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Integration of a Bioacoustics Detection, Classification and Localization Framework (PAMGuard) with a Bioacoustics Archiving Database and Workbench (Tethys)

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Authors	Douglas Gillespie, Jamie Macauley, and Marie A. Roch
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Prepared by	Douglas Gilespie University of Saint Andrews Saint Andrews, Scotland Jamie Macauley University of Saint Andrews Saint Andrews, Scotland Marie A. Roch San Diego State University San Diego, CA
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List of Contributors

Name / Affiliation	Contribution
Ally Rice / Scripps Institution of Oceanography, University of California, San Diego	Contributed to Tethys documentation
Kate O'Laughlin / San Diego State University	Contributed to Tethys programming
Ayushi Dubey / San Diego State University	Contributed to Tethys programming
James Sullivan / University of St Andrews	Programming of Python interface to PAMGuard data files

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List of Abbreviations and Acronyms

AI	artificial intelligence
AMAPPS	Atlantic marine assessment program for protected species
ANSI	American National Standards Institute
ASA	Acoustical Society of America
BOEM	Bureau of Ocean Energy Management
CPU	central processing unit
DOI	digital object identifier
GoMMAPPS	Gulf of Mexico[1] marine assessment program for protected species
NOAA	National Oceanic and Atmospheric Administration
PAM	passive acoustic monitoring
REST	representational state transfer protocol
WHOI	Woods Hole Oceanographic Institution

[1] This program was conducted prior to the 2025 renaming of the Gulf of Mexico to the Gulf of America, we use the name associated with the historical data to enable interested readers to locate details of the assessment program.

1 Study Summary

1.1 Abstract

Sound has proven to be an effective tool in the monitoring of wildlife and for determining and implementing mitigating methods for human disturbance of wildlife (Fleishman et al., 2023). Over the last decades, our ability to produce long-term wide-band recordings has grown exponentially, driving the need to produce automated and semi-automated tools that produce data products in a standardized manner, which increases their usefulness for addressing policy and scientific questions as well as their ability to retain and share these data. In this work, we developed new functionality to further enable large-scale data analysis in PAMGuard, one of the most highly used software packages for capturing and analyzing recordings of wildlife, and developed a PAMGuard interface to Tethys, a reference implementation of the Acoustical Society of America / American National Standards Institute (ASA/ANSI) standard for retaining information about recordings and information that is derived from them.

New functionality in PAMGuard includes an interface for incorporating deep learning models, permitting users to more easily incorporate the functionality of modern artificial intelligence (AI) algorithms into PAMGuard as well as new batch processing capabilities that permit parallel processing of data, significantly reducing the amount of user effort to process data. PAMGuard and Tethys have also been modified to work together. PAMGuard is not designed for archiving data from multiple projects and deployments, and the ability to export data to Tethys provides a new method to ensure that data can be archived in a standardized format. Parallel to this work, a U.S. Navy Living Marine Resources grant provided for development of Tethys that resulted in enhanced performance and functionality. Extensive user documentation was developed, and two instructional workshops were conducted.

1.2 Background

Passive acoustic monitoring (PAM) techniques have improved substantially in recent years. However, management of large PAM datasets remains a significant and time-consuming task. Challenges lie in the analysis of large datasets and the lack of a standard output format. Both issues slow data delivery to end users, including U.S. government agencies (e.g., BOEM, U.S. Navy). Slow data delivery in turn increases the costs of reporting and disseminating results.

PAMGuard software (Gillespie et al., 2026) was first released in 2006 and is widely used by the bioacoustics community both for real-time detection in the field and for offline analysis of archived datasets from autonomous and drifting recorders. New releases typically attract over 1,100 downloads, and the project currently has a greater number of Facebook followers. Several other PAM analysis software packages are available including Ishmael (Mellinger, 2002), Raven (Cornell Bioacoustics Research Program, 2011), and TRITON (Wiggins et al., 2010). PAMGuard is probably the most widely used for the analysis of data collected from mobile platforms, including sonobuoys, shipboard towed hydrophone arrays and drifting recorders. It is used by several National Oceanic and Atmospheric Administration (NOAA) Fisheries Science Centers, particularly for the analysis of odontocete vocalizations (Cholewiak and Soldevilla, 2018; Keating and Barlow, 2013; Rankin et al., 2017; Yack et al., 2009).

