Mobile Autonomous Platforms for Passive-Acoustic Monitoring of High-frequency Cetaceans

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Abstract Increased human activities in coastal and offshore waters, including renewable energy efforts such as the deployment and operation of wind, wave, and tidal energy converters, leads to potential negative impacts on marine ecosystems. Efficient monitoring of marine mammals in these areas using stationary passive-acoustic technologies is challenging. Many recreational and commercial activities (e.g., fishing) can hinder long-term operation of moored listening devices. Further, these waters are often utilized by cetaceans such as porpoise species which produce high-frequency echolocation clicks (peak frequency ~130 kHz) for navigation, communication, and prey detection. Because these ultrasonic signals are

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A. Friebe and F. Haug (eds.), *Robotic Sailing 2015*,
DOI 10.1007/978-3-319-23335-2_3

strongly absorbed during propagation, the acoustic detection range is limited to a few 100 m, and therefore the spatial coverage of stationary recorders is relatively limited. In contrast, mobile passive-acoustic platforms could potentially be used to survey areas of concern for high-frequency cetacean vocalizations and provide increased temporal coverage and spatial resolution. In a pilot study, a commercially available acoustic recorder featuring sampling rates of up to 384 kHz was customized and implemented on an autonomous underwater vehicle (AUV) and an unmanned surface vehicle (USV) and tested in the field. Preliminary results indicate that these systems (a) are effective at detecting the acoustic presence of high-frequency cetaceans such as porpoises, and (b) could be a valuable tool to monitor potential negative impacts of renewable energy and other anthropogenic disturbances in the marine environment.

1 Introduction

Increased development and use of marine renewable energy converters harvesting wind, tidal, and wave energy to generate electricity has raised concerns about potential negative impacts of the installation and operation of such devices on the marine environment [4, 10].

In Europe, the offshore wind energy industry is well established. The first commercial windfarm was installed in Vindeby, Denmark in 1991 and many have followed since. To date approximately 2,500 wind turbines are being used in European waters to generate electricity [5]. Wave and tidal energy have been proposed as possible sources of renewable energy in these and other parts of the world. Prototype devices are currently being developed and tested, for example, in the Pacific Northwest of the United States of America [12].

Potential environmental impacts of renewable energy installations are manifold and include the emission of underwater noise [1, 4, 10, 17]. Elevated underwater noise levels are of concern, especially for noise-sensitive cetaceans including the harbor porpoise, *Phocoena phocoena* [16]. Harbor porpoises can be found in temperate and sub-polar coastal waters including the Baltic Sea and the North Pacific [11], and their habitat overlaps with areas of existing and future renewable energy installations. In the North Pacific, the habitat of three additional high-frequency cetacean species, the Dall's porpoise, *Phocoenoides dalli*, and the dwarf and pygmy sperm whale, *Kogia sima* and *K. breviceps* respectively [11],

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overlaps with areas which recently have been proposed for the installation and operation of offshore floating wind turbines.

Monitoring these species is difficult. They are among the smallest cetaceans (body length <3.5 m) and usually (except for the Dall's porpoise) occur in small groups of a few individuals [11, 19] which are hard to spot visually in most weather conditions (Fig. 1c). Conversely, porpoises and *Kogia spp.* regularly emit echolocation clicks [9, 18] for communication, prey detection, and navigation, and these clicks can be readily detected with passive-acoustic monitoring (PAM) systems, regardless of weather or light conditions [9]. However, these ultrasonic signals (peak frequency ~130 kHz; [9, 18] are highly attenuated when propagating due to absorption; therefore, the acoustic detection range is limited to a few 100 m. This limits the effectiveness of stationary acoustic recorders.

Various autonomous underwater vehicles (AUVs) and unmanned surface vehicles (USVs) have been proposed for use in passive-acoustic monitoring efforts [7]. Over the last couple of years AUVs featuring passive-acoustic recording and detection capabilities [2, 6] have proven to be effective survey tools for low- and mid-frequency marine mammal vocalizations. The goal of this study was to evaluate the potential use both AUVs and USVs to monitor high-frequency cetacean

