Evidences of Intra-group Orca Call Rate Modulation using a Small-aperture Four Hydrophone Array

Marion Poupard[1, 2*], Helena Symonds[3], Paul Spong[3], Hervé Glotin[1, 4]

[1]CNRS, LIS, DYNI, Université de Toulon, France, [2]BIOSONG, SAS, France, France, [3]Pacific Orca Society/Orcalab, Canada, [4]Université de Toulon, INPS, SMIoT, France

Submitted to Journal:
Frontiers in Marine Science

Specialty Section:
Marine Megafauna

Article type:
Original Research Article

Manuscript ID:
681036

Received on:
15 Mar 2021

Journal website link:
www.frontiersin.org

In review

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author contribution statement

All authors conceived the experiment.
H.G. and M.P. defined the protocol.
M.P. and H.G. have built and prepared the antenna.
All authors participated with the installation the antenna.
H.S., P.S. and M.P. participated in the visual data acquisition.
H.S. annotated the recordings with Audacity.
M.P. and H.G. computed the detection and the azimuth of the vocalizations.
M.P., H.G. and H.S. wrote the manuscript and produced the results.
All authors discussed the results and reviewed the manuscript.

Keywords

ORCA, Call-rate, localization, hydrophone array, Intra-group communication

In review

Abstract

Word count: 186

Acoustic emissions are vital to orcas (Orcinus orca) to socialize, hunt, orient, and maintain spatial awareness. In order to better analyze their inter and intra-group communication, we propose a novel protocol that allows us to associate vocalizations with their emitter (individual/matriline). Our approach is based on a low cost small-aperture four hydrophone array fixed near the shore up to a few km away from the orcas' path, operated in conjunction with visual identification. It was conducted in the summer of 2019 off northern Vancouver Island, Canada, at the research station OrcaLab. A total of 722 calls were extracted and localized in azimuth via the hydrophone array from 3 case studies in which different events took place.
We then calculated the Call Rate for each individual/matriline in order to describe their acoustic activity.
Results show that Call Rate is modulated according to the distance of the signaler from the joint group, the presence of another group, and the anthropic pressure (nearby cruise ship). This shows evidence of intertwined calls. This protocol does not interfere with the animals and opens new perspectives towards inter and intra-group communication analysis.

Contribution to the field

Our research presented in this manuscript approaches the open question of the intra and inter group communication of wild orcas. For this purpose, we designed a low cost protocol operated from the shore, thus ensuring that our observation does not induce perturbation to the animals' behavior (to the contrary of techniques used by most studies of the field such as d-tags or listening from a nearby boat). Besides the latter advantage, the data collection method described allows for advanced acoustic analysis such as source azimuth estimation, and in some cases attribution to individuals, rarely found in the literature of the field. Our paper presents the yielded novel results contributing to the common knowledge on orcas' communication. To conclude, compared to state of the art methods, our proposed approach improves the collected data and the possible following analysis while decreasing the induced observation bias. While the protocol is not specific to the orcas species, our demonstrated application contributes to the field with novel material for the study of the orca communication system.

Funding statement

This research is partly funded by :
- MARITTIMO Intereg European FEDER GIAS project: for support in acoustic processing
- MI CNRS MASTODONS sabiod.org: for storage of the data and GPU computation
- Pole INPS Univ Toulon: for the co-development of the JASON DAQ project
- The Gencon Foundation : for the financing of the 'Big Eyes"
- Biosong SAS cofunded M.Poupard PhD

- ANR SMILES: for support in algorithmic
- ANR CHaire IA ADSIL: for support in algorithmic

- FUI ABYSSOUND : for support in acoustic processing
- Anneberg Foundation: For the Orcalab functionment support

Ethics statements

Studies involving animal subjects

Generated Statement: Ethical review and approval was not required for the animal study because This study was carried out on wild Orcas. We did not use boat or d-tags. We just put an acoustic antenna in front of the Orcalab research station..

Studies involving human subjects

Generated Statement: No human studies are presented in this manuscript.

Inclusion of identifiable human data

Generated Statement: No potentially identifiable human images or data is presented in this study.

Data availability statement

Generated Statement: The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: The original recordings samples are available from the 11th 30th, 31st of August, 4 channels, 192 kHz SR 16 bits (under copyright of the authors) at the address: http://sabiod.univ-tln.fr/pub/orca_SR/. An animation of the last observation (31st of August) is available at the address: http://sabiod.univ-tln.fr/media/30_08_Orcalab.mp4..

In review

Evidences of Intra-group Orca Call Rate Modulation using a Small-aperture Four Hydrophone Array

Marion Poupard [1,4*], **Helena Symonds** [2], **Paul Spong** [2] **and Hervé Glotin** [1,3]

[1] *Université de Toulon, Aix Marseille Univ., CNRS, LIS, DYNI, Marseille, France*
[2] *Pacific Orca Society/OrcaLab, Canada*
[3] *Université de Toulon, INPS, SMIoT, France*
[4] *BIOSONG, SAS, France*

Correspondence*:
Marion Poupard
Corresponding Author
poupardmarion@gmail.com

ABSTRACT

Acoustic emissions are vital to orcas (*Orcinus orca*) to socialize, hunt, orient, and maintain spatial awareness. In order to better analyze their inter and intra-group communication, we propose a novel protocol that allows us to associate vocalizations with their emitter (individual/matriline). Our approach is based on a low cost small-aperture four hydrophone array fixed near the shore up to a few km away from the orcas' path, operated in conjunction with visual identification. It was conducted in the summer of 2019 off northern Vancouver Island, Canada, at the research station OrcaLab. A total of 722 calls were extracted and localized in azimuth via the hydrophone array from 3 case studies in which different events took place.

We then calculated the Call Rate for each individual/matriline in order to describe their acoustic activity. Results show that Call Rate is modulated according to the distance of the signaler from the joint group, the presence of another group, and the anthropic pressure (nearby cruise ship). This shows evidence of intertwined calls. This protocol does not interfere with the animals and opens new perspectives towards inter and intra-group communication analysis.

In review

Keywords: Orca, Call-Rate, Localization, Hydrophone array, Intra-group communication

1 INTRODUCTION

Orca *(Orcinus orca)* is a marine mammal that inhabits oceans across globe. For orcas, the ability to emit sound, hear and vocalize is vital to performing activities such as communication, reproduction and hunting (Council et al., 2003; Burham et al., 2016). They can produce a wide variety of sounds including clicks, whistles, and pulsed calls (Ford, 1991). Pulsed calls or vocalizations are primordial for communication, and a pod can share between 7-17 different calls classed by types (Ford, 1989). Vocal activity also depends on the group's activity (Filatova et al., 2013). Numerous acoustic studies have already proven that pulsed vocalization plays an important role in the social life of the group (Bain, 1986; Filatova et al., 2013, 2010). This study focuses on the Northern Resident Killer Whale (NRKW) community composed of different pods and matrilines (Bigg et al., 1990). Three distinct ecotypes of orcas live in the waters of British Columbia (BC) : Resident, Transient (Bigg's) and Offshore (Hoelzel and Dover, 1991). Transient orcas are marine

mammal-eaters whereas Residents hunt mostly salmon (Ford et al., 1998). Offshore orcas eat principally halibut (*Hippoglossus s.*) and shark (Jones, 2006).
There are two communities in coastal BC, the Southern Resident community and Northern Resident community (NRKW).
The NRKW is composed of 15 different pods and inhabits the waters between Vancouver Island and Southeast Alaska. Pods are groups of related orcas that frequently live and travel together. They also share the same acoustic dialect. The smallest unit of socialization within the pods is the matriline, which links individuals through maternal descent (Ford, 2009).
In order to grasp the richness of orcas' intra-group communication, it is necessary to analyze the acoustic production of each individual or matriline during natural activities in the wild. Most studies so far describe pod level call behavior (Miller et al., 2004; Foote et al., 2004). It has proved challenging to demonstrate vocalizations produced by an observed matriline or individual. Therefore it seems useful to put in place methods and protocols that associate vocalizations with an individual or matriline.
Many works have described the vocal exchanges of animals as the response of a receiver after the emission of a particular signal (Krebs et al., 1981; Janik, 2000). Some studies have already identified the signaler in a group of orcas (Miller et al., 2004), finding that the types and timing of calls are influenced by the calling behaviors of other members of the group.
Miller and Tyack (1998) used an array with 15 hydrophones towed from a boat. The results were compelling. Unfortunately, the deployment of a towed array is costly and is therefore not convenient for a long term natural experiment on free ranging whales. Orcas are easily disturbed by boats (Holt et al., 2009, 2021) and as we will see in our results below, the CR changed depending on whether there was a boat present or not.
In this study using our localization method allowed us to accurately assign an azimuth to a surface entity. Once the individuals/matrilines were identified we used a quantitative variable to describe the vocal behavior of the orcas : the Call Rate (CR), equal to the number of vocalizations each 10 s for each individual/matriline. The CR is commonly used in underwater (Luís et al., 2014; Quick and Janik, 2008) and terrestrial (Reers and Jacot, 2011; Leonard et al., 2003) bioacoustics to quantitatively describe the emission of sound signals.
The objective of our research was to proceed with a novel protocol that allowed us to acoustically identify individual/matriline vocalizations in order to study the CR under certain conditions.

This was done by using a low-cost hydrophone array, easily deployed in various sites, equipped with high quality call separation. We employed a novel audio-visual protocol based on the visual identification of orcas from the shore and a four-hydrophone array submerged nearby offshore to separate each of the calls being emitted several hundred meters away.
In our study we will present 3 different case studies to validate our protocol.
The section Material and Methods, presents the recording station and annotation methods. Then, we explain the computing of the azimuth of the calls, and the CR analysis. We applied this protocol on 722 calls taken from 3 cases in which different events took place. Finally, we summarize the results and discuss them.

2 MATERIAL AND METHODS

Over the past 35 years, the non-governmental organization OrcaLab (OL), has developed and maintained a multi-hydrophone recording system around Hanson Island (northern Vancouver Island), Canada to study whales. Throughout the year, OL consistently observes and records orca behaviors and vocalizations. To increase the knowledge surrounding orca communication, our team designed a small aperture four-hydrophone array at a high sampling rate (4*192 kHz 16 bits). One goal was to record highly defined acoustic data from orcas passing in front of OL and connect these data to visual observations made from

In review

land at OL. The goal was to estimate the Time Delays of Arrival (TDoA) of the calls, thus their azimuth by a simple linear solver, and to assess a multi-modal label for each call : the type of call, azimuth and identity of the emitting orca.
Finally, we studied the CR of the emitting individual/matriline.

2.1 Acoustic data acquisition

The four-hydrophone array is a tetrahedral portable antenna of 12 kg (Fig.1) that uses four SQ26-01 hydrophones with a high frequency sensibility between 10 Hz to 50 kHz. The flat frequency response of the hydrophones is available in Supplementary (Fig.S1). The maximum aperture of this array is 77 cm.
It includes a novel low-power high-resolution autonomous sound card (Supplementary, Fig.S2), called JASON (Barchasz et al., 2020), and the recording capability of up to 5 uncompressed channels at a sampling rate of up to 2 MHz, 16 bits. It can be accompanied by a low power acoustic trigger (Fourniol et al., 2018), but this was not necessary at OL because JASON was switched ON/OFF manually from OL when orcas were seen.
In this study we recorded at a 192 kHz sampling rate on four channels (Data Availability Statement: A recordings samples are available from the 11^{th}, 30^{th}, 31^{th} of August, 4 channels, 192 kHz SR).
We over-sampled the bandwidth of the hydrophones (50 kHz) to increase the precision of the estimated angle of arrival and to increase the efficiency of separating the calls individual by individual. The antenna was placed at a depth of 23 m pointing East, which was determined using a compass. Due to its weight and an additional 10 kg of ballast there was no concern regarding its stability, even during strong currents (> 1 m/s).
The device was powered from the shore through 75 m of 12 V cable connected to OL. The ability to power the device from land allowed us to limit our recording to when orcas passed in front of OL. Later, we could correlate the acoustic data with visual observations from OL. The antenna was taken out of the water when the 512 Go uSD storage was full, when we reached 74 hours of recording, or earlier in order to avoid obstacles, such as sea urchins, from settling on the antenna and interfering with the recording.
The recording sessions took place from the 20^{th} of July to the 1^{st} of August, the 4^{th} of August to the $22nd$ of August, and the 23^{rd} of August to the 15^{th} of September 2019. In total, we recorded 42 vocal passages that included multiple orcas.

2.2 Visual data acquisition

When orcas were spotted in BP (Blackney Pass) located in front of OL. The antenna was powered on by a simple on/off button from OL. It was turned off when the orcas were no longer visible (Fig.2). During each passing of the orcas, 5 observers at OL worked together to identify the groups and individuals present. This task was always carried out by the same people :

- Person 1 (H.S.) : Real-time identification of groups and individuals (when possible) with a dedicated 'Big Eyes' binocular (Product, 2014),
- Person 2 (P.S.) : Using spotting scope to help H.S. for identifications (Bushnell Spacemaster 78-1800 with, zoom 15x45),
- Person 3 (M.P.) : Recording of Helena's real time comments and azimuths of each individual/matriline associated with the visual reference points in BP. Each site was assigned a precise azimuth with a compass (eg. "Green House" = 15 degrees). At every surfacing the azimuth was recorded,
- Person 4 (A.Doohan) : Recording of "Big Eyes" positions and photographing individuals,
- Person 5 (E.Vierling) : photographing individuals.

In review

If several groups were present at different azimuths, we used a second ”Big Eyes” to make the identifications. Once the passage was finished, the whole team confirmed the presence of the individuals using the photographs and the photo-identification catalogue (Towers, 2015). The map of viewing and listening ranges is available in Supplementary (Fig.S3) The listenig range was estimate with the Orcalab expert and the actual presence of hydrophone on site 24 hours a day (Poupard et al., 2019a).

2.3 Annotation of the recordings

Manual annotations of the vocalizations were conducted with Audacity to provide waveform and spectrogram visualization (Audacity-Team, 1999). Three recordings were precisely annotated in which calls were identified and correlated. An example of 13 seconds of annotations (Fig.S4) and the list of the calls annotated in the experiments (Fig.S5) are available in Supplementary.

