IQOE Virtual Workshop on Low-Cost, Self-contained Underwater Acoustic Recording Systems
13-14 December 2021

The *IQOE Virtual Workshop on Low-Cost, Self-contained Underwater Acoustic Recording Systems* was convened to gather information to advance the work of the Partnership for Observation of the Global Ocean (POGO) for the development of low-cost instrumentation of various types to increase observation of the global ocean, particularly in developing countries. POGO sets up workshops where scientists, technologists, and users of technology can meet to define novel, affordable, easy-to-use ocean technology, as was the case for this workshop.

In addition to the aims of POGO, the workshop gathered information about systems that could be deployed globally to help achieve the goals of the International Quiet Ocean Experiment (IQOE) and to contribute to measurements related to the Ocean Sound Essential Ocean Variable (EOV) of the Global Ocean Observing System.[1] The implementation of ocean sound observations worldwide will require expansion of the needed infrastructure. This will require a re-thinking of instrumentation, which is expensive to acquire, can be difficult to deploy, and costly to operate. Many applications of ocean acoustics require a reduction of cost and increase in ease of use. In addition, to meet GOOS observation requirements, the calibration chain must be documented and observations must be reliable and sensitive enough to measure the full range of ocean sound. The EOV includes observations important for both biological and non-biological sounds.

The workshop was held virtually, repeated in 3 sessions on 13 and 14 December 2021. Sixty-five participants (see Appendix I) discussed strategies to expand development and deployment of low-cost underwater acoustic recording systems. Peter Tyack chaired the first two sessions and Lucille Chapuis chaired the third session.

The workshop began with 7 pre-recorded presentations, followed by open discussion sessions. The abstracts of the presentations are included in Appendix II. The pre-recorded presentations included the following:

1. Calibration of Digital Hydrophones – Jay Abel (Sensor Technology Canada).
2. Real-time and low-cost passive acoustic monitoring – the CORMA experience – Paolo Diviacco et al. (National Institute of Oceanography and Applied Geophysics - OGS, Italy)
3. HydroMoth: testing a prototype low-cost acoustic recorder for aquatic environments - Timothy Gordon et al.
4. Observations of acoustic fluctuations on the inner continental shelf in Central California – Kaus Raghukumar (Integral Consulting Inc.)
5. Low-cost Ocean Acoustic Observations based on the AI-based Framework for Acoustic Sensors (AFAS) – James Theriault et al. (Ocean Environmental Consulting, Canada)
6. Orcasound's lowest-cost open source live-streaming PAM solution on a Raspberry Pi – Scott Veirs (Orcasound) – Also given live
7. Autonomous computationally efficient power spectral density estimation using performance-weighted blending – Kathleen E. Wage et al. (George Mason University)

Discussions highlighted that there are two important streams of development for low-cost hydrophone systems: (1) those that would be produced for educational and citizen scientist purposes, which do not necessarily need to be calibrated and where sensitivity is not a major consideration; and (2) those intended for calibrated measurements as part of GOOS or other observations that need to be comparable in an absolute sense. System design must balance cost versus data quality, cabled versus autonomous deployment (and real-time versus delayed-mode data), depth rating, and other factors. The intended purposes of the acoustic observations will need to be known before technical requirements are set. This is true for both GOOS and citizen science/education applications.

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[1] The specification sheet for the Ocean Sound EOV can be found at https://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=22567.

Costs

Reducing costs is an important consideration for both education/citizen science and GOOS applications of underwater acoustic recording systems. Some cost considerations for both applications include the following:

  - For education and citizen science, the goal is to reduce the cost per node to less than 200 USD.
- Much of the cost of a recording unit is associated with the hydrophone, implying that cost reductions should focus on this part of the system. Hydrophone costs are driven by quality control, calibration, and the waterproof housing. The cost of connectors can also be significant for systems where the hydrophone is not integrated into the recorder.
- The cost of recording units might be reduced by combining the hydrophone and the unit into a single assembly, with additional reductions in cost for use at depths of <100 m.
  - Used sonobuoy parts can be used for hydrophones, but are protected by the International Traffic in Arms Regulation (ITAR), so would be difficult to distribute worldwide.
  - For very low-cost hydrophones, a larger ceramic capacitor with a voltage bias on it will behave much like a hydrophone does, although there might not be enough output without amplification.
  - A piezoelectric ceramic unit could be a low-cost option for student projects. The ceramics still drive the overall cost.
  - Omnidirectional Beaufort-0 hydrophones cost $1500 or more. If you don't need this sensitivity, you can deploy less expensive hydrophones.
  - For build-your-own preamps, amp chips such as https://www.ti.com/lit/gpn/INA115 work well.
  - For open-source designs, 3-D printable components could be appropriate; 3-D printers are gathering lots of interest.
  - With low-cost systems, self-noise floors and dynamic range are issues.