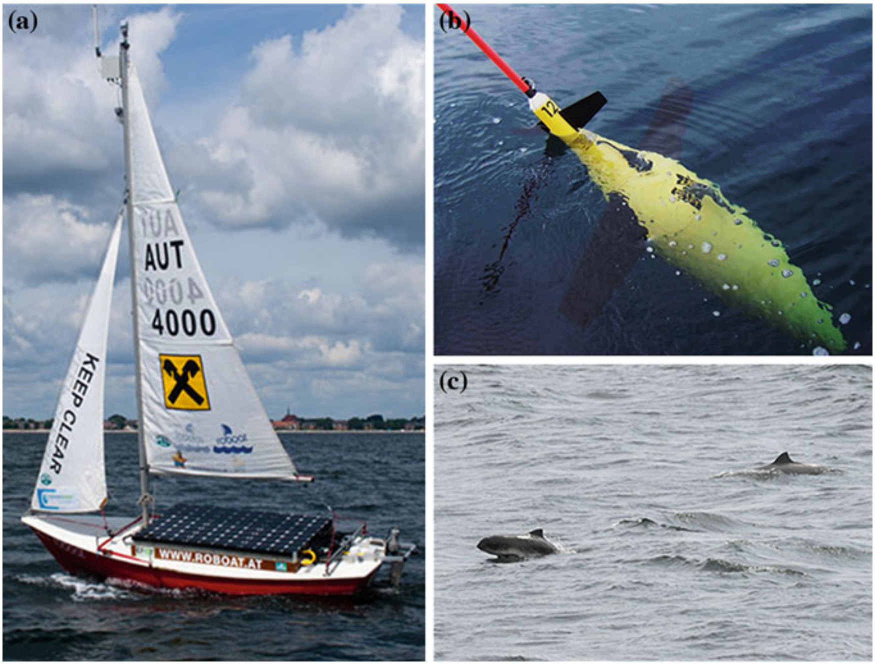

Fig. 1 The USV Roboat **a** and the AUV Seaglider™ **b** The goal of the study was to acoustically detect high-frequency cetaceans including the harbor porpoise **c** Picture credits: **a** Austrian society for innovative computer sciences, Austria, **b** Alfred Wegener Institute, Germany, and **c** Jean-Pierre Bonin, Canada

vocalizations, such as produced by porpoises. These instruments could significantly improve the temporal coverage and spatial resolution of future passive-acoustic survey efforts.

2 Methods

The two vehicles used in this study (Fig. 1a, b) are the Roboat, a prototype autonomous sailboat [15] developed by the Austrian Society for Innovative Computer Sciences (INNOC), Austria, and the Seaglider™ an autonomous deep-diving underwater glider [13], commercially available from Kongsberg, Inc., USA.

Both vehicles were equipped with a commercially available acoustic recorder (Song Meter SM2BAT+, Wildlife Acoustics Inc., USA). The recorders were installed in the science bay of the vehicles, equipped with 896 GB of data storage each (SD memory cards) and programmed to continuously record signals at a sampling rate of 384 kHz and 16 bit resolution. Lossless compression (WAC0) of the audio data was enabled to maximize the available recording duration. Both systems featured a 1 kHz high pass filter and featured a fairly flat frequency response (±10 dB) in the frequency range 1–192 kHz. The Roboat was equipped with a single-ended HTI 96-MIN hydrophone (High Tech Inc., USA) which was mounted to the keel of the boat approximately 0.5 m below the waterline. The overall sensitivity of the acoustic system was −129 dB re 1 V/μPa. The Seaglider was equipped with a differential HTI 92-WB hydrophone (High Tech Inc., USA) mounted to the Seaglider's antenna and a custom-built differential pre-amplifier. The overall system sensitivity was −123 dB re 1 V/μPa. In addition, the acoustic recording system installed on the Seaglider was interfaced with a Persistor CF2 microcontroller (Persistor Instruments Inc., USA) to enable remote control from a base station on shore. The Seaglider also collected environmental data on conductivity, temperature, oxygen, and chlorophyll throughout the mission.

The Roboat test was conducted off of Eckernfoerde, Germany in the Baltic Sea in July 2012. This was the first reported attempt to use an autonomous sailboat to record marine mammal vocalizations. The Seaglider test was conducted off of Newport, OR, USA in the North Pacific in March and April 2014, and was the first reported attempt to sample such high frequencies using a Seaglider.

