Title

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Short Communication

Using two drones to simultaneously monitor visual and acoustic behaviour of gray whales (*Eschrichtius robustus*) in Baja California, Mexico

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ABSTRACT

This study provides an initial demonstration of a combined two-UAV (Unmanned Aerial Vehicle) system for measuring the underwater source levels and behavioural context of vocal and non-vocal marine mammal signals, information that is highly ecologically-relevant in terms of understanding how a species interacts and copes with conspecifics and its acoustic environment. Although the calls of a few species are well known, major gaps exist in our knowledge about the relationship between vocal output and behavioural context, gender and age for most species. Accurate parameter estimates (e.g., typical source levels, frequency ranges, and temporal characteristics of animal sounds) relevant to their behaviour (activities such as foraging, migrating, mating, or parental care) are needed to establish use of critical habitats (when monitored by acoustics) or to assess potential effects of anthropogenic sound exposure (including reduction of the detection space of sounds used for communication). The emergence of UAVs provides new perspectives and data collection capabilities for marine mammal research. Although UAVs have been frequently exploited for visual observations of whales, most approaches for monitoring and recording sounds from individual whales are still performed using overside hydrophones from a boat or using acoustic tags attached to the animals. Laguna San Ignacio (LSI), Mexico, is one of the breeding and calving grounds of the Eastern North Pacific gray whale (*Eschrichtius robustus*) population. LSI area's restricted geography, combined with the short dive times of the whales, provided an excellent field laboratory to test a dual drone approach. We used two UAVs: one to obtain acoustic measurements close to the whales and another one to obtain overhead visual observations. For the acoustic drone, a hydrophone (SoundTrap) was suspended via a 2-m line to a waterproof UAV quadcopter (Swellpro), which has the ability to take off and land from the surface of water. Simultaneously, the visual drone (DJI) monitored the whales in the area. Between 27 February and 17 March 2019, we simultaneously recorded underwater gray whale sounds and visual behavioural observations. During 92 min of underwater acoustic recordings, the acoustic drone recorded 11 call types. By time-synching underwater audio with the behavioural video, we obtained new insights into the source levels and functions of various quiet underwater sound that are difficult to impossible to obtain with standard methods. To our knowledge, no studies combining overhead visual observations and underwater acoustic recordings to describe acoustic behaviour and sound parameters of calls have been previously published.

1. Introduction

Marine mammals use both vocal and non-vocal sounds (e.g., breaches, tail slapping, bubble emissions) for acoustic communication, which play a vital role in their social behaviour and interactions. We can better determine a sound's function whenever the calling individual's behavioural context can be measured simultaneously with sound production (Henderson et al., 2012). Context is defined here as the immediate behavioural states of the animal(s) involved, the identity of the sound producer (e.g. sex, age class) and the number and composition of nearby individuals. The behavioural context of sound production has been determined for a subset of calls produced by some well-studied mysticete (baleen whale) species, including the humpback whale (*Megaptera novaeangliae*; Payne and McVay, 1971; D'Vincent

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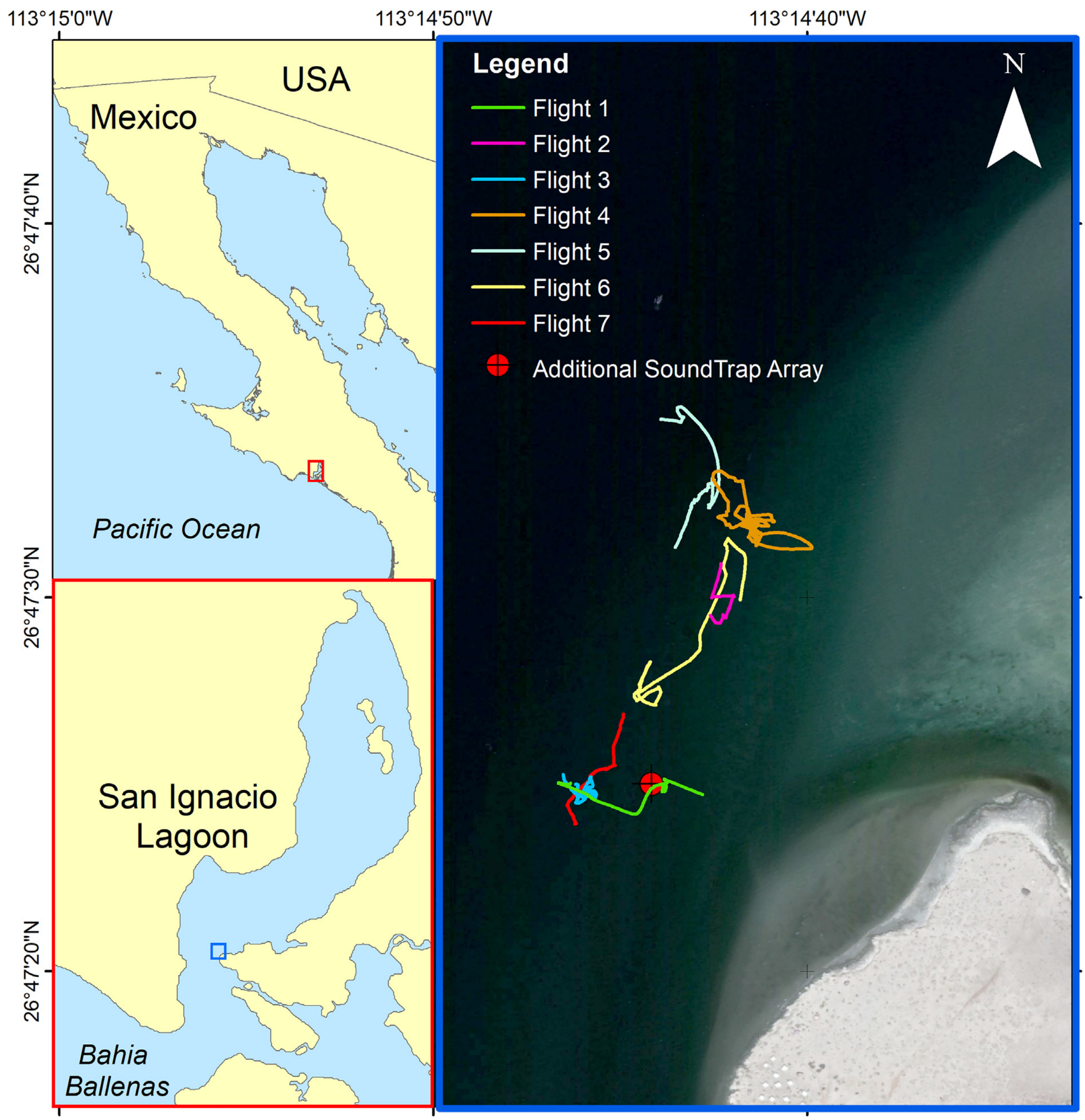