2.4 Azimuth estimation of the orca calls using the hydrophone array

As described in the previous section, each vocalization was detected and annotated. From the four channels we computed the three independent Time Delay of Arrival (TDoA) by inter-correlations : τ_{21},τ_{31}, τ_{41}. The high sampling rate (192 kHz) allowed us to measure precise TDoAs. As the source is at relatively far range, we estimate its azimuths with a linear solver presented in (Bénard-Caudal et al., 2010). Range estimation of the calls was possible in certain conditions (Glotin et al., 2008; Poupard et al., 2019c), but due to surface acoustic effects, we did not estimate the range of orcas in our protocol. However, we show that azimuth estimations are accurate for this study. Then, we joined the azimuth estimates of each call to every identified orca using the visual positions noted by OL observers. We associated individuals or groups of orcas with a vocalization track by using a photo-identification catalogue (Towers, 2015). When orcas were very close to each other, it was difficult to associate a call with an individual, but in some cases we were able to associate vocalizations with a specific male.

Calculation of the Call Rate and statistical tests

Once the individual/matriline were identified we used a quantitative variable : the CR by counting the number of vocalizations every 10 s for each individual/matriline. Thus, we divided the tracks into different periods (80 s, or 5*80 = 400 s), and we estimated the mean and variance of the CR over the non overlapping 10 s intervals in each period. Then we performed statistical tests between periods and individual/matriline. Accuracy was not normally distributed as assessed by Shapiro-Wilk’s test (p-value < 0.05). Since our data did not follow a normal distribution, we performed a Kruskal-Wallis Test (Breslow, 1970) followed by a post Hoc test of Dunn-Bonferroni (Dunn, 1964). All the data processing is summarised in Fig.3.

3 RESULTS

The sessions of this summer totaled 42 passages of orcas with vocalizations and 29 passages of orcas without vocalizations (Tab.1).
Within the 71 passages, 57 passages were during daytime and 29 passages included vocalizations. We are able to isolate calls for three individuals (three males), because the males were somewhat removed from the group (minimum 50m). A total of 85 vocalizations were produced by these three males (Tab.2).
We focused on three particular events : 11^{th}, 30^{th} and 31^{st} of August. See Fig.S5 in Supplementary for the list of the heard and annotated vocalizations. The color of each call corresponds to the color in the scatter plot in Fig.5,8,9,12.

3.1 First observation (11^{th} off August)

The first case study was on the 11^{th} of August, when a group made up of the A25, A50, A54, and I04 matrilines (mat.) came through (BP) at 4:46pm.

During this passage, the orcas were calm, and moved at a moderate swim velocity, but at 5:08:20pm a cruise ship (Fig.4) passed in front (OL) (traveling in the same direction as the orcas). Once the boat was present, the group dispersed and several orcas surfed in its wake. This made individual identification difficult.
The Fig.4 presents the trajectories of a different group during the 11^{th} of August and the associated pictures. We noticed that at the start of the trajectory, the orcas were gathered in a single group (picture on the left). Then different smaller groups formed and some orcas were on the right and left of the boat (picture 2 and 3). During the end of the track some individuals "surfed" behind the ship (last picture, Fig.4). This visual observation confirmed our acoustic position.

The Fig.5A illustrates the passage of this group. Each point represents a call placed in azimuth; the curves are the visual track of the individuals. Each visual observation matches the computed azimuth of each call (green dots). We thus validated the acoustic azimuth estimations.
During the first part (until 5:15pm) of the track, it was possible to recognize eight individuals from A05, A01 and I15 pods (Fig.5A). After the passage of the boat, the orcas split up so we lost the identification of four whales. From 5:16pm to 5:30pm we had the identifications of A61 (mat.A25), A72 (mat. A50), A108 (mat. A50) and I76 (mat. I04). Visual observations were supplemented by acoustic analyses. From 4:56pm to 5:10pm the orcas were together in BP traveling at a slow speed. When the cruise ship arrived, the whales started to accelerate and followed the boat until azimuth 100 °.
We can see this fast track visually and acoustically from 5:06pm to 5:15pm. During the last part of the track, from 5:23pm to 5:33pm, we observed that some orcas continued their trajectory while four individuals (from three different matrilines) turned around : A61 (mat.A25), A72 (mat.A50), A108 (mat.A50) and I76 (mat.I04). The male A61 (orange) is high in azimuth. Individuals A72, A108 and I76 had been traveling together for ten minutes.

In review

We were able to extract the types of vocalizations (Fig.5B). We divided this track in 6 parts. The first and second parts were before the arrival of the cruise ship when the orcas traveled slowly and emitted call types N25, N04, N02, N09iii. The third part happened when the boat came through BP and the orcas followed it (surfing) and produced only N04, N47 calls (1700 to 2000 s). At the end of the boat passage (period 4), they produced a lot of N04 and N03 calls, and some of them turned around. During period 5 and 6, from 2700 to 3200 s, the track from 90° to 120° is composed of N04, N47 calls. This is when the individuals, A72, A108 and I76 were traveling very close to each other. According to these observations, we can suppose that the boat not only had an influence on the velocity of the orcas, but also on the type of calls used.

To determine this, we counted the number of calls in order to check if the boat had an influence on the CR. Fig.6 shows the result associated with the statistical tests. The CR means don't follow a normal distribution (Shapiro test, p-value=0,0003), so the measure of the differences between the medians were calculated (Kruskal-Wallis Test, p-value=4.10e-05). After this the Dunn-Bonferonni test was done and the significant differences are showed in Fig.6.
During the first two periods (before the arrival of the boat), the density of calls is low. When the boat comes through BP (period 3), the density of calls started to increase until the boat leaves.
In fact, during period 4 (corresponding to the end of the passage of the boat) the CR is higher and significantly different from the first 2 periods.

When the orcas turned around there were not as many calls (period 5). Then the density increased again when A108, I72 and I76 traveled together (period 6). This shows that the cruise ship had an influence on the type of calls as well as the CR.

3.2 Second observation (30^{th} of August)

The second case study was on the 30^{th} of August in which the A42 and A25 matrilines of the A05 pod and the A54 matriline of the A01 pod came through BP together. Fig.7 represents the passage of the 30^{st} of August in front of OL with examples of four pictures taken from OL. The visual observations confirmed that the group was very compact and traveled quickly (less than 6 minutes to traverse BP). Fig.8A illustrates the passage of this group. Each point represents a call placed in azimuth; the blue curve is the visual track of the group. Each visual observation (blue curve) matches the computed azimuth of each call. We thus validated the acoustic azimuth estimations.

For each call, we extracted the type of call and plotted it according to the azimuth of the orcas (Fig.8B).

The track is quite compact, and the group (A42s, A54s and A25s) traveled north very quickly. This group was composed of two different pods (A05 and A01). During this track, there were a lot of different calls which eventually subsided into the shared N03 call type. N03 could play a role in communication between these matrilines, because at the end of the track, individuals emitted only this call. It may indicate a change of behavior, i.e slowing down during travel.

Focusing on the track, we see that the A01s and A05s traveled together; attributed the calls to a pod following (Ford et al., 1987). The Fig.9 shows the trajectory of A01s, A05s and their emitted calls. We divided the track into four parts and measured the CR in these periods.

We measured the CR for the A01s and the A05s. The CR means don't follow a normal distribution (Shapiro test, p-value=0,0026), so the differences between the medians were calculated (Kruskal-Wallis Test, p-value=1.10e-05). After this, Post-hoc testing was used to evaluate differences between each distribution pair (Dunn-Bonferroni tests) (Fig.10).

This graph shows significant differences between time periods and pods. During periods 1 and 2, the CR is higher for the A01 pod, then this is reversed for periods 3 and 4. During the last period (4), the CR for A01 pod is different from periods 1 and 2. When the density of calls of A01s increases, the CR of the A05s decreases (Fig.10), but the CR for the two pods (A05 and A01), during the same period are not statistically different. This result suggests that when these 2 pods travel together, A05s could emit while A01s are silent, and vice versa. Hence, they do not overlap their calls, possibly maximizing their communication efficiency.

This case study showed us that when individuals were too close together it was difficult to identify matrilines or individuals by azimuth. But we were able to study the CR thanks to the acoustic identification of the different pods present.

3.3 Third observation (31^{st} of August)

We focused here on the 31^{st} of August, when a large group group made up of I16s, I65s, I04s and I27s came through BP. The majority of the four matrilines traveled together; the male I76 (mat.I04), traveled by himself behind the large composite group, eventually joining them at the end of the track. Fig.11 shows the visual trajectory photographed from OL and the representation of the trajectory in BP. The orange curve represents the large group and the white curve the male I76. Visual observations allowed us to validate our azimuthal positions from the acoustic antenna. In the figure 12A, each point represents a vocalization placed by the estimated acoustic azimuth. The blue and orange curves are the interpolated visual azimuths of the male I76 and the large group, respectively. We see that it is possible to assign vocalizations either to the individual male or to the larger group because

In review

each acoustic position corresponds to a visual position. This result allowed us to isolate 24 calls from the male I76.
From the manual annotations, we made correlations between the azimuth and the type of calls for the large group and I76.
For these recordings, seven different calls were produced (Fig.12B). Each point represents a call with its type in color. We see that the right track (I76) is composed of N48 (green), N25 (pink) and N23i (brown). Thus, we could assume that when the male was alone, he made a combination of two calls, N48 and N25, and when he was close enough to his group, he produced N23i calls to which his group answered with the same type. The large group produced all types of calls, including type N23i (brown) at the end of the track. We can see that the N23i type call is produced just before and after I76 merged with the larger group.

We measured the CR for the group and the male I76, in order to see if there were different periods of call exchanges. To do this, the number of vocalizations was counted every 10 s and its average was calculated for each period.
The means don't follow a normal distribution (Shapiro test, p-value=0,0043), so the measure of the differences between the medians was calculated (Kruskal-Wallis Test, p-value=0,0022).
So, p-value $\leqslant \alpha$: The differences between some of the medians are statistically significant. Post-hoc testing was used to evaluate differences between each distribution pair (Dunn-Bonferroni tests).
The result is showed in Fig 13. In the first period, only the large group was acoustically active compared to the male I76 (Post-hoc Bonferroni test, $p<0.00006$). During the second and third periods, the group and I76 had the same CR statistically. We observed that when the male started calling (period 2) the group did not call (compared to period 1). And during the third period (meeting) the CR of the group and I76 both increased.

In review

4 DISCUSSION

Orcas prefer group life, and in fact, it could have a variety of beneficial functions : localization of food, reproduction, socialization and traveling. In order to coordinate their activities, maintain group cohesion, or recognize members in the group, orcas need to communicate (Grebner et al., 2008).

Whistles have been shown to be important during socialization (Thomsen et al., 2002). Echolocation clicks are used during hunting and to aid navigation. Discrete calls are often used during travel, hunting and socializing. The CR is different according to behavioral categories and particular events. In fact Grebner (2009) proved that orcas can initiate contact using discrete pulsed calls during pre-joining events.
Our results show that we can track individual calls of wild orcas in their natural habitat in order to demonstrate CR modulations according to various parameters including, the presence of boats, and the relative position of an individual versus a group of whales. To accomplish this we analyzed three different natural scenes or observations.
The CR increased significantly at the end of the passage of the boat and when the boat moved away, whereas the CR was stable before the arrival of the boat.
Anthropogenic noise has an influence on orca emissions. Holt et al. (2009) has proven that orcas increase their call amplitude in response to vessel noise. Our study complements this observation, showing that orcas change both their trajectory and CR when a large vessel is present.
Recently, Holt et al. (2021) showed that the hunting behavior of this population was affected by the close presence of boats, and that females and males respond differently to nearby vessels. These results are coherent with our study which shows different behaviors of orcas when they face the presence of ferry : surfing or taking distance and increasing CR.
In fact, both large (e.g. cruise ship or tanker) and small vessels are very noisy and produce noise in the

10-1000 Hz range. The propagation in water is important, resulting in frequencies that could span more than 5 kHz. There is an overlap between the vocalizations emitted for communication and anthropogenic noise. Cetaceans may have different options to adapt : they can maintain the communication by increasing the call amplitude, Lombard effect (Noad et al., 2012), they can increase the duration of the signal (Foote et al., 2004), or they can change the type of their calls or their CR to avoid the overlap with the boat noise (Castellote et al., 2012; Poupard et al., 2019b).

Here, it seems we have an example of the last option.
In the second observation (30^{th} of August), one big group passed in front of OL, composed of A05 pod (mat. A42 and A25), and the A01 pod (mat. A54). The tracks of these groups were interesting : two pods traveled together and exchanged a lot of calls for several minutes and at the end of the trajectory a lot of N03 calls were emitted. In Ford (1989) it was realized that N03 calls are produced after periods of social activity or high-arousal contexts like active foraging. Moreover, the lower source level of the N03 call makes this call more suitable during close range vocal exchanges (Miller, 2006).

We found that pods emit calls in turns, alternating low and high CR when traveling together and the track is split in different parts in time (Fig.9), or when there are particular combinations of calls. Our study shows that individuals from different pods (A05 and A01) can communicate and travel together. Resident orcas are organized in a fission-fusion society that is flexible in time and space.

We propose two hypotheses : first, when more than one pod travels closely and one pod begins communicating, individuals from the other pod will try to be silent in order to facilitate the communication between individuals of the first pod.
Second, and following (Krebs et al., 1981), we can assume the existence of a veritable interaction between these two pods. For example, when the first pod vocalizes, then a 2^{nd} pod may respond to them (and vice-versa).

According to the second hypothesis, the type of call provides particular information to the original signaler : the combination of particular calls from A05 depends on the emission of particular A01 calls (Fig.9).
In the third observation, on the 31^{th} of August, a big group made up of the I16, I65, I04 and I27 matrilines came through BP. Behind them was a lone male orca, I76 (mat. I04). This scene is noteworthy because the male traveled far behind his group and made specific types of calls. When he was far from his group he made a combination of N25 and N48 calls, but once he approached his group, he vocalized with the N23i call type and his group answered with the same type of call. We conclude that any modulations of call types could improve the ability of orcas to give information on their relative positions and help to localize each other.
Furthermore, there may be a greater need for redundancy in communication signals in large groups as is typical of common dolphins, requiring faster signal production to facilitate inter-individual or group cohesion. Our results have complemented the study of (Grebner, 2009) who highlighted the production of calls before the meeting of two groups. Orcas could use particular types of calls in order to improve good propagation in the water and facilitate the reception of the signal.
When somewhat isolated, the male made a particular type of call and modulated his CR (Fig.12). As he got closer to his group he increased his CR (period 3) and emitted other call types in the direction of his group (Miller, 2002) presumably in order to facilitate communication. Additionally, the group decreased its CR. Such changes in the CR may occur when individuals are separated from their group. A similar pattern is shown for other species : Bottlenose dolphins (Cook et al., 2004), Spider monkeys (Ramos-Fernández, 2005) and Chimpanzees (Mitani and Nishida, 1993).

