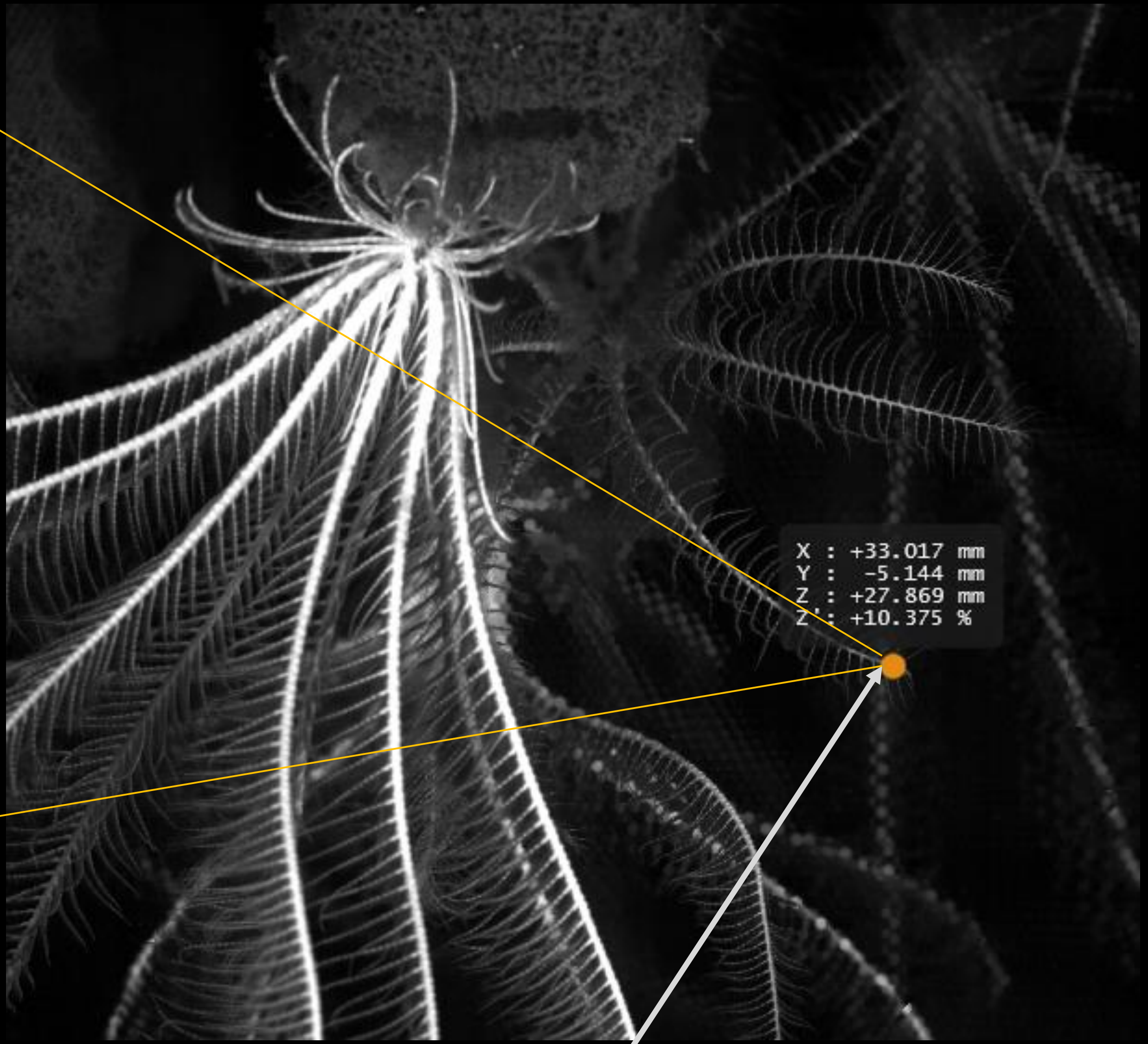
- Imaged volume 65 cm from viewport
- Canon zoom lens 70-200 mm, f/2.8
  - Field of view from 12 cm x 12 cm down to 4 cm x 4 cm
- 6 Photo Red (660 nm) spot lights up to 275 W
- Light array folds/unfolds with hydraulics
- 110-240 VAC or up to 390 VDC power input





Measurement Repeatability



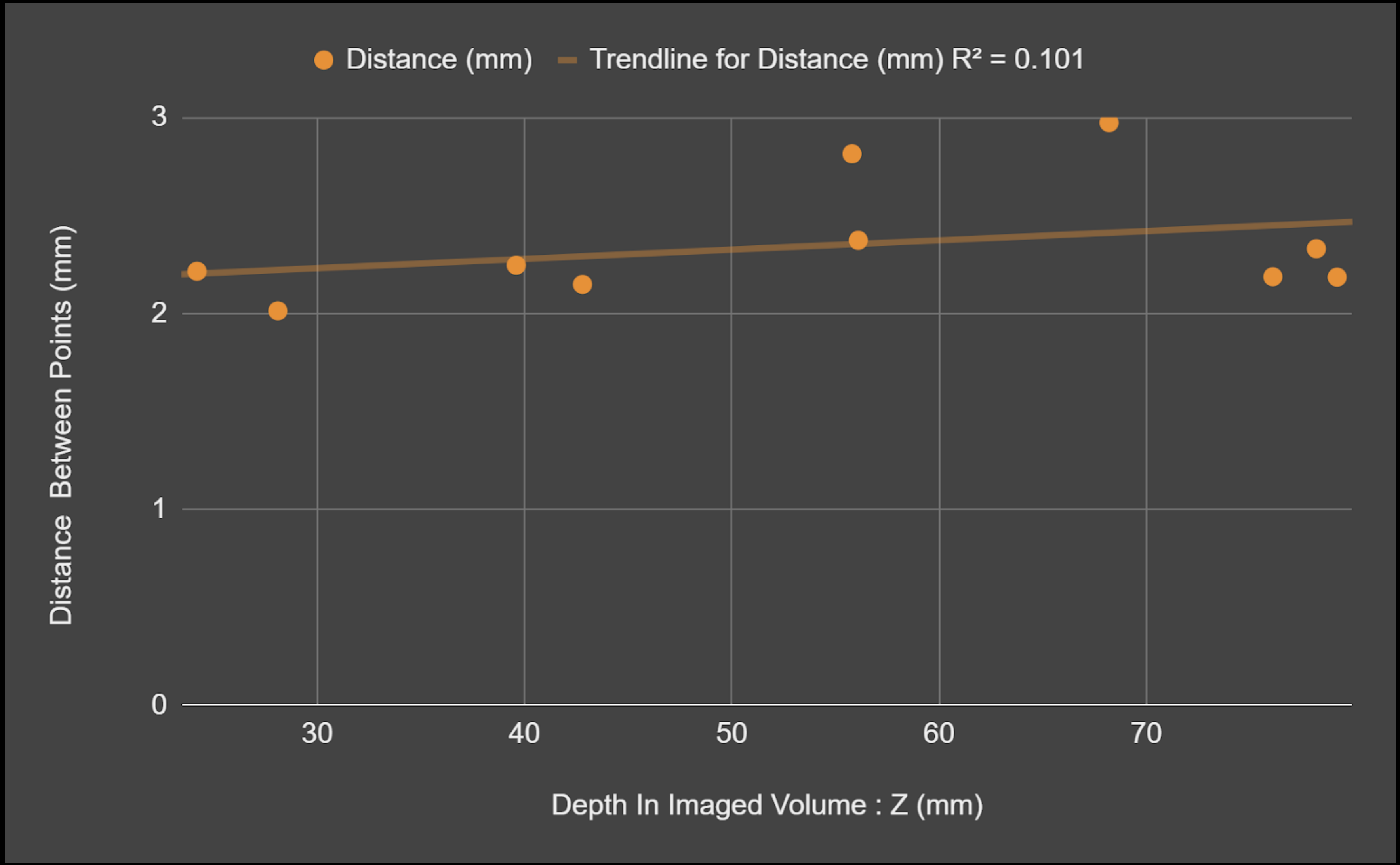


Measuring the same branch segment 10 times in Different locations of the field of view and distance to the camera

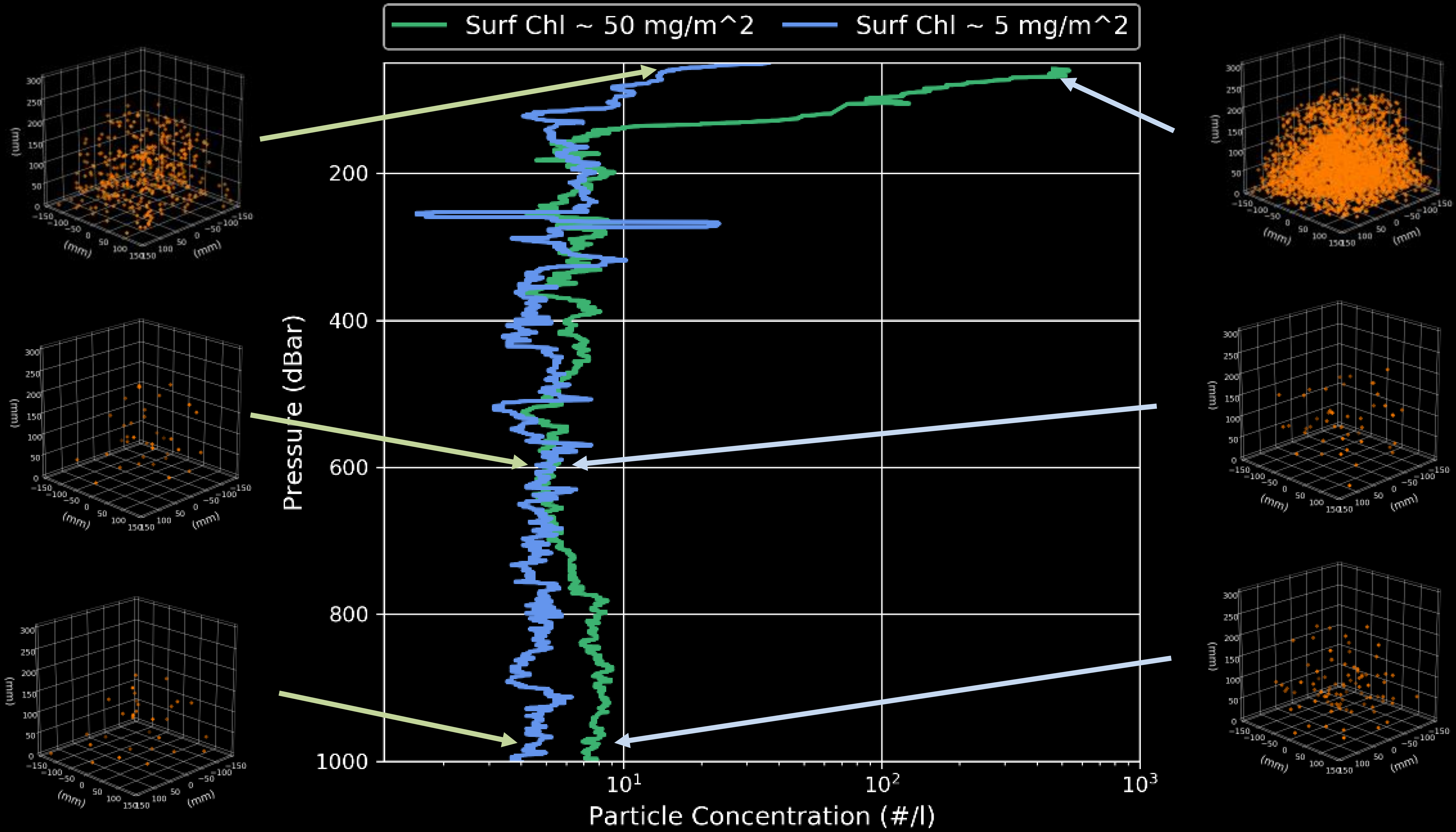
Measurement Location

Measurement Repeatability

Mean = 2.34 mm
Standard Deviation = 0.3 mm

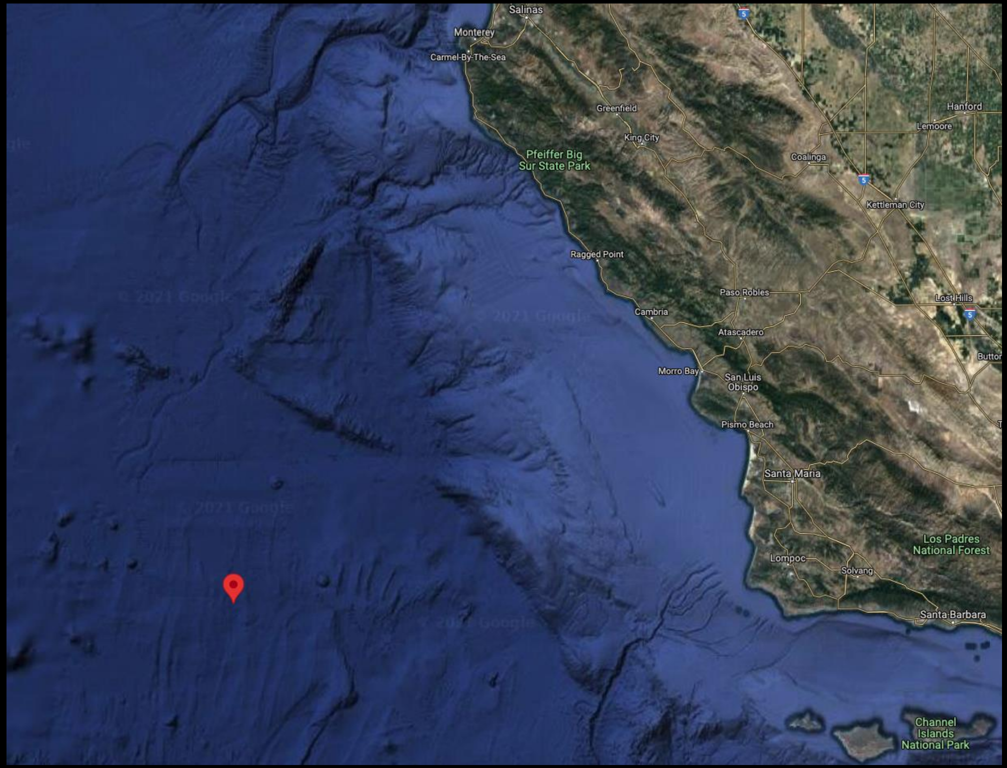


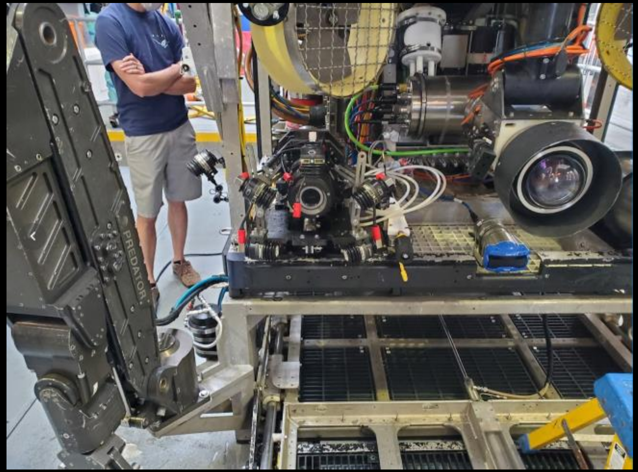
3D Particle Statistics



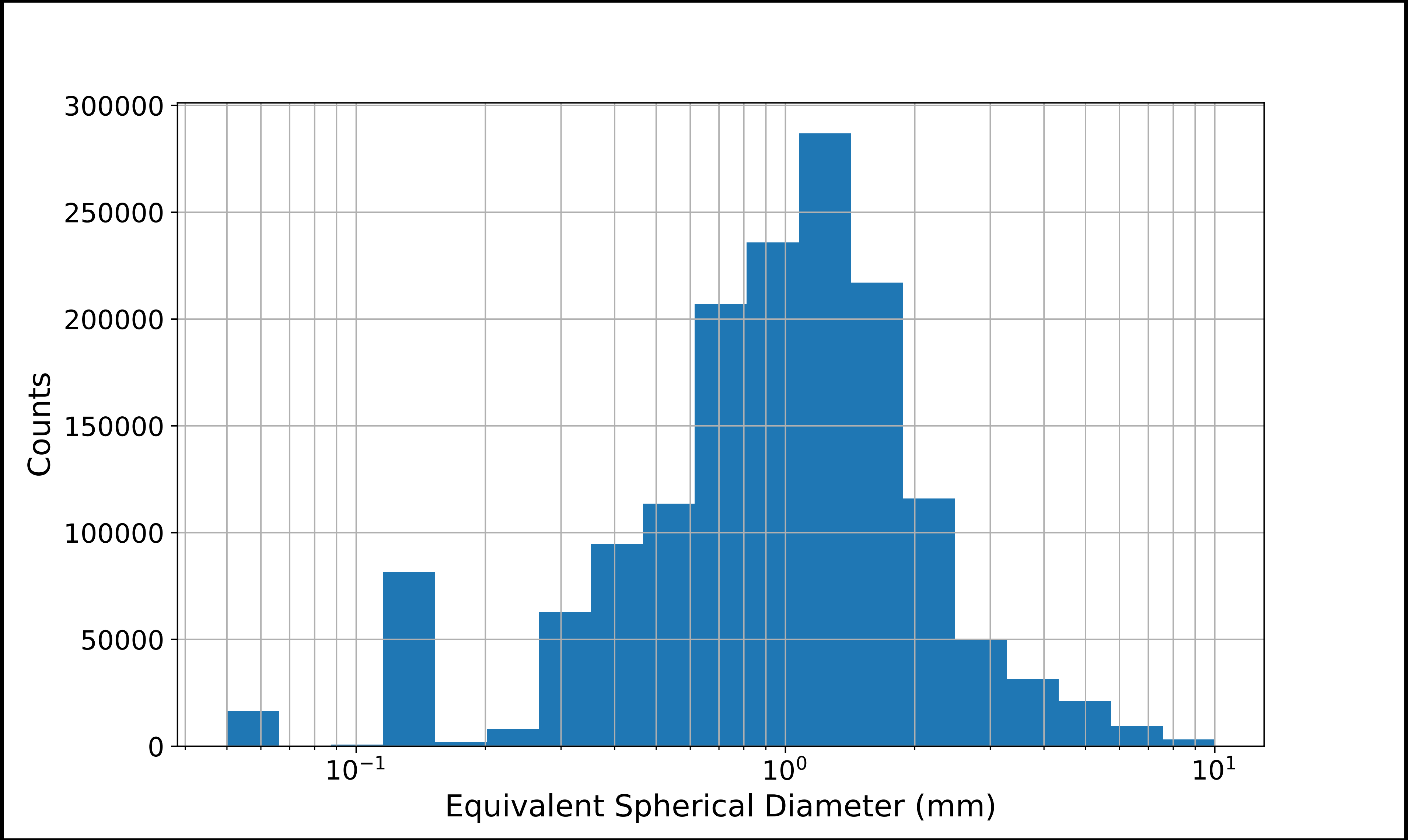
Particle Size Estimation (EyeRIS at Station-M)