A hydrophone cost spreadsheet is available at https://docs.google.com/spreadsheets/d/1yRxvllcRFqCD2XoBE96YamPgboD5sRBOzdUdtEHt2kk and additional information can be added to the spreadsheet. Examples of costs provided by meeting participants follow:

  - The cost of the sound board and Raspberry Pi used by Orcasound (https://www.orcasound.net/) is well under 200 USD.
  - Wiggins and Hildebrand produced a $100-150 hydrophone for the U.S. Navy's Ocean of Things initiative (see https://orcasound.net/pubs/Wiggins+Hildebrand-2019.pdf). The ceramic element used by Wiggins and Hildebrand cost US$30.
  - GoPros include electronic microphones sealed in a plastic box (see Chapuis et al. 2021).
  - Open Acoustic Device's AudioMoth/HydroMoth appears to be the lowest cost commercially available hydrophone for applications where calibration is not necessary (see https://www.openacousticdevices.info/). HydroMoths can be left underwater for months and programmed to record for some portion of each hour to extend battery life. The air-filled housing acts like an amplifier. The HydroMoth housing is waterproof to 100 m. The recording system is not onmi-directional. The Mems microphone on the HydroMoth is connected to the air-filled housing, which helps transfer underwater sound into airborne sound that is picked up by the internal microphone case and acts as a pseudo-hydrophone. There is no hydrophone, although it is possible to solder connect a real hydrophone to the device. For example, calibrating the AudioMoth could be connected with the Aquarian Audio H2A hydrophone (total cost about $300).
  - Orcasound's cheapest successful experiments have included Labcore40 elements ($300 each, made by a local one-person shop), SQ260-08 hydrophones ($500 each) from Cetacean Research Technologies in Seattle, and HTI-96-min ($1,500 each for calibrated noise level monitoring, flat response from 10-50,000 Hz), each with 10m cables. Since Orcasound tries to deploy dual elements for redundancy, binaural listening, and bearing computation, the hydrophone costs above are doubled for each node. For the other hardware (Rpi+Pisound), the total cost is <~$300, so Orcasound typically budgets $1000 for a low-cost listening node or $3300 for a calibrated noise monitoring node.

- Geospectrum Technologies Inc. did have a "low cost" over-the-side hydrophone that could be used with a cell phone, but it may not be available any longer. OceanSonics sells a similar capability using a wireless connection between a deck box and the phone.
- The quality of the pre-amp linked to the hydrophone is also important. A $4-5 integrated circuit can result in a 20 dB improvement in sound quality. It is important that the input impedance of the pre-amp matches the high impedance of piezoelectric ceramics.
- The cost of the CORMA systems is about 800 euro. Most of the cost is for the hydrophone and the pre-amp. Cost is related to the quality of data that can be obtained. CORMA observations are fed into models, which need high-quality data (see Diviacco et al., 2021).

Hydrophones for GOOS

Ocean sound observations are important for listening to animals and anthropogenic sounds, but also for non-human abiotic sounds, like rain, wind, and waves, which are influenced by climate change, and thus important for GOOS. Available systems that can be calibrated cost several thousands of dollars (see above). The stability and sensitivity of hydrophones are issues for GOOS applications. GOOS hydrophones must be calibrated so the precision of measurements is known when they are made and aspects about the calibration should be reported (e.g., how long ago calibration was done, stability of calibration), so measurements from different locations can be compared. Hydrophones for GOOS need to be able to differentiate system noise from ocean noise, with appropriate sensitivity and dynamic range for the sound environment where they are deployed. Other technical specifications for GOOS hydrophones will depend on the needs for GOOS measurements, including deployment depth(s), ability to re-calibrate and service the hydrophone, whether it is operating in cabled or autonomous mode, frequency range, and expected received levels of signals of interest. Real-time monitoring is important for detecting prohibited activities near and in the vicinities of marine protected areas, or for other detections requiring rapid responses, such as underwater earthquakes that might generate tsunamis.

Calibration, Time Synchronization, and Location

Calibrations: Participants discussed a variety of calibration methods for hydrophones, including the following:

- Calibration facilities provide good calibrations, but are costly. The HydroMoth is being tested at the UK National Physics Laboratory, using the reciprocal calibration method mentioned by Jay Abel in his presentation. Establishing a network of such facilities that meet National Institute of Standards and Technology (NIST) calibration standards could facilitate requirements for calibrated measurements for systems that can be calibrated before and after deployment. However, long deployments may benefit from in-situ methods for calibration.
- Calibration of digital hydrophones using free-field reciprocity (Abel presentation). Digital systems can be modified to combine the preamp with a low-power projector amplifier and switching the preamp channel to measure the projector current. This method should be compared against traditional methods. SensorTech is planning to do such testing with a new calibration tank.
- Calibration using "underwater calibration drones" that would have high-quality calibrated sound transducers, and could "drive by" inexpensive hydrophones, and AI algorithms could work out the calibrations. Such "calibration drones" could be made available to different projects as a community resource.
- Use a passing ship as a broadband source for inter-calibration within an array.
- Calibrating low frequencies can be difficult in water; methods are available to calibrate hydrophones in a sealed pressure chamber in air (e.g., Bruel & Kjaer hydrophone calibrator type 4229). These can be compatible with measurements when the hydrophone is in-hand in the field. At higher frequencies, this method can do broad-band calibration with 1 dB accuracy.
- Deploy a frequently calibrated hydrophone with less-frequently calibrated hydrophones and then use observations with the former to correct the observations of the latter in the processing stage.
- Calibration sound sources could be shared among users, being sent from place to place to use for calibrations, including in developing countries.