In review

To sum up, this study of nearly one hundred calls suggests that intra-group acoustic communication in orcas may depend on the :

- distance between the group and the individual,
- acoustic emissions of another pod,
- presence of a boat,
- physical behavior of individuals (surfing behind a boat).

Our shore based study looked at orca communication in the wild at a unique level of precision. Other shore based fixed hydrophone systems enabled the detection and tracking of orcas from the same population (Poupard et al., 2019a; Bergler et al., 2019; Best et al., 2020) but did not succeed in associating individuals with calls, or determine precise individual pattern variations of communication between groups. This work does not pretend to provide all explanations for the type of calls, but rather the CR. Results offer evidence that this low cost and easy to deploy protocol, brings to light relevant features of CR of these complex communication systems.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

In review

AUTHOR CONTRIBUTIONS

All authors conceived the experiment.

H.G. and M.P. defined the protocol.

M.P. and H.G. have built and prepared the antenna.

All authors participated with the installation the antenna.

H.S., P.S. and M.P. participated in the visual data acquisition.

H.S. annotated the recordings with Audacity.

M.P. and H.G. computed the detection and the azimuth of the vocalizations.

M.P., H.G. and H.S. wrote the manuscript and produced the results.

All authors discussed the results and reviewed the manuscript.

FUNDING

This research is partly funded by : FUI 22 Abyssound, ANR-18-CE40-0014 SMILES, ADSIL ANR-20-CHIA-0014-01 National H.G. Chair in AI for bioacoustics, MARITTIMO Intereg European FEDER GIAS project, MI CNRS MASTODONS sabiod.org, and Pole INPS Univ Toulon. M.Poupard was cofunded by Biosong SAS. We thank the Annenberg Foundation grant 18-581 and the Gencon Foundation.

ACKNOWLEDGMENTS

We thank OrcaLab and its volunteers for welcoming M. Poupard and H. Glotin during the summer of 2019 to set up this protocol. We thank M. Hockin-Bennett for her indispensable help on the dives. We thank E. Vierling and A. Doohan for their essential support. We thank SMIoT Scientific Instrumentation (V. Gies, V. Barchasz), and INPS of UTLN for the development of the JASON DAQ project.

SUPPLEMENTAL DATA

The frequency response of the hydrophone SQ26 (Fig.S1), the JASON CARD (Fig.S2), the range map of the antenna (Fig.S3), an example of annotation (Fig.S4), and the list of all calls (Fig.S5), are in the Supplementary Material.

DATA AVAILABILITY STATEMENT

The original recordings samples are available from the 11^{th} 30^{th}, 31^{st} of August, 4 channels, 192 kHz SR 16 bits (under copyright of the authors) at the address: `http://sabiod.univ-tln.fr/pub/orca_SR/`.
An animation of the last observation (31^{st} of August) is available at the address: `http://sabiod.univ-tln.fr/media/31_08_Orcalab.mp4`.

REFERENCES

[Dataset] Audacity-Team (1999). Audacity: free audio editor and recorder. *Website:* `https://www.audacityteam.org/`

Bain, D. (1986). Acoustic behavior of *Orcinus*: Sequences, periodicity, behavioral correlates and an automated technique for call classification. *Behavioral biology of killer whales* , 335–371

Barchasz, V., Gies, V., Marzetti, S., and Glotin, H. (2020). A novel low-power high speed accurate and precise DAQ with embedded artificial intelligence for long term biodiversity survey. *In Proc. of the Acustica Symposium*

Bénard-Caudal, F., Giraudet, P., and Glotin, H. (2010). Whale 3D monitoring using astrophysic nemo onde two meters wide platform with state optimal filtering by rao-blackwell monte carlo data association. *Applied acoustics* 71, 994–999

Bergler, C., Schröter, H., Cheng, R. X., Barth, V., Weber, M., Nöth, E., et al. (2019). Orca-spot: An automatic killer whale sound detection toolkit using deep learning. *Scientific reports* 9, 1–17

Best, P., Ferrari, M., Poupard, M., Paris, S., Marxer, R., Symonds, H., et al. (2020). Deep learning and domain transfer for orca vocalization detection. In *Proc. Int. J. Conf on Neural Net (IJCNN)*

Bigg, M., Olesiuk, P., Ellis, G. M., Ford, J., and Balcomb, K. C. (1990). Social organization and genealogy of resident killer whales *(Orcinus orca)* in the coastal waters of British Columbia and Washington state. *R. of the Int. Whaling Commission* 12, 383–405

Breslow, N. (1970). A generalized kruskal-wallis test for comparing k samples subject to unequal patterns of censorship. *Biometrika* 57, 579–594

Burham, R., Palm, R., Duffus, D., Mouy, X., and Riera, A. (2016). The combined use of visual and acoustic data collection techniques for winter killer whale *(Orcinus orca)* observations. *Global ecology and conservation* 8, 24–30

Castellote, M., Clark, C. W., and Lammers, M. O. (2012). Acoustic and behavioural changes by fin whales (B*alaenoptera physalus*) in response to shipping and airgun noise. *Biological Conservation* 147, 115–122

Cook, M. L., Sayigh, L. S., Blum, J. E., and Wells, R. S. (2004). Signature–whistle production in undisturbed free–ranging Bottlenose dolphins (*Tursiops truncatus*). *Proceedings of the Royal Society of London. Series B: Biological Sciences* 271, 1043–1049

Council, N. R. et al. (2003). Ocean noise and marine mammals

Dunn, O. J. (1964). Multiple comparisons using rank sums. *Technometrics* 6, 241–252

Filatova, O., Burdin, A., and Hoyt, E. (2010). Horizontal transmission of vocal traditions in killer whale *(Orcinus orca)* dialects. *Biology bulletin* 37, 965–971

In review

Filatova, O., Guzeev, M., Fedutin, I., Burdin, A., and Hoyt, E. (2013). Dependence of killer whale *(Orcinus orca)* acoustic signals on the type of activity and social context. *Biology Bulletin* 40, 790–796

Foote, A. D., Osborne, R. W., and Hoelzel, A. R. (2004). Whale-call response to masking boat noise. *Nature* 428, 910–910

Ford, J. K. (1989). Acoustic behaviour of resident killer whales *(Orcinus orca)* off vancouver island, british columbia. *Canadian Journal of Zoology* 67, 727–745

Ford, J. K. (1991). Vocal traditions among resident killer whales *(Orcinus orca)* in coastal waters of British Columbia. *Canadian journal of zoology* 69, 1454–1483

Ford, J. K. (2009). Killer whale: *(Orcinus orca)*. In *Encyclopedia of marine mammals, Elsevier* (The Royal Society). 650–657

Ford, J. K., Ellis, G. M., Barrett-Lennard, L. G., Morton, A. B., Palm, R. S., and Balcomb III, K. C. (1998). Dietary specialization in two sympatric populations of killer whales *(Orcinus orca)* in coastal British Columbia and adjacent waters. *Canadian Journal of Zoology* 76, 1456–1471

Ford, J. K. et al. (1987). *A catalogue of underwater calls produced by killer whales (Orcinus orca) in British Columbia* (Department of Fisheries and Oceans, Fisheries Research Branch, Canada)

Fourniol, M., Gies, V., Barchasz, V., Kussener, E., Barthelemy, H., Vauche, R., et al. (2018). Low-power wake-up system based on frequency analysis for environmental internet of things. In *IEEE Int. Conf. on Mech. and Embedded Sys. and App. (MESA)*. 1–6

Glotin, H., Caudal, F., and Giraudet, P. (2008). Whale cocktail party: real-time multiple tracking and signal analyses. *Canadian acoustics* 36, 139–145

Grebner, D. M. (2009). Individual killer whale vocal variation during intra-group behavioral dynamics. *Phd Thesis, Pennsylvania State Univ.*

Grebner, D. M., Bradley, D. L., Capone, D. E., Parks, S. E., Miksis-Olds, J. L., and Ford, J. K. (2008). Localization of killer whale mother, juvenile, and calf vocalizations. *The Journal of the Acoustical Society of America* 124, 2507–2507

Hoelzel, A. R. and Dover, G. A. (1991). Genetic differentiation between sympatric killer whale populations. *Heredity* 66, 191–195

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., and Veirs, S. (2009). Speaking up: Killer whales *(Orcinus orca)* increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America* 125, EL27–EL32

Holt, M. M., Tennessen, J. B., Ward, E. J., Hanson, M. B., Emmons, C. K., Giles, D. A., et al. (2021). Effects of vessel distance and sex on the behavior of endangered killer whales. *Frontiers in Marine Science* 7, 1211

Janik, V. M. (2000). Whistle matching in wild bottlenose dolphins (*Tursiops t.*). *Science* 289, 1355–1357

Jones, I. M. (2006). A northeast pacific offshore killer whale (*Orcinus orca*) feeding on a pacific halibut (*Hippoglossus stenolepis*). *Marine mammal science* 22, 198–200

Krebs, J. R., Ashcroft, R., and Van Orsdol, K. (1981). Song matching in the great tit *Parus major L. Animal Behaviour* 29, 918–923

Leonard, M. L., Horn, A. G., and Parks, E. (2003). The role of posturing and calling in the begging display of nestling birds. *Behavioral Ecology and Sociobiology* 54, 188–193

Luís, A. R., Couchinho, M. N., and dos Santos, M. E. (2014). Changes in the acoustic behavior of resident Bottlenose dolphins near operating vessels. *Marine Mammal Science* 30, 1417–1426

Miller, P. J. (2002). Mixed-directionality of killer whale stereotyped calls: A direction of movement cue? *Behavioral Ecology and Sociobiology* 52, 262–270

In review

Miller, P. J. (2006). Diversity in sound pressure levels and estimated active space of resident killer whale vocalizations. *Journal of Comparative Physiology A* 192, 449

Miller, P. J., Shapiro, A., Tyack, P., and Solow, A. (2004). Call-type matching in vocal exchanges of free-ranging resident killer whales, *(Orcinus orca)*. *Animal Behaviour* 67, 1099–1107

Miller, P. J. and Tyack, P. L. (1998). A small towed beamforming array to identify vocalizing resident killer whales *(Orcinus orca)* concurrent with focal behavioral observations. *Deep Sea Research Part II: Topical Studies in Oceanography* 45, 1389–1405

Mitani, J. C. and Nishida, T. (1993). Contexts and social correlates of long-distance calling by male chimpanzees. *Animal Behaviour* 45, 735–746

Noad, M., Dunlop, R., and Cato, D. (2012). The lombard effect in Humpback whales. *J. of the Acoustical Soc. of Am.* 131, 3456–3456

Poupard, M., Best, P., Schlüter, J., Prévot, J.-M., Symonds, H., Spong, P., et al. (2019a). Deep learning for ethoacoustics of orcas on three years pentaphonic continuous recording at OrcaLab revealing tide, moon and diel effects. In *IEEE OCEANS*. 1–7

Poupard, M., de Montgolfier, B., and Glotin, H. (2019b). Ethoacoustic by bayesian non parametric and stochastic neighbor embedding to forecast anthropic pressure on dolphins. In *IEEE OCEANS*. 1–5

Poupard, M., Ferrari, M., Schlüter, J., Marxer, R., Giraudet, P., Barchasz, V., et al. (2019c). Real-time passive acoustic 3D tracking of deep diving cetacean by small non-uniform mobile surface antenna. In *Int. Conf. on Acoustics, Speech and Signal Proc. (IEEE ICASSP)*. 8251–8255

[Dataset] Product, R.-C. B. E. (2014). Big eyes™ binoculars - product repair. *Website:* `http://www.bigeyes.ca/f_03_specifications_binoculars.htm`

Quick, N. J. and Janik, V. M. (2008). Whistle rates of wild Bottlenose dolphins (T*ursiops truncatus*): Influences of group size and behavior. *Journal of Comparative Psychology* 122, 305

Ramos-Fernández, G. (2005). Vocal communication in a fission-fusion society: do spider monkeys stay in touch with close associates? *International Journal of Primatology* 26, 1077–1092

Reers, H. and Jacot, A. (2011). The effect of hunger on the acoustic individuality in begging calls of a colonially breeding weaver bird. *BMC ecology* 11, 3

Thomsen, F., Franck, D., and Ford, J. K. (2002). On the communicative significance of whistles in wild killer whales *(Orcinus orca)*. *Naturwissenschaften* 89, 404–407

Towers, J. (2015). *Photo-identification catalogue and status of the northern resident killer whale population in 2014* (Fisheries and Oceans Canada)

FIGURE CAPTIONS

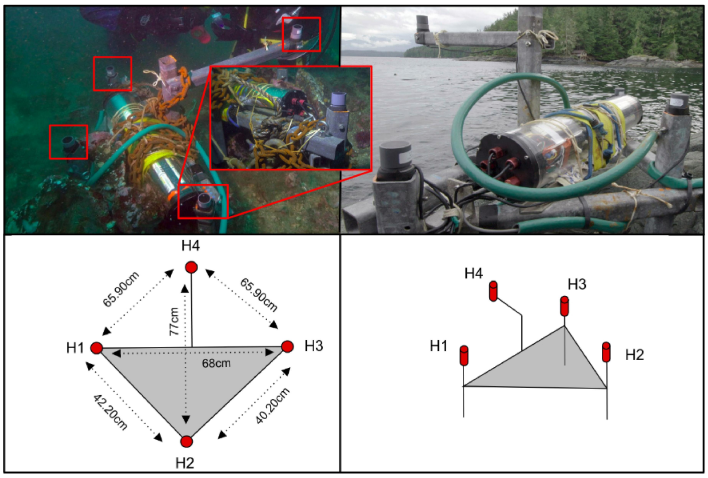


Figure 1. Top : the four-hydrophone antenna, with the 12 V (green) cable connected into OL. Bottom : diagram of the antenna and its inter-hydrophone distances.