- Abyssal monitoring station
- Deployed on ram
- Dives to 4000m

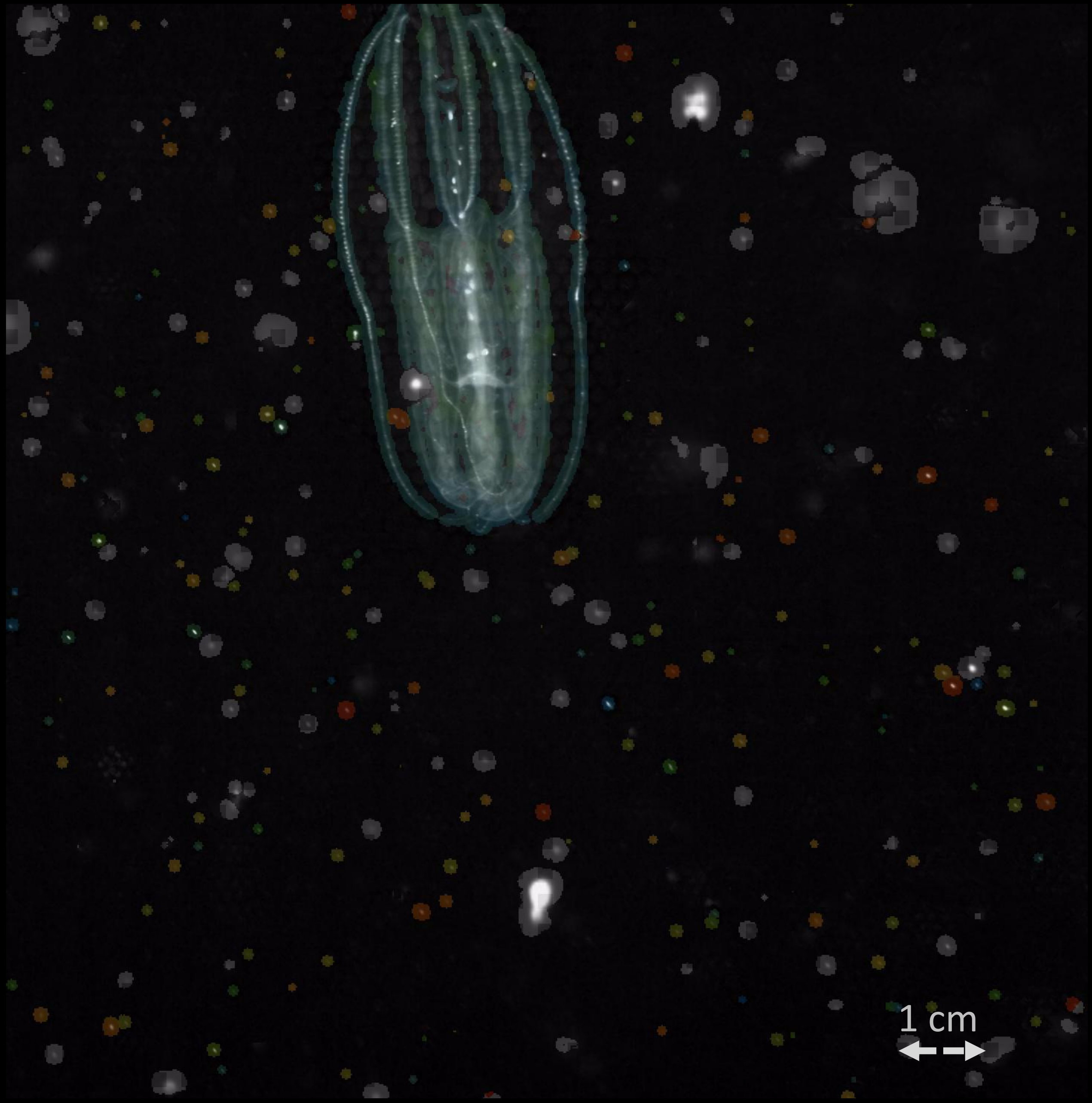




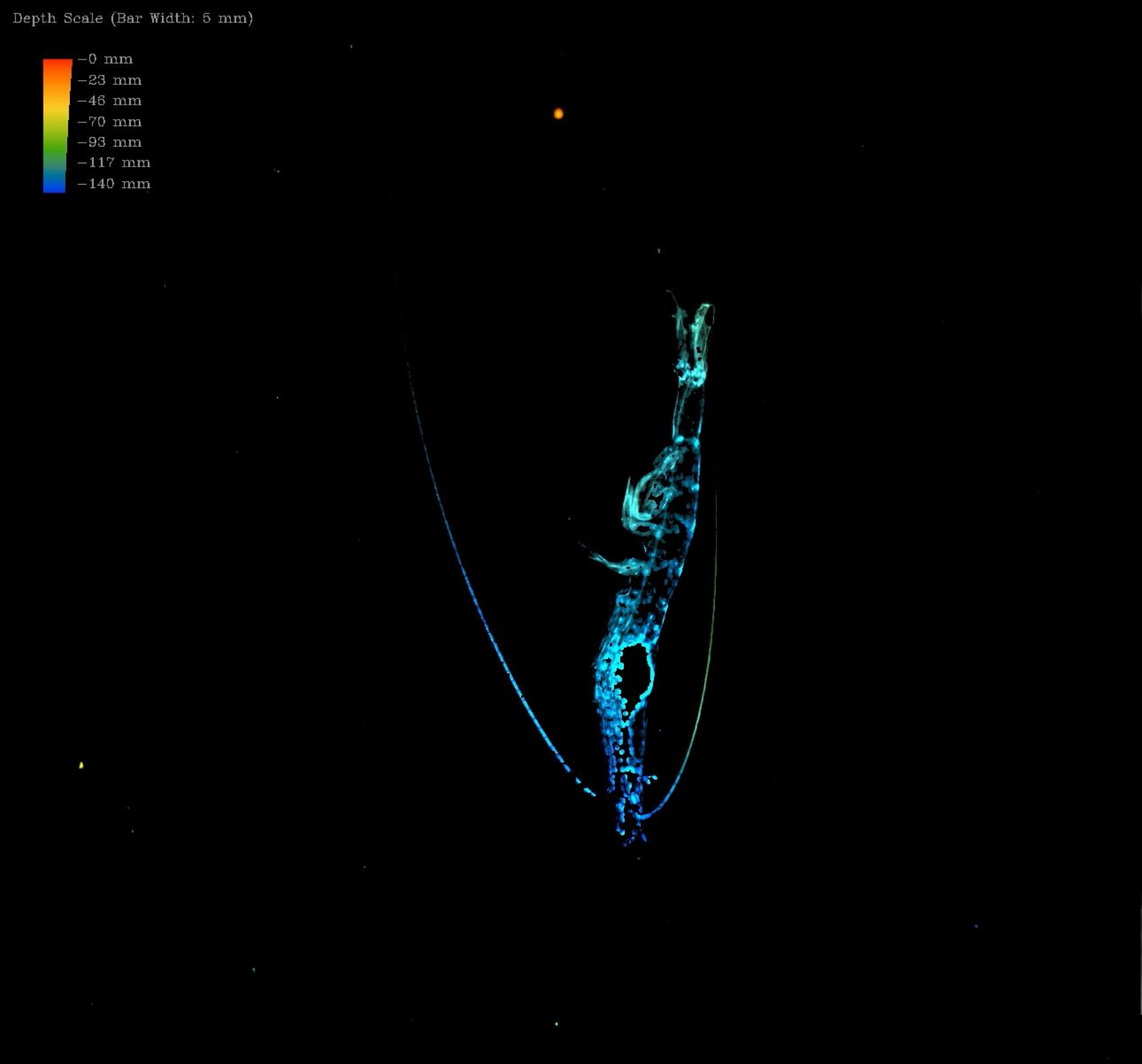
EyeRIS at Station-M

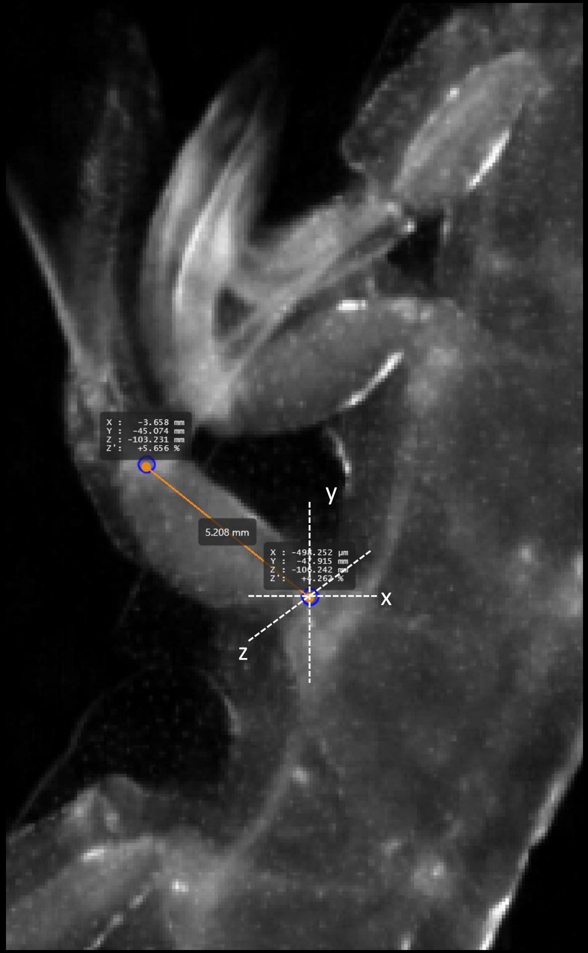


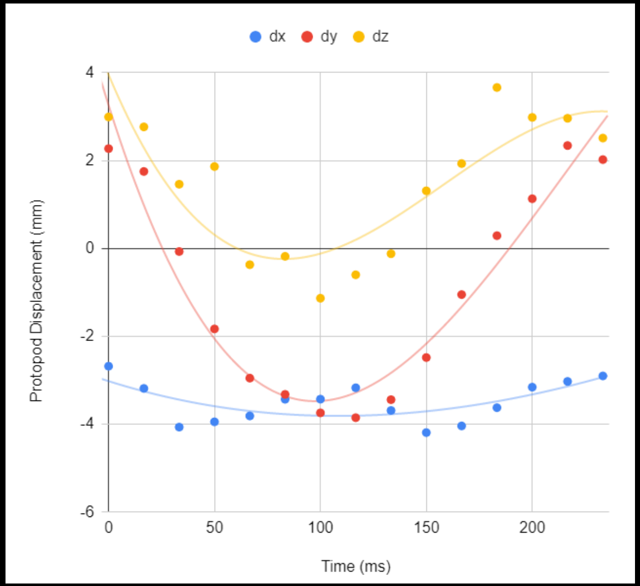
Copepod Escape Response to Ctenophore



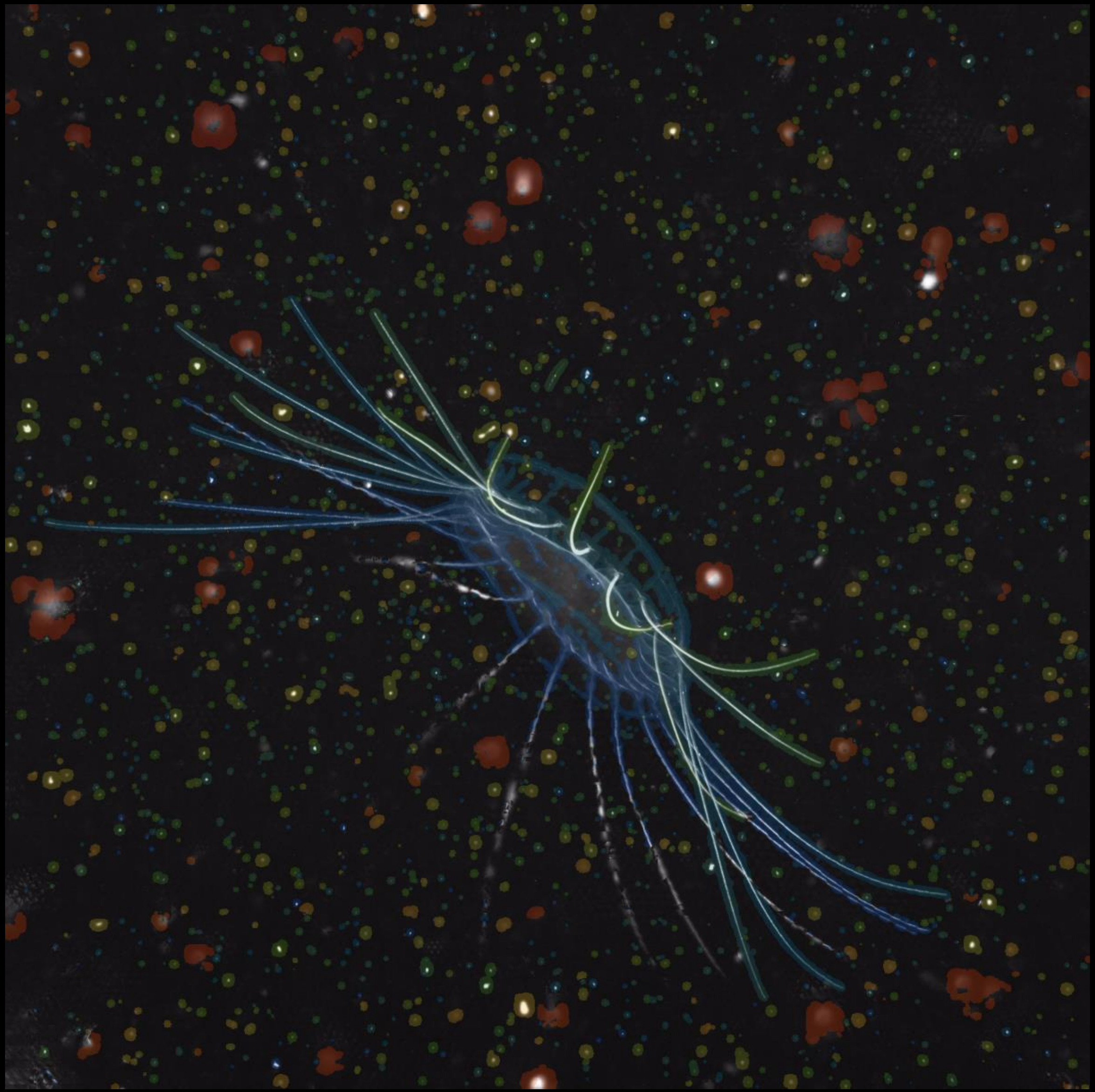
Observations of pasiphaeid Ecomechanics







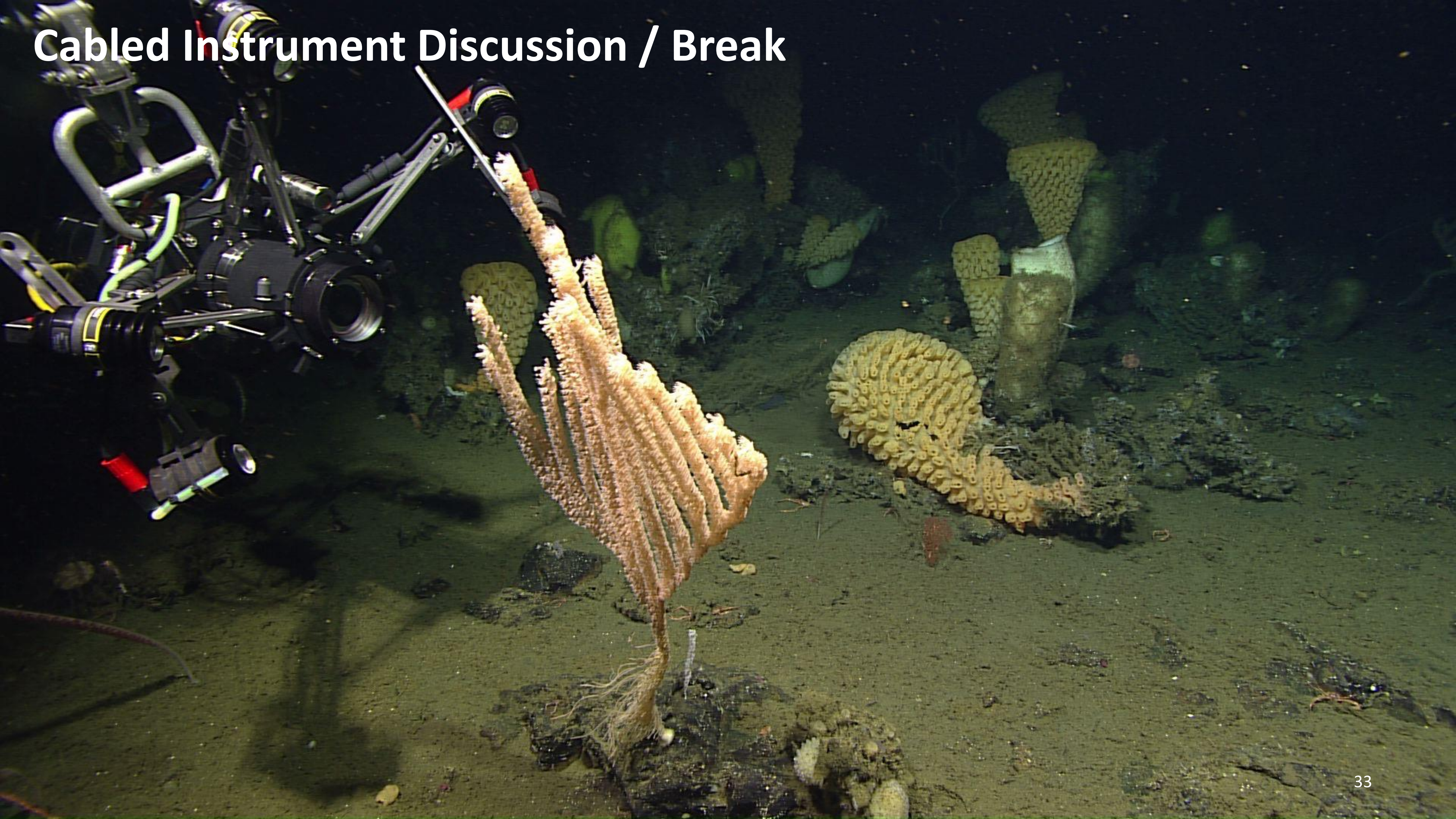
Visualization of Surface-Fluid Interactions: Solmissus & Gonatus