Time Synchronization: Low-cost systems often have pretty bad clocks. Better clocks would make it easier to use independent instruments as arrays, which is generally cheaper than using an actual array. Orcasound hydrophones each have their own clocks on their soundcards, rather than sharing a time signal across the ethernet. Electronic systems to maintain precise timing can be power hungry, and the more precise, the more power is required. This is especially an issue for battery-operated systems. GPS provides very accurate time signals, so it is useful to synch a GPS to recording systems when they are deployed and recovered if they are to be used as arrays.

Localization: Transceivers may be able to be used to synchronize time bases and estimate array geometry for localization purposes. Orcasound has some surface exposure, so GPS can be used for some localization, within the errors of GPS. Some Orcasound nodes are 4-6 km apart, but they are checking on whether the time stamps on their nodes are good enough to determine the location of sound producers.

Engineering

Ocean Environmental Consulting is considering potting a Sensor Technology Canada hydrophone directly to the connector in the 2" form factor, to move the preamp inside the pressure vessel.

There was a question about whether it was possible to attach a cable through some sort of waterproof gland to the AudioMoth. Open Acoustic Systems has done this with the Aquarian Audio H2A hydrophone, similar to what Jay Barlow has done. What about using the cable for data transfer? There are glands available for USB connections that could be used with HydroMoth and there are some good waterproof attachments available. When building an underwater preamp-hydrophone, the hardest problem is waterproofing the preamp with cables attached.

For SS0, frequency matters. SS0 requires an element sensitivity of -190 dB re 1 µPa or better, assuming a state-of-the art 1 nV / rtHz preamp noise floor. It's much easier to get that kind of sensitivity from a lower frequency element.

Raspberry Pi’s are power hungry, so they are better for serving live data, as Orcasound does, rather than archiving data. It is possible, however, to disable some features of Raspberry Pi’s to decrease their power requirements.

Soundscape metrics could be moved directly to the sensors, which would increase the cost somewhat.

Data Transmission and Access

The FAIR approach (see https://www.nature.com/articles/sdata201618) is absolutely vital for GOOS data access, although there are sometimes classification and national security issues with ocean acoustic data.

Transmission of data also has implications for the power supply needed. Orcasound hydrophones are cabled and are deployed on “docks of convenience” that have AC power, reach deep enough water, and have the capability of an ethernet connection, then run the more expensive hydrophone cable to deeper water. CORMA systems are autonomous, deploying hydrophones in deeper water further from shore, so their designers need to worry about power requirements. They use solar cells for power and mobile phone networks for data transmission. As they move further from shore, they will have to switch to other data transmission methods.

Audacity is a free and open source. For educational purposes, it is useful for students to write their own analysis software. A variety of options are available to students interested in digital signal processing applications. These should be assessed for suitability.

Education

Hydrophone systems that are not calibrated and have lower sensitivities can be useful for citizen science and for education purposes. There is an overlap between these categories, but it is useful to discuss them separately. HydroMoth appears well suited to these applications because of its low cost.

One participant in the workshop was Artash Nath, a Grade 10 student from Toronto, Canada, who is researching changes in underwater ambient noise - currently analyzing data from Ocean Networks Canada and MBARI. He noted that ocean acoustic data are more difficult to find than for the seismic data he used to create www.MonitorMyLockdown.com, which provided real-time analysis of seismic data to monitor effectiveness of lockdowns for 10 Canadian cities. See also https://hotpoprobot.com/2021/12/13/silence-of-global-oceans-underwater-acoustics-impact-of-the-covid-19-lockdown-agu-2021/

There was discussion about different aspects of the training required for educational applications of underwater sound recording systems. Approaches range from online instruction (YouTube tutorials, plans on GitHub) to kits of varying levels of pre-assembly to in-person instruction. There is a need for education and training in both developed and developing countries, and experience with developed country students could help in designing training for developing country students.

