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Management of acoustic metadata for bioacoustics

Marie A. Roch [a,*], Heidi Batchelor [b], Simone Baumann-Pickering [b], Catherine L. Berchok [c], Danielle Cholewiak [c], Ei Fujioka [d], Ellen C. Garland [c], Sean Herbert [b], John A. Hildebrand [b], Erin M. Oleson [c], Sofie Van Parijs [c], Denise Risch [c], Ana Širović [b], Melissa S. Soldevilla [c]

[a] San Diego State University, Dept. of Computer Science, 5500 Campanile Dr., San Diego, CA 92182-7720, USA
[b] Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0205, USA
[c] NOAA National Marine Fisheries Service, Fisheries Science Centers, 1315 East-West Highway, Silver Spring, MD 20910, USA
[d] Marine Geospatial Ecology Lab, Nicholas School of the Environment, Duke University, PO Box 90328, Durham, NC 27708, USA

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ABSTRACT

Recent expansion in the capabilities of passive acoustic monitoring of sound-producing animals is providing expansive data sets in many locations. These long-term data sets will allow the investigation of questions related to the ecology of sound-producing animals on time scales ranging from diel and seasonal to inter-annual and decadal. Analyses of these data often span multiple analysts from various research groups over several years of effort and, as a consequence, have begun to generate large amounts of scattered acoustic metadata. It has therefore become imperative to standardize the types of metadata being generated. A critical aspect of being able to learn from such large and varied acoustic data sets is providing consistent and transparent access that can enable the integration of various analysis efforts. This is juxtaposed with the need to include new information for specific research questions that evolve over time. Hence, a method is proposed for organizing acoustic metadata that addresses many of the problems associated with the retention of metadata from large passive acoustic data sets. A structure was developed for organizing acoustic metadata in a consistent manner, specifying required and optional terms to describe acoustic information derived from a recording. A client-server database was created to implement this data representation as a networked data service that can be accessed from several programming languages. Support for data import from a wide variety of sources such as spreadsheets and databases is provided. The implementation was extended to access Internet-available data products, permitting access to a variety of environmental information types (e.g. sea surface temperature, sunrise/sunset, etc.) from a wide range of sources as if they were part of the data service. This metadata service is in use at several institutions and has been used to track and analyze millions of acoustic detections from marine mammals, fish, elephants, and anthropogenic sound sources.

1. Introduction

A large variety of marine organisms, including marine mammals, fishes, and invertebrates, produce species-specific acoustic signals, or calls (Anorim, 2006; Hawkins, 1986; Richardson et al., 1995; Versluis et al., 2000). Knowledge of the occurrence of these calls has been valuable in increasing our understanding of the biology and ecology of these often visually elusive organisms (e.g. Aguilar de Soto et al., 2011; Baumann-Pickering et al., 2014; Hernandez et al., 2013; McDonald et al., 2006; Oleson et al., 2007c; Risch et al., 2013; Simpson et al., 2005; Širović et al., 2004). The marine bioacoustics community has invested considerable resources in developing tools to detect, classify, track, localize, and determine the density of animals based on calls (e.g. Barlow and Taylor, 2005; Blackwell et al., 2013; Deecke and Janik, 2006; Erbe and King, 2008; Gillespie et al., 2013; Kandia and Stylianou, 2006; Marques et al., 2009; Mellinger et al., 2011; Nosal, 2013; Zimmer, 2011). These calls are recorded on a variety of fixed (e.g. moored instruments, bottom seafloor packages) and mobile (e.g. towed arrays, autonomous underwater vehicles, animal tags) instrument configurations.

The tools for analyses of bioacoustic data sets, whether automated, manual, or some combination thereof, can provide a range of information about the calling animals and their environments such as signal characteristics, temporal patterns in vocal behavior, source levels, density estimates, measurements of anthropogenic noise, etc. It is often possible to infer biologically relevant information, such as daily and seasonal activity patterns over potentially large temporal and spatial scales. Information derived from these recordings such as detections of calling animals and the methods used for detection is considered to

* Corresponding author.
E-mail address: marie.roch@sdsu.edu (M.A. Roch).

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be metadata (information describing the data) of the acoustic record. However, these metadata have frequently been generated and stored in idiosyncratic formats on the computers of individual researchers. While combining multiple datasets or the results from multiple analyses might often lend more power to the ability to interpret patterns in the data, consistent metadata formats and mechanisms of retrieval are required to remove the formidable obstacles that often hinder merging results from multiple analyses.

The proliferation of such tools for producing large quantities of metadata poses a new set of data management challenges as well as providing exciting opportunities for the bioacoustics community to ask new types of questions in a data rich environment. By pooling metadata from multiple sources, the scope of study that can be undertaken can be significantly expanded, but care must be taken to ensure that the data and methods are compatible.