Cabled Instrument Data Summary

- Measurement repeatability on crinoid
- Particle concentration profiles from Monterey Bay
- Particle size spectra during benthic transects at station-M
- Copepod escape response to ctenophore swimming
- Echomechanics of pasiphaeid shrimp
- Visualization of surface-fluid interactions of gonatus squid and solmissus jelly

Cabled Instrument Discussion / Break

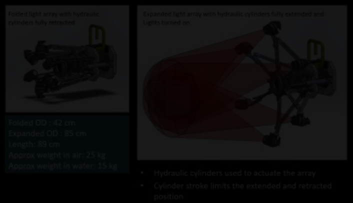


Autonomous Instrument Timeline

MiniROV / WF

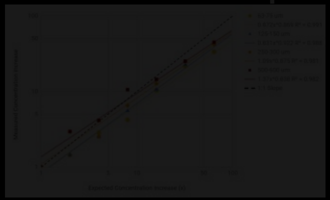
Apr 2019

Cabled Instrument
Preliminary Design Review



Jun 2019

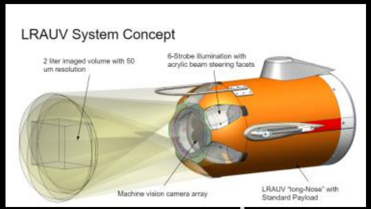
Aug 2019

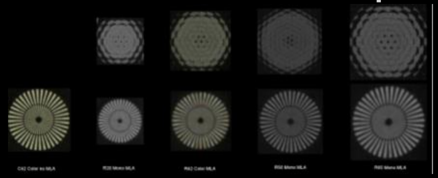


Marine Imaging Workshop 2019
3D particle counting lab studies

Nov 2019

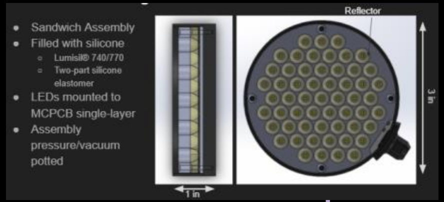
Concept for AUV system





Visit to Raytrix, Camera Selection

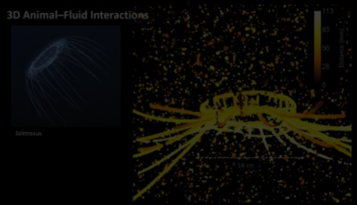
Jan 2020



Strobe Concept Review

Feb 2020

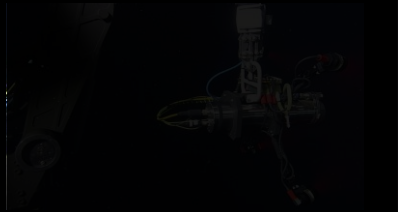
Apr 2020



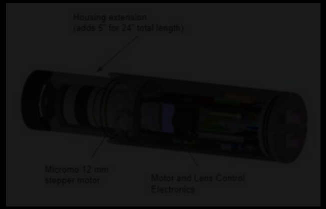
Ocean Sciences 2020

Jun 2020

Deployment on
ROV Doc Ricketts / WF



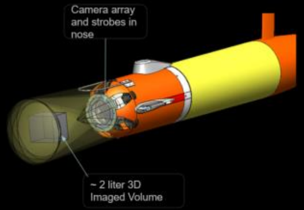
Aug 2020



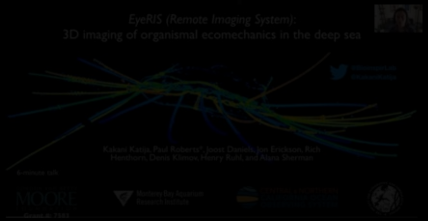
Zoom Lens Addition

Oct 2020

LRAUV Integration
Preliminary Design Review



Jan 2021



SICB 2021

Mar 2021

LRAUV Payload
Completed Drawings

May 2021

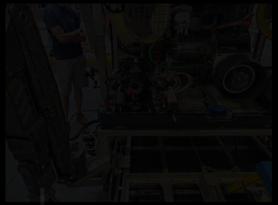
Deployment on ROV
Doc Ricketts / WF

July 2021

Deployment on ROV Ventana / RC

Aug 2021

Deployment on ROV
Doc Ricketts / WF



Oct 2021

Deployment on ROV SuBastian / FK

Nov 2021

Deployment on LRAUV

Design Review
Field Deployment
Synthesis and Dissemination

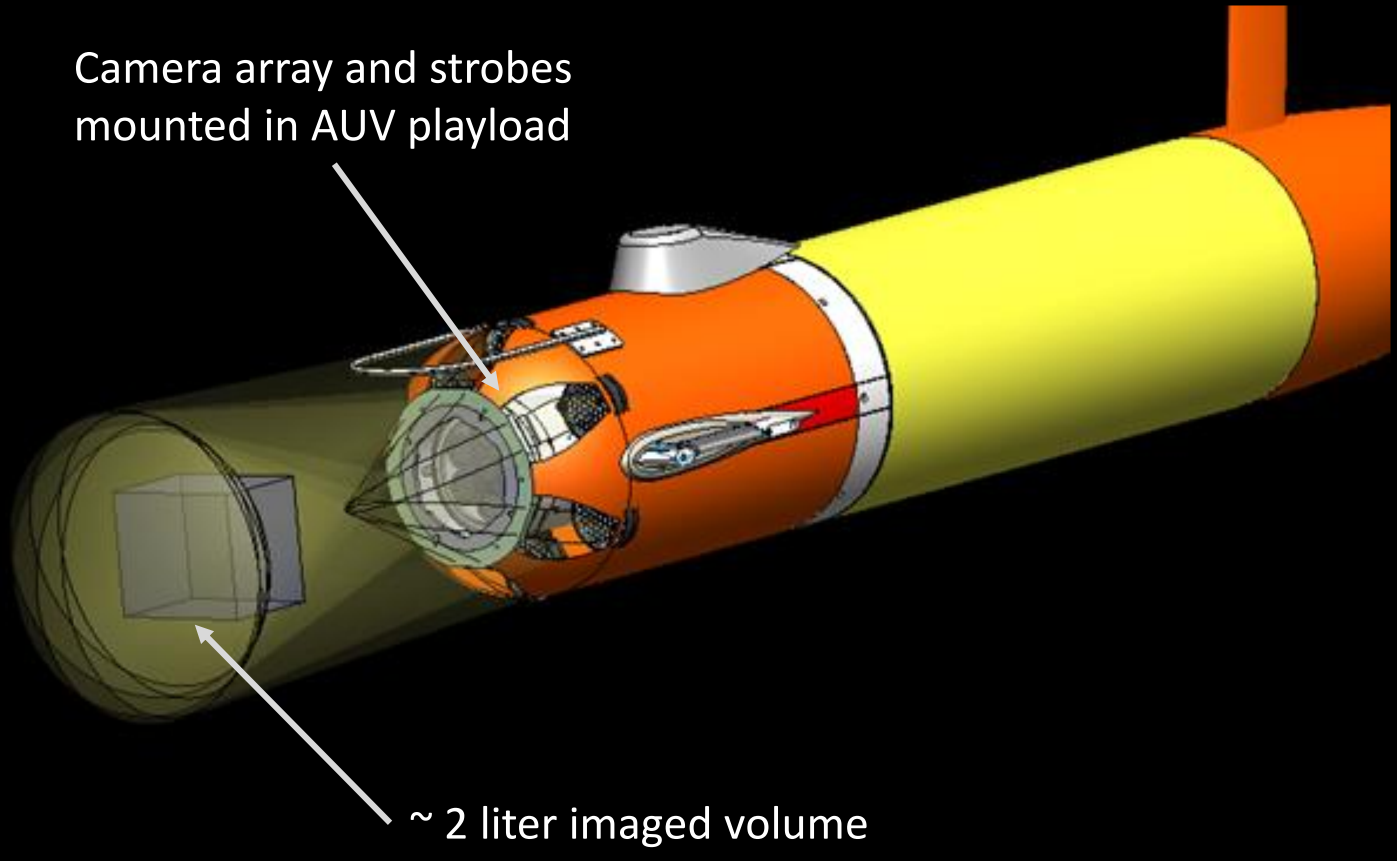
MBARI’s Tethys Long Range AUV

- Multi-Mission Payloads
- Long Range/Endurance
- Inter-vehicle acoustic positioning and communication for collaborative operations
- Lagrangian observation
- Mature system with over 22,000 hours offshore across 12 vehicles
- Collaborations and licensing with U-Hawaii and WHOI

Autonomous Instrument Concept

Three-dimensional, small-scale, high-resolution imaging of plankton, particles, and fluid dynamics on autonomous vehicles

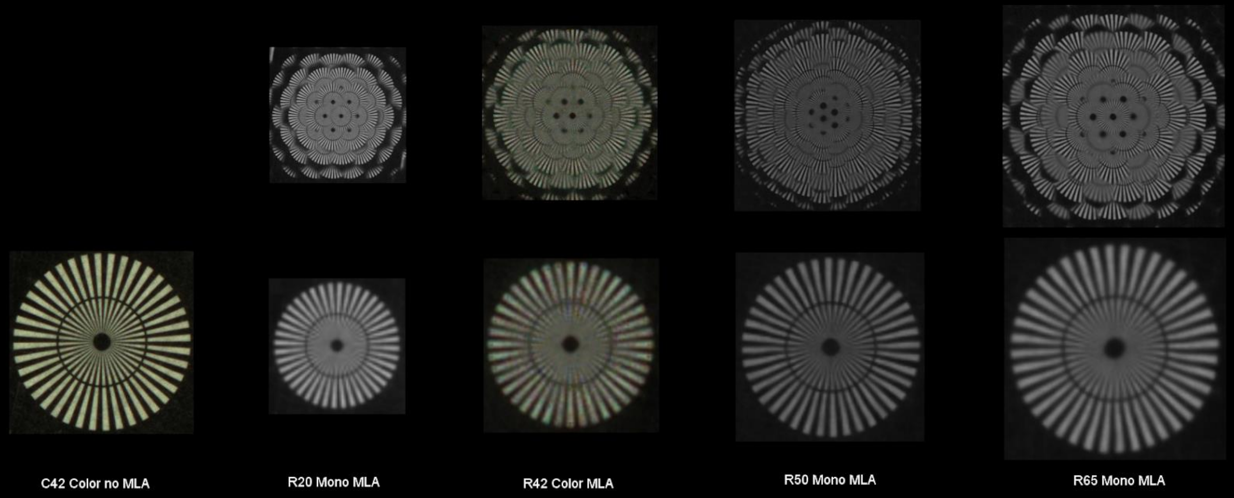
Autonomous EyeRIS = AyeRIS

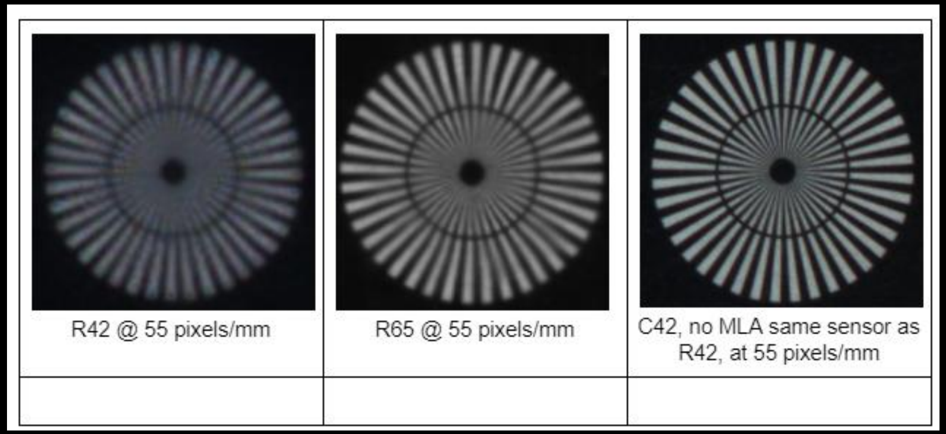


Autonomous Instrument

- Key requirements
  - Self-contained and can integrate into vehicle payload and retain streamlined profile
  - Power requirements allow for deployment durations of days to weeks
  - Sufficient light to image millimeter-sized objects/particles without motion blur at typical vehicle speeds of 1 m/s
  - Real time object detection and processing
- Key challenges
  - Embedded camera / compute hardware
  - High peak power requirements for flash exceed vehicle power bus
  - Limited space and weight

AUV Camera Selection

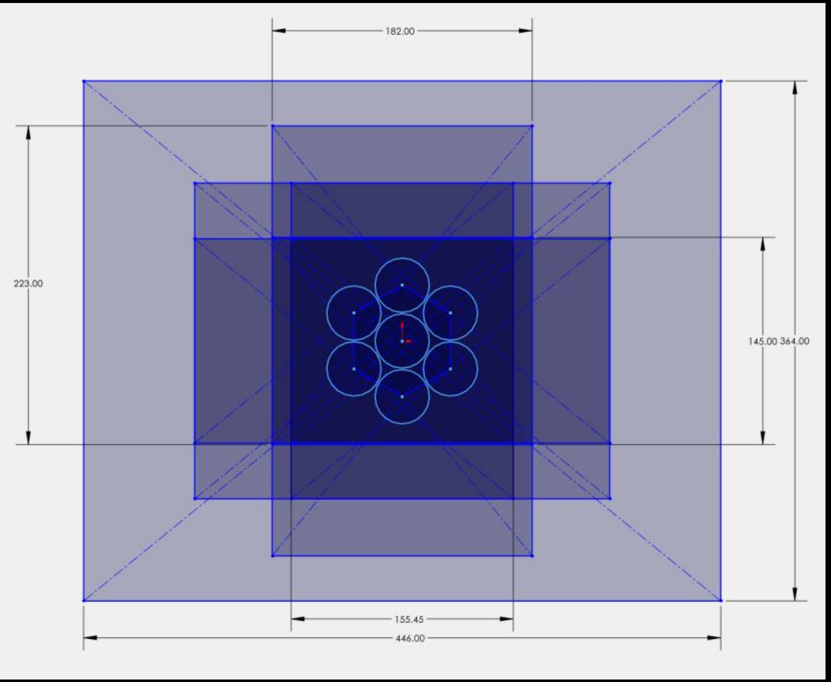




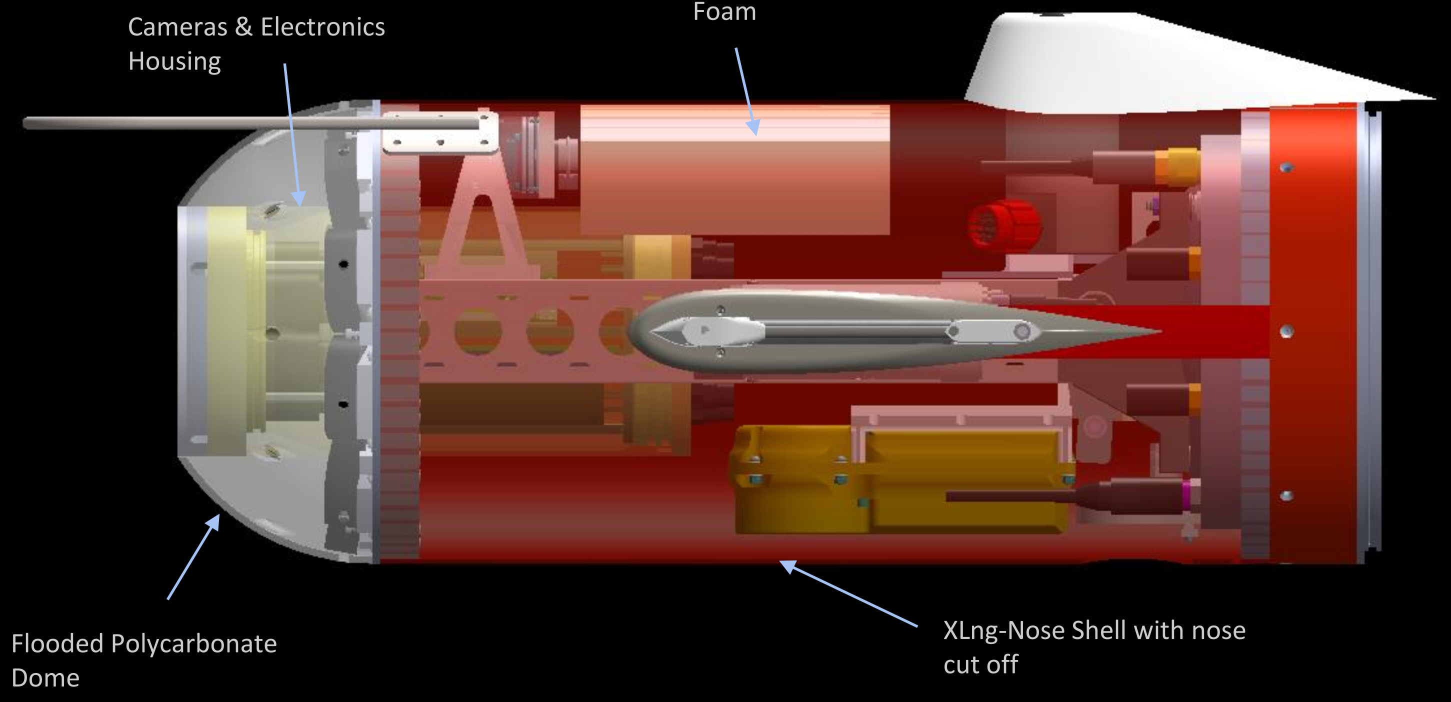
- Spent a week with Raytrix in Nov 2019
- Tested all available cameras for image quality
- Determined the only suitable camera for AUV deployment (R42) has insufficient image quality due to color filter interactions with microlens array