After recovery of the instruments, collected acoustic data were manually analyzed in the lab. Long-term spectral average plots (LTSAs) were screened for the presence of porpoise echolocation clicks using the Triton software package developed by the Scripps Whale Acoustics Lab, USA (available online at: http://cetus.ucsd.edu/technologies_Software.html).

3 Results

Roboat: The intended transect line for the Roboat was a north-south roundtrip (~130 nm) between Eckernfoerde, Germany and Assens, Denmark. The sea trial was started on 14 July 2012. Unfortunately, the weather conditions during the field test were poor. Average wind speed was measured at 15 kn with gusts of up to 29.5 kn. The Roboat sailed at an average speed of 2.9 kn. After 71 nm of autonomous sailing, severe weather conditions caused a malfunction of the motor necessary to trim the mainsail. Consequently, the trial had to be abandoned after 27 h, on 15 July 2012.

The collected passive-acoustic data were very noisy, which prohibited a semi-automated analysis (application of harbor porpoise-specific detectors and classifiers) of the data set. The manual analysis was difficult; it took approximately 8 work days to thoroughly analyze the 27 h of collected acoustic data (73 GB total). Several noise sources were identified: mechanical noise generated by the rudder and sail motors (mainly solid-borne sound), waves splashing against the boat hull, and general surface activity such as breaking waves and rain.

Nevertheless, the manual acoustic data analysis revealed that during the 27 h survey, 98 harbor porpoise click trains were registered. An example is shown in Fig. 2.

The registered click trains were comparatively short, each lasting between 1 and 3 s in duration. A map indicating the locations of the harbor porpoise acoustic encounters is shown in Fig. 3. About 10 % of the encounters were recorded during

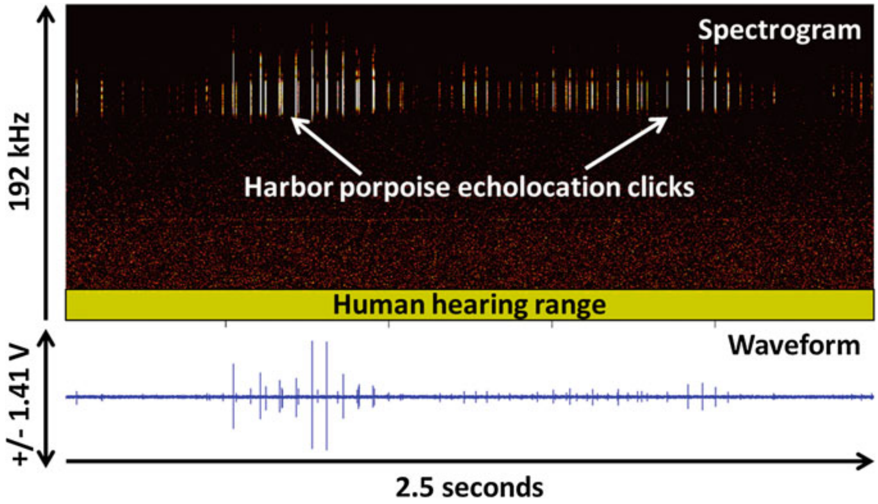

Fig. 2 Spectrogram and waveform of a harbor porpoise echolocation click train recorded with the Roboat. The *yellow box* in the spectrogram indicates the frequency range of human hearing (roughly 20 Hz–20 kHz). De-noising algorithms were applied to the data to eliminate electronic noise artifacts