In review

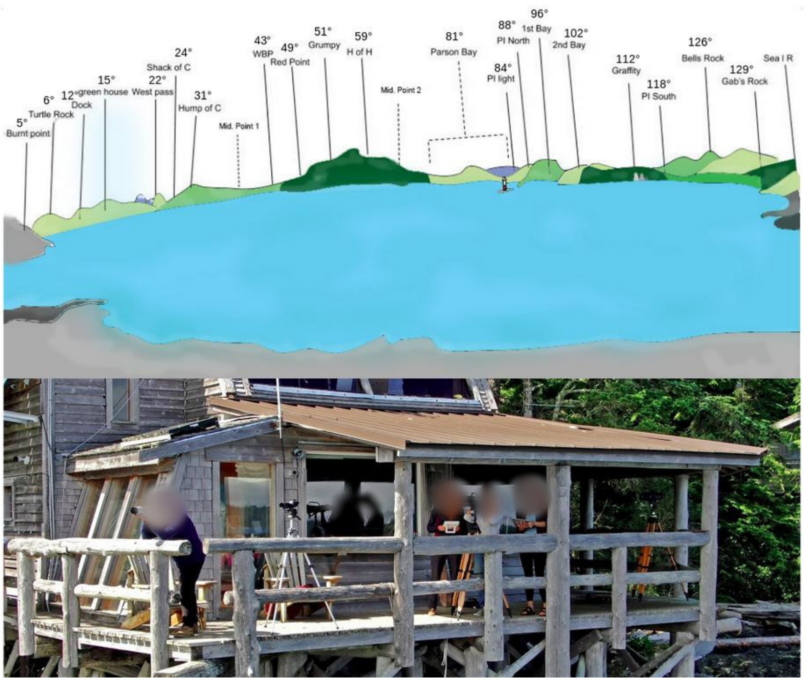


Figure 2. (Top) Representation of the view of BP from OL. Each site was assigned a precise azimuth using a compass (ex : "Pi Light" = 84 degrees.). (Bottom) Picture of the visual protocol.

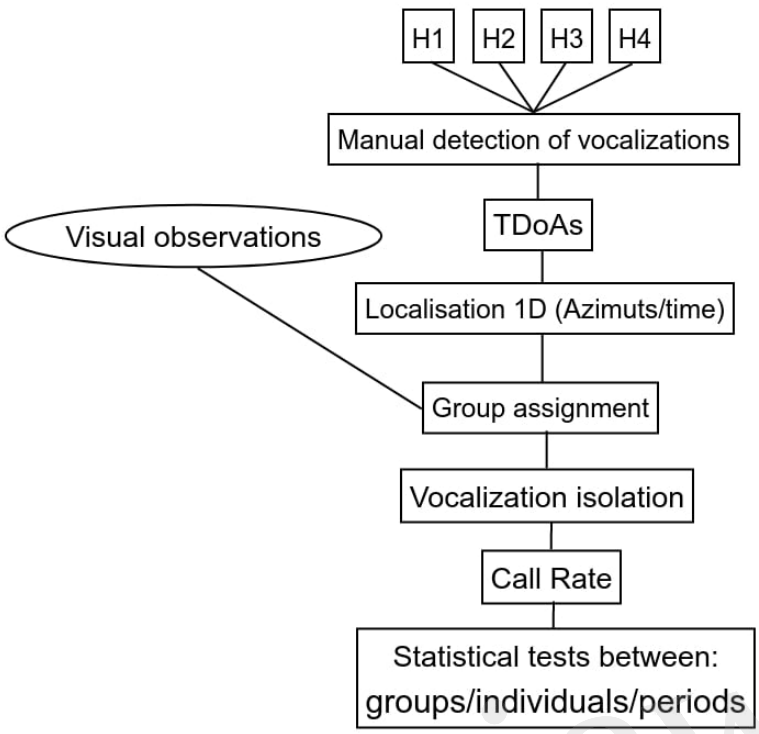


Figure 3. Synopsis of the protocol.

In review

Table 1. Summary of the records of all of the sessions.

Session	Start (dd/mm)	End (dd/mm)	Cumul. Time (hh:mm)	Cumul. Day	Vocal Passage	Non Vocal Passage	Total of the passage
1	20/07	01/08	17:40	11	10	9	19
2	04/08	22/08	17:30	17	12	6	18
3	23/08	15/09	17:40	11	19	15	34
Total			52:50	39	42	29	71

Table 2. Summary of the 3 individuals for which we isolated calls. A66 appeared twice.

Date	Pod Id.	Matriline Id.	Individual Id.	Call Count (85 in Tot.)
04/09	A05	A42	A66	16
31/08	I11	I4	I76	24
22/07	A05	A23	A60	19
30/08	A05	A42	A66	26

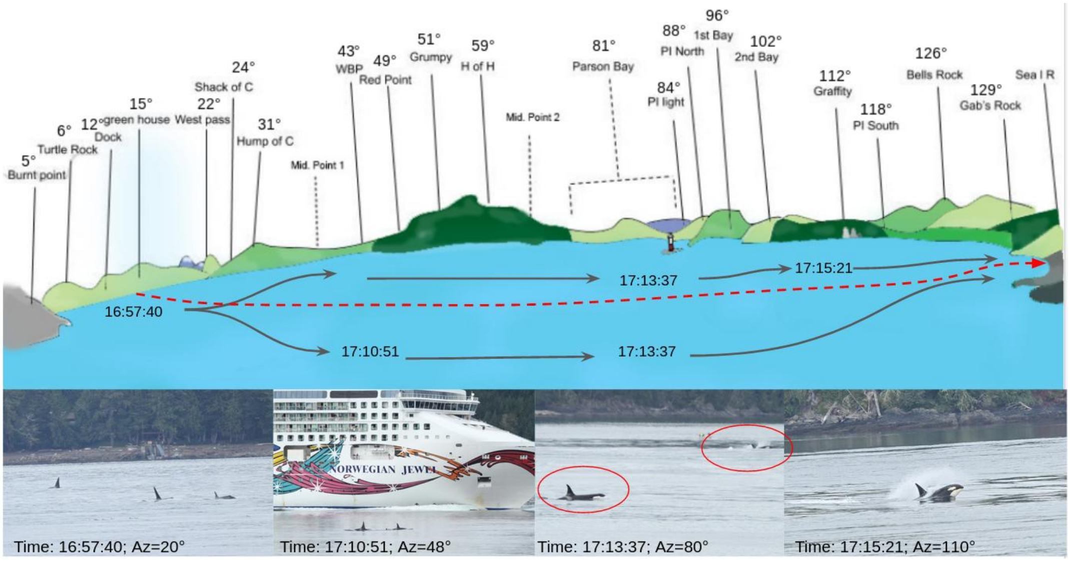
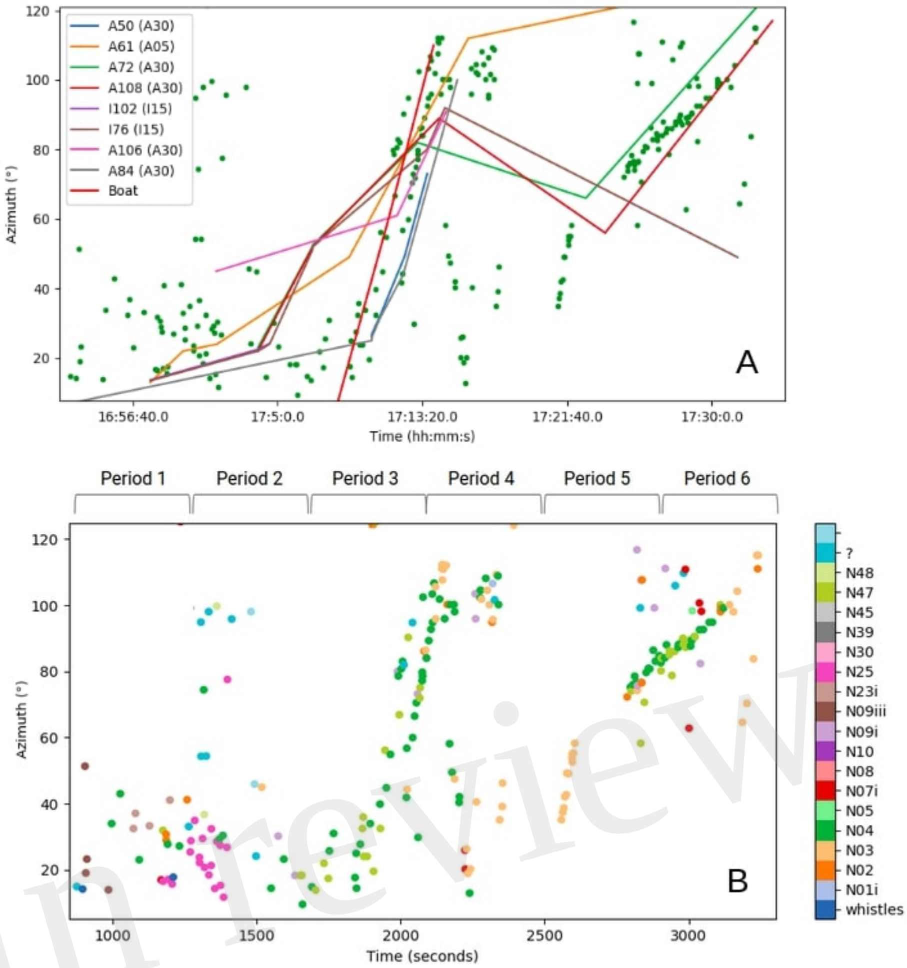


Figure 4. Graph of the passage of the 11^{th} of August. Top : representation of the view of BP from OL with the visual position of the group.The red line is the boat trajectory. Bottom : pictures taken from OL deck.

In review



In review

Figure 5. **A**:Graph of the passage of the 11^{th} of August. Each green point represents a vocalization placed in azimuth. The different curves are the positions of each individual visually detected. The red line is the visual trajectory of the boat. **B**: Graph of the passage of the 11^{th} of August. Each point represents a vocalization placed in azimuth. Each color represents a type of call. The most common types are N04, N03, N48.

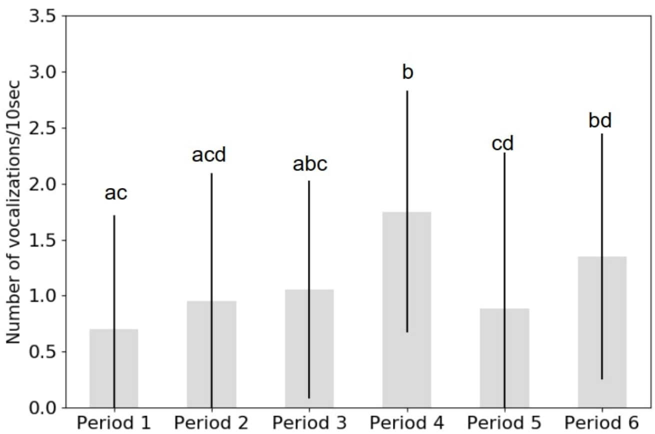


Figure 6. Graph of the CR of the 11^{st} of August for each period (1 to 6).

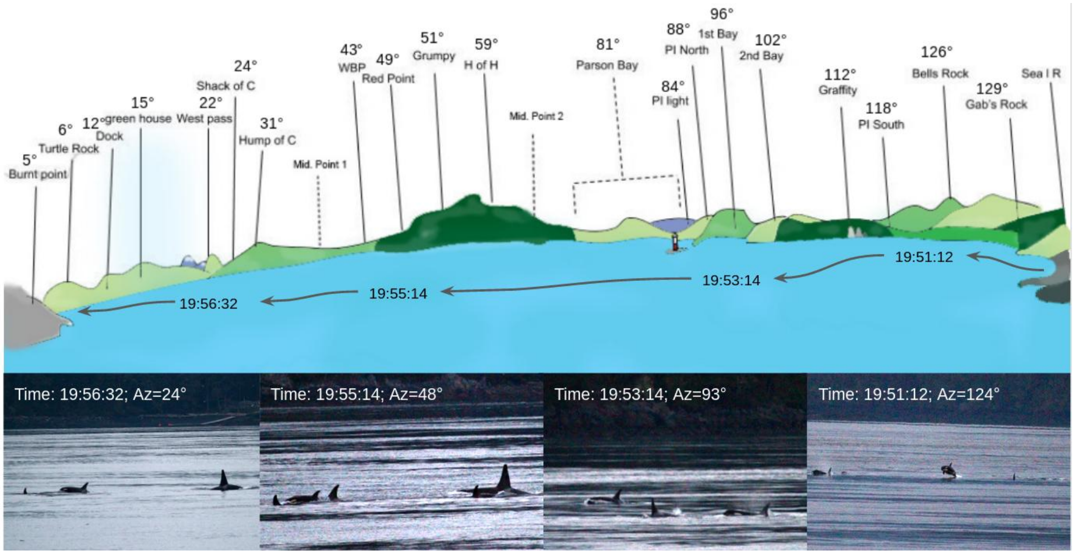


Figure 7. Graph of the passage of the 30^{st} of August. Top : representation of the view of BP from OL with the visual position of the group. Bottom : pictures taken from OL deck.

In review

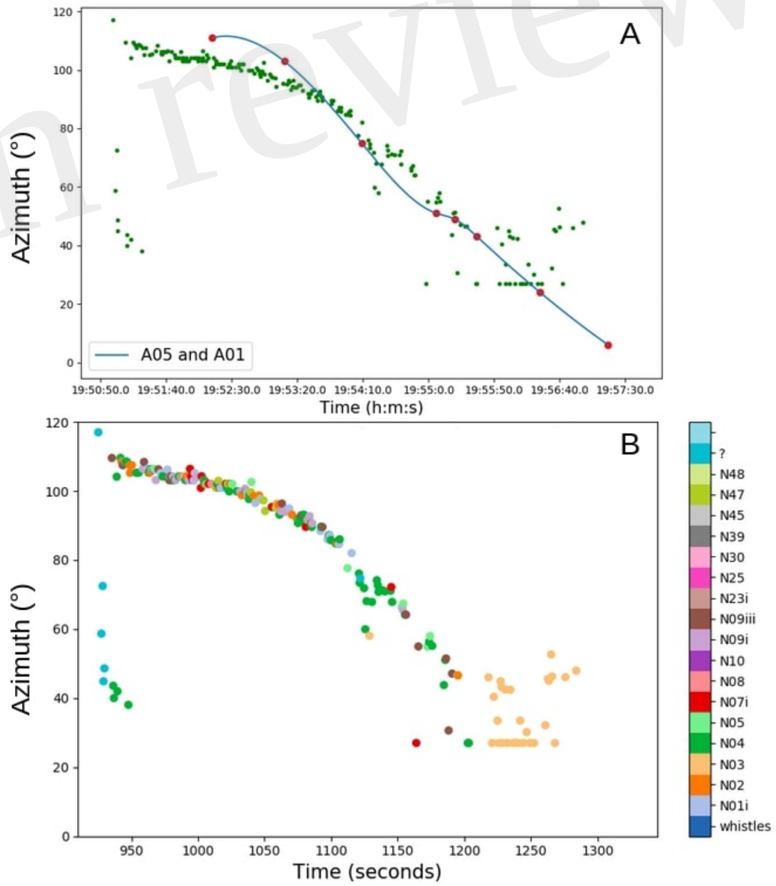


Figure 8. **A**: Graph of the passage of the 30^{th} of August. Each green point represents a vocalization placed in azimuth. The blue curve is the interpolation of the A05 and A01 visual azimuth estimations. **B**:Graph of the passage of the 30^{th} of August. Each point represents a vocalization placed in azimuth. Each color represents a type of call.