Imaging System Geometry

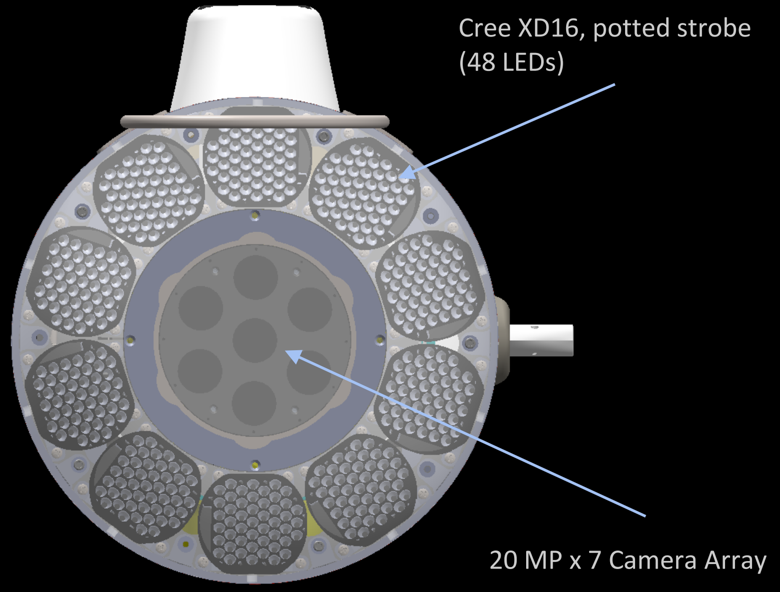
- 6 IMX183 MIPI cameras
  - 16 mm Fujinon lens
  - 28 cm x 18 cm FOV (50 um res)
- 1 IMX183 USB3 camera with 100 um resolution
  - 8 mm fujinon lens
  - 55 cm x 36 cm (100 um res)
- Want to retain streamlined profile of the vehicle



Mechanical Design: Overview

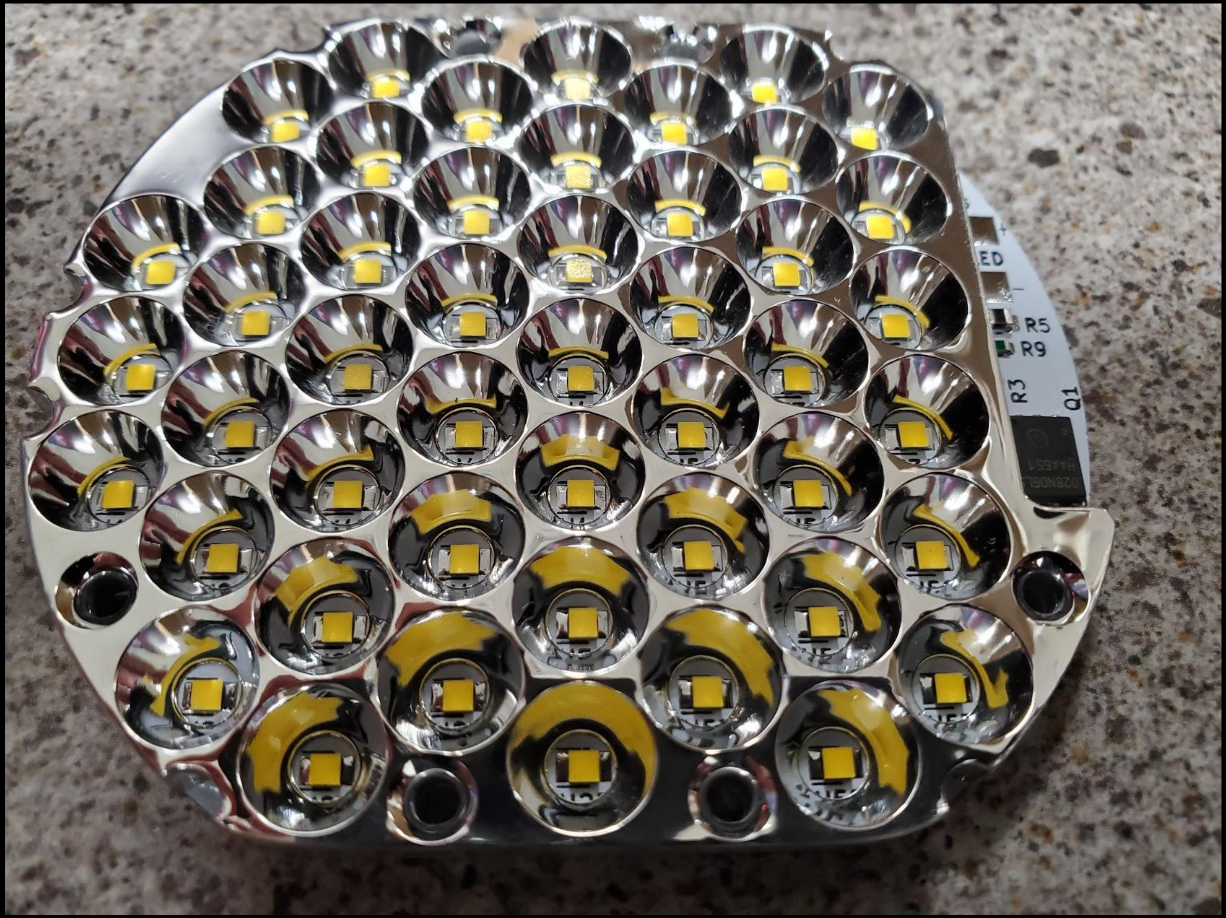


Side View

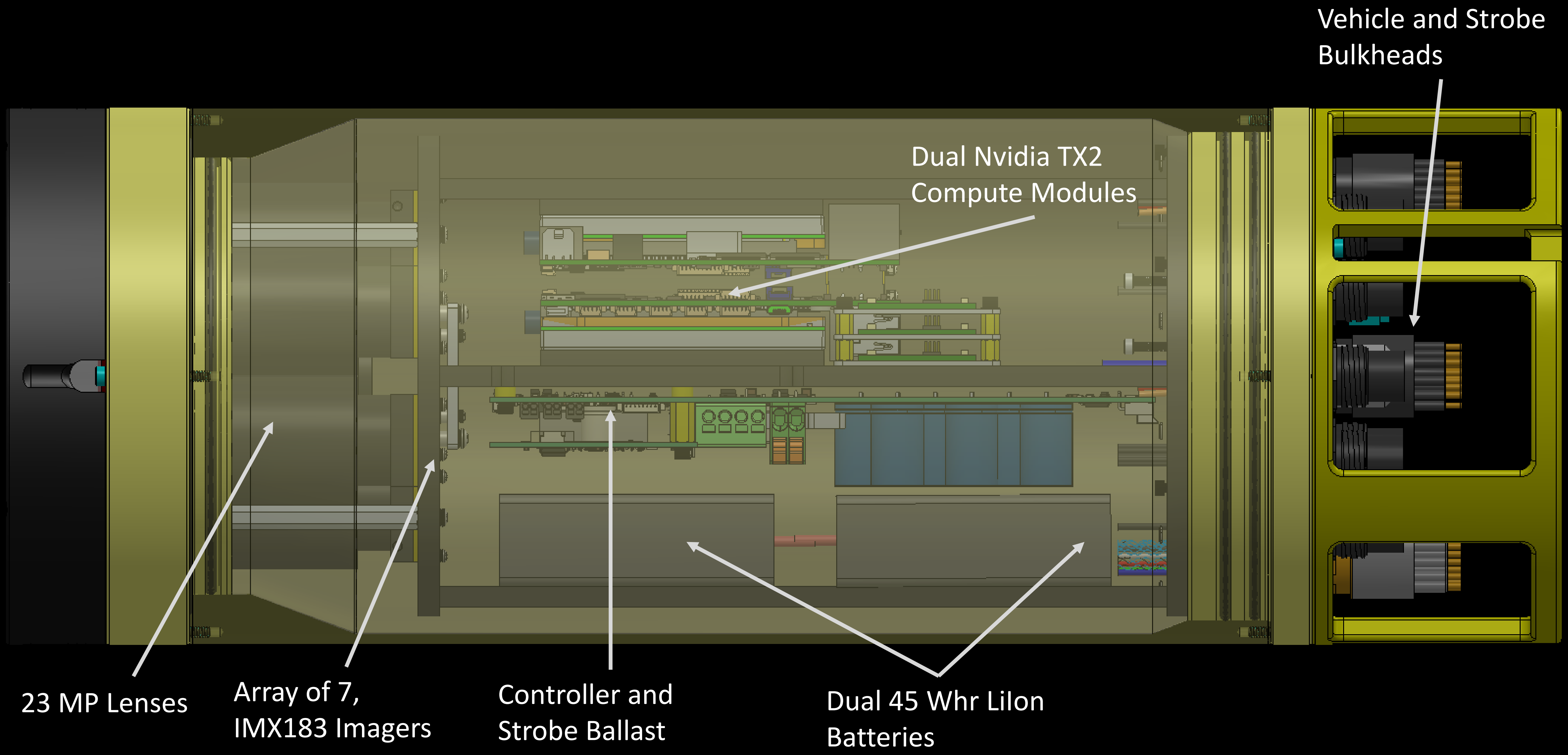


Front View

Mechanical Design: 3D Printed LED Reflectors

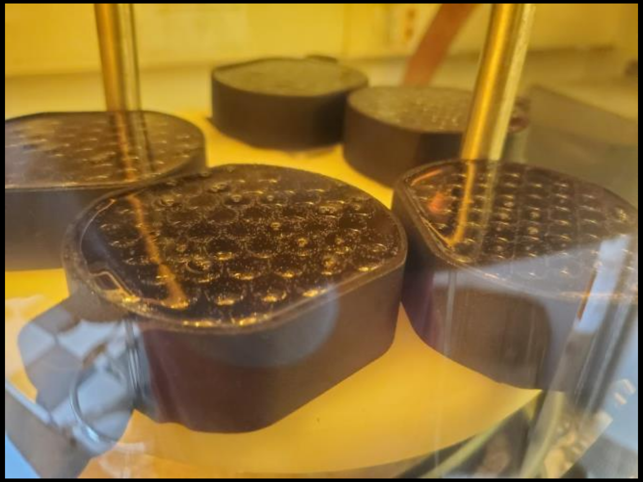


Mechanical Design: Camera and Electronics (300m)



AyeRIS Integration on LRAUV

Strobe vacuum potting



AyeRIS Endcap

Mounted payload

Chassis and Internal Assembly

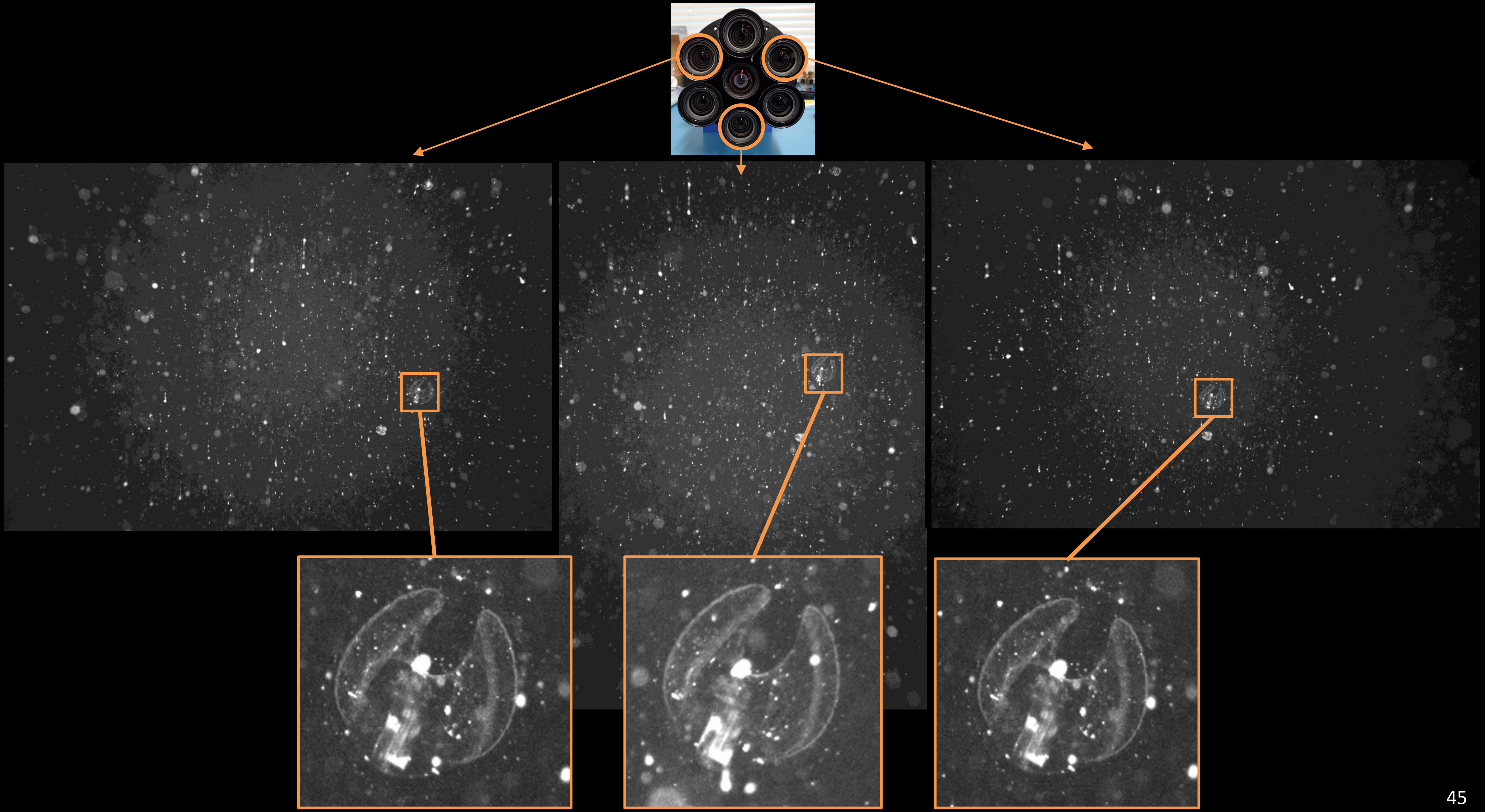
Payload, 10 strobes, 7 cameras

Testing in MBARI’s tank

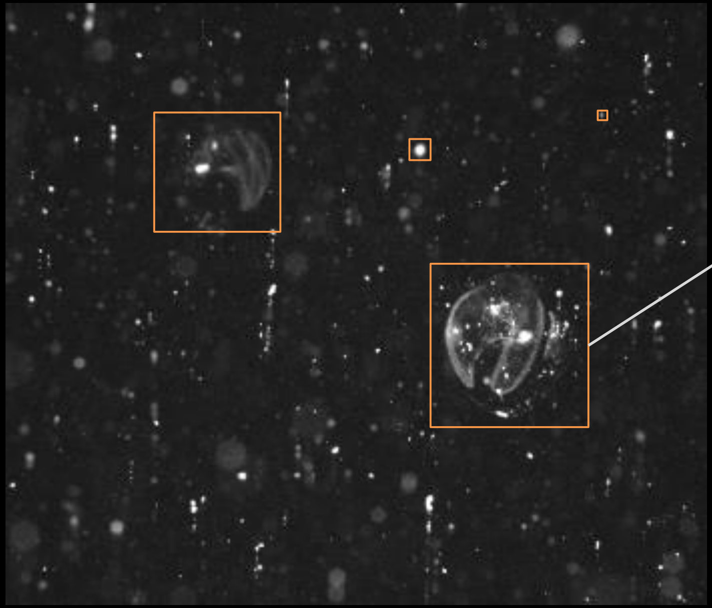
Deployment on LRAUV Galene

- Deployed for 48 hours in Monterey Bay
- New vehicle missions were created on shore and sent to the vehicle over cell network
- Tested several vehicle behaviors
  - circular profiles around waypoints
  - Yoyo transect between waypoints
  - Station keeping
- Recorded over 4TB of data, stored locally on the instrument