PAMGuard is also frequently used for the detection hydrophone and drifting recorder data from the NOAA-BOEM Marine Assessment Program for Protected species surveys (e.g., AMAPPS for the Atlantic and GOMMAPPs for the Gulf of America), which have received support from parts of the U.S. Navy. Data from these surveys are of direct relevance to Navy exercise planning and to understanding the impacts of Navy exercises.

Tethys software (Roch et al., 2013; Roch et al., 2016) addresses a different need. The numerous detection, classification, and localization algorithms used by researchers store results in custom formats, creating challenges for long-term retention, sharing of data, and use in meta-studies. Tethys established a community standard data format with the input of major academic and government research programs. Work by our ASA/ANSI standards committee recently extended this work and submitted a proposed standard to ASA/ANSI for accreditation. In addition to the Tethys reference implementation of these standards, projects that conform by and large to the standard include NOAA's National Centers for Environmental Information's Passive Acoustic Data Archive and NOAA's Passive Acoustic Cetacean Map. The Tethys project provides a database designed for institution-level access, web server, and client software, and provides simple point and click data exploration as well as programmatic interfaces for researchers wishing to conduct large-scale analysis in MATLAB, R, Python, and Java. A well-documented representational state transfer protocol (REST; Fielding, 2000) for accessing the Tethys database allows relatively simple integration into any other language that supports web queries. Since the Tethys 3.1 release in September 2024, Tethys 3 and subsequent versions have been downloaded 185 times.

1.3 Objectives

The objectives of this project were three-fold:

1. **To integrate PAMGuard and Tethys to make exporting PAMGuard data products to Tethys straightforward:** PAMGuard manages data on a per project basis and does not support combining multiple investigations. In contrast, Tethys excels at this but does not support detection, classification, and localization products generated by PAMGuard directly. Consequently, the integration of PAMGuard—a system with a large user base—with Tethys provides an opportunity to ease a large user community into a system that lets them leverage the full scale of their data collection in a standardized, archival format.

2. **To permit efficient parallel batch processing of multiple datasets with PAMGuard:** With increasing numbers of deployments of archival autonomous recorders, whether moored or attached to autonomous vehicles, the ability to apply the same set of operations specified in a PAMGuard configuration file to multiple separate datasets is becoming increasingly important to analysists. Batch processing greatly reduces PAM operator burden when processing multiple datasets both in the complexity of conducting operations and in the time needed to complete data processing.

3. **To enable users to more easily use AI to further analyze their acquired data:** Bioacoustics has seen many deep learning algorithms advance the state of the art (see Stowell, 2022 for an overview). However, these algorithms are often not packaged in a form that makes them accessible to many biologists, and they do not typically provide the required infrastructure for human data validation and integration into established workflows. A new module in PAMGuard can call a wide variety of deep

learning models in PAMGuard's biologist-friendly environment. By providing a standard module specification of signal processing that needs to be done to create a deep learning input (e.g., spectrograms with specific characteristics) and an engine for executing deep neural networks given a model in a standardized format, PAMGuard can be extended in a straightforward manner to use many deep learning algorithms and has extensibility to integrate new models as they become available.

In addition, we have produced training material available through updated PAMGuard and Tethys websites. All software and training materials are available under open-source license agreements, meaning that anyone can use and modify them. For example, third party bioacoustics training providers may freely take our training material and incorporate it into their own courses.