Fig. 1. Aerial visual transects for the seven joint visual and underwater recording flights at Punta Piedra (San Ignacio lagoon, California Baja Sur, Mexico). Red dot shows additional SoundTrap array. [Photo from Google Earth]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 1985; Parks et al., 2014), the southern right whale (*Eubalena australis*; Clark, 1983), the north Atlantic right whale (*E. glacialis*; Parks and Tyack, 2005), and the blue whale (*Balaenoptera musculus*; Oleson et al., 2007). Observing the behavioural context of calling cetaceans is challenging for two reasons. The first reason is the logistical difficulties in conducting visual observations of behaviour in the open ocean. The second reason, which is the most restrictive, is the intrinsic difficulty of associating vocalizations (which typically occur underwater), with specific behaviours that occur at the surface prior to or after a call has been produced in the same area.

Acoustic ecology investigates how organisms use sound to interact with one another and their environment. Behavioural contexts of sound production, along with the timing of calls from individuals and the trends in calling behaviour based on age, sex, and/or time of day, are needed when designing acoustic surveys, and monitoring and mitigation efforts. In these applications, statistical models for calling rates and the source parameters of signals (including source level, i.e. the "loudness" of a sound) are essential for estimating the probability of detecting animals (Marques et al., 2009). The spatial and temporal extent of critical habitats might be determined acoustically if the ecological role of sound can be better determined (e.g., whether specific call types are associated with activities such as foraging, migrating, mating, or parental care). Such insights have remained elusive due to the difficulty in observing natural behaviour and simultaneously recording underwater sounds in the wild; therefore, there is a critical need for the development of a reliable technique to study properties and functions of underwater sounds, particularly sounds too quiet to be observed through traditional means, such as tagging or boat-based observations.

Conventional methods of acoustic monitoring have been recently complemented by the new possibilities opened by Unmanned Aerial Vehicle (UAV), or drone technology, which has already proven to be a

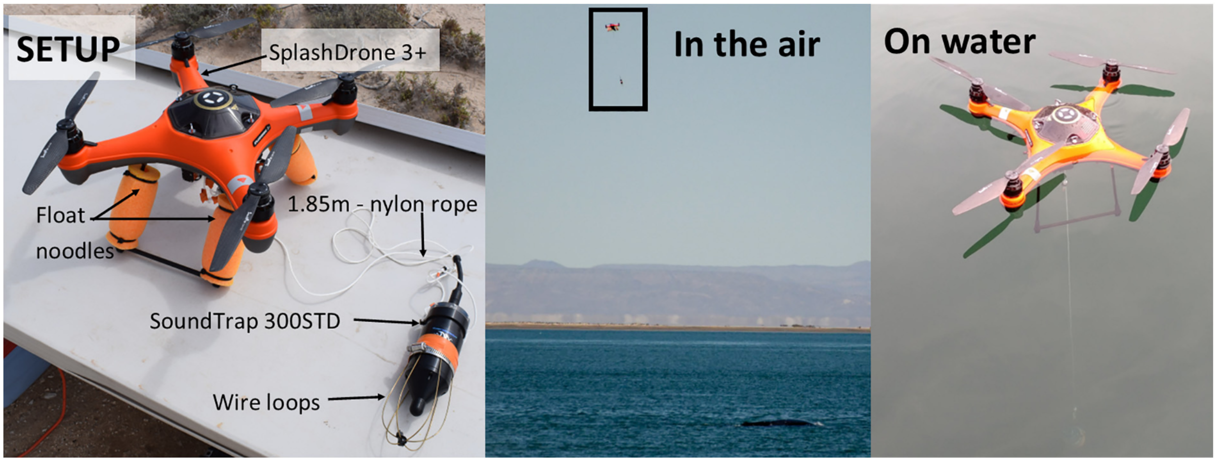

Fig. 2. Photos of the acoustic drone setup (left), the acoustic drone in the air above a whale (middle, credit photo: Regina Lobo Barrera, UABCS) and the acoustic drone on water (right, photo taken before that float noodles have been mounted).