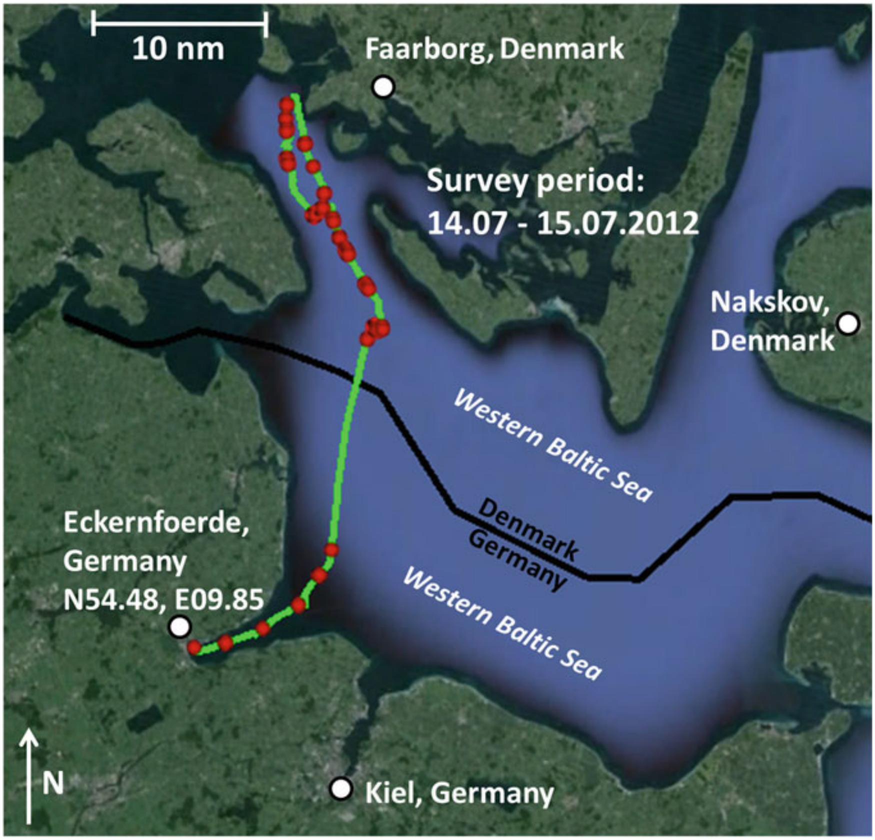

Fig. 3 Overview map of the Roboat survey. The *red dots* on the *green trackline* indicate harbor porpoise detections. Map: Google Earth

the first 4 h of the survey in German waters. No detections occurred during the following 4 h of the survey. Most encounters (90 %) occurred during the remaining 19 h in Danish waters north of 54.81°N. These observations match results from previous aerial surveys (e.g., [14]) which indicated a high abundance of harbor porpoises in the Danish waters surveyed by the Roboat.

Seaglider: The Seaglider was deployed approximately 20 nm off the coast of Newport, OR, USA on 18 March 2014 and recovered on 20 April 2014 (Fig. 4). During the west-east survey the Seaglider covered a distance of approximately 320 nm over ground (average speed: 0.42 kn). The glider completed 148 dives to 1,000 m depth with the PAM system activated. A total of 896 GB of WAC0 compressed (approximately 1,800 GB uncompressed) audio data were collected in the 25–1,000 m depth range. Vehicle-related self-noise was minimal and limited to times when glider-internal control and steering mechanisms (buoyancy pump, etc.)

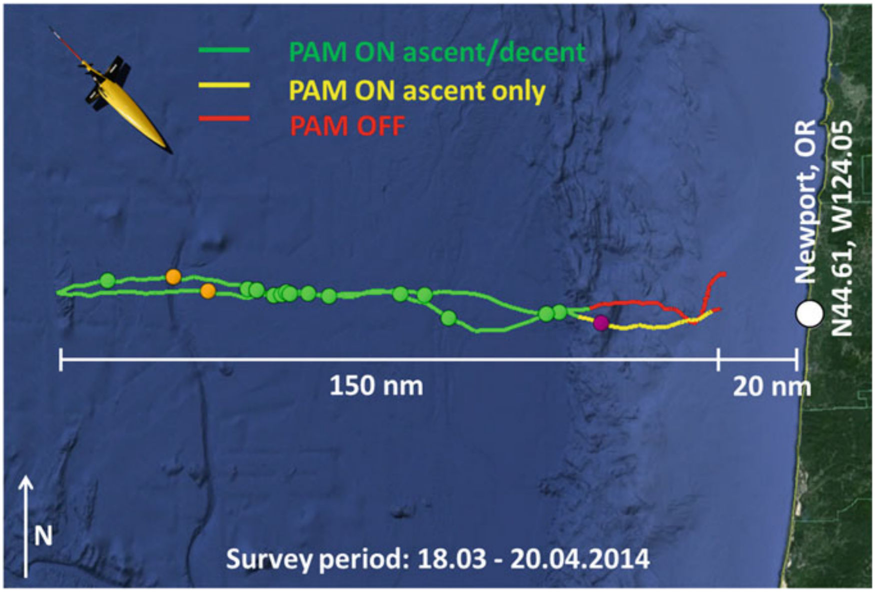

Fig. 4 Overview map of the Seaglider survey. The *green dots* on the trackline indicate Dall's porpoise detections, *orange dots* potential *Kogia spp.* detections, and the *purple dot* a potential detection of a mixed harbor and Dall's porpoise group. Map: Google Earth

were activated. The associated data loss is typically on the order of less than 10 % of the total dive time, but differs from dive to dive.