Preliminary Example Images from Camera Array



Realtime object detection and 3D Localization

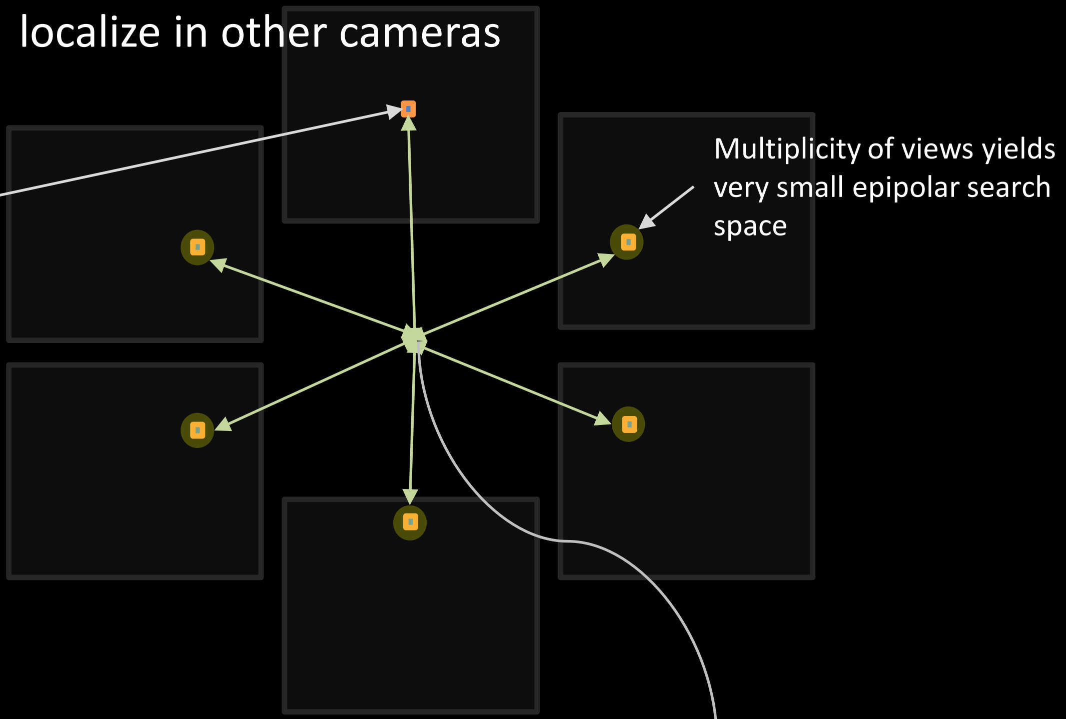


For each camera frame and each camera detection…

Store object coordinates, timestamp, and features as roi_record

```
{
  bounding_box :   [top, left, width, height],
  timestamp:       unixtime in microseconds,
  camera_id:       0-6 number of camera
  region_props:    [eccentricity, angle, are
}
```

Match detections across epipolar lines to localize in other cameras



[x,y,z,roi_records]

Store list of matching objects and triangulate to estimate 3D position

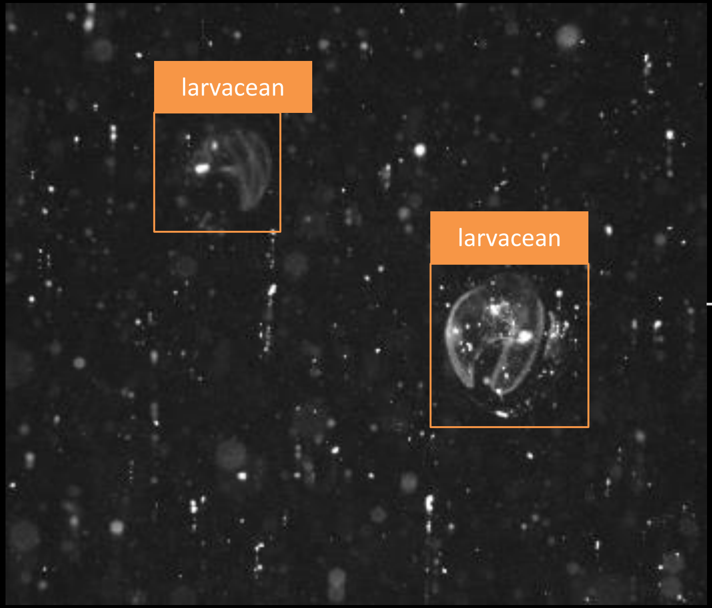
Enumerate and Distribute

LRAUV Data Slate (Realtime)

Particle Logs (at surface)

LRAUV Image transfer (at surface)

Realtime object detection and supervised autonomy



Run an on-board object detector

Collate counts from images

```
{
  larvacean :   2,
  copepod:      0,
  jelly:        0,
  aggregate:    0,
}
```

Update vehicle behavior

```
if num_larv > threshold:
    stop yoyo
    signal partner LRAUV
```

Enumerate and Distribute

LRAUV Data Slate (Realtime)

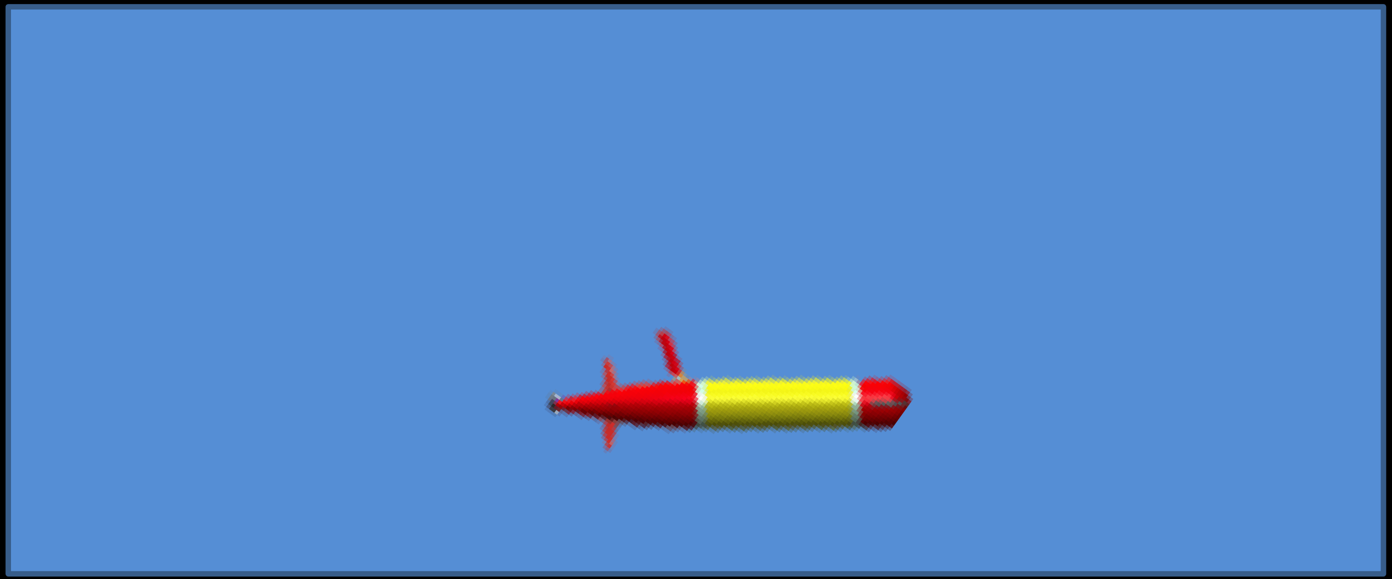
Object Logs (at surface)

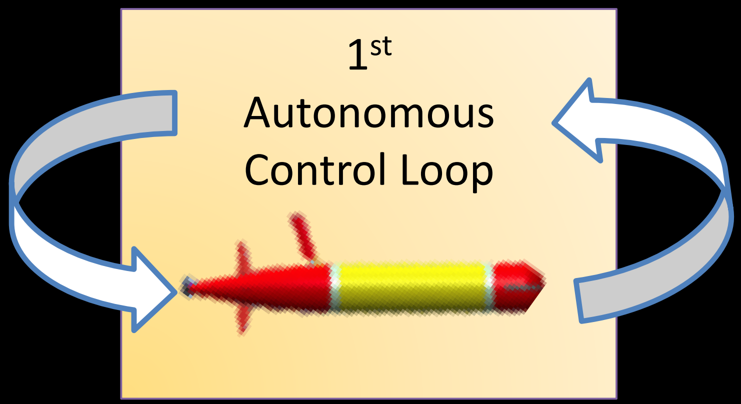
LRAUV Image transfer (at surface)