valuable tool for gathering marine mammal data in natural marine habitats. The application of UAVs in wildlife monitoring and conservation (Gonzalez et al., 2016) has allowed scientists to collect data under logistically challenging circumstances and answer previously inaccessible research questions. UAVs are driving new and innovative research and have been used for a wide variety of applications including aerial surveys, monitoring, habitat use, abundance estimates, photogrammetry, behavioural observations, health observations, and biological sampling (Hogg et al., 2009; Acevedo-Whitehouse et al., 2010; Durban et al., 2015; Pomeroy et al., 2015; Pirotta et al., 2017; Torres et al., 2018). UAVs, despite short duration flights and limited distance restrictions, also provide an alternative, non-invasive, and often cost-effective option for monitoring marine species, and in doing so are replacing expensive manned systems such as helicopters and fixed-wing aircraft (Nowacek et al., 2016; Fiori et al., 2017). The use of UAVs to acoustically survey an area of interest has the potential to significantly reduce the cost of conventional methods (Lloyd et al., 2016).

This paper presents a new method for studying marine mammal acoustic behaviour and their sound properties, and provides what we believe are the first underwater marine mammal sounds collected by an UAV, with visual behavioural observations collected from a second UAV deployed simultaneously. When the underwater audio is time-synched with the aerial behavioural video, we obtain new insights into the properties and functions of underwater sounds. In this paper, we illustrate the potential of this approach by a limited case study. We employed the combined two-UAV system to report sounds produced during different events and to measure the underwater source levels of vocal sounds, non-vocal underwater bubble releases, and surface exhalations (blows) of the eastern North Pacific gray whale (*Eschrichtius robustus*), a coastal mysticete species that migrates and breeds along the western coast of North America.

2. Material and methods

The proposed approach is illustrated here with a small-scale case study: the eastern North Pacific gray whale in Baja California, Mexico. The eastern North Pacific gray whale population breeds and calves during the winter months along the eastern Pacific coast and in lagoons along the west coast of the Baja California, Mexico, where whales migrate from summer feeding grounds along the northwest coast of North America into the Pacific Arctic (Swartz et al., 2006). Laguna San Ignacio (LSI; Fig. 1) is one such lagoon where wintering whales gather to breed and calve. It lies within the southern portion of Mexico's “Vizcaino Desert Biosphere Reserve”, the largest wildlife refuge in Latin America, which is administered by the Secretaria de Medio Ambiente y Recursos Naturales de Mexico (SEMARNAT).

2.1. Sampling location and protocol

The results presented here were obtained from a remote desert site at Punta Piedra (26^0 47′ 20” N, 113^0 14′ 40” W) inside LSI, Baja California Sur, Mexico (Fig. 1) adjacent to Bahia Ballenas. This location has been the site of extensive visual and acoustic observations of gray whales over past decades (Dahlheim and Castellote, 2016) and is populated with two distinct demographic groups: single whales and mother/calf pairs (Urbán et al., 2003).

The LSI area's restricted geography, shallow waters, and good weather, combined with the short dive times of the whales, provided an excellent proof-of-concept location, by permitting frequent visual and acoustic drone surveys to be conducted. Previous studies used an overside hydrophone from a boat (Wisdom, 2000) or acoustic tags attached to the animals (López-Urbán et al., 2016) to monitor and record calls from individual gray whales.

Drone flights for the visual observations were conducted using a DJI Phantom 4 Advanced Plus UAV quadcopter (35 cm diameter, 1.4 kg) (www.dji.com). This drone includes a multi-axis flight controller, GPS and compass that compensates for variable wind effects, thus permitting stable flight conditions with consistent altitude. During each flight a camera recorded 4 K resolution videos with 3840 × 2160 pixel resolution at 30 frames/s. When recording, the camera was positioned straight down so that GPS coordinates of the center of the frame could be extracted from the flight log. The UAV was flown at a consistent altitude of 30 m to avoid affecting animal behaviour. Christiansen et al. (2016b) previously demonstrated that UAV (SplashDrone and DJI Inspire 1 Pro) noise was only quantifiable above ambient noise when flown less than 10 m above the sea surface. The Phantom had a flight endurance of approximately 30 min, and internally logged GPS position, drone orientation and altitude data 20 times per second ($Fs = 20$ Hz).

A second drone was used to record underwater sound, by suspending a SoundTrap 300STD acoustic recorder (Ocean Instruments, NZ) 2-m underneath a waterproof Swellpro SplashDrone 3+ quadcopter (www.swellpro.com), using a 3 mm diameter nylon braided rope (Fig. 2). The SoundTrap was configured to collect continuously acoustic data sampled at 96 kHz. Foam noodles were fitted to the drone's landing frame in order to improve its buoyancy. Wire loops from a kitchen whisk were also fitted to the SoundTrap in order to protect the hydrophone when landing onshore or in shallow water. The distance between the UAV and the field station was usually less than 300 m to