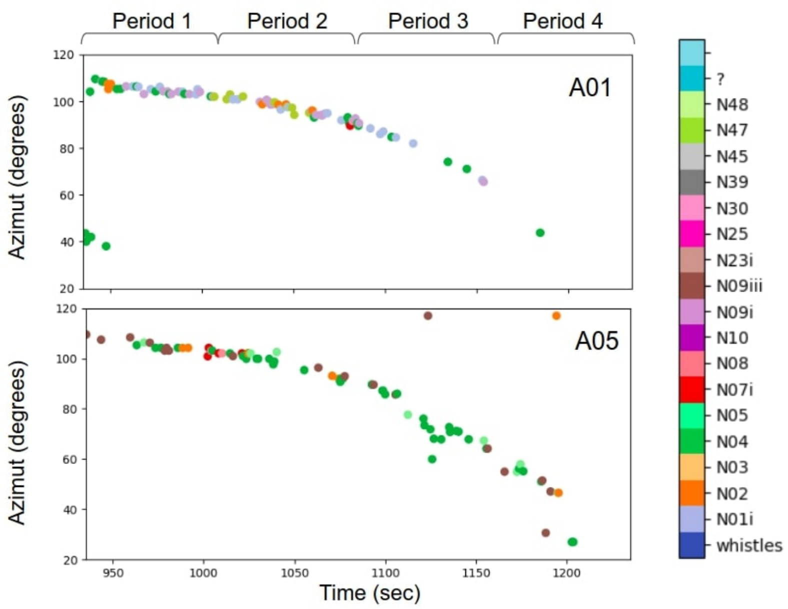


Figure 9. Graph of the passages of the 30^{th} of August. Each point represents a vocalization placed in azimuth. Each color represents a type of call. Top : trajectory of the A01s, Bottom : trajectory of the A05s.

In review

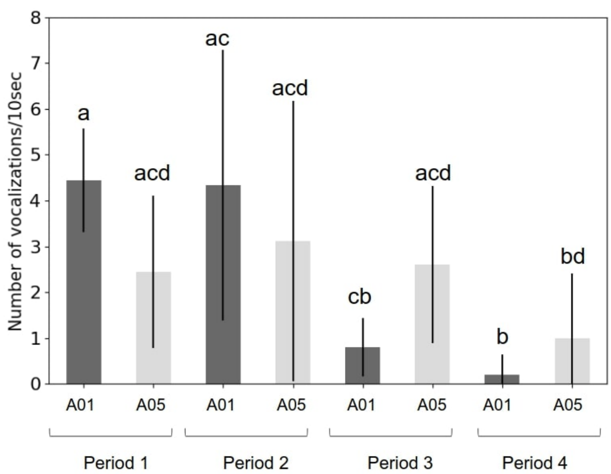


Figure 10. Graph of the CR of the 30^{st} of August for each period and for the A01s (dark grey) and the A05s (light grey).

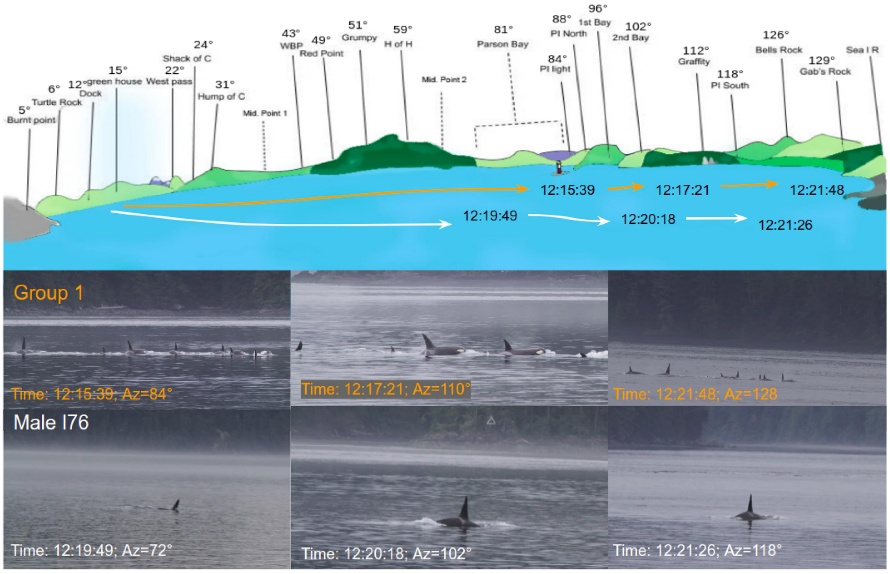
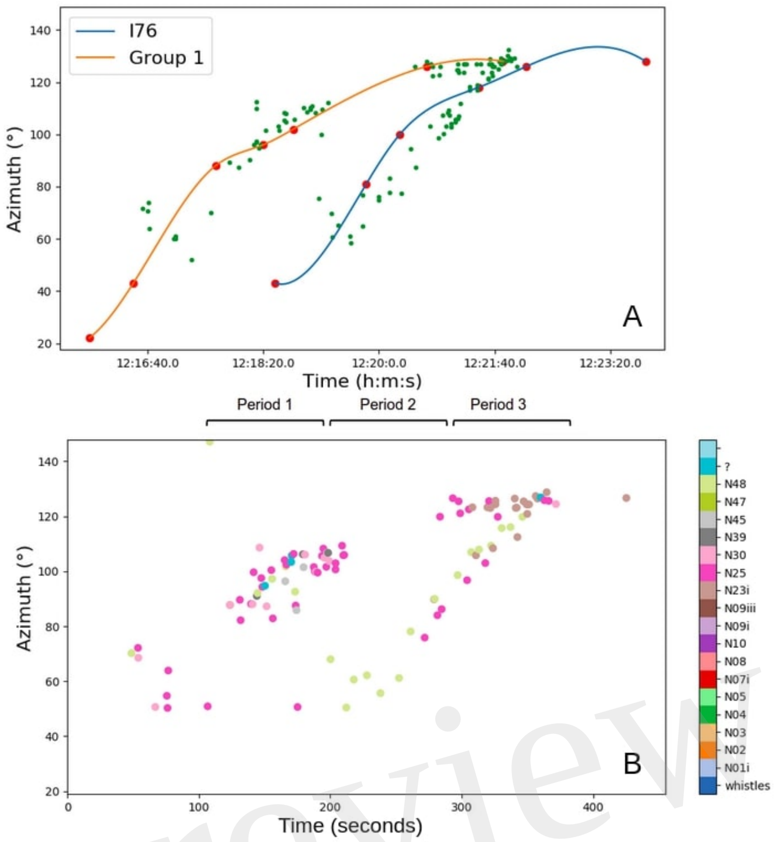


Figure 11. Graph of the passage of the 31^{st} of August. Top : representation of the view of BP from OL with the visual position of the group (orange) and the male I76 (white). Bottom : pictures taken from OL.

In review



In review

Figure 12. A: Graph of the passage of the 31^{st} of August. Each green point represents a vocalization placed in azimuth. The blue curve is the interpolated position of the male I76 visually detected, the orange curve is the large group. **B**: Graph of the passage of the 31^{st} of August. Each point represents a vocalization placed in azimuth. Each color represents a type of call. The most common types are N25, N48 and N23i. The track was split into three 80 s periods.

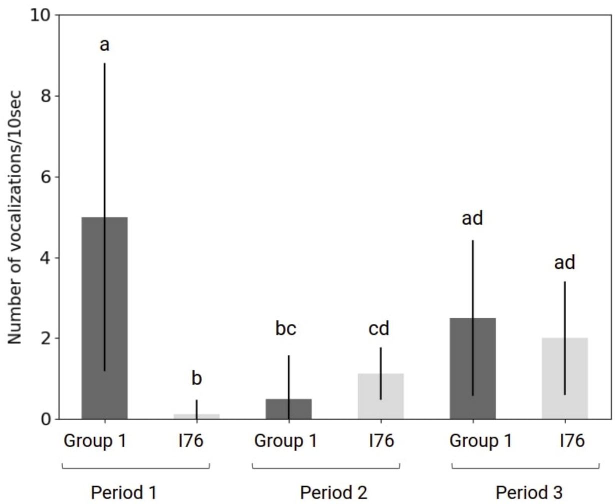


Figure 13. Graph of the CR of the 31^{st} of August for each period and for the group (dark grey) and the male I76 (light grey).

Figure 1.JPEG

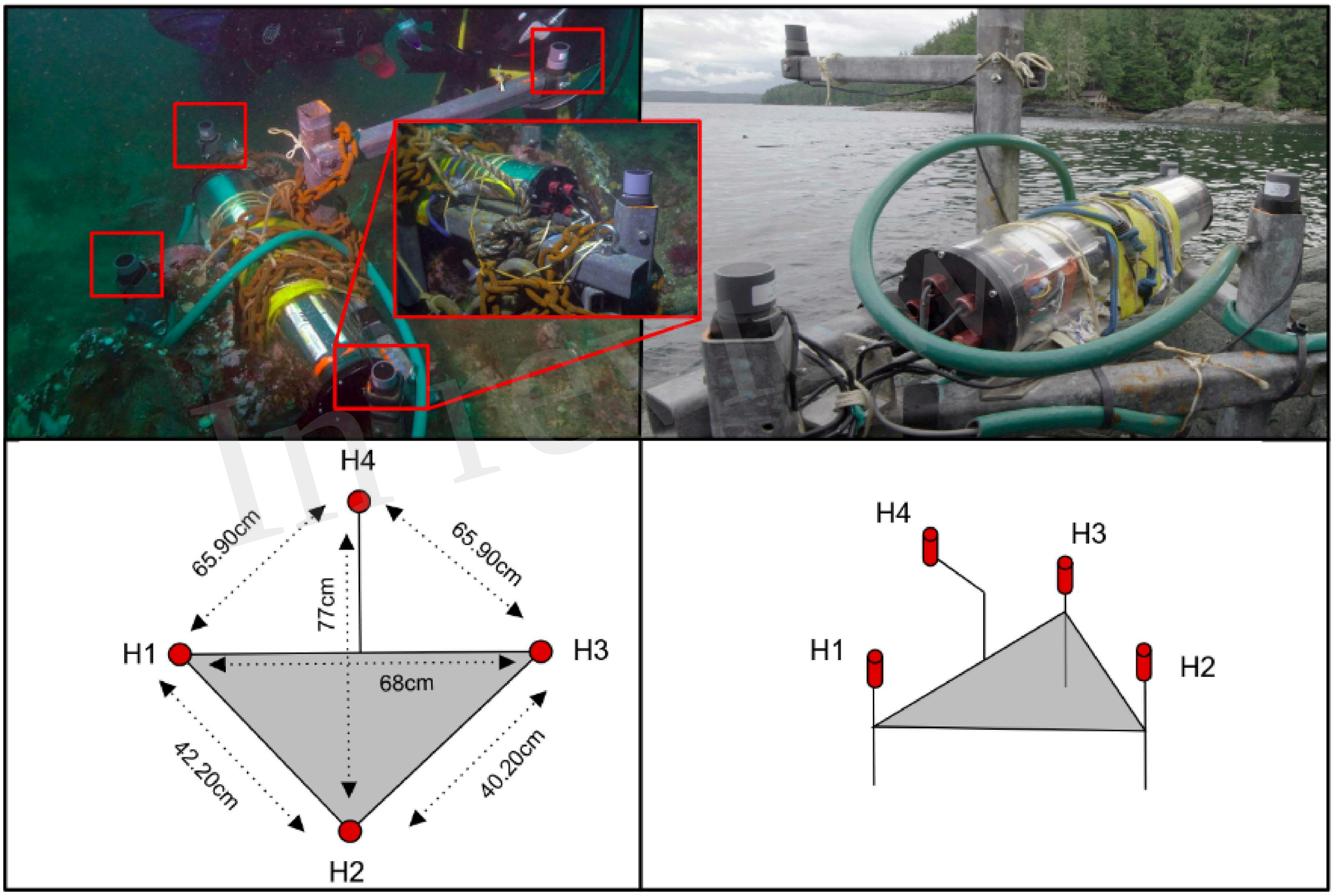
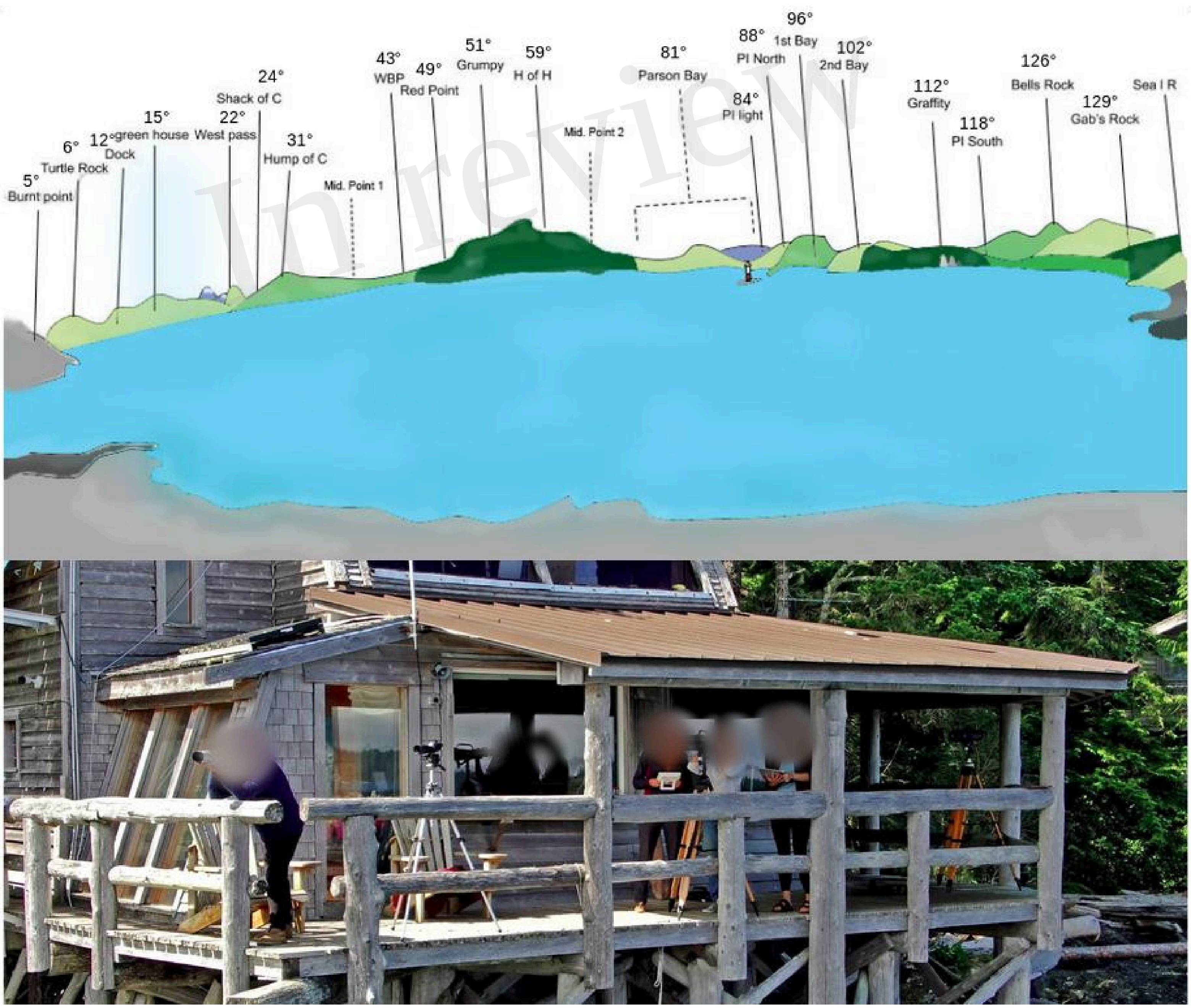
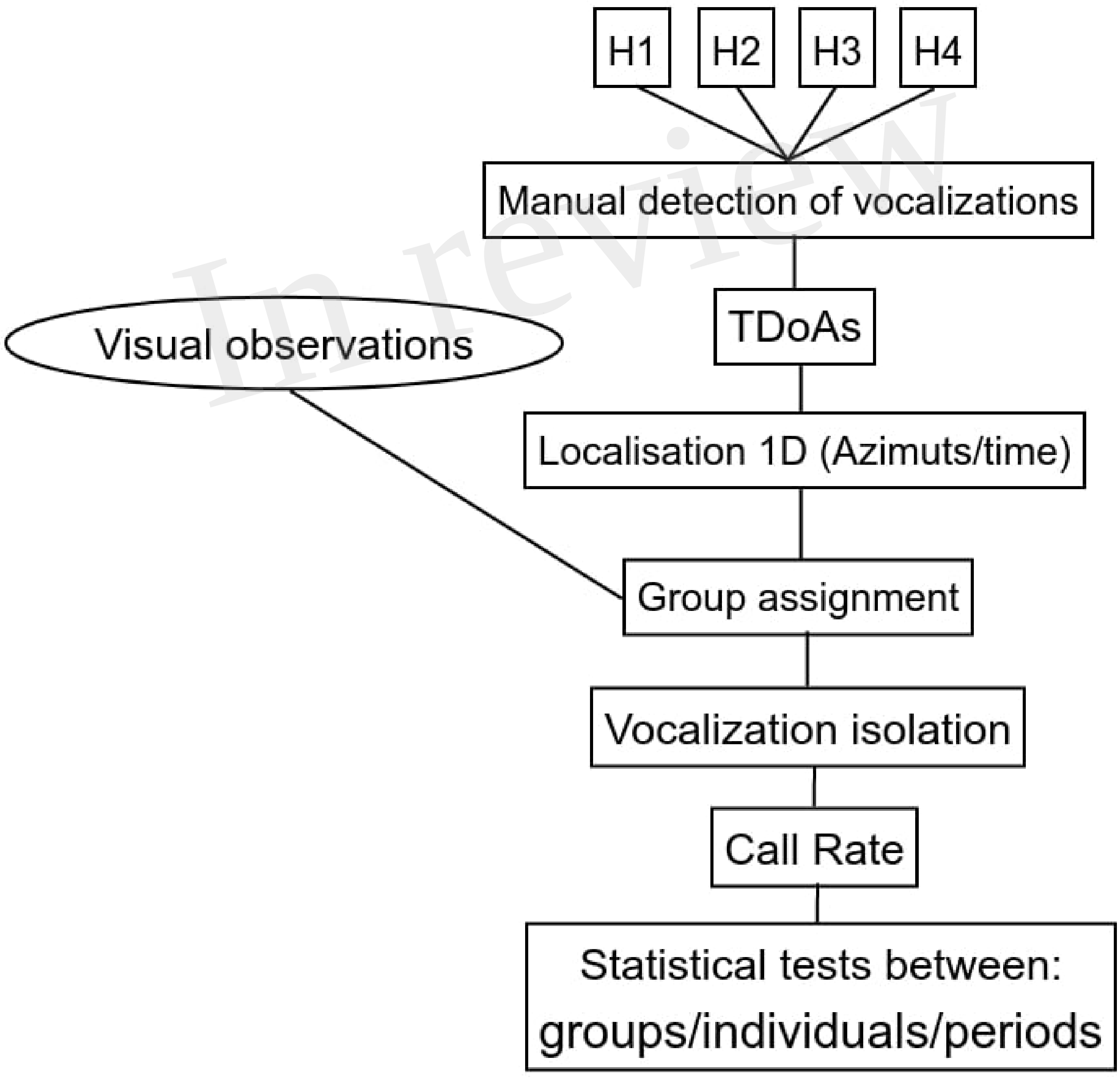