Online resources: DOSITS (https://dosits.org/) is a good source of introductory material about ocean acoustics and bioacoustics. There are many sites on the Web to assist hydrophone building (e.g., Hackaday). Ocean acoustic systems would make a wonderful subject for a massive open online course (MOOC), complete with components, to go from kit to deployment to analysis. This could be augmented by YouTube videos on a YouTube channel on the hydrophone topic. However, more than YouTube videos are necessary; it is important to stimulate people to use the content, with a series of questions to answer and/or applications to use. Mini-challenges can be presented to help students learn the material. This could be linked to sending kits for building ocean sound observing systems (see next section). GitHub is being used to share software, but also giving instructions to use the software. Monterey Bay Aquarium Research Institute put their data on the Amazon Web Service open data registry (https://registry.opendata.aws/pacific-sound/) with tutorials about how to use the data (https://docs.mbari.org/pacific-sound/).

Kits: Kits should be provided with multiple levels of pre-assembly already done, to engage people at different levels of experience; not everyone will want to do assembly. Kits should include a cheap piezo-ceramic. Low-cost, easy-to-solder hydrophone elements with leads already soldered would be useful for educational purposes. Paraffin encapsulation or food-grade compounds to pot microphones should pass health and safety requirements for schools. A kit with a cabled hydrophone that attaches to and works with cell phones (power, data acquisition) would be exciting and spur development of (open source?) marine mobile apps analogous Cornell's Merlin or BirdNet for birds. Students should gain experience building their own hydrophones because they are certain to break in the field and the student would have to fix the hydrophones. This could be an important component of any educational activities that IQOE supports. This is aligned with POGO's vision of inexpensive observing technology that can be fixed by the people using it, rather than having to send it back to the manufacturer when it stops working. Any dissemination of kits should be linked with online and/or in-person instruction.

In-person training: Training needs a long-term, complete approach, starting with finding out what capabilities trainees already have, and what their needs and drivers are in terms of why they want to make the measurements. Kits and/or parts can be provided, and then training and long-term mentoring or financial support is needed. This can be done quickly with surveys to trainees at an institutional level. A good model for this is what the Ocean Foundation does with the Global Ocean Acidification Observing Network (GOA-ON). They provide equipment as well as training. Training is needed for using devices, as well as signal processing. IQOE is interested in getting more acoustics into undergraduate curricula. Capacity-development activities of POGO and the Scientific Committee on Oceanic Research (IQOE's sponsors) include sending visiting scientists to developing countries and bringing developing country early-career scientists to other countries to learn observing skills. Both of these programs are open to ocean acousticians and bioacousticians. The Intergovernmental Oceanographic Commission's International Oceanographic and Information Data Exchange (IODE), runs an OceanTeacher Global Academy, which is a network of worldwide training centers and virtual learning. This could also be a resource for ocean acoustics and bioacoustics.

Considering what the Bahamas Marine Mammal Research Organisation (BMMRO) does with their whale camps, one could extend the concept for locally offered workshops on hydrophone use. These camps include getting on the water and trying things. Using students to teach each other can be effective, in a two-year program where Junior and Senior year students work together, and this year's juniors become next year's seniors (and teachers). This has worked very well in robotics competitions, including underwater robotics. In-person training is required for parts of the world in which Internet access is difficult.

Citizen science

Citizen science can be implemented in different ways and there are a variety of definitions, from raising environmental awareness to using volunteers to collect observations that will be used for research ("crowd-sourced science").

Environmental awareness can often be raised best by providing access to real-time sound feeds, either at locations on the coast or through the Internet. Environmental awareness can involve not only listening for organisms, but also non-biological noise sources, to increase public understanding of human and natural (non-biological) sound sources. Web-based access to ocean sound is important to experiential learning because the number of students that can be taken out on ships or travel to the coast is limited. Web-based access is also important to reach a worldwide audience. Near-shore water environments are not very quiet, so the hydrophones used in this application do not need to be too sensitive. Orcasound has been very effective at using social media platforms to reach a wide audience. There have been exercises where schools have adopted oceanographic instruments and/or deployed small ship-shaped floats from ships and tracked by GPS. Perhaps something with acoustics could be deployed like this.

In some projects, acoustic signals have been analyzed by citizen scientists in a crowd-sourced way. Zooniverse.org and similar platforms are compelling and a big multiplier. Batdetective.org did a great job of leveraging recordings into annotations and the current https://www.zooniverse.org/projects/cetalingua/manatee-chat is inspiring. NOAA has a real-time whale map for the eastern seaboard that could be fed by a swarm of uncalibrated hydrophones — https://whalemap.org/

To increase the availability of low-cost hydrophone systems for citizen science, it is necessary is to create systems that are inexpensive enough that they can be widely deployed, used in a comparable way, and the observations are reported to a standardized system and compiled for scientific purposes. The main value of such a system would be detecting transient acoustic events or signals, rather than providing calibrated sound levels. Detections by citizen scientists could contribute to a system that notifies experts for when unknown or significant known signals are detected. Reliable citizen data would depend on the objectives. But if good spatial coverage can be achieved through citizen science projects with decent data (that may be post-collection "calibrated or adjusted"), could this then be used to identify areas of interest to deploy more expensive equipment? Steve Simpson's group is working with the paddleboarding community to put HydroMoths on paddleboards to understand their sound outputs, but also as a science platform. They are trying the same thing with surfboards. Jim Thierault has worked with lobster fishermen to deploy hydrophones on lobster traps. Sometimes parents and grandparents get involved in citizen science because of the interests of their kids and grandkids, such as the lobster fishermen who deployed acoustic sensors on their lobster traps.