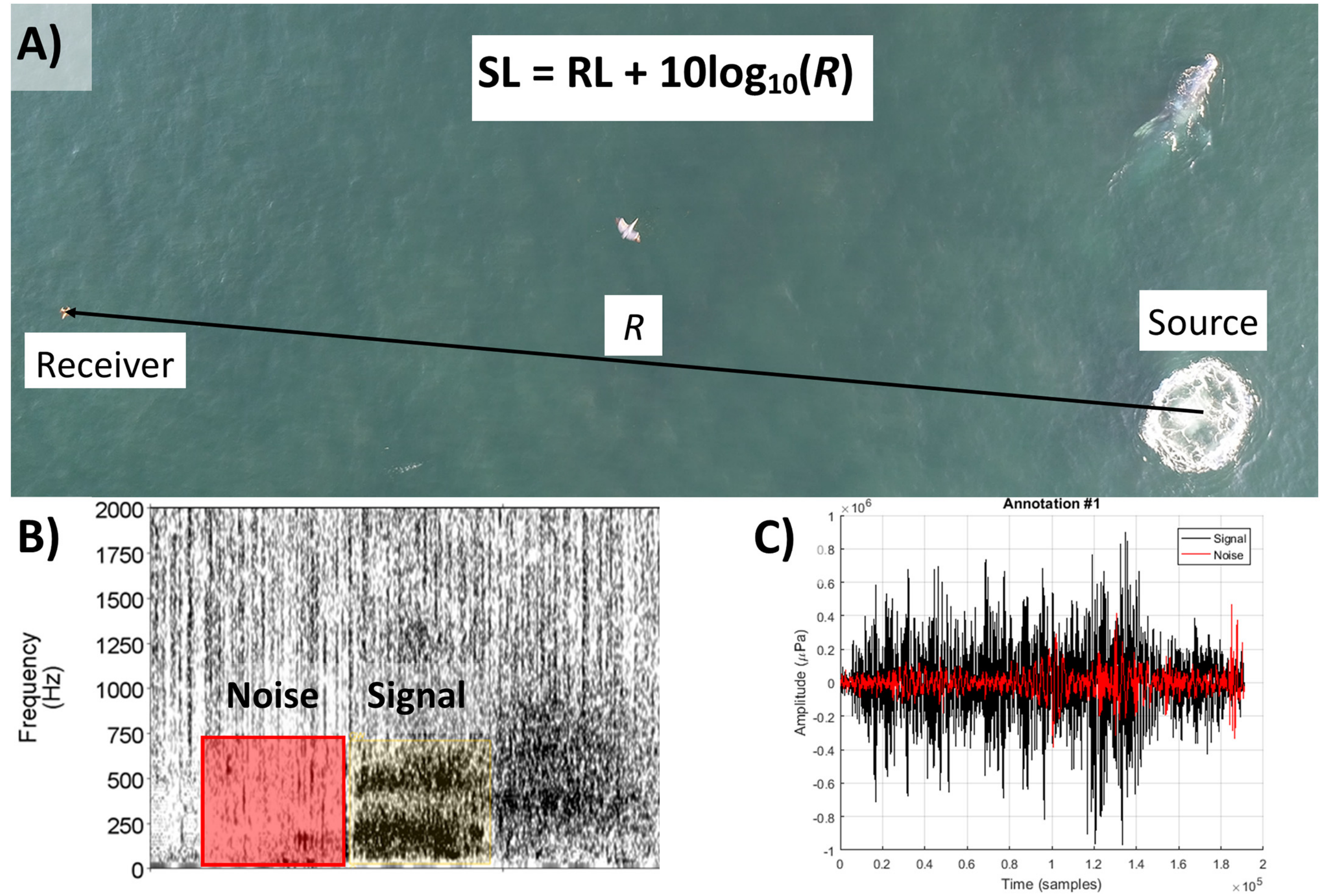

Fig. 3. Illustration of source level calculation method for a S5 (bubble blast) signal. A) illustration of distance (R) between receiver (drone) and source (whale) used in the source level (SL) eq. B) definition of noise sample (in red) and signal bounding box (active component of the S5 signal, in yellow). C) Oscillograms of the signal (black) and the noise (red) used for "denoised" received level (RL) calculation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

provide a clear line of sight to the UAV and to facilitate landing near the whales. The SplashDrone had a payload capacity of 1 kg, and its flight duration was typically less than 20 min. The SplashDrone does not log GPS position, but when the acoustic drone was in of the center of the visual drone's frame, GPS coordinates could be extracted from the visual drone's flight log.

Whenever a group of animals was sighted less than 300 m from shore, the observation drone was deployed to locate the precise position of the group, and then the acoustic drone was launched and directed by the observation drone to within 50 m of the animals. The acoustic drone would then land on the water surface, switch off its motors (in order to keep the system's self-noise to a minimum), and drift with the tethered hydrophone suspended at about 2 m depth, while the observation drone simultaneously recorded video footage of the surface behaviour of the animal(s), as well as their distance (determined post-flights as explained further) from the acoustic drone.

Flights were undertaken on 5 different days between 27 February and 17 March 2019 (Fig. 1). Flights only occurred when weather conditions were favorable (wind speeds less than 5 knots), and a boat ("panga") was available for potential recovery of downed drones. As discussed further below, technical issues with the acoustic drone limited the total number of flights for the season.

Additional SoundTraps (model 300STD) were deployed on the ocean floor around the study area at known positions. As discussed below, one of these instruments was used to determine the best-fit propagation law over short ranges in this shallow-water environment.

2.2. Video and audio synchronization

For each simultaneous video and audio recording, post-processing time synchronization was accomplished using video editing software (Shotcut). The synchronization was performed two ways: first, if the acoustic drone was seen landing or launching in the video, the associated time on the audio where the hydrophone "splashed" in or out was easily identified; second, if the acoustic drone could not be seen in the video footage, visually-and-acoustically recorded whale surface blows were used as timestamps. We estimate that the audio and video data could be synchronized to within a half a second, precise enough for behavioural and source level analysis.

