Executive Summary

The sperm-whale population that inhabits or crosses the Hellenic Trench is estimated ~200 individuals, and may represent the entire eastern Mediterranean population unit. The Mediterranean sperm whale population qualifies, since 2006, as “Endangered” under the IUCN Red List criteria, and the marine area of the Hellenic Trench is listed, since 2007, among the areas urgently needing the status of “Protected Areas” for cetaceans. To date, a significant number of them keep dying because of collisions with large vessels, which constitutes the most important threat locally. On average, one dead sperm whale reaches the Greek coasts yearly having signs of collision, and more deaths go unrecorded since the carcasses sink in offshore waters and are never seen. The high death rate due to collisions is obviously unsustainable and underlines the necessity to drastically mitigate this threat in a critical habitat.

A possible solution to this problem is to set up a listening/notification network of acoustic listening stations that will detect and localize sperm whales from the pulsed sounds (clicks) that they produce. The automatic detection and localization will be followed by a notification of large vessels in the bordering area, such that they can reduce the probability of collision by slightly changing their course (stay outside the border of international waters) or reducing their speed.

The Edelweis’14 experiment was an initial step, for a preliminary feasibility study in that direction, undertaken by CINTAL, FORTH, PCRI, and Univ. Basel; and kindly supported by OceanCare. Its objectives were to acquire acoustic data transmitted from an acoustic source at frequencies and deployed at depths compatible with sperm whale diving, in various configurations and setups, so as to

- Test and validate acoustic localization techniques requiring only a small number of spatially distributed equipment,
- Acquire concurrent environmental data sufficient for propagation modeling of the area, and, if possible,
- Try to obtain actual sperm whale vocalization samples and correlation data to use for testing animal localization and tuning/customization of the algorithms and system.

The first two objectives (controlled localization experiment and environmental data collection) were accomplished. The last objective was not met due to absence of sperm whale encounters in the duration of the experiment[1].

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The experiment Edelweis’14 took place in the Ionian Sea from 3-11 August 2014 in deep waters (~1000m water depth) southeast of the Zakynthos Island in the Ionian Sea. The weather conditions were not as favorable as we would have liked (limiting on one hand the number of trials and~~,~~ the source-receivers spatial arrangement for optimal measurements, ~~and~~ and on the other hand the sea area where sperm

1 Only 4 days before the Edelweis’14 experiment a group of 10 individuals had been sighted in an expedition of PCRI, whereas the total operational time to look for whales during Edelweis’14 was limited to less than 4 ½ days.

whales could be searched for), and a number of technical issues further limited the quality of the data. Nevertheless, the experiment was successfully completed and the results are pleasing, despite these difficulties. The collected datasets are available with the *Edelweis’14 Data Report*. The detailed analysis of the controlled localization is available in the *Edelweis’14 Acoustic Localization Analysis Report*. A brief overview of the results, outcomes and conclusions follow.

The data were acquired by two buoys (Acoustic Oceanographic Buoys – AOBs) with suspended vertical hydrophone arrays deployed up to distances of ~4 km from the acoustic source. The localization method exploits time of arrival differences (TOADs) between direct, and also between direct and surface-reflected arrivals at two spatially dispersed hydrophones (one from each array) and produces estimates of source range, depth and azimuth (bearing). For the estimation of source range and depth it is not required to know the horizontal location of the hydrophones but merely the hydrophone depths. If in addition the horizontal location of the two hydrophones is known then the source bearing can be estimated as well. For the localization a~~A~~ ray-theoretic propagation modeling approach is used, ~~for the localization~~ taking into account acoustic refraction, caused by the spatial variability of the sound speed with depth (the sound-speed profile is obtained from temperature and salinity measurements).

Regarding the effectiveness of the localization method, the results achieved are particularly encouraging, despite technical difficulties[2]. The results demonstrate the ability of the employed technique to perform localization at variable accuracy, yet always usable for conservation objectives, depending on whether detection has been effected by one, two, or three detection units as well as on possible additional information (e.g. regularity of received clicks ~~pointing~~ originating from animals at depth). This is an advantage over the *all-or-nothing* effectiveness of typical triangulation/trilateration methods that depend on 3-4 functional geographically dispersed detection points. Specifically, for this technique

- If detection from one geographic point is available with known hydrophone depth, it is possible to estimate the locus of depths and distances from the detection point that a vocalizing animal lies on. This defines a conic area of detection, the tip of which is close to the detection point and the base of the cone being at the sea bed.

  ***Use-case*:** Under conditions depending on the slope of the cone (how the distances from surface change with the range), its evolution with time, and the proximity and speed of a nearby vessel, it is likely to identify an “alert zone” for a ship to avoid or slow down.

- If detections from two separate geographic points are available with known hydrophone depths but unknown hydrophone position on the horizontal plane,

[2] Such a difficulty was the lack of accurate depth information for the hydrophones. To address this shortcoming, information about the source depth was used and estimation focused on the source range and azimuth as well as on the hydrophone depths.

it is possible to estimate the source ranges (one from each hydrophone) and source depth. Range estimation accuracy increases with hydrophone separation (horizontal distance between hydrophones) and depth, and is better for sources at endfire positions and worse for sources close to broadside positions (of the line connecting the detection points).

Use-case**:** Although in absence of positioning data this information is not usable for dashboard presentation (e.g. ship console), it may still be useful for such a system to start beaconing (specified RF or light at night) in the area around, to alert *near-passing* ships to reduce speed below a threshold that could allow an animal to react.