Of particular importance in these metadata associated with acoustic detections is documentation of the data processing method applied to a given dataset: What portion of the data were analyzed? What was the target and methodology of the analysis? Which detections were gathered in a systematic manner and which were opportunistic or incidental? The methods require enough detail to determine whether studies are compatible. For example, consider combining two studies that used different signal-to-noise ratio thresholds for detecting animals with similar call source levels; for some analysis questions, this difference should be factored into the analysis of the combined data to prevent bias. In most cases, the study with the lower SNR threshold will detect animals from farther away, thus increasing the area over which animals are monitored. Assuming a spherical spreading model (Urick, 1983 pp. 100–101) and a lower detection threshold of half the acoustic pressure (6 dB) will result in increasing the radius of the monitoring area by a factor of 2, with a corresponding increase in area by a factor of 4. Studies testing hypotheses related to call rates would need to take into account the number of calls detected with respect to the monitored area while those considering characteristics of calls should consider that there would be frequency-dependent differences in the attenuation of the received signal.

Indicating what portion of the data were analyzed is important for constructing valid inferences and is a separate issue from the actual recording regime of the instrument. It is common to subsample data from long-deployment passive acoustic monitoring data sets. The decision of what portion of the acoustic data to analyze can be thought of as a secondary stage of sample design or survey effort, and in this article, we will refer to it as analysis effort.

One must also indicate the species and calls for which systematic analysis effort is conducted. Studies focusing on a single species may not typically record these types of details, especially when all of the data are consistently analyzed due to manageable data size or efficient automated classifiers. However, specification of the details of systematic analysis effort facilitates the retrieval of records appropriate to a researcher's question and is critical for the selection of metadata from data repositories containing diverse analysis effort. It should be noted that in many fields, researchers will record opportunistic or incidental detections that are not part of their systematic effort. Analogs to these type of detections exist in other types of survey studies such as visual point transect (Buckland, 2006) and trap surveys (Buckland et al., 2006). Examples include an ornithologist noting a rare species of bird when moving from one point transect to another or an entomologist electing to perform several opportunistic net sweeps to collect additional samples around a bee trap. In both cases, additional information can be gained from the analysis of these incidental detections or animals and they should be retained. However, during analysis, they must be distinguished from data that were obtained in a systematic manner. Systematic observations are necessary for well-founded inference about spatio-temporal patterns.

Data analysis over large, spatially and temporally varied acoustic data requires *consistency*, which is the first key feature of our approach. This means that standardized names describing data types in the metadata must be selected along with constrained sets of values that can be stored. As an example of this, one may elect to store a species' common name, scientific name, or a coded value representing the species name such as the taxonomic serial numbers provided by the Integrated Taxonomic Information System (ITIS Organization, 2014). Similarly, one might elect to specify that acoustic sampling rate be measured in Hz or kHz; specification of units is necessary to effectively query metadata.

A hierarchy of concepts can be provided by grouping names together under the umbrella of a name that describes the group (sometimes called a frame or structure). An example of this is to use the name “parameters” to describe a collection of settings for a detection algorithm. Names, their values, and hierarchical structure form the basis of an ontology (McGuiness, 2003), a definition of how data are encoded and related to one another.

Consistency must be balanced with the need to be *extensible*. As the body of knowledge about species increases, new questions are posed. An acoustic signal that was considered at one time to be stereotyped may be found to have categorical or graded variations (e.g. Risch et al., 2013 recently showed that minke whale, *Balaenoptera acutorostrata*, thump trains had more pulse structure than previously thought), and researchers may wish to study those variations with respect to individuals, activity state, context, or ecosystem pressures such as habitat loss. In addition, researchers with different goals, analysis techniques, and working in a variety of habitats may have varying needs. Consequently, our goal was to define a system to capture acoustic metadata that is both consistent and extensible.

In this article, we focus on acoustic metadata for marine mammals and anthropogenic sources (e.g. shipping, naval operations, and oil exploration). We have used this type of approach to analyze the calls of numerous species of cetaceans on multiple datasets collected throughout the Pacific, merging results from over 36 years of analysis effort (Baumann-Pickering et al., 2014; Širović et al., 2015).

While the developmental effort focused on sounds from the marine environment, the methods have been extended to include the terrestrial environment with few modifications. Preliminary unpublished work conducted by Peter Wrege and Sara Keen at Cornell's Bioacoustics Research Program on calls from African forest elephants, *Loxondonta cyclotis*, has shown that this can be done without changes to the data representation (personal commun. Sara Keen). The only change to the implementation required was to update the subset of taxonomic serial numbers (ITIS Organization, 2014) stored in our database to include the family *Elephantidae*. The current implementation has expanded this to all species described in ITIS. In cases where altitude is needed (e.g. bird flight calls), our marine centric name depth would need to be changed or negative depth values could be used.

We describe a set of metadata structuring rules that we call Tethys and provide a brief introduction to the Tethys Metadata Workbench, an implementation of this data framework that includes a server program and client libraries. The Tethys Metadata Workbench can manipulate the metadata as well as access a large variety of Internet-available geophysical, biological, and astronomical data sources. The workbench is designed to be used by individual laboratories. A web-services-based server permits data exchange between research groups, and summary data can be exported into the Ocean Biogeographic Information System – Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP; Halpin et al., 2009).

We are developing data representations for instrument deployments and calibration information, acoustic detection, classification, and localization data, and supplemental information. In this paper, we restrict our discussion to metadata related to instrument deployments