2.3. Acoustic data analysis

All gray whale sounds recorded by the drone-deployed Soundtrap were examined both aurally and visually using a custom software program, PAMlab (JASCO), for viewing spectrograms and annotating sounds. Gray whale sounds were classified following Dahlheim et al. (1984), Ollervides (2001), Wisdom et al. (2001), Charles (2011), and López-Urbán et al. (2016). Other acoustically active species, such as bottlenose dolphins (*Tursiops truncatus*), fish (i.e groupers, sea bass and croakers – D'spain and Batchelor, 2006), and invertebrates (snapping shrimp, Everest et al., 1948) were also present in the lagoon. Gray whale sounds share acoustic bandwidth with some of these other biological sources, but their temporal and spectral features are sufficiently distinct that misclassification was unlikely.

The acoustic time series was converted into units of acoustic pressure, and in-band received levels (RL) were computed using the calibration data provided for the SoundTrap, after band-pass filtering the signal to remove noise outside the call bandwidth. A power estimate of the background noise was obtained by measuring the received level before or after the call occurred, using the same bandwidth and duration as the call. This noise power was subtracted from the call power to estimate the received level on the drone (RL_1) due to the call only. In most cases the signal-to-noise ratio (SNR) of the calls were so high that the impact of subtracting the noise contribution was nearly negligible.

S5 signals (subsurface bubble blasts or bubble bursts; Dahlheim, 1987) identified in the drone acoustic record were used to locate the same signals in the bottom-mounted hydrophones, where the received levels RL_2 were obtained in identical fashion.

2.4. Source level calculation

The source level of a sound is a key acoustic parameter, in that it permits one to determine ecologically important parameters such as detection range and communication space (Clark et al., 2009). While gray whales make a variety of sounds, only the croak sound, S5 (bubble blast) and surface exhalations were analyzed for source level estimations, because they could be quickly and unambiguously associated with animals visible in the video. The S5 and surface blows were readily identified on camera, and the croak sound was generated just before a S5 signal by the mother in a mother-calf pair. Fig. 3 illustrates the method used for estimating source levels (SL) from the received level measurements from the acoustic drone. The source level estimate can be obtained from the simplest version of the sonar equation, expressed here in terms of dB re 1 uPa (rms) units, also known as "sound pressure level" or SPL.

$$SL = RL + TL\,(R, \gamma) \tag{1}$$

The broadband received level was calculated as discussed above. The transmission loss (TL) represents the attenuation of sound as it propagates from the source to the hydrophone, and is shown here as an explicit function of the distance R between the hydrophone and a calling whale; other parameters that influence TL are collectively represented by the symbol γ. Such parameters for a detailed propagation model include acoustic frequency, source and receiver depth, ocean bathymetry, waterborne sound speed profile, sediment compressional and shear speeds and gradients, and sediment density and attenuation. However, in many cases a simple one-parameter "power-law" propagation model, $TL = A\log_{10}(R)$, accurately captures the main range-dependent effects of the transmission loss. R represents the horizontal separation between the source and receiver in meters, and A is a coefficient that characterizes the propagation environment. In a "spherical spreading" case, where a source is radiating into free space, $A = 20$, whereas a source radiating into a waveguide with perfectly reflecting and lossless boundaries experiences $A = 10$. Most realistic ocean environments display values for A that lie between these two values.

To determine whether a power-law model could be used for the study environment, the acoustic normal mode propagation code KRAKEN (Porter, 1991) was used to model the transmission loss for sounds generated between 100 and 500 Hz in a representative environment. The detailed simulation used a homogenous water sound speed of 1500 m/s, a bottom compressional speed of 1700 m/s, bottom density of 1500 kg/m^3, and an attenuation of 0.15 dB per acoustic wavelength. These bottom parameters are representative of a sandy/silty bottom. A receiver was modeled at 1 m depth and whale sounds were simulated at 2, 5, and up to 9.5 m depth in 5–10 m deep water, which are the typical water depths of the study location. Simple regressions of these simulations against range found that TL could be represented by propagation laws ranging from $10\log_{10}(R)$ to $16\log_{10}(R)$, depending on the exact sediment composition.

Photogrammetric methods (Christiansen et al., 2016a) were used to extract the distance R_1 (in pixels) between the source (whale) and the receiver (acoustic drone) from close-up videos of the whale(s) using a custom-written script in R (R Core Team, 2019). The relative distance (in pixels) was converted into absolute horizontal distances (R, in m), using the size of the drone as a scale reference. The GPS location of the visual drone, when centered over the whale, was combined with the known positions of fixed underwater recorders to yield a range R_2 to the closest bottom recorder.

To get more precise bounds on the transmission loss model, we used the received levels of the same sound detected on the drone and the bottom recorders. When two received levels (RL_1 and RL_2) are measured simultaneously at two different ranges R_1 and R_2, the propagation parameter A can be derived using the formula:

$$A = (RL_1 - RL_2)/\log_{10}(R_2/R_1) \tag{2}$$

if one assumes an azimuthally uniform acoustic source (no directivity). The majority of the sounds discussed below have spectra with dominant frequencies below 500 Hz, so the wavelengths involved are close to the size of the entire whale and the signal can be assumed omnidirectional. When Eq. (2) was applied to our data, we found $A = 10$ to be a consistent fit, so $TL = 10\log_{10}(R)$ was used for all SL estimates presented below.