- If detections from two separate geographic points are available with known hydrophone depths and hydrophone position on the horizontal plane, it is possible to also estimate source azimuth (bearing), subject to left-right ambiguity. Bearing estimation accuracy increases with hydrophone separation and depth and is better for sources close to broadside positions and worse for sources close to endfire positions. This gives practically two localization points/areas. If subsequent localizations take place by a shifted horizontal location of the hydrophones, or if the sea-bed morphology of the detection area permits inference, one of the localization points can be singled out, and the ambiguity is resolved.

  Use-case**:** One or both of the localization points/areas can be notified to a ship as “alert areas” for avoidance. Moreover, if moored detection points are to be used, careful selection of deployment points in the specific area can render only two stations sufficiently effective.

- If detection from a third geographic point is also available (triangle constellation on the horizontal plane) then it is possible to resolve a priori the aforementioned left-right ambiguity and also obtain a more homogenous error distribution with respect to the location of the source relative to the receiving array.

  Use-case**:** A single localized alert point/area can be provided to a ship for avoidance.

- Regarding the actual animal detection range, which would entail the area of coverage of a single detection point, during Edelweis'14 the sound source was tracked up to 4 km away. However, this does not gives us definite information about the detection range of actual animals since sperm whale vocalizations are on one hand in principle much louder than the sound source, but on the other hand they have signal characteristics overall different from the sound source (with the exception of the frequency range).

The ability to yield usable results under such varying operational detection capacities entails a number of important logistic advantages for the implementation of a conservation system able to function even under constraints: including energy harvesting and autonomy, deployment, maintenance, and not least cost for all these aspects. A similar logistic advantage is that increasing the coverage area, it is not always a requirement for more geographically dispersed detection units, but can be partly compensated by employing more hydrophones at different depths on the same line arrays (increasing the range-depth domain for TOADs).

Regarding the validation of the model, the results were also pleasing in concluding that the preliminary study gave accurate enough parameter prediction, despite unusual for the season weather conditions. This means that model-based localization (which is at the advantage of less equipment) seems to be robust enough even in face of unusual seasonal weather variability. This robustness can be further increased if needed in an operational system, by allowing for runtime adaptive tuning of the model parameters.

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Overall, while scientifically the experiment can be characterized as successful, in what regards the pragmatic implementation of an operational conservation system, it is only a positive first of several steps (essential for assessing the value and return for a larger investment in such as system). The following topics/areas aim to provide a map of the puzzle pieces where work needs to be spent for the synthesis of the big picture in the implementation of such an operational conservation system.

1. **Experimentation and localization data collection with real animals**. Sperm whales live and appear in groups, which means that localization should be effective in presence of multiple vocalizing individuals (either localizing independent individuals at a distance from each other, or localizing the whole group when they are in near-by each other proximity). Furthermore, as the wave energy from their vocalizations is not uniformly dispersed in all directions (directionality of vocalization), it remains to qualify the effectiveness of the system (e.g. possible boundary conditions for TOADs, etc) when detection is made along or at an angle from the *axis of vocalization*. There was hope that this objective would be possible to explore during the experiment Edelweis'14, but the absence of sperm whales made it impossible.
2. **Engineering requirements and testing**. For the Edelweis'14, the AOB2 technology was used due to its broad purpose capabilities and because the availability of the systems served as a cost-cutter for the expenses of the experiment. However, being an aged technology, combined aspects of power autonomy and consumption, communication and detection ranges, and optimal packaging, are not representative or indicative for a purpose-built system by today's standards. A number of engineering choices pertaining to powering and communications is moreover related to the area of deployment; including the possibility of moored solutions at strategic points, communication possibilities (with land, telemetry, direct with ships, etc), energy harvesting options in the area, fail-over mechanism for detection stations to synchronize or compensate for loss of positioning information, and other. To propose therefore and prototype an effective purpose-built design,

these aspects need to be backed by engineering studies and ideally some in-situ testing.

3. **Real time communication and localization processing**. To implement a pragmatic conservation measure, the aspect of real-timeliness needs to be evaluated in a holistic context of the provided service. This means that from the time point of detection until the time point that a notification is received by a ship, the time lapse needs to be short enough to allow for a maneuvering action to be implemented. This time overhead includes a communication delay for the detection data to be transmitted to a processing system, a processing delay to compute the localization algorithm, and a second communication delay to transmit the result to a ship or a dashboard service that the ship has access to (e.g. AIS). While at the moment it is possible to assess the computation delay for the algorithm, the communication delays are a function of the amount of data needed and the communication technologies available/chosen. First an evaluation of the different options (in face of cost and reliability) needs to be made along with an assessment of this time overhead for each. Then a multivariate optimization study needs to be carried out, where given this time overhead, and ship-whale distance as parameters, acceptable/sustainable maximum speed margins for ships are qualified; in order to allow time for reaction. The results can then be used as guidelines or requirements for the implementation of the conservation measure.

From those work items, as an essential next step (as immediate and strategic) we see the first and part of the second. Our rationale for this proposition is as follows: The first work item entails the risk of becoming logistically costly. Due to the uncontrollable chance factor in finding sperm whales and sufficiently good weather for the data collection, the risk of completing the experiment empty-handed can only be reduced by increasing the time allocated for the experiment. On the other hand, unless the first work item has been successfully concluded, it makes no sense to proceed with a complete engineering study and design prototype (work item 2). However, a partial prototype system that can be deployed and evaluated while trying to complete work item 1, is not only reasonable but also seen as prudent; it will “pay-off” for the time investment for an experiment on work item 1 irrespective of its outcome, and at the same time it will narrow the focus of subsequent engineering as part of work item 2.

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