1.4 Methods

This project was the combined effort of two coordinated BOEM environmental studies, NT-22-05a and NT-22-05b. NT-22-05a was a cooperative agreement with San Diego State University, where the Tethys metadata system had been developed over many years. NT-22-05b was a contract with the University of Saint Andrews, where the PAMGuard data acquisition and analysis software had been developed over many years. The two groups of software developers merged their knowledge to integrate the functionalities of the two popular software packages and then to educate the wider community of scientists employing acoustic monitoring of wildlife. The new, integrated software was developed with critical feedback and guidance from a steering committee and from test (beta) users. In addition, we held two workshops to educate prospective users on the new integrated software and solicit their feedback on way to make the package easier to use and add capabilities. The software was made available to the public during the studies' period of performance and additional changes have been made based on further user feedback.

1.5 Results

A new interface was developed for exporting PAMGuard data to Tethys (**Figure 1**). A data crosswalk was established to map PAMGuard field names to Tethys names and certain new fields were introduced into PAMGuard for data items that did not exist. Challenges included areas that were not historically standardized in PAMGuard, such as taxonomic encoding. New user interfaces were developed for exporting, requiring changes to both the PAMGuard and Tethys software. Users can now easily export data to Tethys by specifying a Tethys server and clicking the appropriate export button. Additional dialogs lead users through any additional information that is required such as descriptions of objectives and methods.