There needs to be a repository for the data generated from citizen science projects. This will determine the training and capabilities required.

What citizen science experiments could be carried out with low-cost uncalibrated hydrophones, to move citizen science beyond just experiential learning? If you could spread 1,000 hydrophones up and down the U.S. East Coast, is there a science question you could address? Orcasound has engaged citizen scientists in identifying vocalizing organisms, documenting their presence and locations. Citizen scientists on the U.S. West Coast have contributed data useful to model where whales will be one hour from the observation time, which is an important time frame for re-routing ships to reduce noise and potential for ship strikes. The models use a combination of visual sightings, acoustic observations, and artificial intelligence to make predictions. The scarcity of acoustic sensors on the U.S. East Coast has made it hard to do the same thing to protect northern right whales.

Citizen scientists might borrow more expensive underwater acoustic recording systems that they could deploy in useful locations. Lucille noted that they have had great experience sharing the HydroMoth with volunteers because these units are inexpensive, easy to power (AA batteries), and easy to use. They can be deployed by snorkelers.

Hack-a-thons

Participants were enthusiastic about convening hack-a-thons, which have already been used to some extent in ocean acoustics (e.g., the October Microsoft Hackathon — https://aifororcas.azurewebsites.net/Dashboard). Hack-a-thons can be online or in-person. Online hackathons, like the ones done by NASA SpaceApps Challenge every year, attract more than 25,000 people. Lessons could be learned from the spin-up of the Infragram multispectral camera kit for terrestrial plant imaging and analysis. It was a DIY kit but included a community website where people would post their products and discuss. This could provide a model for how to rally the citizen science and STEM communities for ocean acoustics. DemocracyLab is rapidly evolving (due to COVID) from local in-person events to ones that have national and increasingly international reach (see https://www.democracylab.org/).

Possible topics to be included in one or more hack-a-thons include the following:

- Development of low-cost pre-amps
- Calibration methods
- Calibrated hydrophones that can be connected to mobile phones
- Making online acoustic data more accessible and usable
- Repository of "Open-Source" algorithms (e.g.: on GitHub: Python libraries and tool kits) to analyze hydrophone data

Jesse Ausubel noted that the Lounsbery Foundation would probably welcome a proposal to help support a hack-a-thon, and Andy Hill added that Open Acoustic Devices would be happy to be involved in hack-a-thons and to supply low-cost educational HydroMoth kits (contact theteam@openacousticdevices.info). It would be useful to measure the long-lasting educational impacts of hack-a-thons, and to open the doors wider and diversify the groups of people we get involved in hack-a-thons.

Web-based Discussion Forums

Web-based discussion forums are important means of virtual communication and are important not only for data and results, but also for some of the hardware design and other curriculum materials. It might be useful to share circuit diagrams in the public domain. It would be worth to convene a team to produce instructions for building DIY hydrophones.

Several possibilities exist:

- Orcasound Slack workspace for hardware and software discussions — https://join.slack.com/t/orcasound/shared_invite/zt-bd1jk2q9-FjeWr3OzocDBwDgS0g1FdQ
- There is a GitHub site for IQOE: https://github.com/iqoe, which has not yet been used. GitHub or Slack could be used to create an IQOE discussion forum for instrument development.

Follow-up actions

The outcomes of the workshop were discussed at the 23rd POGO Annual Meeting in late January 2022, and will be discussed at the next SCOR Annual Meeting later in 2022, and at the next IQOE Science Committee meeting, with the aim of developing a plan to support further work on this topic.

Some of the ideas raised include the following:

- How would you put together a kit to send out?
- How would you design the necessary training?
- Interactions with the ISO working group on soundscape metrics (chair: Michael Ainslie). We should find out how other EOVs relate to formal standards processes like ISO.
- Working groups on (1) citizen science and (2) GOOS-capable calibratable hydrophones, with a bit of cross-over to coordinate.
- Interaction with Detection, Classification, Localization and Density Estimation (DCLDE) workshops: Jim Theriault will follow up with them. It is too late to do much in relation to the March 2022 workshop.
- Convene people who have run ocean acoustics summer schools to compile lessons learned and design schools for developed and developing countries.