Figure 2.JPEG



In review

Figure 3.JPEG



In review

Figure 4.JPEG

In review

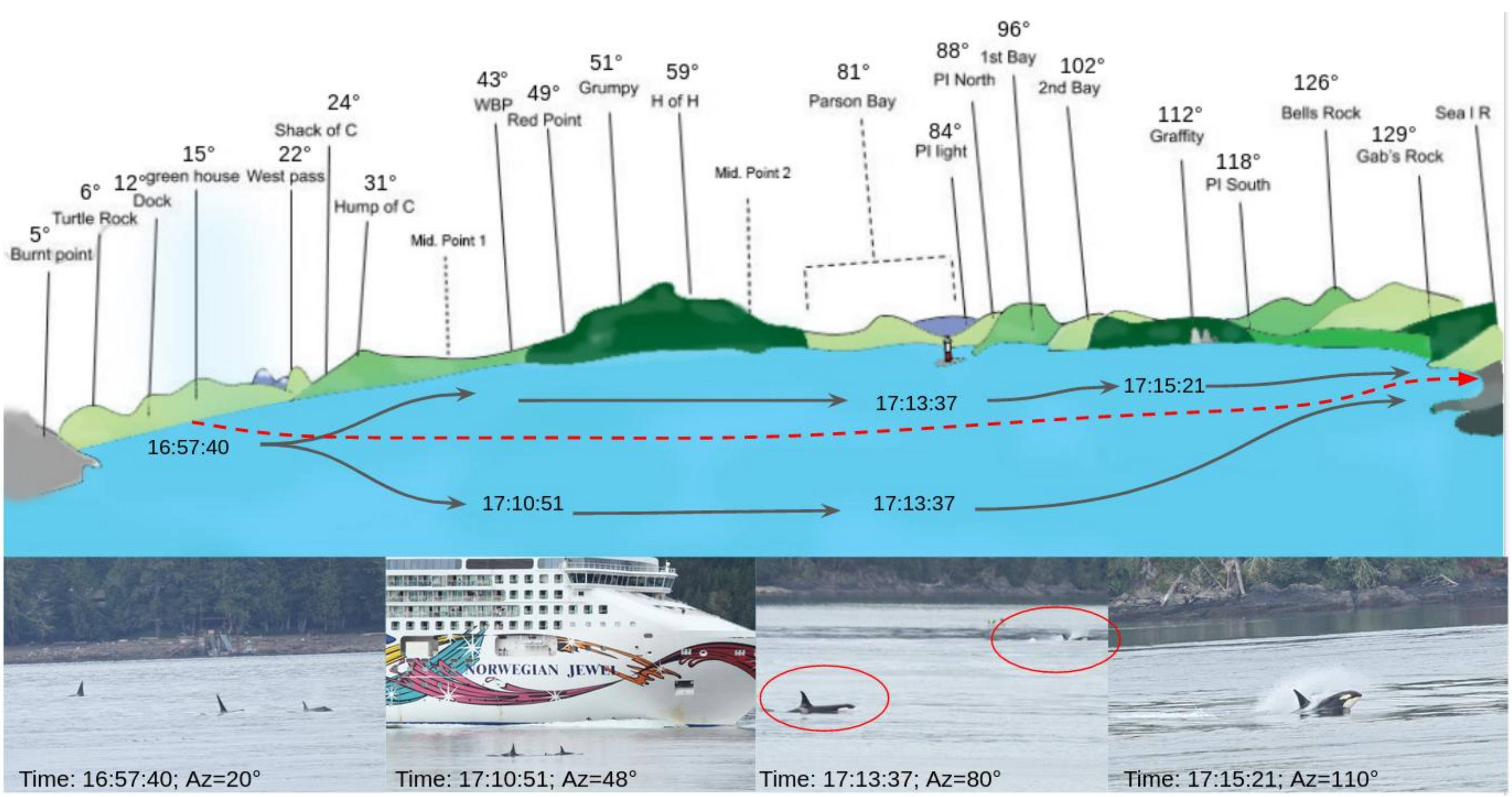


Figure 5.JPEG

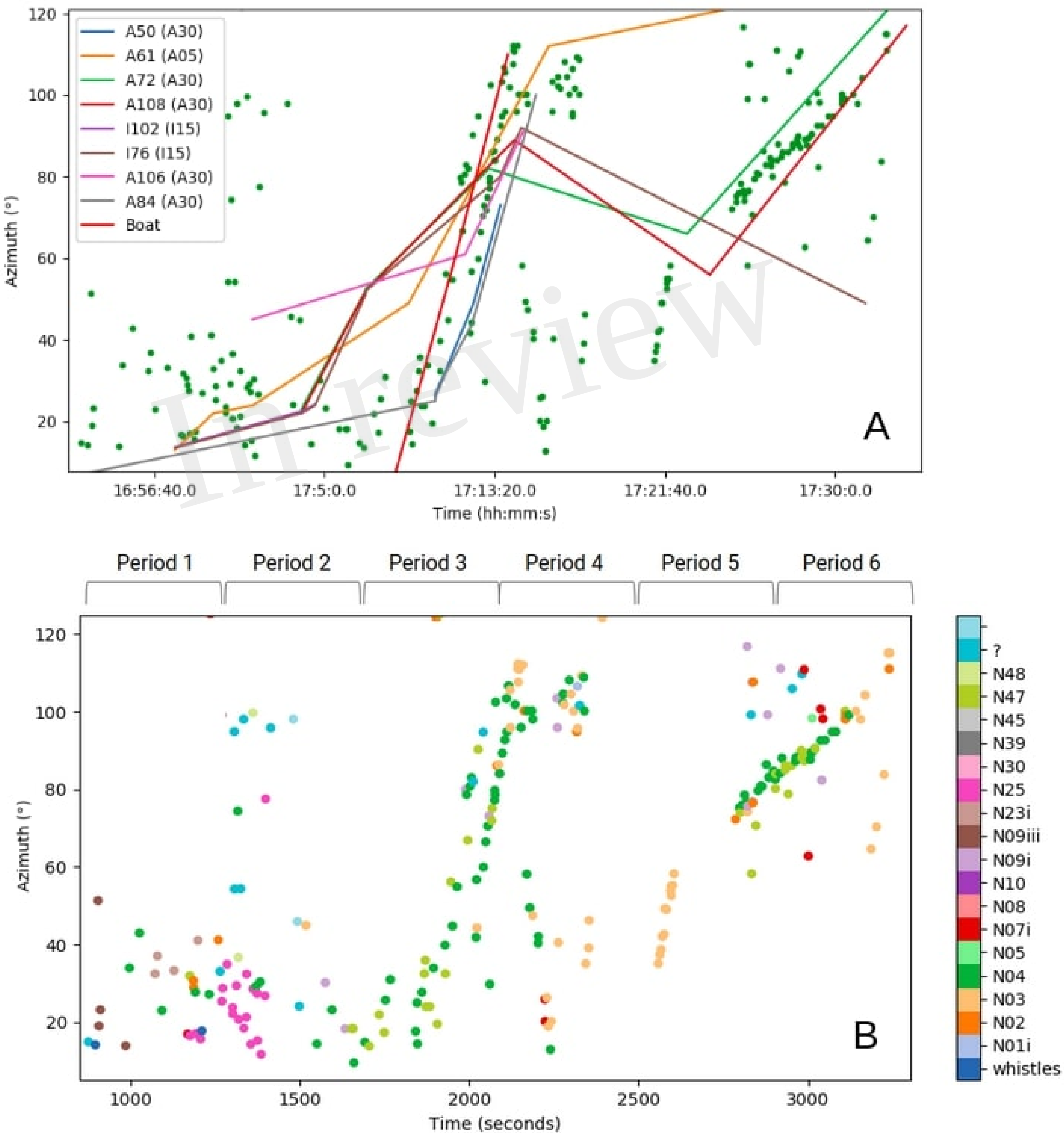
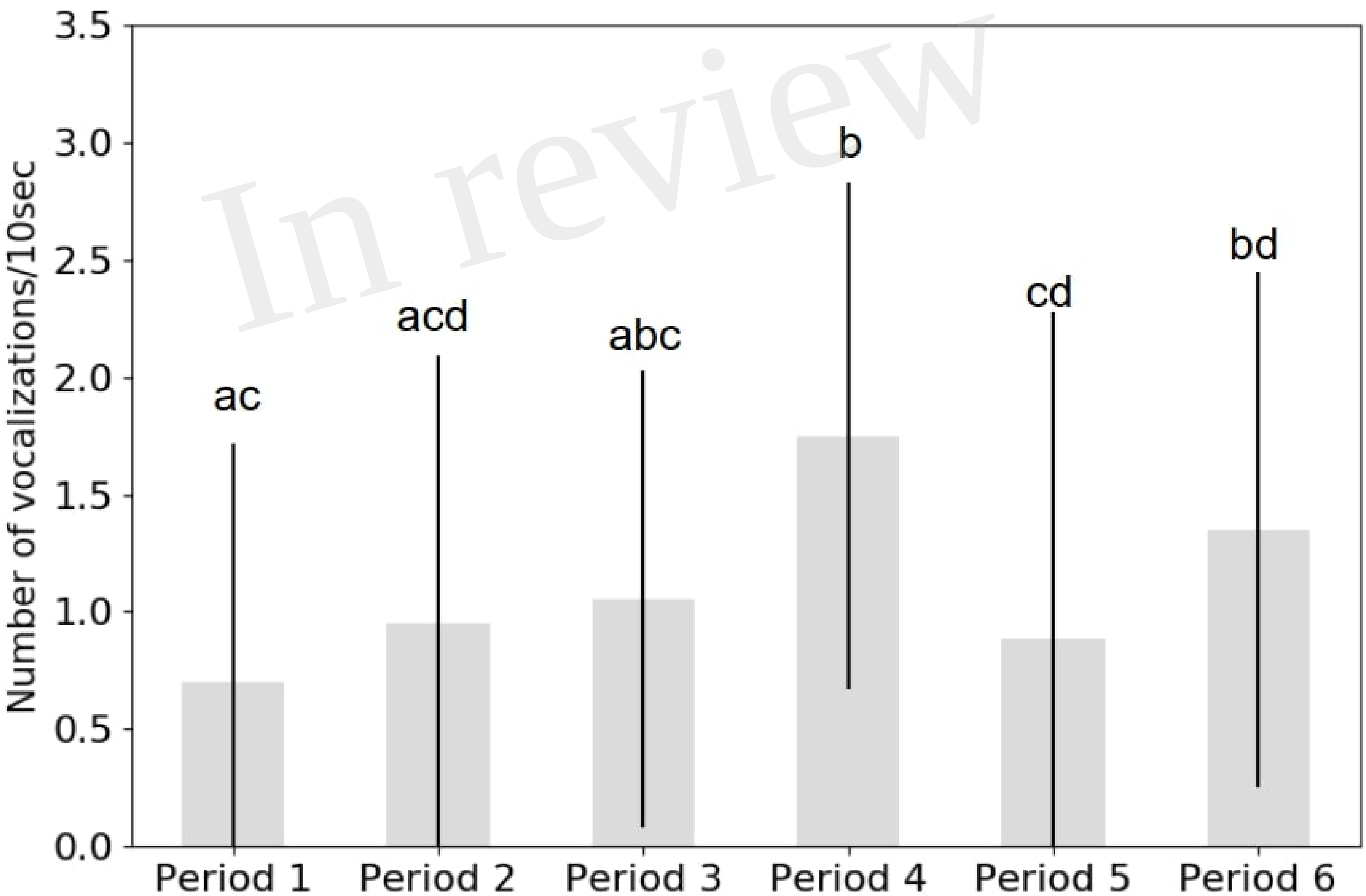