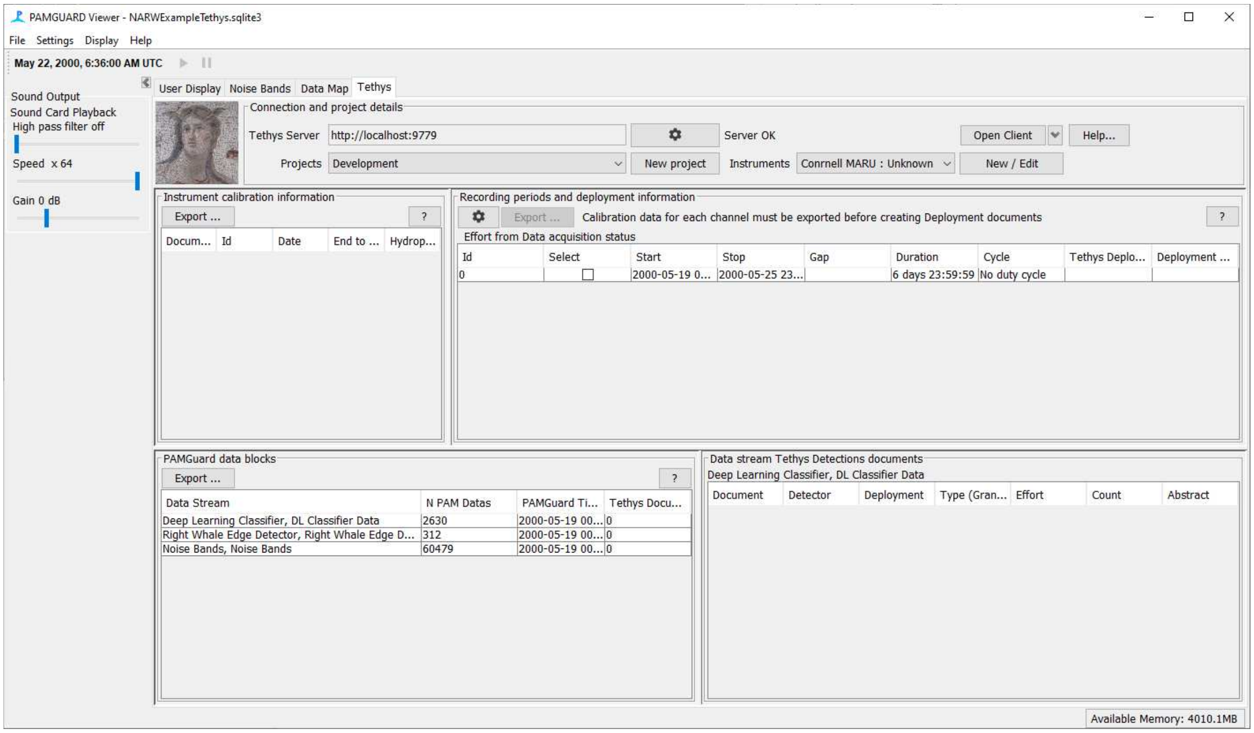

Figure 1. Tethys export from PAMGuard

The top panel allows users to specify the Tethys server. Lower panels permit the export of information related to deployments, calibrations of hydrophones, sets detection, and classification and localization algorithms.

The PAMGuard batch processing module allows users to design a processing configuration that is applied to multiple data sets. It exploits the multiple central processing unit (CPU) cores available in most modern microprocessors. In 2025, this is typically six to twenty cores, with high-end models such as the Advance Micro Devices (Santa Clara, CA) ThreadRipper Pro having up to ninety-six cores. The “specify once, apply multiple times” paradigm starts a pool of PAMGuard processes, each of which will handle a set of data in the same manner (**Figure 2**). Multiple jobs are started in parallel based on the capabilities of the CPU and operator direction, and new jobs are taken from the queue as running processes are completed. This results in PAM operators spending less time indicating which analyses should be conducted and obtaining those results in a more consistent and timely manner.