Recommendations

The participants were in general agreement that acoustic recording devices in the 200 USD price range were within reach for educational and outreach purposes (e.g., citizen science). However, for the purpose of collecting calibrated data that can contribute to global ocean observing efforts, a more realistic lower limit would be closer to 1,000 USD. There was also general agreement that an important aspect would be to teach students to build (and repair) their own hydrophones. This would help with the cost and sustainability aspects, as well as improving students' understanding of acoustic measurements. Recommendations and actions items from these discussions are listed below:

- Form smaller working groups to follow-up on specific topics (e.g., calibration, platforms such as autonomous underwater drifters and gliders, sensor and digital hardware and software development).
- Create a forum for further discussion/interaction using a collaborative platform (e.g., Slack).
- Create sensors, recording systems, and analysis software that are adapted for citizen science.
- Involve young scientists and engineers through equipment hack-a-thons or competitions (e.g., XPrize).
- Create a connection between the working group focusing on the Ocean Sound EOV and the working group focusing on ISO standardisation; there is a need for overlap.
- Provide a set of technical specifications necessary for GOOS Ocean Sound EOV recordings - this could be referred to the IQOE WG on Standards
- Create two working groups: one on citizen science/education and one more technical WG to define what is necessary for the Ocean Sound EOV and other research needs
- Add a summary of the outcomes of this workshop to the Ocean Sound EOV Implementation Plan.

Appendix I
Participants[2]

Name	Organization
Jay Abel	Sensor Technology Canada
Enrico Armelloni	University of Parma (Italy)
Jesse Ausubel	Rockefeller University (USA)
Tim Awbery	Scottish Association for Marine Science
Diogo Destro Barcellos	University of Sao Paulo (Brazil)
Jay Barlow	
Sebastien Bonnieux	
Rafael Mazza Buchmann	Brazilian Navy
Mihai Burca	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (Italy)
David Burnett	Portland State University (USA)
Bill Burns	
Laura Casali	NOAA (USA)
Lucille Chapuis	University of Exeter (UK)
Silvio Cordeiro	
Alasdair Davies	Shuttleworth Foundation
Paolo Diviacco	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (Italy)
Henry Edwards	Defence Science and Technology Laboratory (UK)
Mike Gardener	
Luke Garrett	Pennsylvania State University (USA)
Stephen Hicks	Orcasound
Andy Hill	Open Acoustic Devices (UK)
Craig Hillis	Craig Hill Acoustics
Lincoln Hood	University of West Australia
Erwin Jansen	TNO (Netherlands)
Maxhoba Jezile	Department of Environmental Affairs (South Africa)
Dimitris Kassis	Hellenic Centre for Marine Research (Greece)
Maziar Khosravi	Iranian National Institute for Oceanography and Atmospheric Sciences
Lica Krug	Partnership for Observation of the Global Ocean
Emilia Lalander	Swedish Defence Research Agency
Joyce Liao	Orcasound
Justin Manzo	DARPA (USA)
Emma Marotte	Department of Fisheries and Oceans (Canada)
Bruce Martin	JASCO
Jim Martin	Georgia Institute of Technology (USA)
Perrin Meyer	

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[2] Participants' institutions were determined from their email addresses, which was not possible for people with gmail addresses

Mark Milnes	Australian Antarctic Program
Anita Murray	Wildlife Conservation Society
Mirko Mustonen	Tallinn University of Technology (Estonia)
Artash Nath	Grade 10 Student, Toronto, Canada
Matt Pine	Ocean Acoustics Ltd.
Michelle Pretorius	Department of Environmental Affairs (South Africa)
Peter Prince	Open Acoustic Devices (UK)
Aris Prospathopoulos	Hellenic Centre for Marine Research (Greece)
Susanna Quer	Government of Scotland
Ben Reeder	National Park Service (USA)
Athena Rycyk	New College of Florida (USA0
Marcos Rossi Santos	
Kevin Scharffenberg	
Sophie Seeyave	Partnership for Observation of the Global Ocean
Steve Simpson	University of Exeter (UK)
Kyle Smith	South African National Parks
Ludovic Tenorio	NOAA (USA)
Jim Theriault	Ocean Environmental Consulting
Jeffrey B Tucker	George Mason University (USA)
Peter Tyack	University of St. Andrews (UK)
Ed Urban	Scientific Committee on Oceanic Research
Hilary Kates Varghese	Bureau of Ocean Energy Management (USA)
Scott Veirs	Orcasound
Val Veirs	Orcasound
Kathleen Wage	George Mason University (USA)
Carl Wainman	
Jody Willis	
Jessica Wingfield	Department of Fisheries and Oceans (Canada)
Christian	
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Appendix II

Title: Calibration of Digital Hydrophones

Jay Abel, Sensor Technology Canada

Keywords: Calibration, Reciprocity, Digital, Transducer

Calibration by reciprocity allows primary calibrations without using a standard reference. For analog hydrophones, the procedure requires a tank, tone source, projector, data acquisition system, and processing, and requires three devices, at least one of which being able to operate as a transducer (first as a projector, then as a hydrophone). Normally, amplified hydrophones and digital hydrophones cannot be used as a transducer because the preamp and other electronics restrict the use of the device to receive only.