Human operator confirms behavior change

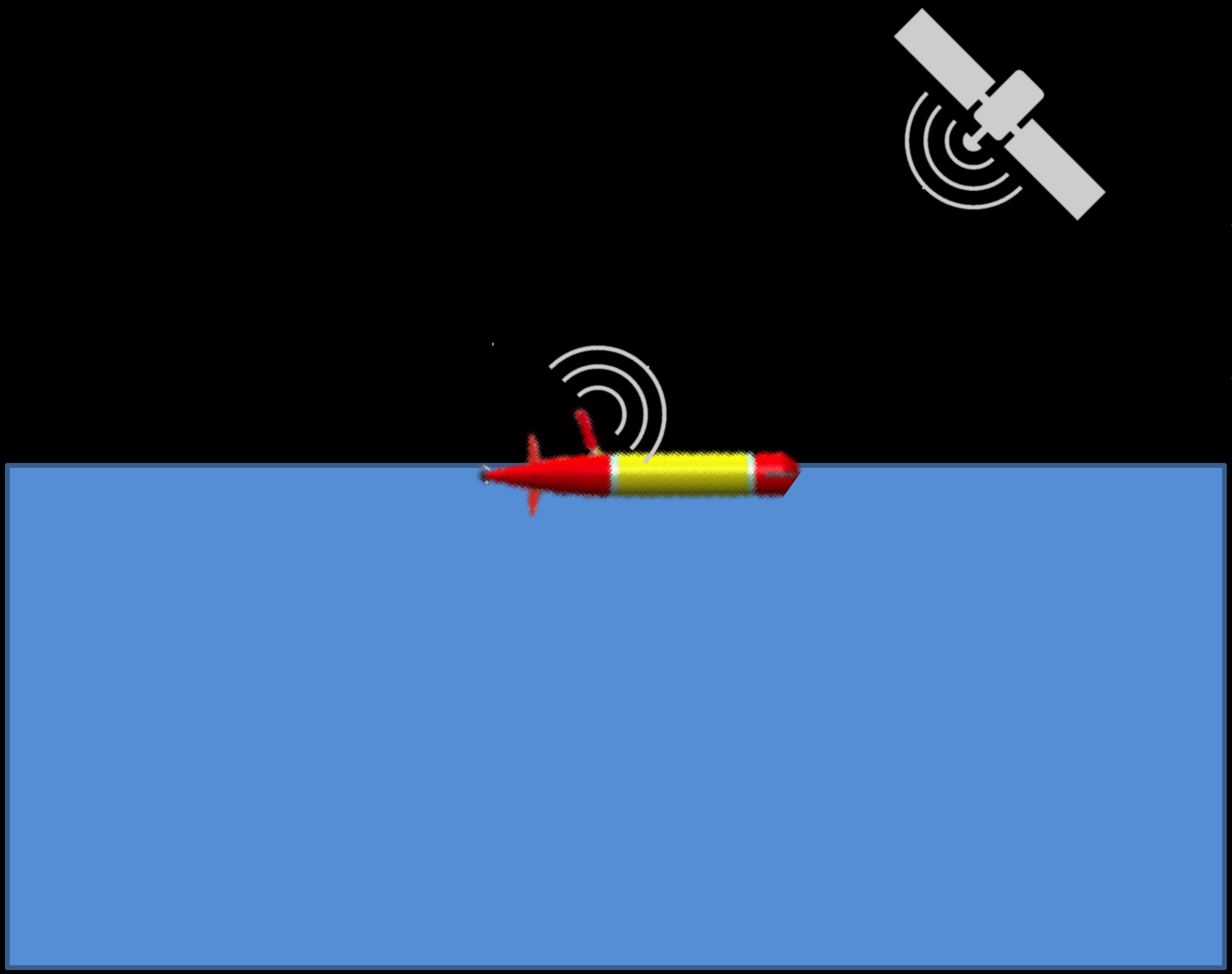
Supervised autonomy

When the vehicle is underwater, we do not know what is going on



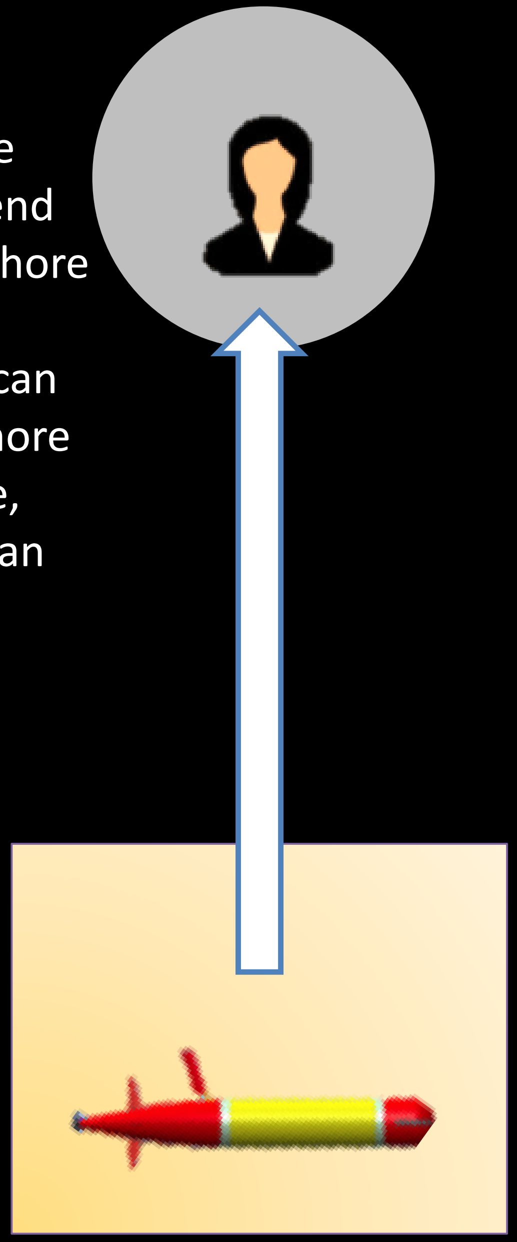


Supervised autonomy

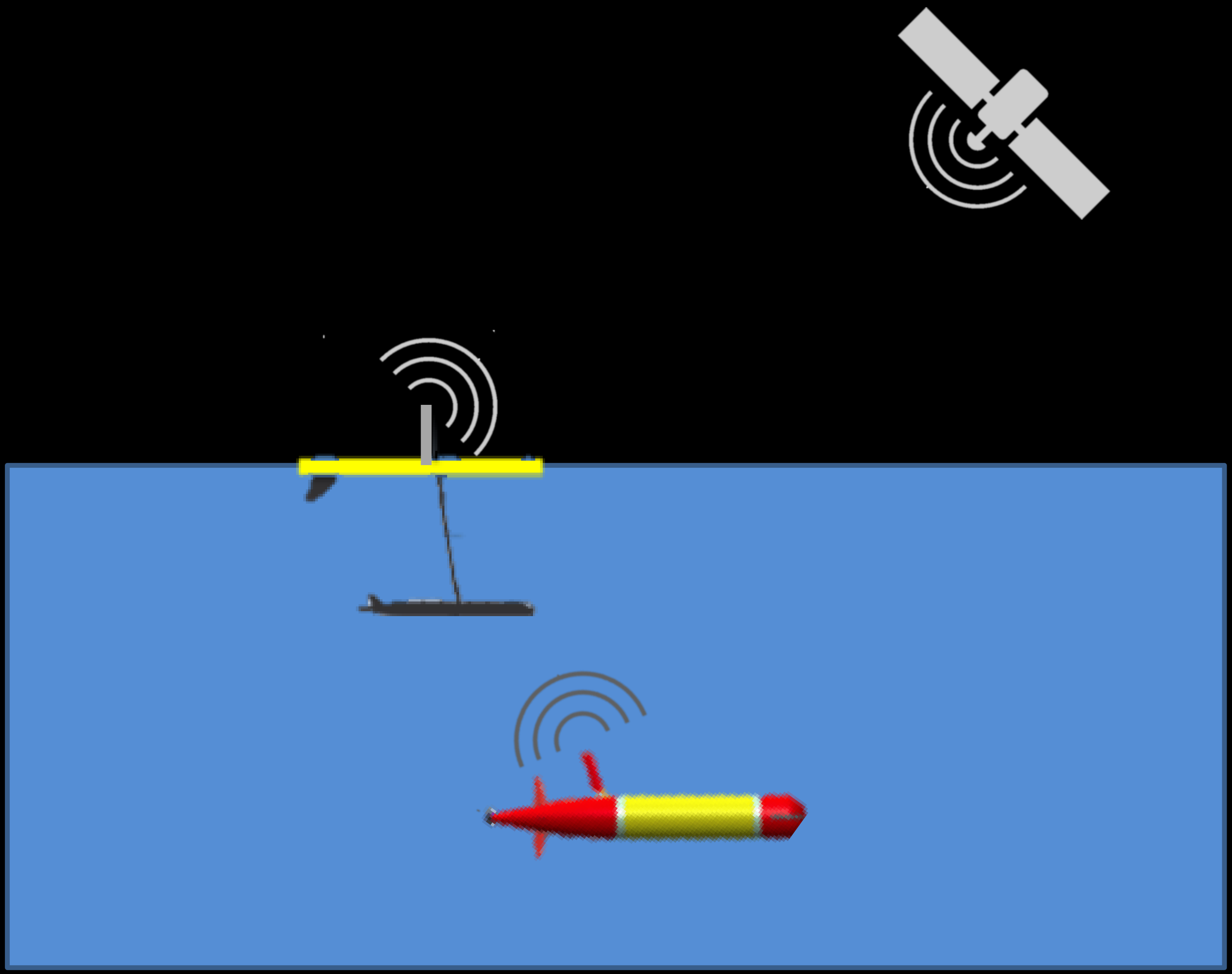


Only when it reach the surface, it is able to send some information at shore

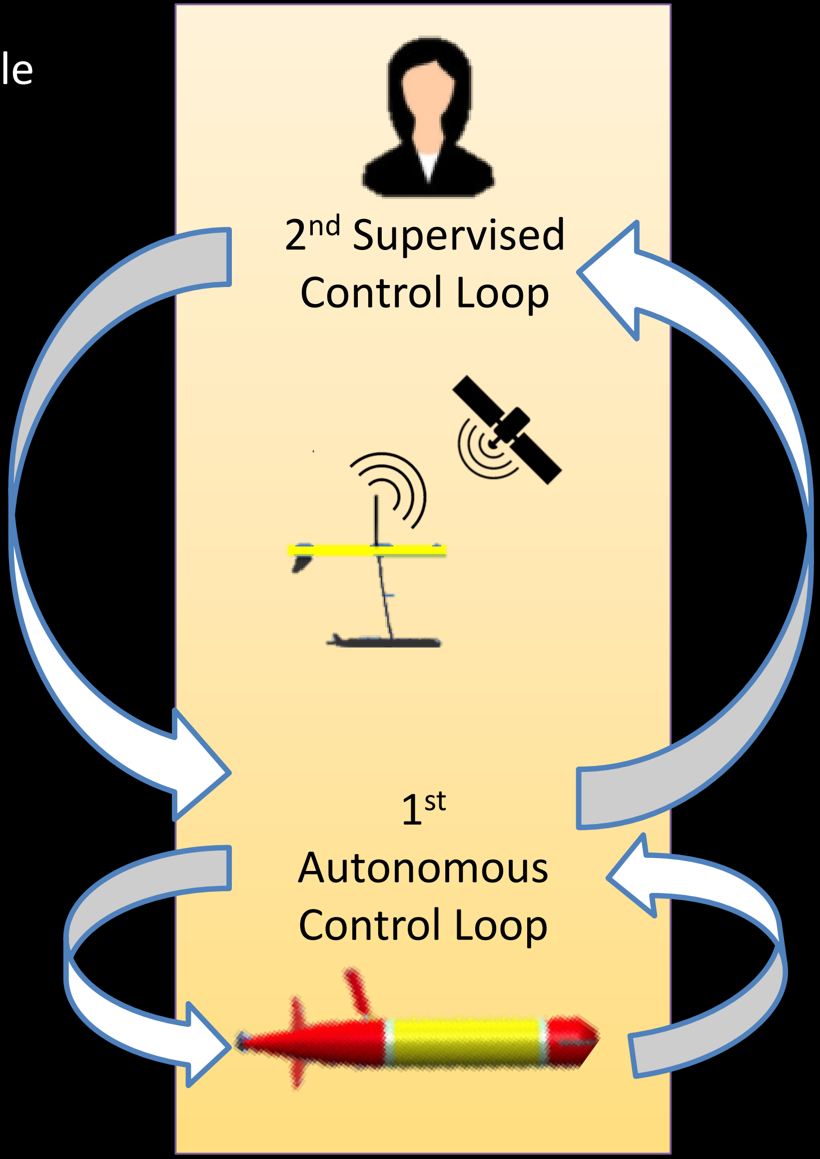
However, the vehicle can stay underwater for more than 24h. For example, conducting a Lagrangian movement to follow a thermal front



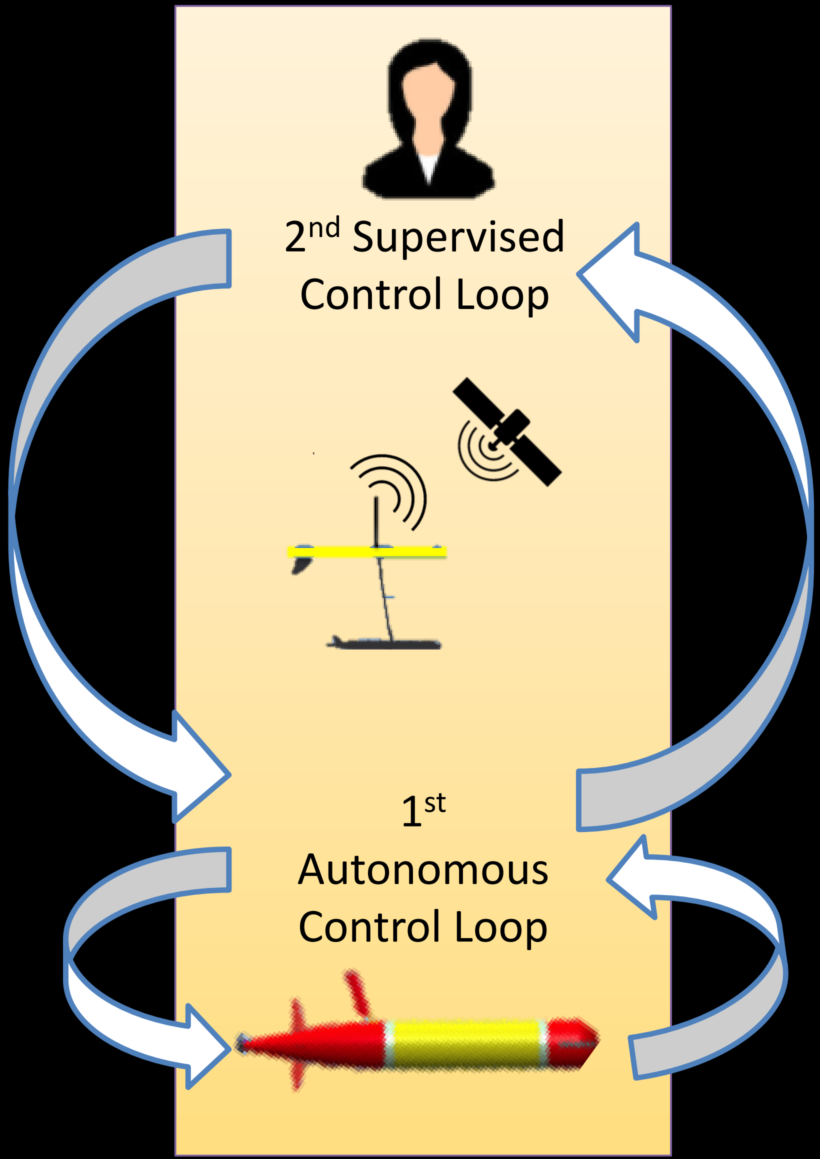
Supervised autonomy



Multi-vehicle approach



Supervised autonomy



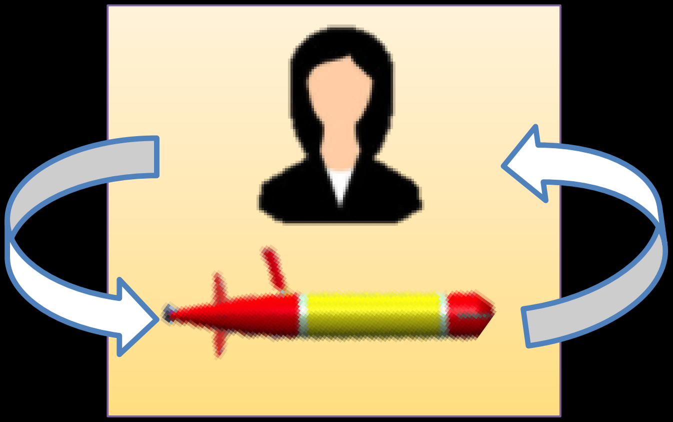
1st Autonomous Control Loop:

- Fast response time
- Automatic mission change based on in situ measurements

2nd Supervised Control Loop (Human-in-the-loop):

- Real-time human interaction
- Validating (or invalidating) an output
- Fine tune hyperparameters
- Define new missions on the fly

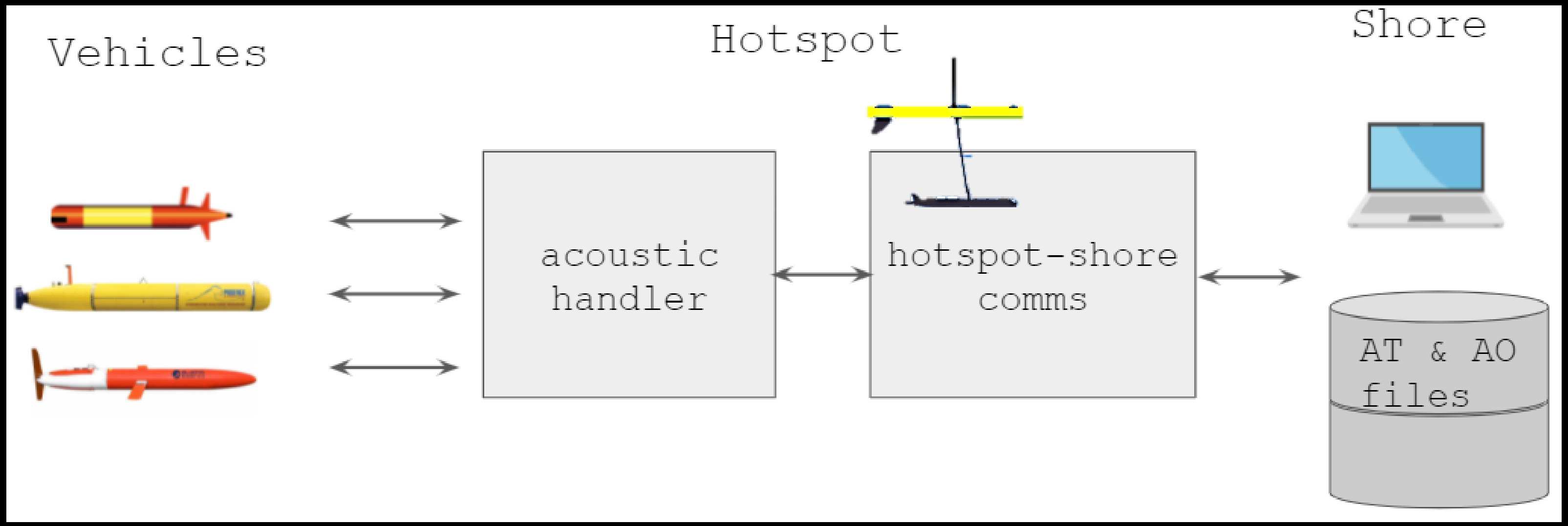
Supervised autonomy

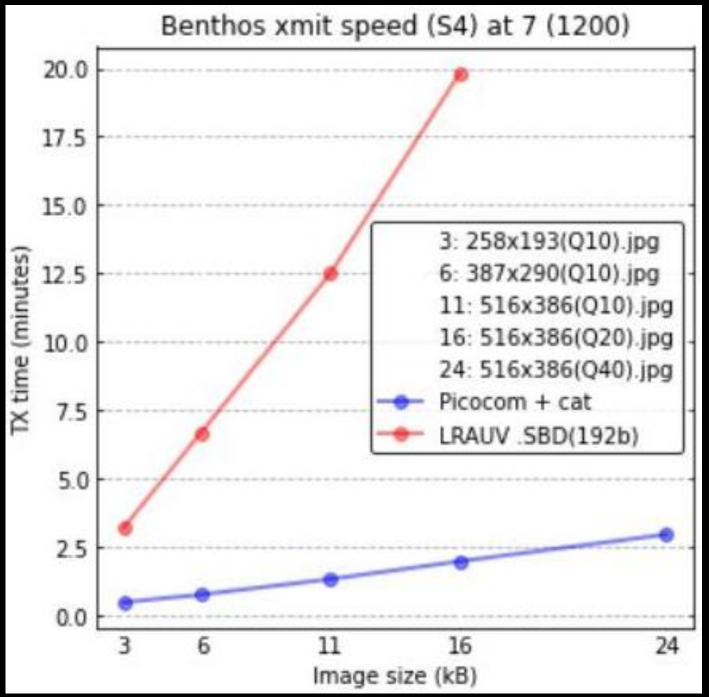


To create this supervised autonomy system two aspects are key:

1- To have bidirectional communications between the LRAUV and the on shore server while the vehicle is underwater

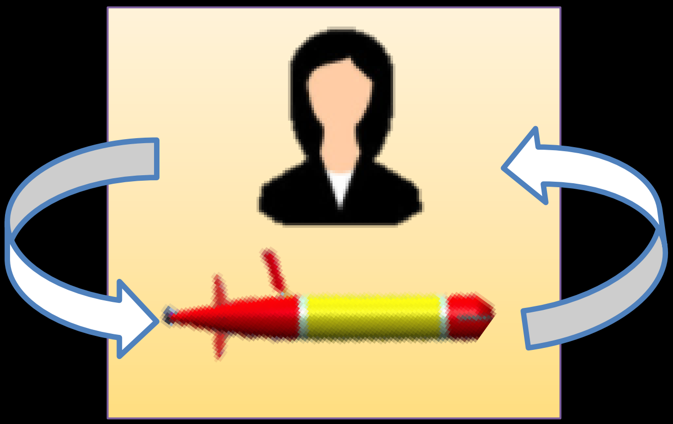
Hotspot Acoustic Relay system:





Status: we just completed the first field tests yesterday.

Supervised autonomy

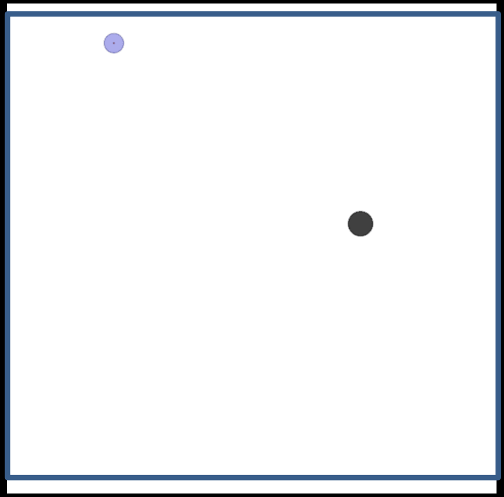


To create this human-in-the-loop system two aspects are key:

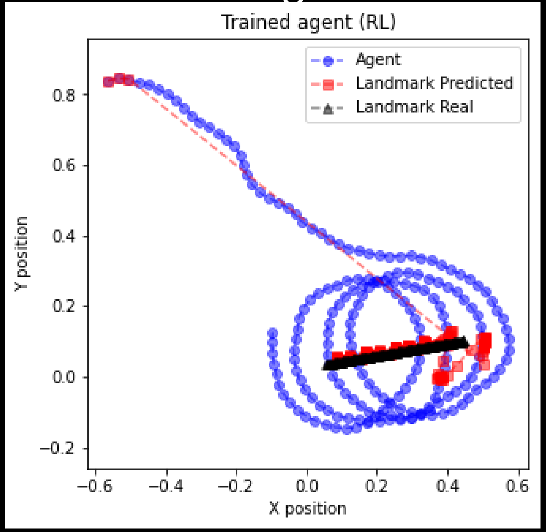
2- To have a great localization/tracking system between vehicles

Studying Reinforcement Learning methods to train an agent to learn the best policy for both tracking and communication purposes:

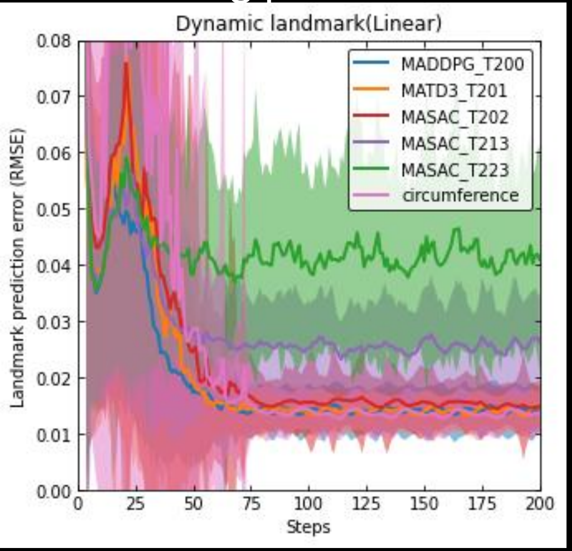
Trained agent in action



Trained agent result



Tracking performance

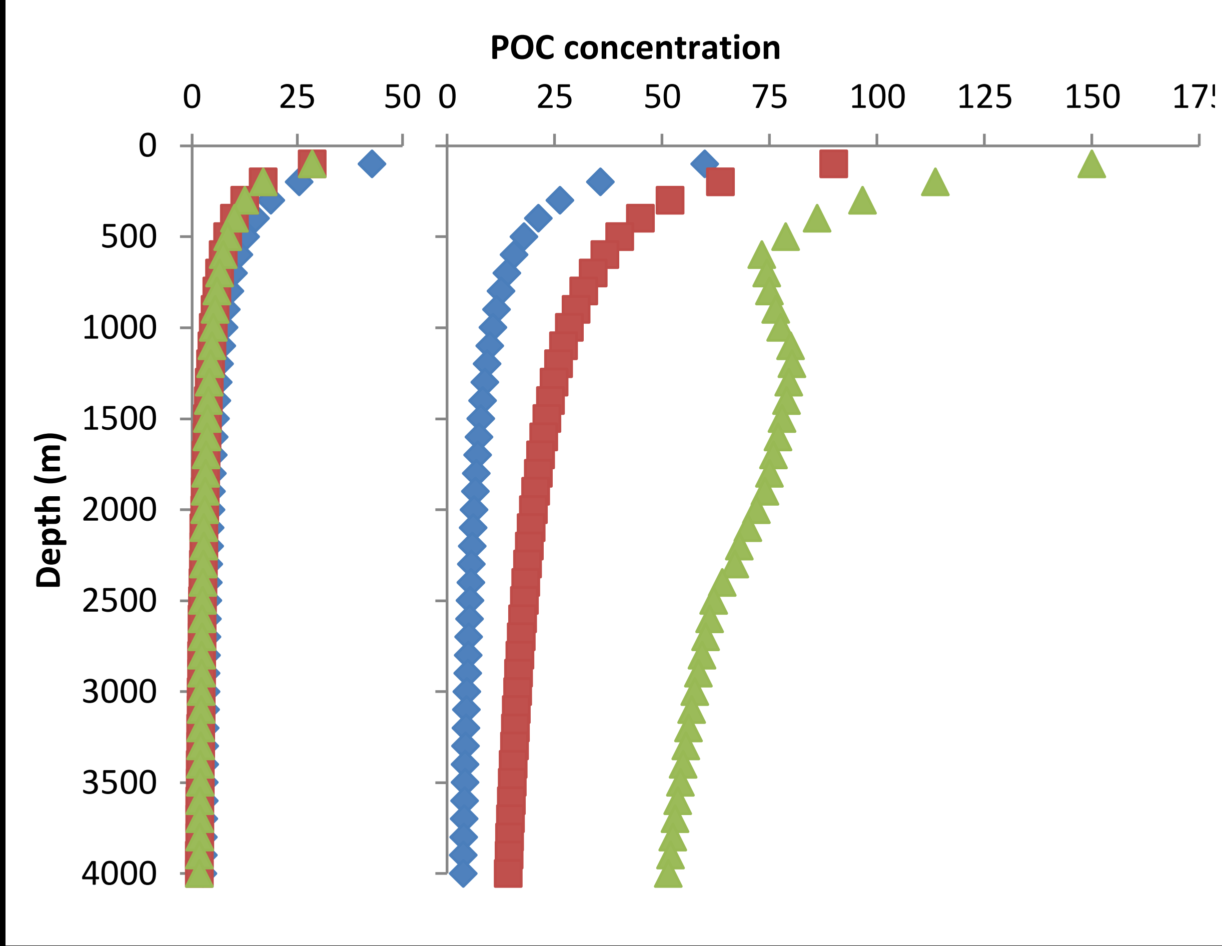


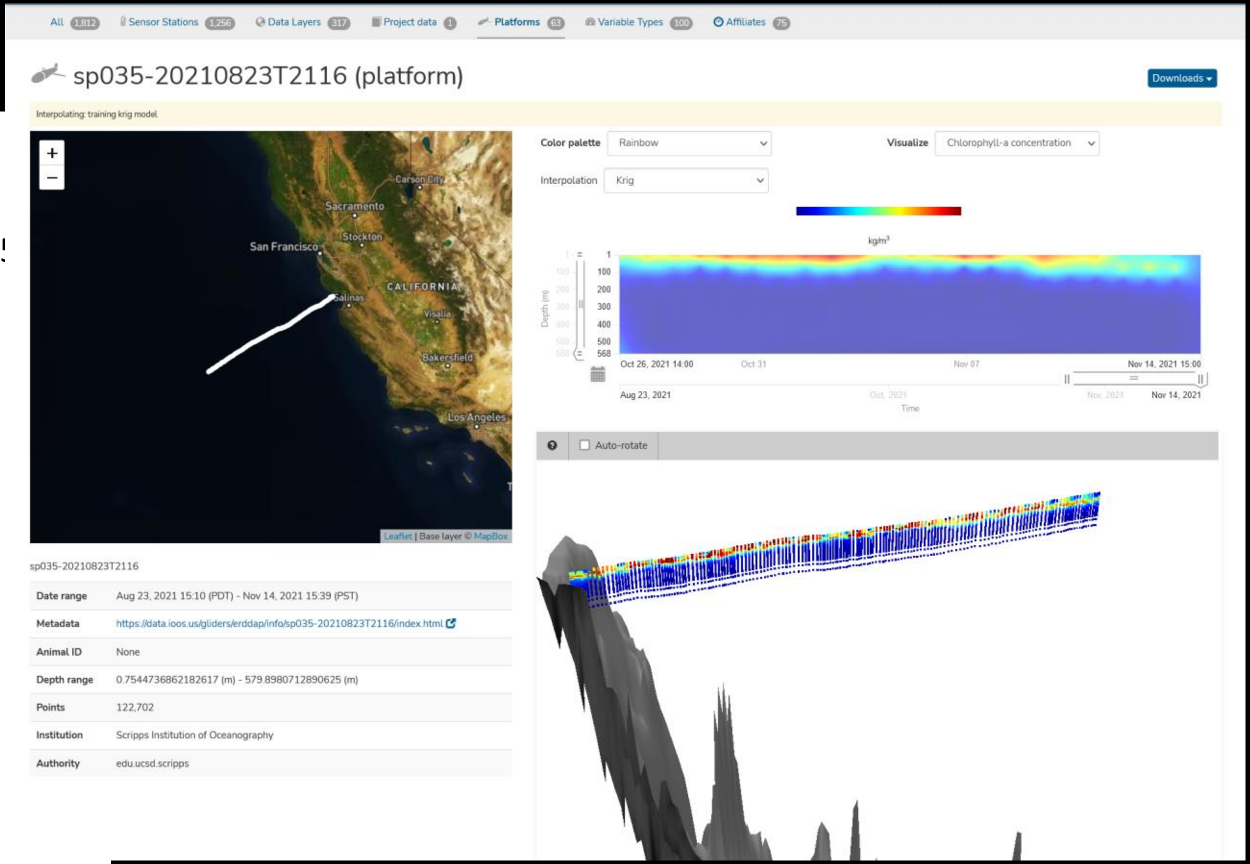
Status: we have the first simulation results of a trained agent, which has a better performance than traditional methods (greater accuracy at the beginning of the tracking)

Potential Scenarios Over Time And Space

Initial bloom - RLS equal size classes Profiles follow exponential or power curves.

Intense export - Production is 3x higher, RLS is ~3x higher for larger particles than small





Next Steps/Links to UN Decade for Ocean Science

EXPORTS
EXport Processes in the Ocean from RemoTe Sensing

JETZON

National Oceanography Centre

DEEP OCEAN OBSERVING STRATEGY

GOOS
The Global Ocean Observing System

IOOS Integrated Ocean Observing System

MBON Marine Biodiversity Observation Network

CENTRAL & NORTHERN CALIFORNIA OCEAN OBSERVING SYSTEM

MBARI

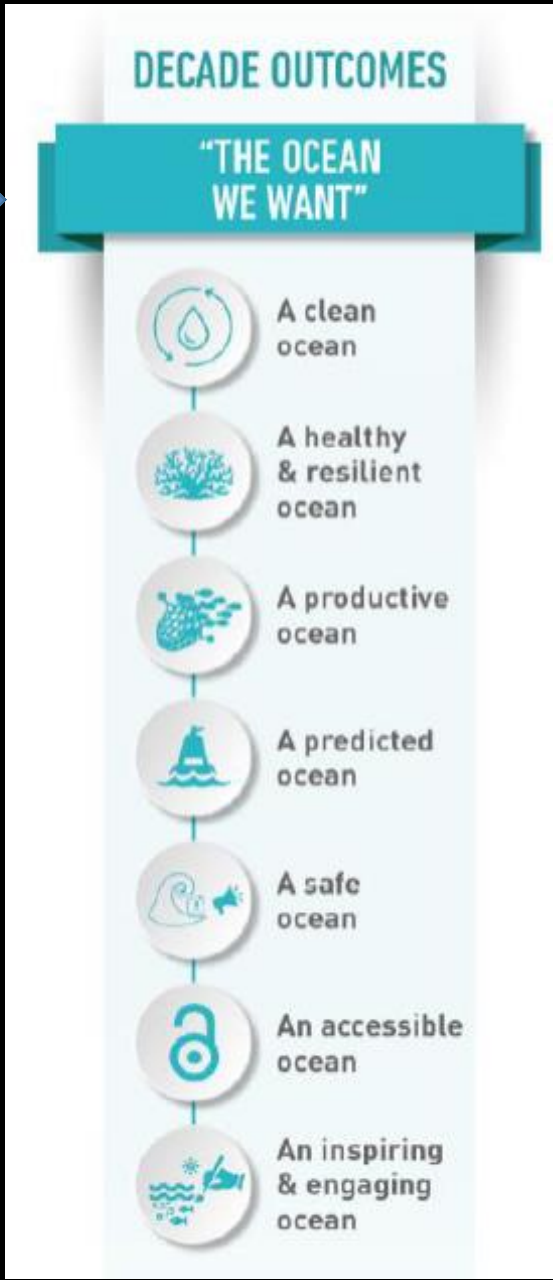
UNESCO Organisation des Nations Unies pour l'éducation, la science et la culture

Commission océanographique intergouvernementale

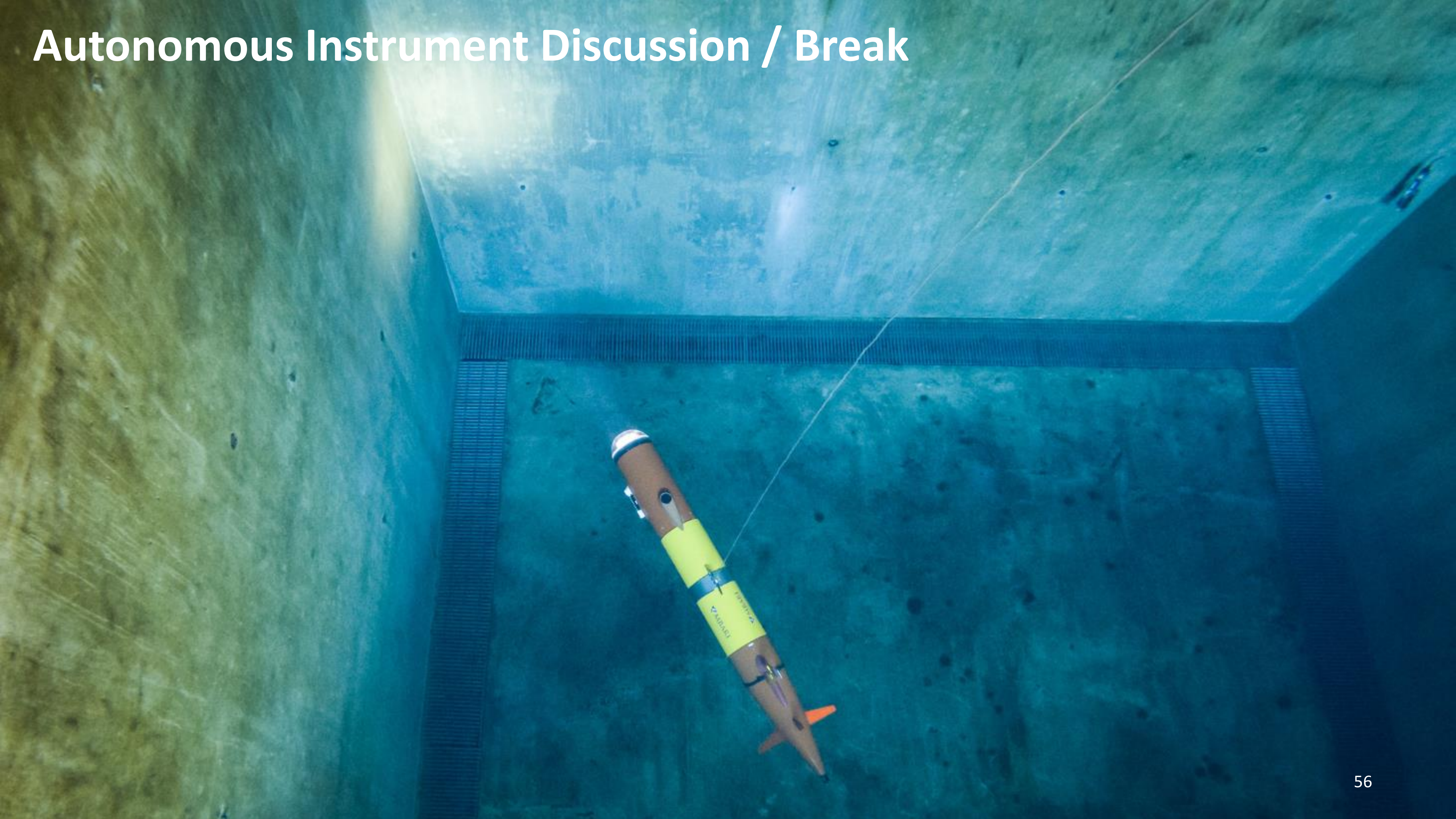
2021 2030 United Nations Decade of Ocean Science for Sustainable Development

The science we need for the ocean we want

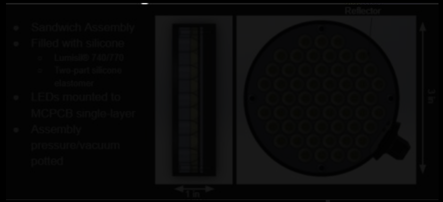
- Initiative is aligning global efforts to common goals and outcomes
- Many, many organizations planning how they can contribute



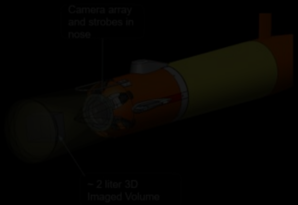
Autonomous Instrument Discussion / Break



Synthesis and Dissemination Timeline

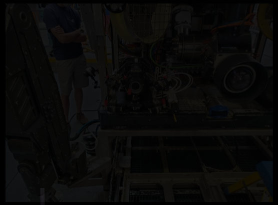


Strobe Concept Review



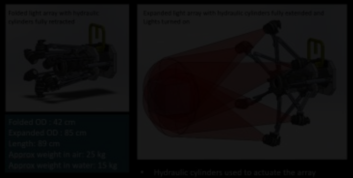
LRAUV Integration
Preliminary Design Review

Deployment on ROV
Doc Ricketts / WF

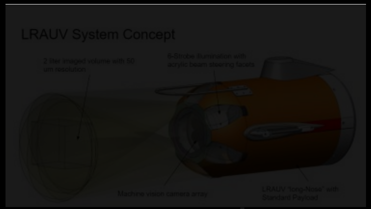


Deployment on ROV
Doc Ricketts / WF

Cabled Instrument
Preliminary Design Review



Concept for AUV system



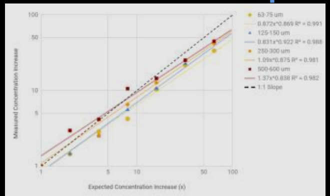
Deployment on
ROV Doc Ricketts / WF

LRAUV Payload
Completed Drawings

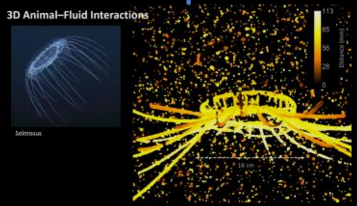
Deployment on LRAUV

Jun 2019 | Nov 2019 | Feb 2020 | Jun 2020 | Jan 2021 | May 2021 | Aug 2021

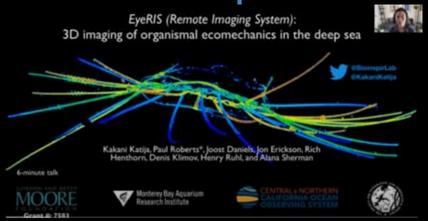
Apr 2019 | Aug 2019 | Jan 2020 | Apr 2020 | Aug 2020 | Oct 2020 | Mar 2021 | July 2021 | Oct 2021 | Nov 2021