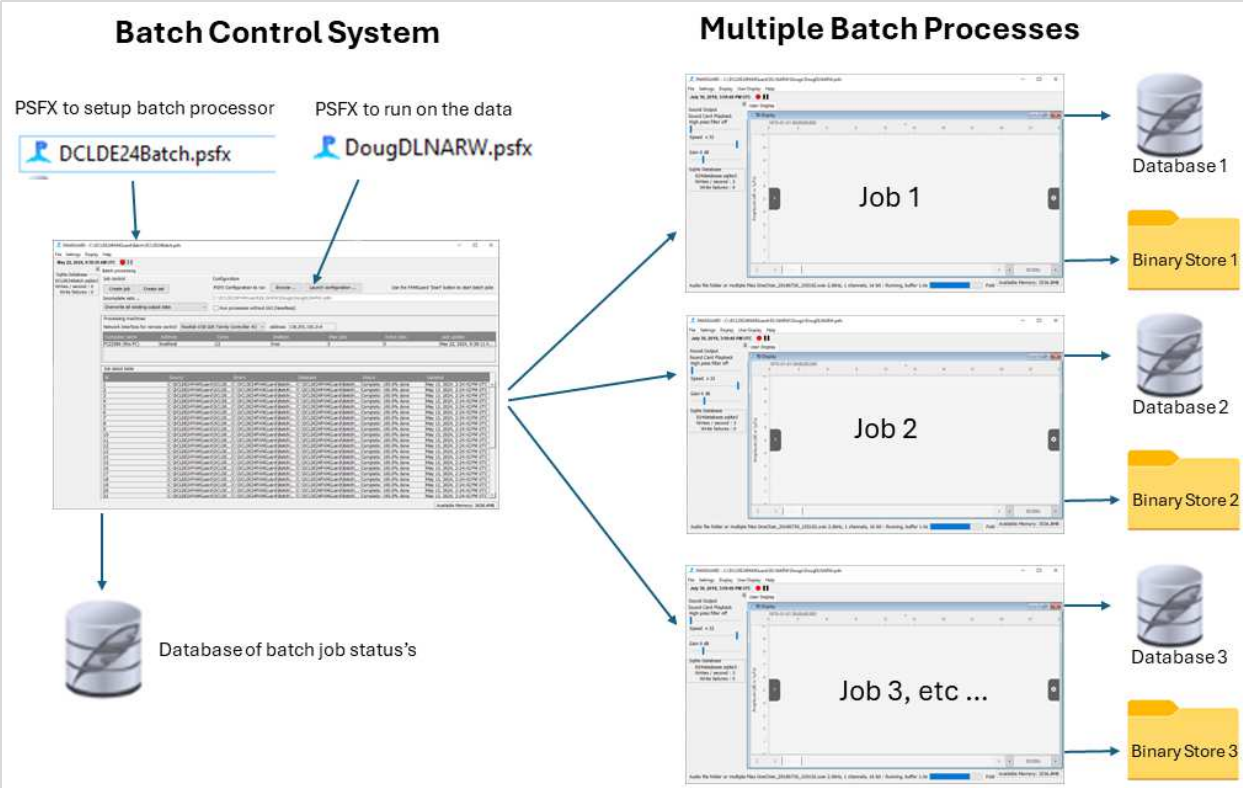

Figure 2. PAMGuard batch processing system

The user has established a set of processing operations and data to which the operations will be applied (left side). PAMGuard dynamically allocates processing operations and data to a pool of data processing jobs that are executed in parallel (right side). As jobs are completed, new ones are selected from the batch control system until all jobs have been processed.

PAMGuard's new deep learning module functions on two levels. For bioacousticians without machine learning expertise, it provides the ability to download other researchers' models and apply them to data without the need for any programming. To facilitate this, we created a web page to disseminate published models that are compatible and tested with PAMGuard, and we and currently provide models for humpback whale (*Megaptera novaeangliae*) song detection (Allen et al., 2021), North Atlantic right whale (*Eubalaena glacialis*) upcall detection (Shiu et al., 2020), and dolphin species classification from whistles and clicks (Kleyn, 2025). We will expand this library of models over time. All deep learning models are automatically integrated into PAMGuard's display architecture (**Figure 3**), permitting manual review of output.

More technically proficient users can also train and run their own models, either by using a common framework such as Koogu (which automatically generates PAMGuard compatible models) or by following online instructions on how to incorporate bespoke models into the PAMGuard's deep learning framework. This approach means that PAMGuard can be used in a wide variety of use cases; for example, it is accessible to those wishing to explore the use of deep learning in data analysis for the first time via pre-packaged models online and can be used by private companies and researchers creating their own (and possibly proprietary) models.