With some additional complexity, the preamp can be combined with a low power projector amplifier, and the preamp channel can be switched to measure projector current. The result is a digital transceiver that either records the voltage across the ceramic element in hydrophone (receive) mode, and records the current through the ceramic element in projector (transmit) mode. This composite device can be used with two other devices to implement a reciprocity calibration by analysis of the recorded receive voltages and transmit currents.
While the power available for the projector function is too low to use the device as a general purpose projector, the available power is sufficient to allow calibration to take place.

Title: Real-time and low-cost passive acoustic monitoring – the CORMA experience

Paolo Diviacco [1],* , Antonio Nadali [2], Massimiliano Iurcev [1], Mihai Burca [1] , Rodrigo Carbajales [1] ,Matteo Gangale [2], Alessandro Busato [1], Fabio Brunetti [1], Lorenzo Grio [2], Alberto Viola [1] and Nikolas Potleca [1]
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Keywords: Passive acoustic monitoring; real-time; low-cost; web; scalable infrastructure.

Within the CORMA project a real-time and low-cost Passive Acoustic Monitoring (PAM) system has been developed that is able to record and transmit data to a central server where they can be automatically processed and published on a web platform (Diviacco et al., 2021). The system is based on off-the-shelf and low-cost technologies combined with a scalable infrastructure developed with open-source tools only, which allows great flexibility in extending what developed so far. In fact, although currently the system has been tailored and successfully tested to fit mainly the needs of shallow coastal areas it can be redesigned to match the needs of other environments. The hydrophone is deployed at sea and connected through a 100 meters long shielded cable to the acquisition box installed on a buoy. The box is composed of an analog to digital converter with a frequency range 20-20.000 Hz, a Raspberry Pi board and a transmission system. This latter is currently based on 3G/4G GSM mobile telephone networks which of course have a limited range of distances between antennas but that has a proper bandwidth that allows the device to send data packets with the correct schedule. We are currently working on extending the types of data transmission technologies in order to extend the range of distances from the coast of the listening points. Electric power is provided by solar panels installed on the buoy. The low-cost characteristic of the system allows for the deployment of multiple units at the same time without exploding the budget. This allows to monitor larger areas or the same area with a denser network of observation points, which is particularly important while integrating monitoring and modelling. The real-time monitoring characteristic can be particularly relevant in identifying anomalous events and try to warn or mitigate their effects in particular in the vicinities of marine protected areas. We installed a small network of listening points in the Gulf of Trieste (North Adriatic Sea) and acquired a large dataset of recordings. These can be accessed through the project websites while each recording provides on the fly data products such as spectrum, spectrogram, and time dependent sound pressure level. Reference: Diviacco et al. (2021), JMSE, 9 (4), 390, DOI: 10.3390/jmse9040390

Title: **HydroMoth: testing a prototype low-cost acoustic recorder for aquatic environments**

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Keywords: hydrophone, audiomoth, low-cost recorder, passive acoustic monitoring

We test a prototype low-cost, low-specification aquatic recorder called ‘HydroMoth’. This device is a modified version of the widely used terrestrial recorder (AudioMoth), altered to include a waterproof case and customisable gain settings suitable for a range of aquatic applications. We test the performance of the HydroMoth in both aquaria and field conditions, recording artificial and natural sounds, and comparing outputs with identical recordings taken with commercially available hydrophones. Although the signal-to-noise ratio and the recording quality of HydroMoths are lower than commercially available hydrophones, the recordings with HydroMoths still allow for the identification of different fish and marine mammal species, as well as the calculation of ecoacoustic indices for ecosystem monitoring. Finally, we outline the potential applications of these low-cost, low-specification underwater sound recorders for bioacoustic studies, discuss their likely limitations, and present important considerations of which users should be aware.

Title: Observations of acoustic fluctuations on the inner continental shelf in Central California

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The recently completed Inner Shelf Direct Research Initiative (IS-DRI) experiment examined in great detail the physical oceanographic processes involved in the exchange of heat and momentum from outside the surf zone to the inner continental shelf, with a focus on features such as rip currents, fronts, and nonlinear internal waves. During this experiment, a low cost 27 kHz source was utilized, along with multiple self-contained underwater acoustic recording systems, with the goal of understanding nearshore acoustic fluctuations and their impact on acoustic communications and sonar performance. Acoustic intensity fluctuations are examined during two week-long periods during which intensity fades greater than 20 dB were observed. Variability spectra were found to be dominated at lower frequencies by tidal oscillations and higher frequency variability is attributed to intense nonlinear internal wave activity. Ambient noise spectra were found to be anisotropic, with low frequency spectral levels dominated by noise from wave breaking. When significant wave heights exceeded 3 m, a significant drop in spectral levels is observed, likely due to attenuation of sound by bubble plumes from breaking waves which are then ejected offshore by rip currents. Images from airplane flight missions confirmed the presence of offshore bubble plumes during swell events.