Figure 6.JPEG



In review

Figure 7.JPEG

In review

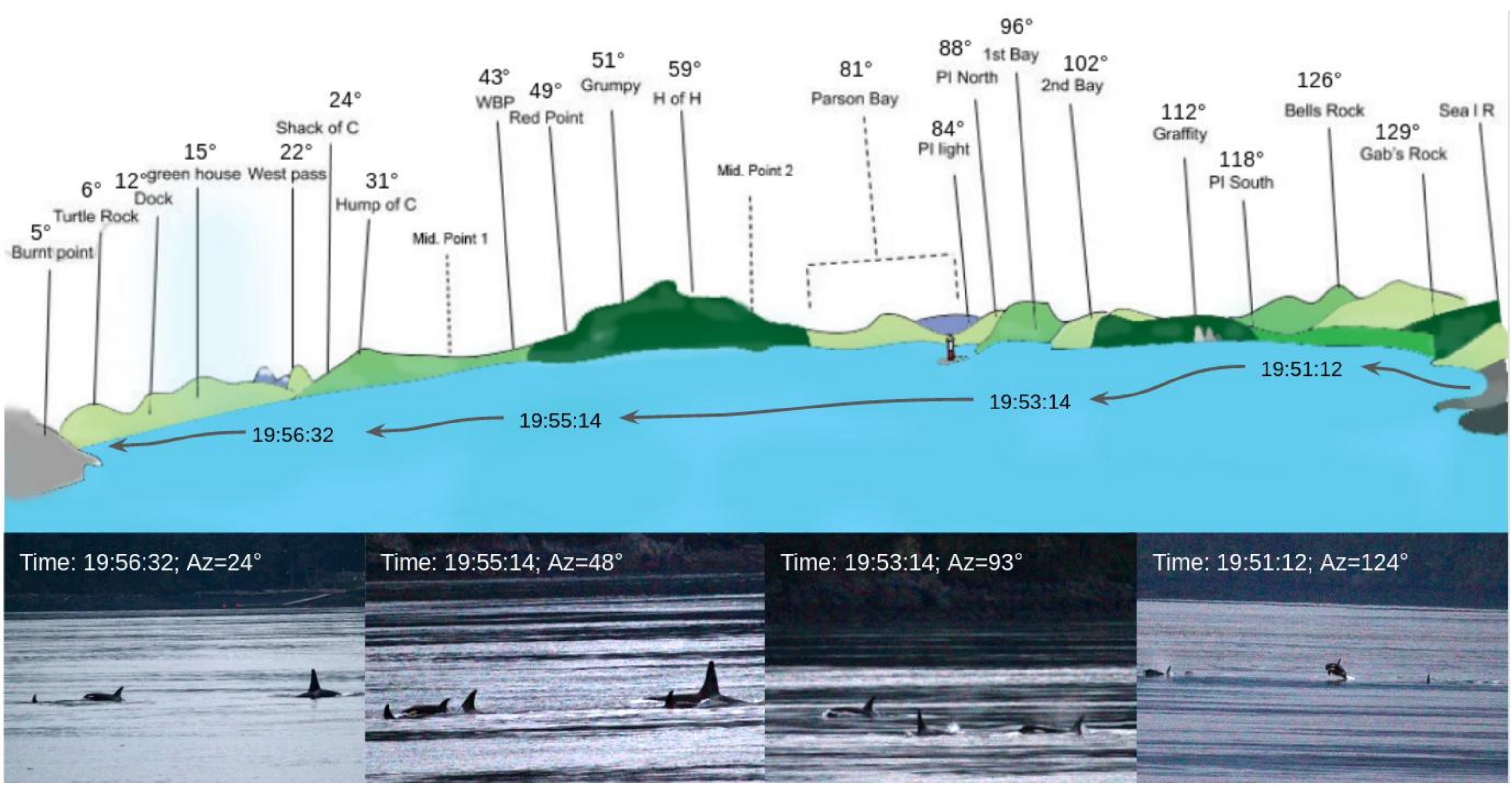
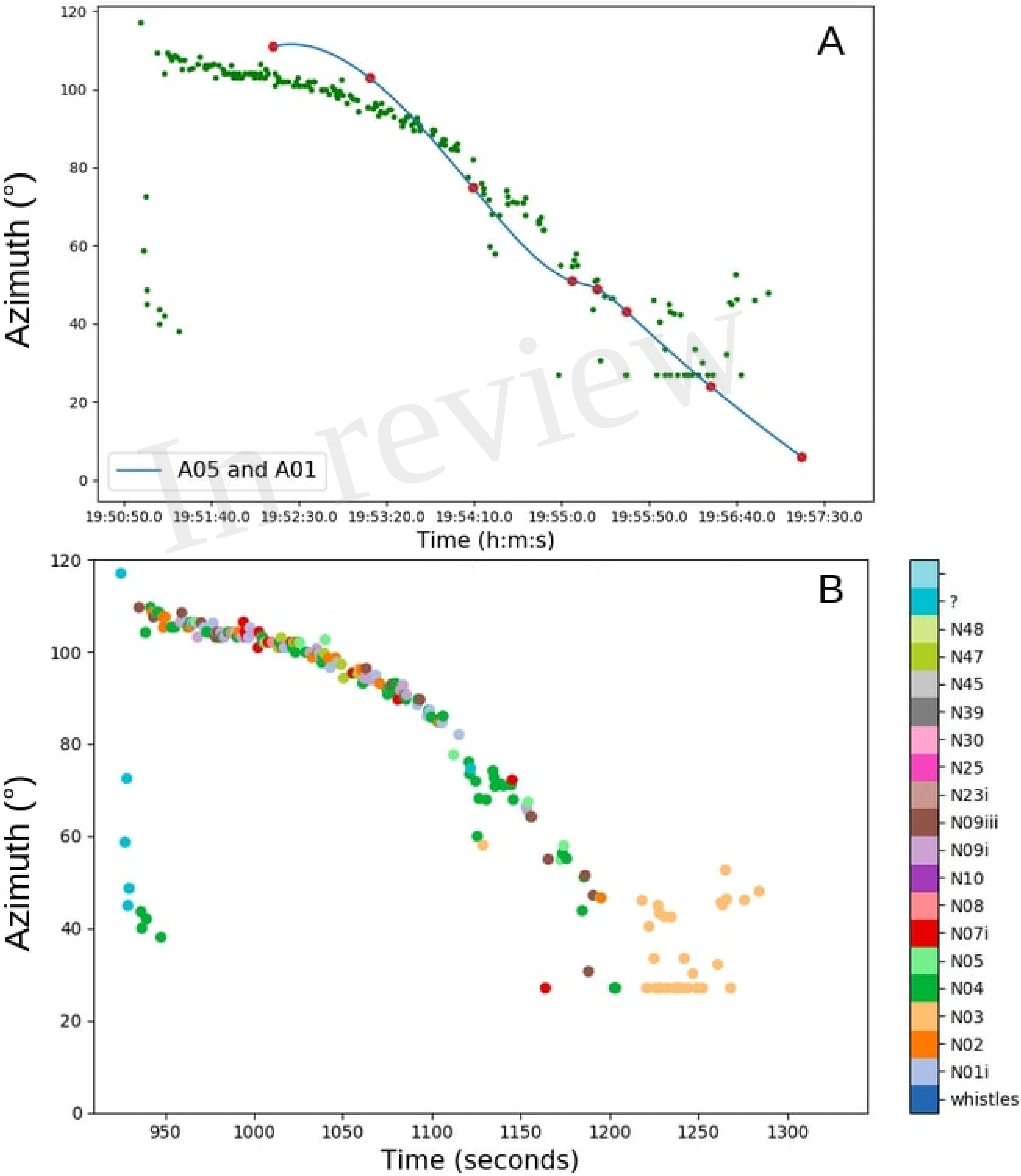
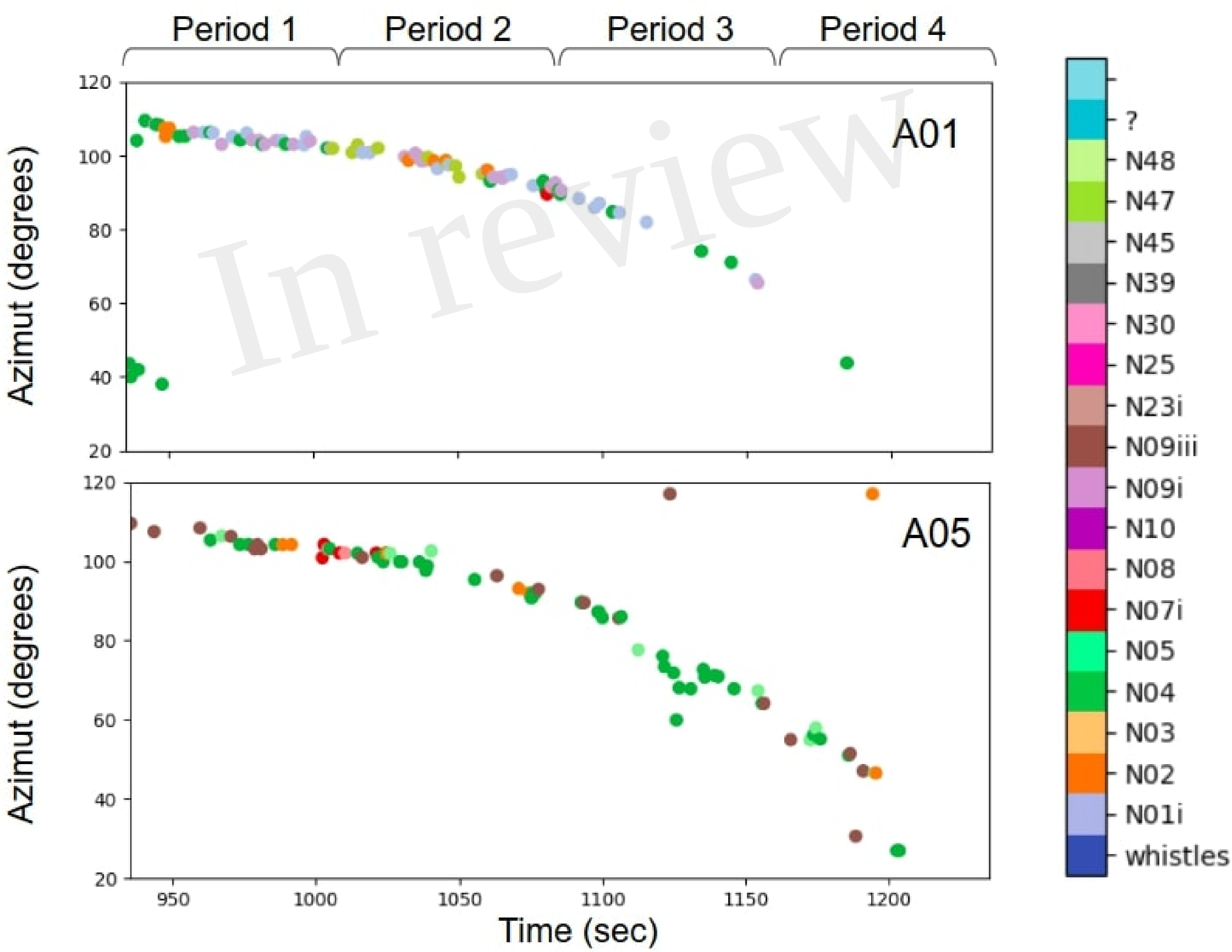