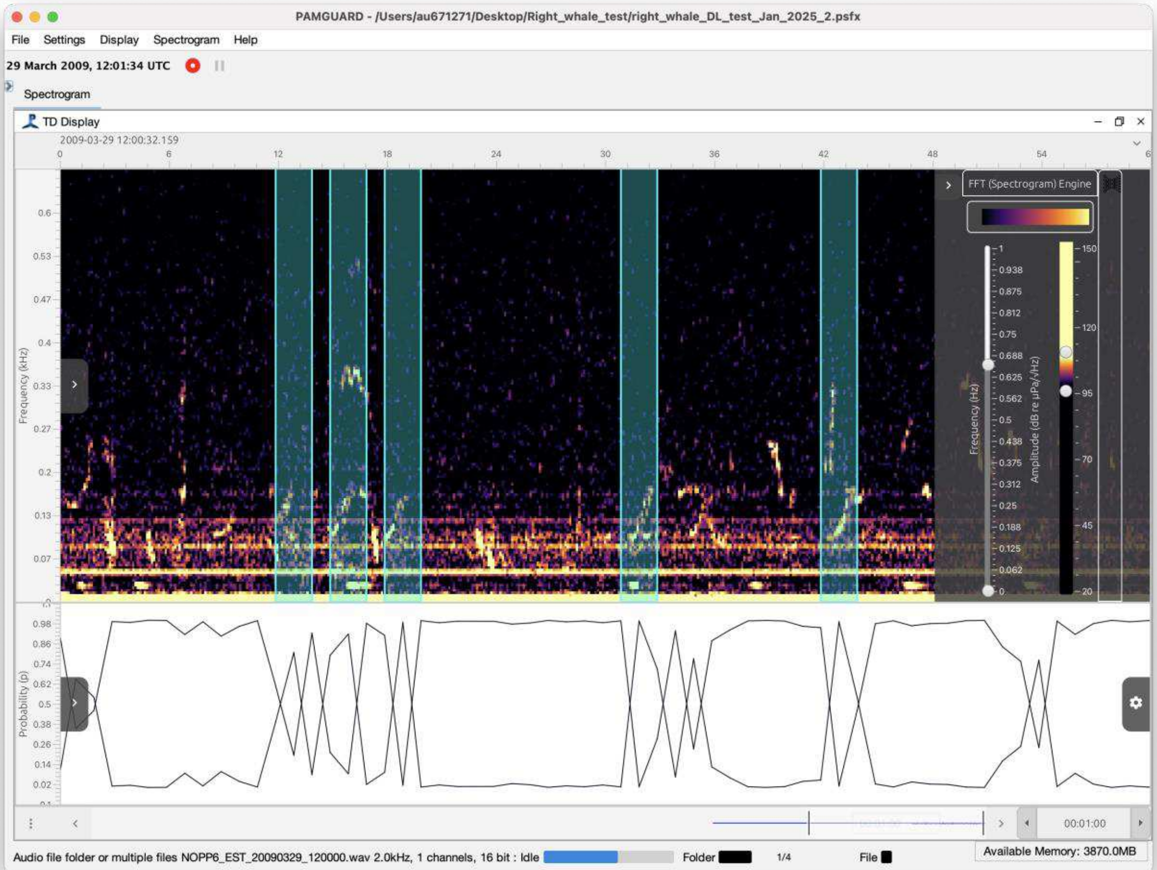

Figure 3. Application of the North Atlantic right whale detector to an acoustic stream

Top panel: spectrogram with detections of upcalls highlighted in transparent blue. Lower panel: two prediction signals, one for upcall present and the other for anything else. Prediction signals cross during times of transition as calls start and end.

BOEM has generated and reviewed extensive documentation for both PAMGuard and Tethys. Two four-day workshops were conducted: the first at San Diego State University, San Diego, CA in March 2025; and the second at Woods Hole Oceanographic Institution (WHOI) in April 2025. Each workshop hosted 14 attendees from academia, industry, the U.S. Navy, NOAA, and BOEM. While originally planned to be strictly delivered in person, a U.S. government travel ban resulted in us shifting to create a virtual option for the WHOI workshop.

BOEM collaborated on this work by providing guidance throughout the project, reviewing documentation, participating in one of the workshops, and participating in the standards committee.

1.6 Conclusions

The PAMGuard and Tethys integration is now complete, enabling PAMGuard users to store their data in a standardized archive format. Additional tools have been added to increase PAMGuard functionality and usability. Batch processing will result in non-trivial productivity gains, and the deep learning modules enable rapid integration of developing technologies into a tool that many PAM practitioners already use.

2 Study Products

2.1 Software Downloads

The primary outputs of the study are updated PAMGuard and Tethys software. These are available from the following links. Users should download and install the built software products. Developers and others may access the software source code.

Software releases

Gillespie, Douglas, Macauley, Jamie, "PAMGuard version 2.02.17," https://www.pamguard.org/releases/download.html.

Roch, Marie A., "Tethys, version 3.2," 2025, https://tethys.sdsu.edu/install/.

Long-term archives of software releases

Permanent and citable archives of releases can be found at the open science archive Zenodo, a long-term data archive hosted by the European Organization for Nuclear Research (**Table 1**), where release can be referenced by digital object identifiers (DOIs):

Table 1. Long-term archives of projects

Project	DOI Link
PAMGuard	https://doi.org/10.5281/zenodo.13378950
Tethys	https://doi.org/10.5281/zenodo.13626338

Software source code

PAMGuard source code is available at https://github.com/PAMGuard.

Tethys source code is available at https://bitbucket.org/tethysacousticmetadata/workspace/repositories.