The acoustic data were manually analyzed for echolocation clicks of harbor porpoises, Dall's porpoises, and dwarf and pygmy sperm whales which are common in the study area. These four species are known to produce high-frequency echolocation clicks with a peak frequency of around 130 kHz. However, because of the similarity in the acoustic characteristics of their echolocation clicks, identifying to the species level remains challenging (e.g., [8]).

High-frequency cetaceans were recorded in 20 of 148 dives (14 %). As indicated by the green marks in Fig. 4, the gilder most frequently registered vocalizations produced by Dall's porpoise. The average acoustic encounter duration was 3 min.

4 Discussion

The different deployment scenarios did not allow a direct performance comparison between the two platforms. There were also no stationary passive acoustic recorders deployed concurrently which might have provided further insights into the effectiveness of the tested systems. However, the primary goal of this study was to evaluate the capabilities of mobile autonomous platforms (AUVs and USVs) to monitor high-frequency cetaceans producing echolocation clicks at frequencies beyond 100 kHz.

Roboat: The acoustic data recorded with the Roboat were very noisy. For future surveys one or more hydrophones should be towed at some distance behind the boat and at a greater depth. This will help to reduce both surface-induced and boat-induced noise. One of the advantages of USVs is that they can be operated in (very) shallow water, which is especially important in the context of tidal and wave energy efforts. Furthermore, some USVs are capable of moving faster than the animals being monitored and consequently standard distance sampling methods [3] can be applied to derive animal densities. Disadvantages include the 'liability issue' when operating the boat autonomously in coastal near-shore waters, where potential interference with recreational and commercial activities is likely. Also, USVs, and particularly autonomous sailboats, have not been used extensively for long-term passive-acoustic monitoring efforts. Thus more research and development is necessary to evaluate the full potential of these platforms, particularly with regard to effects of weather on monitoring ability.

Seaglider: The Seaglider persisted throughout the deployment and collected high-quality acoustic data for an extended period of time (almost 1 month). The specific glider used in this study is a deep-diving platform which can't be efficiently operated in shallow water. For this reason, this platform is most useful to monitor deeper, offshore areas, such as monitoring in conjunction with the installation and operation of offshore floating wind turbines. However, other types of commercially-available gliders are better suited to monitor coastal inshore areas. Once deployed, AUVs can be operated in most weather conditions and don't pose any navigational hazard. One of the disadvantages of AUVs, and particularly gliders, is that they move slowly through the water column (max. 0.5 kn) and therefore have difficulties dealing with strong currents.

Both the Roboat (in the Baltic Sea) and the Seaglider (in the North Pacific) successfully registered these transient signals and exemplified the potential of these platforms to be used for passive-acoustic monitoring efforts. This was the first time high-frequency echolocation clicks have been recorded using these platforms. In fact, this is the first report of a successful at-sea trial to acoustically monitor any marine mammal vocalizations using an autonomous sailboat.

Because of the limited detection range of the high-frequency echolocation clicks (a few 100 m), moving platforms are more effective in scanning and monitoring areas of interest than stationary recording devices. This is especially true for areas of low animal density (e.g., harbor porpoises in the eastern Baltic Sea).

Acknowledgments The authors would like to thank the sailing club in Eckernfoerde, Germany and especially Hans-Juergen Wurm for their assistance with the Baltic Sea field trials. We furthermore thank Zen Kurokawa and Sorqan Chang-Gilhooly for their help implementing the high-frequency PAM system into the Seaglider. Also thanks to Niki Diogou, Amanda Holdman, Jay Peterson, Ken Serven and the crews of the R/V Pacific Storm and R/V Elakha for assisting in the deployment and recovery of the Seaglider. This project was partially funded by the U.S.

Department of Energy, the U.S. Navy's Office of Naval Research, and NOAA. Co-author Selene Fregosi was supported by the U.S. Department of Defense through the National Defense Science and Engineering Graduate Fellowship (NDSEG) Program.

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