Figure 8.JPEG



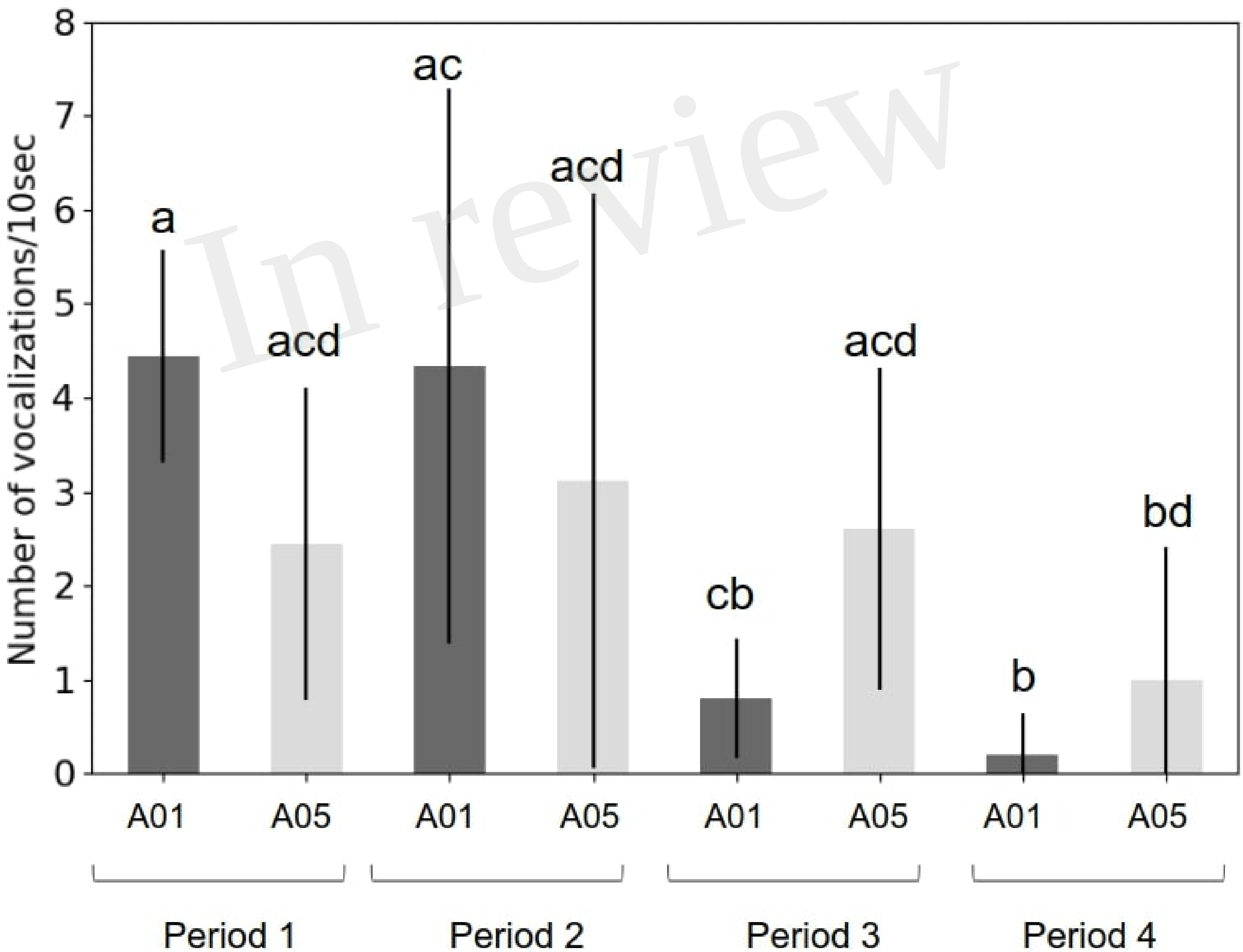
In review

Figure 9.JPEG



In review

Figure 10.JPEG



In review

Figure 11.JPEG

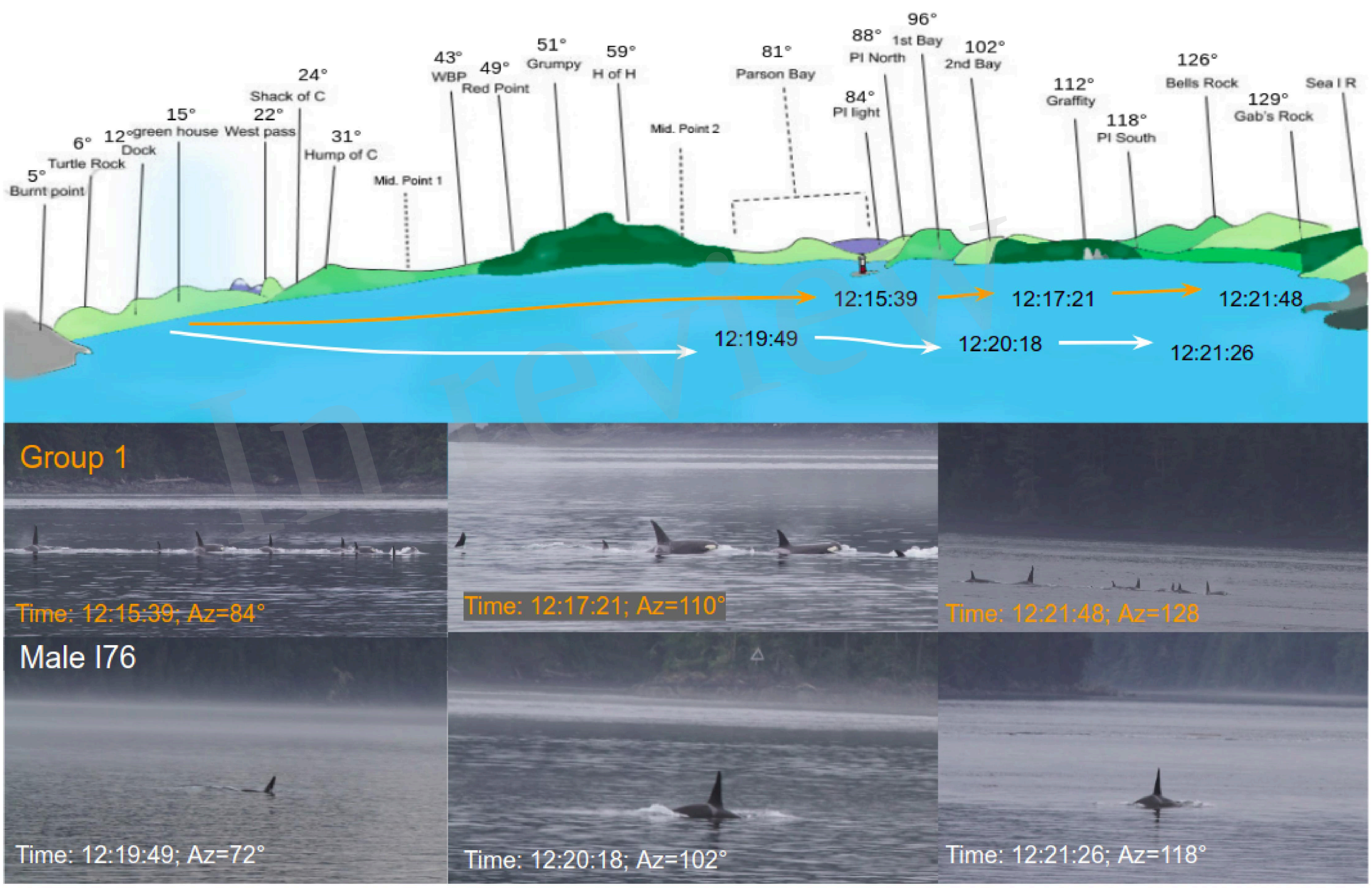


Figure 12.JPEG

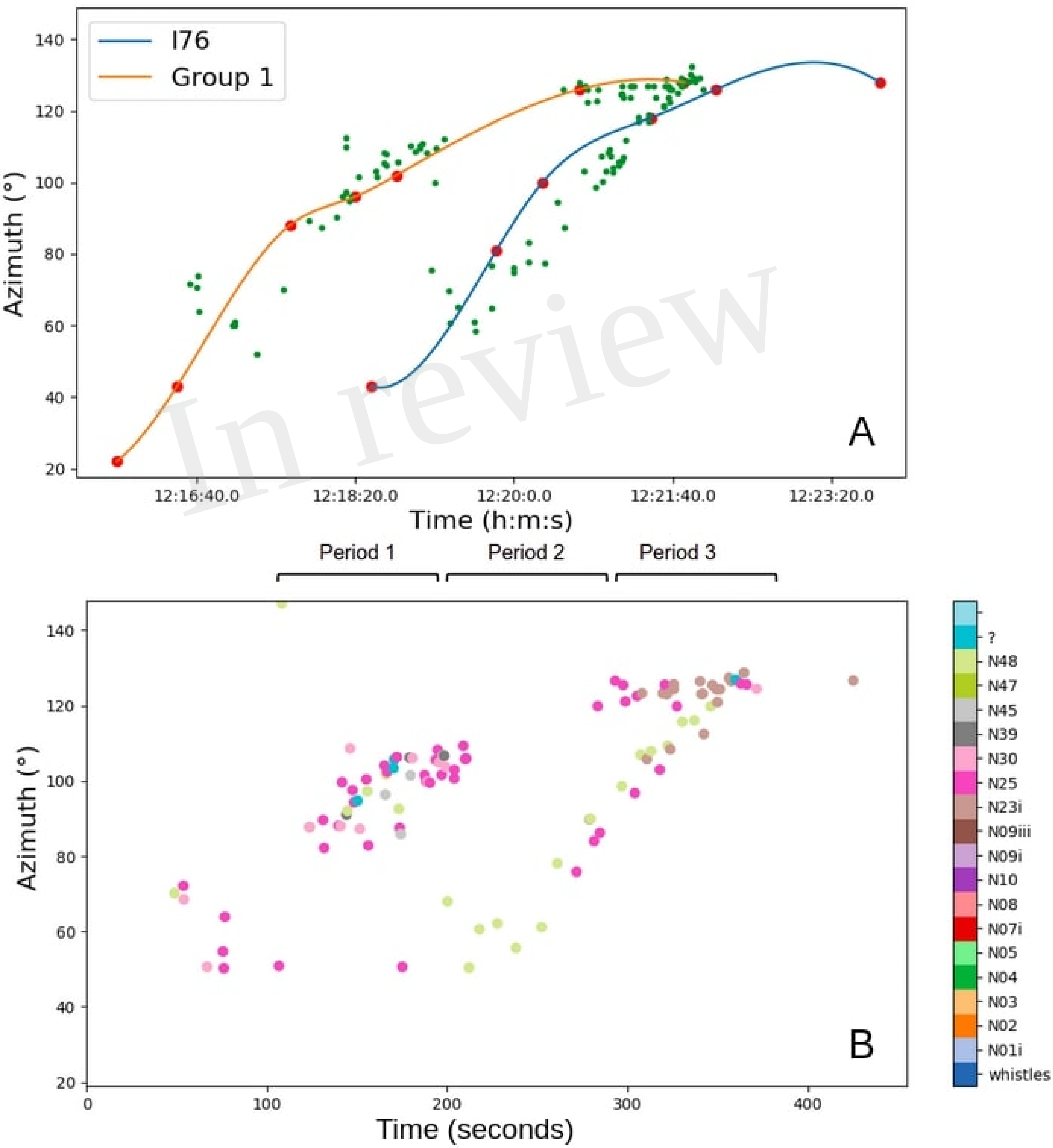
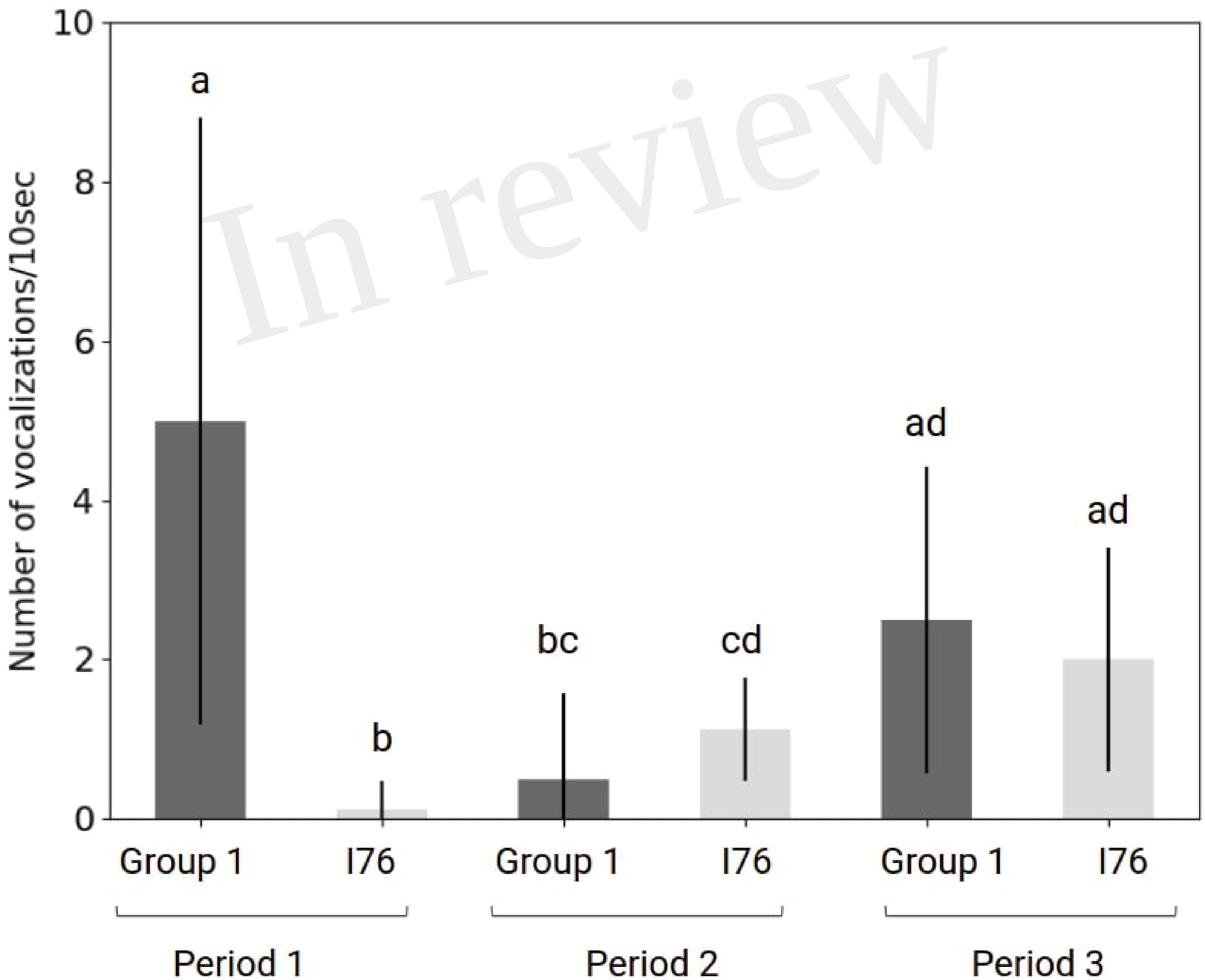


Figure 13.JPEG



In review