Title: Low-cost Ocean Acoustic Observations based on the AI-based Framework for Acoustic Sensors (AFAS)

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The AI-based Framework for Acoustic Sensors (AFAS) has been developed and prototyped as an extensible architecture. The framework is intended to be constructed at a low cost, but have significant self-contained processing capability. The current prototype has been specifically designed to allow modular hardware and software components for testing, profiling, and optimization. For example, the integrated system enables the testing and efficiency profiling of deployed North Atlantic Right Whale classification models generated by the MERIDIAN KETOS neural-network classification package. The design also allows the deployment of the MERIDIAN MARNOISE soundscape metrics package (which is being developed in parallel to ISO 7605 Standard: Measurement

of Ambient Underwater Sound development). In its most basic form, AFAS consists of a hydrophone, analogue-to-digital converter, and data capture system. The first prototype consisted of the most basic form using a mixture of off-the-shelf and custom supplier and was specifically designed for application in a low-cost ocean profiling buoy. The current enhanced prototype has relied on primarily off-the-shelf components, with only the power control board being a custom board. Even the pressure cases use the Open ROV standards that allows the components to be obtained from multiple sources. Though the effort is generating a low-cost design, further cost reductions can be achieved but at a performance price. Dynamic range, frequency range, self-noise, operating depth, and deployment life can be sacrificed in order to reduce the overall production cost. Future evolutions will likely see a further balancing of the off-the-shelf versus custom components in order to reduce cost and build complexity. Decisions on performance sacrifices will occur after further testing of the current build. Integral to the project is the enhancement of a broadband projector system used for testing and calibration.

Title: Orcasound's lowest-cost open source live-streaming PAM solution on a Raspberry Pi

Presenter and co-author order tentative/TBD, could vary depending on who is available/interested and/or by date-time workshop, too…

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Keywords: Real-time, Raspberry Pi, killer whale, cabled

For about 20 years, the Orcasound hydrophone network has monitored the habitat of endangered Southern Resident killer whales (SRKWs) in Washington State, USA. Because these salmon-seeking orcas emit many types of signals that humans can hear (<15kHz), for real-time detection of SRKWs Orcasound nodes can be put into listening-only mode and use very inexpensive hardware: a single-board computer and a USB-based ADC that cost <$100 U.S. In contrast, the least-expensive hydrophones that are durable enough for these year-round near-shore cabled deployments cost $300-600 U.S. per element. Depending on the deployment method, these hydrophones have lasted for 3-5 years, so their per/year cost is tolerable.

Nevertheless, we are looking for ways to drive the initial cost of our hydrophones down to <$100. In 2018 we deployed Raspberry Pi computers with the Pisound HAT (2 channel, 24 bit, 192kHz) and have been extremely satisfied with their durability (no failures after ~2 years in 3-5 locations). Our open-source software is free and our on-going cloud-based storage/streaming costs are about $10 per month per node. We would welcome additional deployments of our solution for monitoring noise at other "docks of convenience" where power and Internet access are available and a short cable run can reach water depths of ~5 m-10 meters. We also are interested in open source code contributions via github.com/orcasound, including possible modification of our code and open machine learning algorithms for edge computing or autonomous recorders. Our focus has been on optimizing real-time performance for both human and machine detection and classification, but a goal for 2022 is to improve how we measure and monitor ambient noise and ship levels, using calibrated and/or relative noise metrics.

Autonomous computationally efficient power spectral density estimation using performance-weighted blending

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Keywords: power spectral density estimation

Calibrated power spectral densities (PSDs) provide important information about the frequency content of natural and anthropogenic sources of ocean ambient sound. The classic Welch method (IEEE Trans. Audio Electroacoust., 1967) computes PSD estimates by averaging windowed Fourier transforms of the data. The choice of window controls the estimators frequency resolution and its ability to isolate loud signals within a band, enabling quiet

signals in other frequency bands to be measured. Choosing an appropriate window typically requires knowledge of the dynamic range and variability of signals in the environment. Since this information is not generally available prior to deployment, signal processing analysts typically tune the window parameters once data becomes available, and adjust them whenever the environment changes significantly. This talk describes a novel approach to power spectral density estimation that computes a PSD estimate as a weighted blend of an ensemble of Welch estimators. The estimators in the ensemble are based on a set of windows that provide different tradeoffs between resolution and interference rejection. The Performance Weighted Blended (PWB) estimator automates the work of a skilled signal processing analyst and adapts to find the best estimate in each frequency band. In addition, it can be implemented efficiently since it is based on a small set of conventional spectral estimators that use Fast Fourier Transforms. This talk summarizes the PWB approach to spectral estimation and illustrates its performance using data from a hydrophone mounted on an underwater glider.

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