2.2 Training Resources

PAMGuard training materials are available at https://www.pamguard.org/tutorials.html. Large datasets required for some of the tutorials are archived elsewhere and may be accessed through links from that website.

Key materials for use with the output of this study include the following:

- PAMGuard Tethys Interface - https://www.pamguard.org/tutorials/tethys.html
- Batch Processing - https://www.pamguard.org/tutorials/batchprocessing.html
- Deep Learning in PAMGuard - https://www.pamguard.org/tutorials/deeplearning.html

- Tethys tutorials and documentation - https://tethys.sdsu.edu/documentation

Novice users are recommended to work through other tutorials on the site prior to those developed under this work program.

Source material underlying the training materials (e.g., Word documents, rather than PDFs) can be accessed through https://github.com/PAMGuardLearning and https://bitbucket.org/tethysacousticmetadata/documentation.

3 Additional Products Resulting from this Study

Peer-reviewed Articles

Gillespie, D., Macaulay, J., Oswald, M., and Roch, M. A. (2026). "PAMGuard: Application software for passive acoustic detection, classification, and localisation of animal sounds," J Acoust Soc Am 159(1). 437-443, doi:10.1121/10.0042245.

Conference Presentations

Roch, M. A, Baumann-Pickering, S., Frasier, K., Gillespie, D. and Whitney, R. "Data Management for Detection, Classification, and Localization," Detection Classification, Localization, and Density Estimation, June 2024, Rotterdam, Netherlands.

Workshops

Gillespie, D., Macauley, J., and Roch, M. A., "PAMGuard/Tethys Introduction," Detection, Classification, and Density Estimation, June 2024, Rotterdam, Netherlands – One-day tutorial workshop.

Gillespie, D., Macauley, J., and Roch, M. A., "PAMGuard/Tethys Course," March 2025, San Diego, CA – Four-day tutorial workshop.

Gillespie, D., Macauley, J., and Roch, M. A., "PAMGuard/Tethys Course," April 2025, Woods Hole, MA – Four-day tutorial workshop.

Standards

Standard for Acoustic Metadata for Passive Acoustic Monitoring – Standard submitted and approved by the ASA/ANSI accreditation committee. Dr. D. Gillepie's (U. Saint Andrews) participation in this committee was funded by these efforts. Dr. M. A. Roch chaired this effort; her funding was through the U.S. Navy Living Marine Resource Program. The working group associated with the standards effort had the following membership at the time of submission:

- Marie A. Roch, Chair, San Diego State University, San Diego, CA, USA
- Simone Baumann-Pickering, Scripps Institution of Oceanography, Univ. California, San Diego, CA, USA
- Danielle Cholewiak, National Oceanic and Atmospheric Administration (NOAA) Northeast Fisheries Science Center, Woods Hole, MA, USA
- Douglas Gillespie, University of St. Andrews, St. Andrews, Scotland
- Shane Guan, Bureau of Ocean Energy Management, Sterling, VA, USA
- Jasper Kanes, Ocean Networks Canada, Victoria, BC, Canada
- Katherine H. Kim, Greeneridge Sciences, Inc, Santa Barbara, CA, USA
- Holger Klinck, Cornell University, Ithaca, NY, USA
- Xavier Mouy, Woods Hole Oceanographic Institution, Woods Hole, MA, USA (formerly of JASCO Applied Sciences, Victoria, BC, Canada)
- Ana Širović – Norwegian University of Science and Technology, Trondheim, Norway

Carrie Wall – University of Colorado Boulder and NOAA National Centers for Environmental Information, Boulder, CO, USA

In addition to the standard, the working group produced a “how to” guide that provides real world examples of passive acoustic monitoring and illustrates how the standards apply to different situations.

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Stowell, D. (2022). "Computational bioacoustics with deep learning: a review and roadmap," PeerJ 10, pp. e13152, doi:10.7717/peerj.13152.

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