3. Results

A total of 7 joint visual and underwater recording flights were conducted over 5 days. From the resulting 92 min of underwater acoustic recordings, 38 min overlapped the aerial visual observations.

3.1. Vocal repertoire detected by drone deployment

Gray whales were soniferous during each recording period. Fig. 4 illustrates some of the recorded calls identified as produced by gray whales following description by Cummings et al. (1968), Dahlheim et al. (1984), Ollervides (2001), Wisdom et al. (2001), Charles (2011), and López-Urbán et al. (2016). We also recorded several other types of sounds, including grunts, belch-like sounds and some unclassified sounds. Our 90-min dataset managed to capture most gray whale call types documented in the literature over the past three decades.

3.2. Source level estimates

Source level measurements were made for four S5 (bubble blast), one croak sound, and nine surface blows (which could be detected underwater). From Eq. (2) the propagation law parameter A was computed from the four S5 sounds and shown in Table 1. All were relatively consistent with a value of A near 10 (nearly lossless propagation), so this value of A was used for the final source level estimate column. If A is set to 12 for S5 samples 3 and 4, the estimated source levels increase by 3 dB (123 and 121 dB re 1 μPa @ 1 m).

The broadband source levels of S5 ($n = 4$) ranged from 119 to 126 dB re 1 μPa @ 1 m (Table 1). The 126 dB re 1 μPa @ 1 m croak source level was similar to the S5 values (Table 1). The broadband source levels of surface exhalations, or "blows" ($n = 9$) were much quieter than the underwater air releases, and varied from 111 to 117 dB re 1 μPa @ 1 m (Table 1). Despite these relatively low source levels, surface blows were detectable up to 57 m from a whale under calm (Beaufort 1) conditions (distance measured directly from the video). Mean background noise levels were measured to be 96 dB re 1 μPa @ 1 m (± 2 dB, 0.01 to 1 kHz).