Marine Imaging Workshop 2019
3D particle counting lab studies

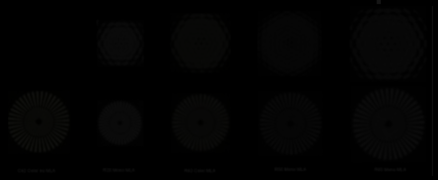


Ocean Sciences 2020

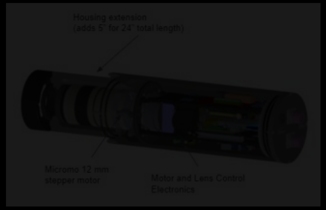


SICB 2021

Deployment on ROV SuBastian / FK



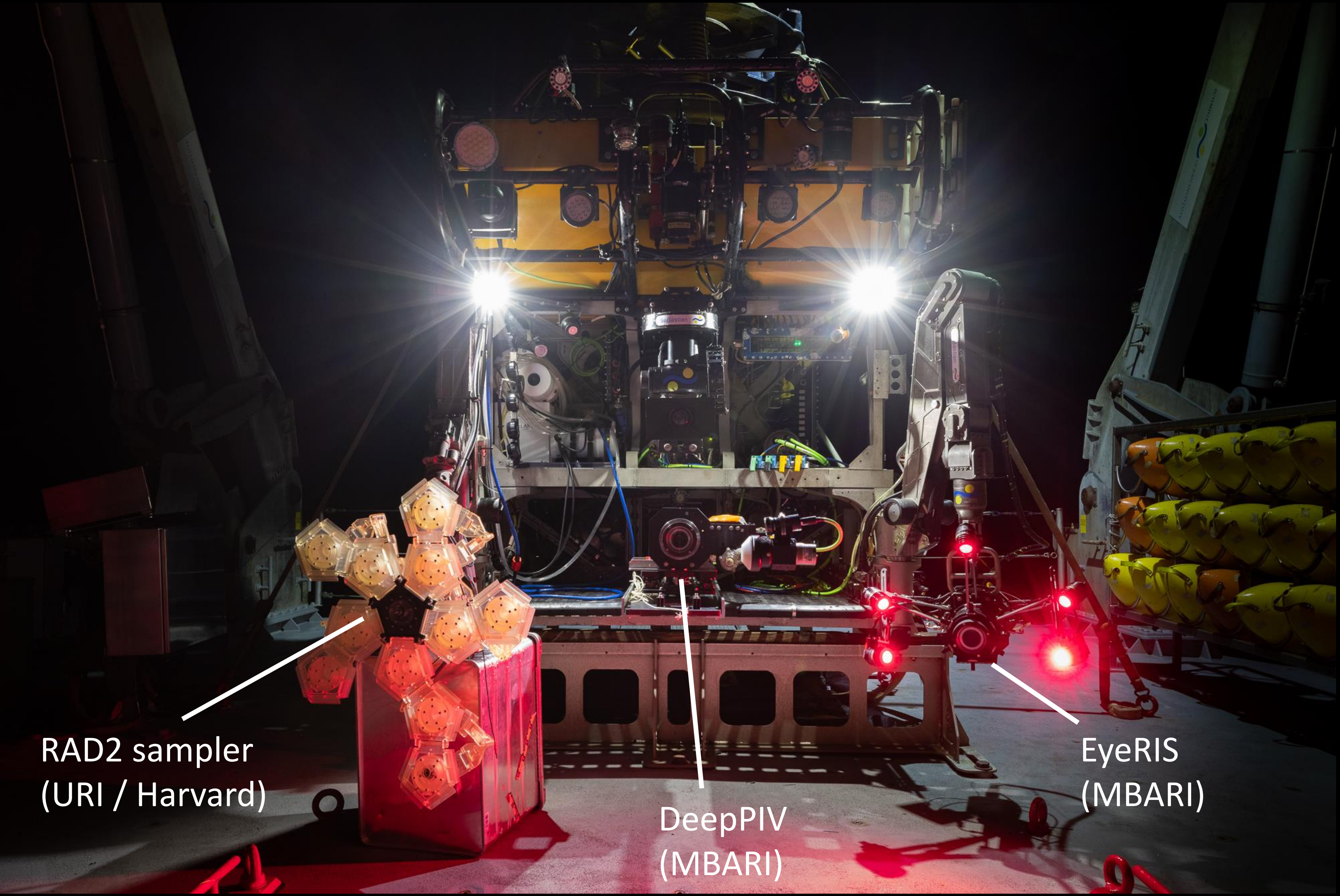
Visit to Raytrix, Camera Selection

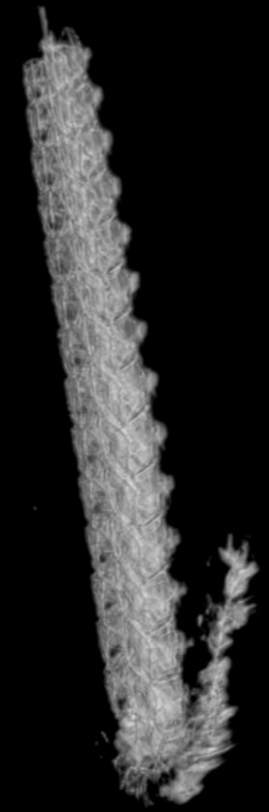


Zoom Lens Addition

Deployment on ROV Ventana / RC

Digital specimen ”vouchers” using ROV SuBastian (SOI)

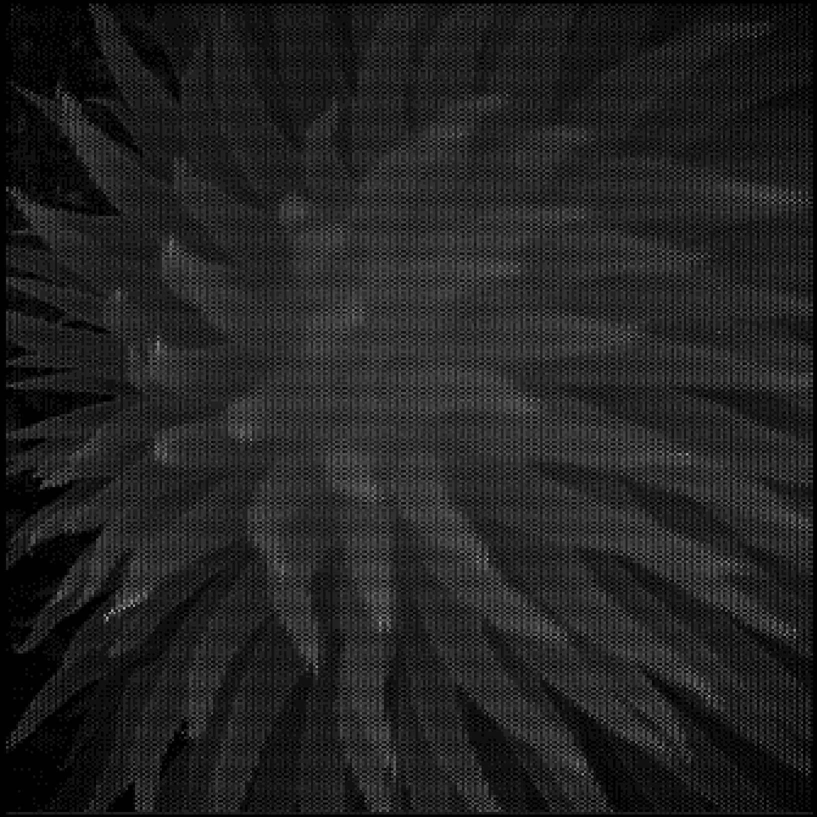




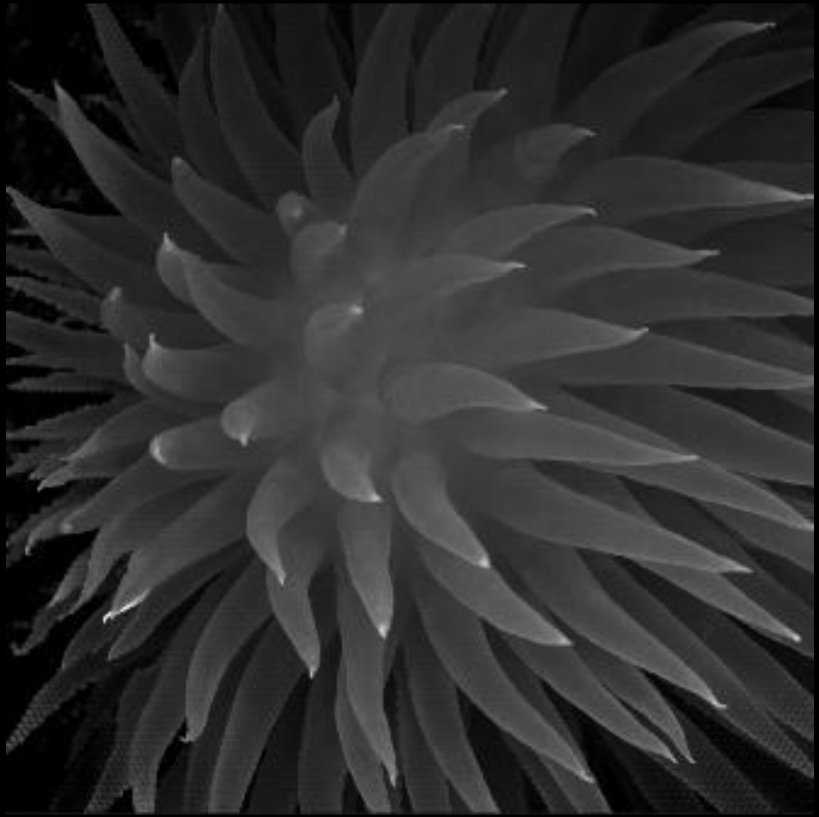
Bargmannia elongata
3D reconstruction using DeepPIV

Benefit of using EyeRIS:

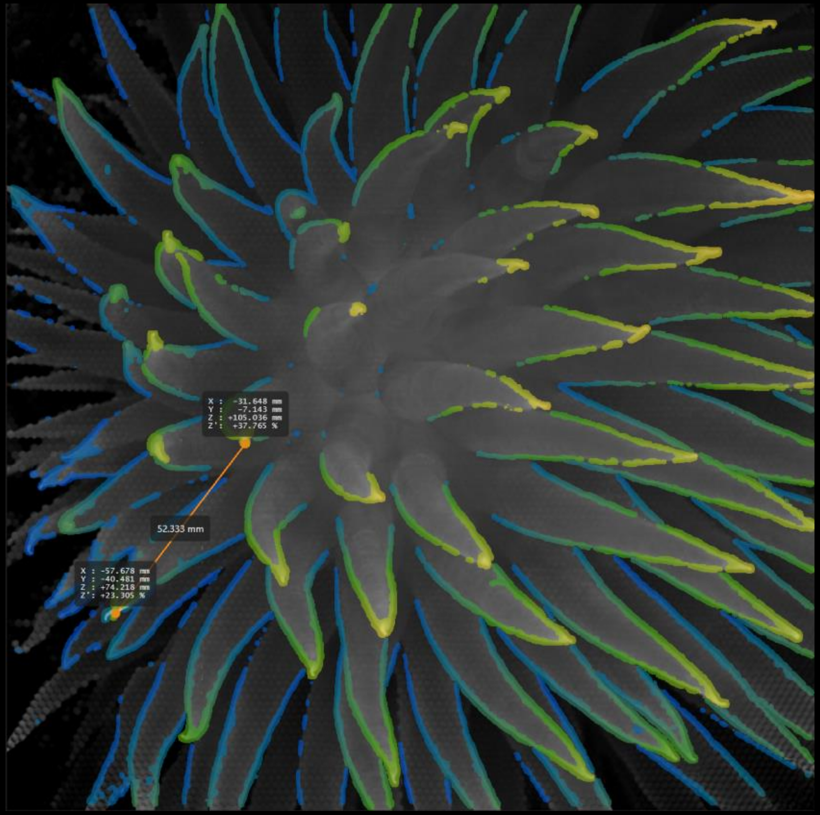
- Worked when animal was too opaque for DeepPIV
- When moving too fast
- Documents movement in 3D (4D capture)
- Larger depth of field than DeepPIV
- Quick sizing before sampling with RAD2



Raw



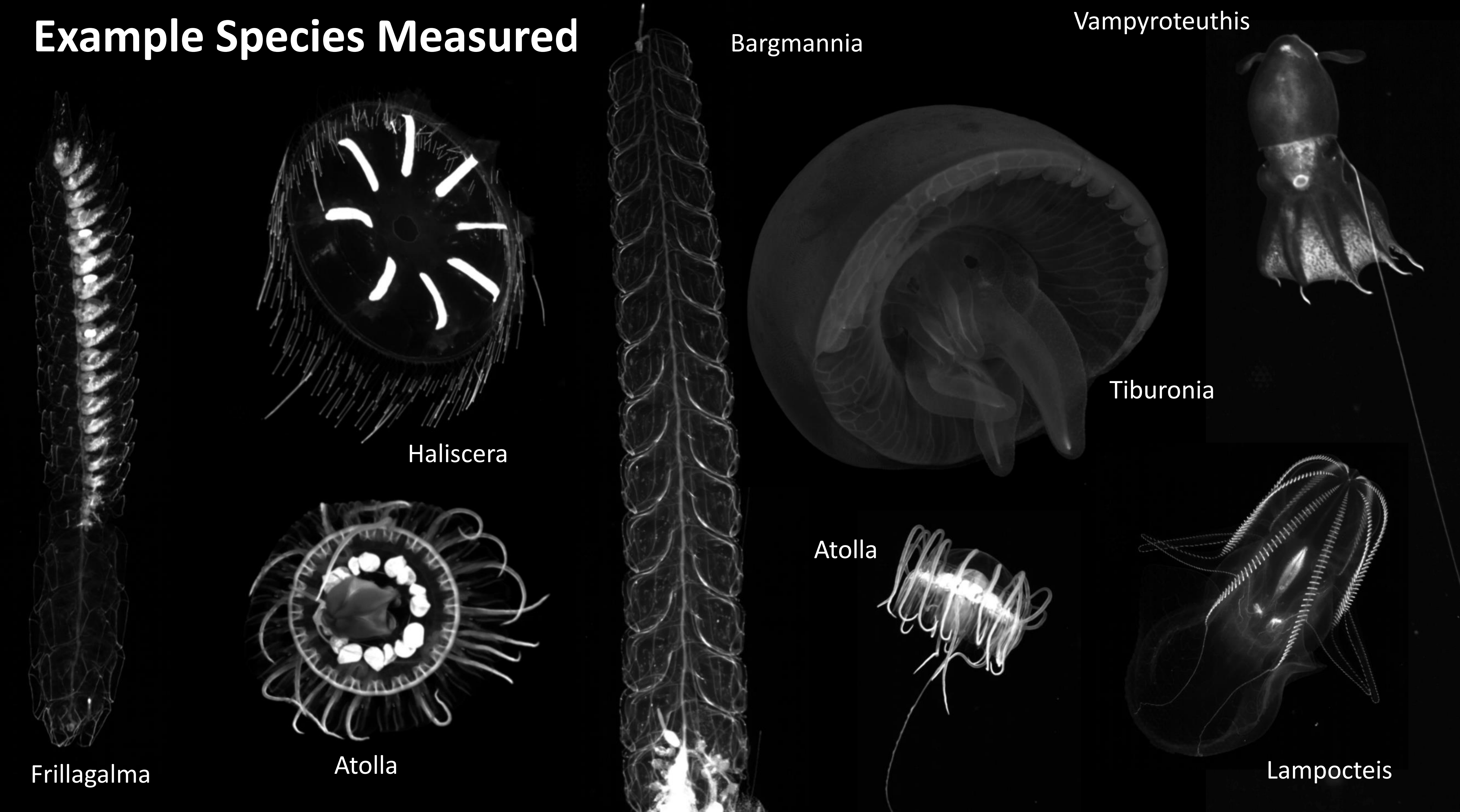
Total focus



Total focus + Depth map

Liponema (“pom-pom anemone”)

Example Species Measured



Project Summary

Outcome 1:

With a new underwater imaging system, scientists can directly observe and quantify fluid motion, particles, and living organisms in three dimensions

Output 1 **100%**

All hardware has been acquired and tested in the laboratory

Output 2 **100%**

The cabled instrument has been packaged as tested 4000m operation

Output 3 **100%**

The cabled instrument has been demonstrated on all three of MBARI's ROVs on over 30 dives with depths down to 4000 m

Output 4 **80%**

A 300m AUV deployable version has been designed and fabricated, 1500m and 6000m will be built next year

Output 5 **100%**

The 300m version of the AUV instrument has been deployed on MBARI's Long-Range AUV for over 48 hours of continuous operation

Output 6 **10%**

Data from the instruments have been reported at conferences in 2019, 2020 and 2021. Journal articles on the instrument design and scientific use cases are planned

Future Work on Existing Instruments

- Cabled Instrument
  - Addition of higher resolution R65 sensor to system
  - Addition of wider zoom range lens
- Autonomous Instrument
  - Fabrication of 1500 m and 6000 m rated versions
  - Improved integration with LRAUV and dash
  - Improved contrast in images with adjustments to illumination

Future Work on Camera Arrays: Borrowing From Advances Elsewhere

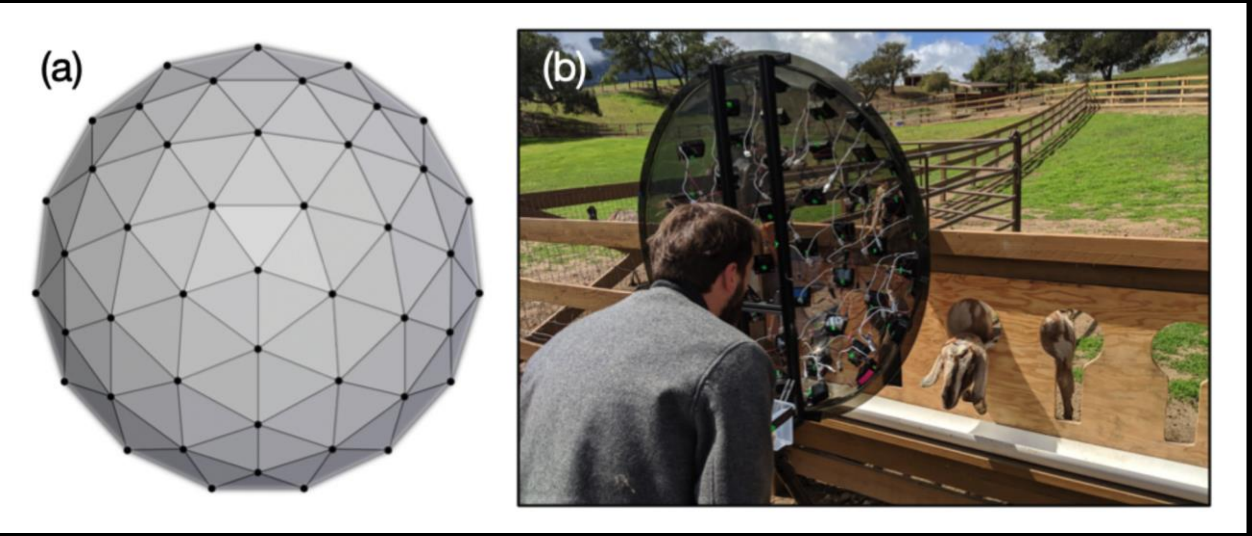


Fig. 3. Our camera array is built using a low-cost, semi-transparent acrylic dome. (a) Cameras are placed at vertices of an icosahedral tiling of a 0.92 m diameter hemisphere. This yields an average inter-camera spacing of 18 cm. (b) The plastic dome acts as a natural viewfinder, making it easy to compose a shot by looking through the surface of the camera rig.

Broxton, Flynn, Overbeck, Erickson et al, SIGGRAPH (2020)

Broxton, Flynn, Overbeck, Erickson et al, SIGGRAPH (2020)