3.3. Acoustic behaviour – Mother-Calf interaction

During our study mother-calf pairs were observed to be engaged in

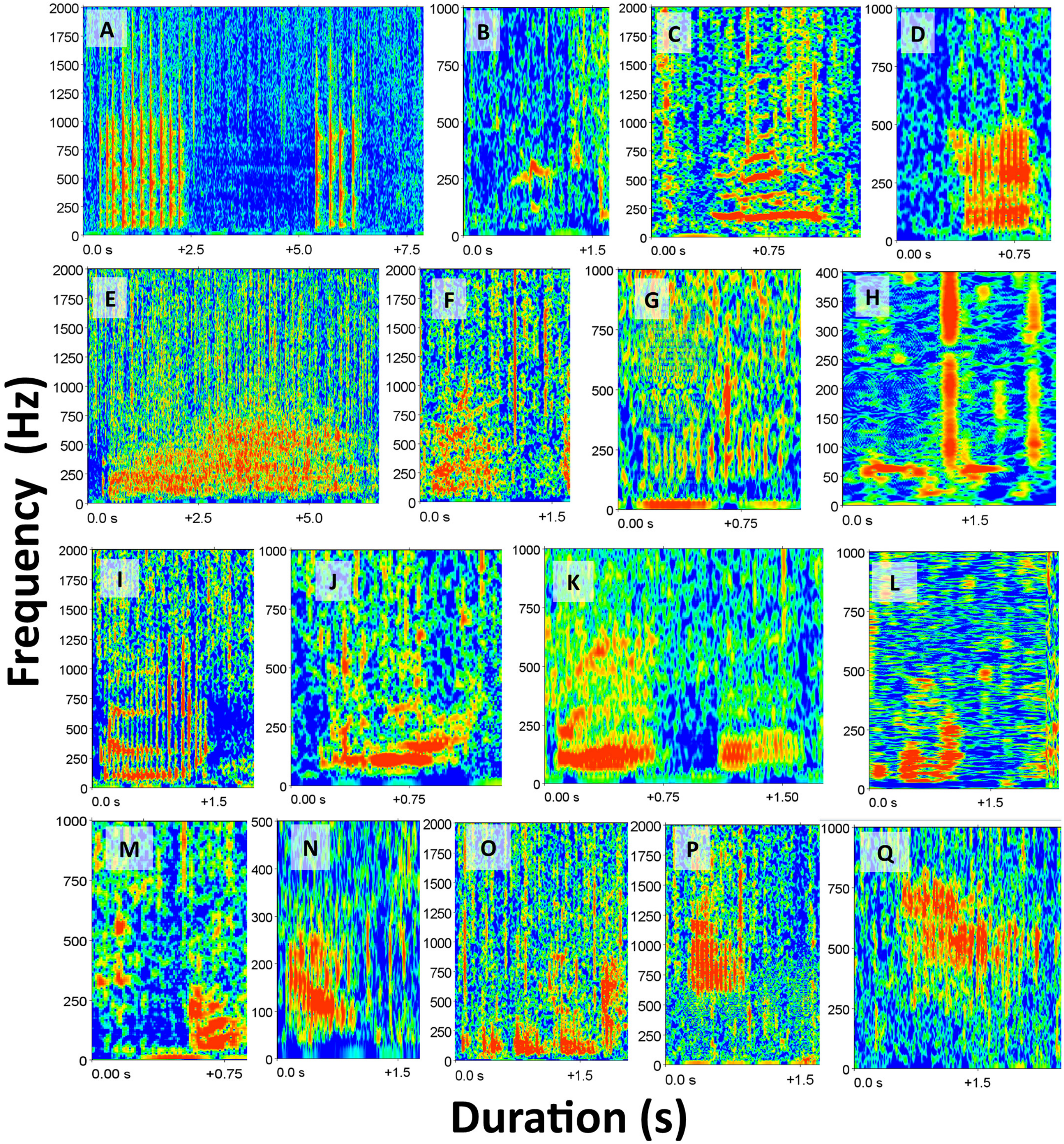

Fig. 4. Example of sounds attributed to gray whales and recorded with the acoustic drone. A (S1, Dahlheim et al., 1984; 1B, Wisdom et al., 2001), B (S2, Dahlheim et al., 1984), C (S3, Dahlheim et al., 1984), D (S4, Dahlheim et al., 1984), E (S5, underwater bubble cloud, Dahlheim et al., 1984), F (Underwater blow sounds from surface exhalations, Cummings et al., 1968), G (S8, López-Urbán et al., 2016), H (S9, López-Urbán et al., 2016), I (croak, Wisdom et al., 2001), J (BMC02, Ollervides, 2001), K (BMC07, Ollervides, 2001), L (Belch-like sound), M (grunt), N – Q: possible unclassified gray whale sounds. Spectrogram parameters: A – F, I, J, M – Q: Frequency step 2.93 Hz, Frame length 0.05 s, Time step 0.01 s, Hamming Window; G: Frequency step 5.86 Hz, Frame length 0.04 s, Time step 0.002 s, Hamming Window; H & L: Frequency step 1.46 Hz, Frame length 0.255 s, Time step 0.0128 s, Hamming Window; K: Frequency step 5.86 Hz, Frame length 0.05 s, Time step 0.01 s, Hamming Window).

different behavioural states: mainly *social* (cf. Supplemental Material video SV1, SV3 and SV4) and *resting* (cf. video SV2). Broad behaviour state(s) was assigned using the definitions from Torres et al. (2018). *Social* was defined as interactions between the mother and calf. *Resting* was categorized when the individuals remained in the same location, lying at or just below the surface, with minimal to no active fluking actions to promote movement. For each behavioural event, the associated acoustic detections were different. During a social behaviour

Table 1
Underwater received levels ("raw" and "denoised"), range between the caller and the drone, propagation law computed from the four S5 sounds, and final source level estimate for each bubble blast, croak, and surface blow. All levels are given in terms of root-mean-square intensity (RMS). N/A: Not Applicable.

Sound	"Raw" received level (dB re 1 μPa)	"Denoised" received level (dB re 1 μPa)	Range (m)	Best-fit *A*	Source level estimate (dB re 1 μPa @ 1 m)
Bubble blast (S5) – 1	106.6	106.1	48.7	9.36	123.0
Bubble blast (S5) – 2	108.9	108.5	59	9.15	126.2
Bubble blast (S5)– 3	103.7	103.0	52.7	11.94	120.2
Bubble blast (S5) – 4	100.5	99.1	92.5	11.3	118.8
Croak	109.4	109.0	52.7	N/A	126.2
Surface exhalation - 1	106.2	104.5	5.5	N/A	111.9
Surface exhalation - 2	106.5	105.9	6.9	N/A	114.3
Surface exhalation - 3	110.5	110.2	4.5	N/A	116.7
Surface exhalation - 4	98.1	94.8	57	N/A	112.4
Surface exhalation - 5	110.1	99.9	48.4	N/A	116.8
Surface exhalation - 6	96.4	93.4	52	N/A	110.8
Surface exhalation - 7	98.8	97.2	37.3	N/A	112.9
Surface exhalation - 8	101.0	99.8	23.4	N/A	113.5
Surface exhalation - 9	105.3	104.3	15.7	N/A	116.3

(movie clip SV1), only S1 (click, knock and/or "bongo" sound; Dahlheim, 1987) and S9 (slightly frequency-modulated call; López-Urbán et al., 2016) signals were recorded. During another social behaviour (movie clip SV3), S3 (low frequency-modulated moan; Dahlheim, 1987), S5, S8 (broadband impulsive call; López-Urbán et al., 2016) and croak signals were frequently recorded. Interestingly, one croak signal was produced just before the mother did a bubble blast under the calf. During another social behaviour (movie clip SV4), signals similar to S1 and some grunts were recorded. Finally, during the resting behaviour (movie clip SV2), mainly S8 and belch-like signals were recorded.

4. Discussion and conclusion

UAVs have become a powerful tool for marine mammal scientists to collect information on their study species. Recently, Torres et al. (2018) demonstrated the significant value added of using UAV to gray whale behavioural studies, with UAV data providing longer observations of primary behaviour states in comparison to boat-based data. To our knowledge, the study presented here is the first to successfully demonstrate the potential of using of two consumer-grade drones to record both the visual and acoustic behaviour of marine mammals. This approach provides the opportunity to observe free-ranging whales in their natural environment and collect acoustic data without intrusive or disruptive methods. The data collected using our approach can inform about acoustic behaviour of baleen whales and their sound parameters and it can be further used for other marine mammal species in shallow clear water.

Not all gray whale signals recorded with the acoustic drone fell into obvious or distinct categories. Despite a small sample size, the data recorded using the acoustic drone has shown a rich diversity in the call types, in comparison to data collected in previous years from the traditional bottom deployments (Dahlheim, 1987; Ponce et al., 2012). We speculate that many of the drone-recorded sounds are fairly quiet and/or with low frequency components which have poor propagation characteristics in the 15 m or shallower water depths of the lagoon. Most of the drone-recorded sounds were not recorded by the bottom mounted Soundtrap. Those sounds were probably picked up by the acoustic drone because of its close proximity to the whale(s).

Due to our small sample size, care must be taken when interpreting our results. Our observations of mother-calf pairs suggest that there was acoustic communication between the two. To date, no gray whale sound has been described explicitly as a contact call between mother and calf; however, a lower "pulse" and a higher "click" have been described occurring in contexts in which a contact call (or separation call) would be expected (Fish et al., 1974; Norris et al., 1977). S8 and S1 were the predominant calls in mother and calf groups, suggesting these calls could be a mother/calf contact call. S3, S5, S9, and croak signals were also recorded during interactions (tactile actions) between mother and calf (social behaviour). It is uncertain whether the mother or calf produced those sounds (S5 signals and, at least one croak, were produced by the mother). From a bioacoustic tag study, S8 signal was predominantly associated with females (with calves) and S9 signal was predominantly associated with calves (López-Urbán et al., 2016). Additional recordings are clearly needed from mother-calf pairs, to fully explore such contact calls.

In addition to being a novel tool to study acoustic behaviour, the combined acoustic/visual dual-drone approach allowed estimation of the source level of certain calls, which are still poorly known for gray whales. The estimated broadband source levels of S5 ranged from 119 to 126 dB re 1 μPa @ 1 m (rms), which is comparable to bubble type signals previously reported (82 to 125 dB re 0.0002 dyn/cm2 equivalent to 118 to 165 dB re 1 μPa-m, Cummings et al., 1968). The estimated broadband source level of the croak was 126 dB re 1 μPa @ 1 m. Surprisingly, surface exhalations were recorded underwater up to 57 m from the source. The underwater bubble blasts (S5) are estimated to have a detection range of 378 ± 134 m (mean ± std), given background noise levels of 96 ± 2 dB. While a mounted underwater hydrophone was used to derive the transmission loss characteristics of the ocean, future drone source level estimates in this area can now be made without the use of bottom-mounted equipment.

Acoustic masking from anthropogenic noise is a key concern to marine mammals, notably low-frequency specialists such as baleen whales. To better estimate communication masking on marine mammals, we need to know more about the characteristics of communication signals (e.g., source levels), the conditions under which animals actually produce these signals, and how they might vary their communications under different contexts (Clark et al., 2009). At present we can only speculate because we do not know enough of the details about when and how the whales use their calls to communicate relative to the behavioural and ecological contexts, and how reductions in these capabilities (impact on communication space) translate into biological cost (to an individual or a population). The source levels and the ambient noise conditions derived from this study can now be used to model masking effects from tourist traffic and other anthropogenic activities.

The small number of flights arose from several difficulties. First, due to a defective video transmitter, the live video link, providing the UAV operator with direct feed from the SplashDrone camera, was not working, limiting the ability to fly. Second, because one of the antennas is on the bottom of the Splashdrone 3+, when the drone landed on water at long ranges (more than 300 m) from the pilot, the remote signal was blocked by water, leading to loss of communication with the drone (and thus the ability to take off). Due to a combination of issues #1 and issue #2, the maximum distance for operating the drone was limited to approximately 300 m and, thus the opportunities for recording whales were further restricted. Moreover, common issues with drones, which include wind speed, battery life, payload and potential compass issue (if deployed from a large vessel due to the metal of ship superstructures) need to be taken into consideration. Nevertheless, for this study in a small, shallow, protected lagoon, we managed to record nearly every type of gray whale sound and derive underwater source levels from three different vocal and non-vocal signals from a limited dataset. This trial study has thus demonstrated the potential of this approach.

The techniques used here are relatively crude, in that the ability to link a sound with an individual is limited by the need to detect whales at the surface or at shallow depths. How long a surfacing whale is visible for (including when just below the surface) is highly dependent on ocean conditions, particularly water clarity. The trial deployments explored here are best suited for clear, shallow waters.

Associating sounds generated deeper underwater with specific whales that may surface minutes later would require more complex deployments. Future work will examine whether multiple waterproof drones can "swarm" to provide a portable distributed grid of sensors to permit 2-D call localization (Kia et al., 2016), and thus provide more confidence in assigning particular call detections to individual animals and behavioural states, even when the calls are generated at deeper depths and not visible from above.

Despite the limitations of the current trial study, these preliminary results demonstrate how even consumer-grade drones can be effective for recording video and audio in order to study the acoustic behaviour and call parameters of marine mammals, allowing some deduction of the context of their call production and the ranges at which the calls can be detected for various background noise levels. When the context of calling is known, monitoring the presence of mother-calf calls may provide a powerful approach of assessing health of the population (calf presence), evaluating potential anthropogenic noise impacts (e.g, masking) and monitoring the development of calf vocal behaviour. To our knowledge, no studies combining overhead visual observations with underwater acoustic recordings, to describe acoustic behaviour and sound parameters of calls, have been previously published.

Author contributions

HFM, AT, LTH led the conception and design of the work. HFM and LTH acted as pilots for the acoustic drone and the visual drone, respectively. SS and JU provided technical support in Mexico. HFM analyzed and interpreted the data and drafted the manuscript. AT and LTH completed the KRAKEN analysis of transmission loss. All authors have approved the final article.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article (including audio files from Fig. 4 and videos SV1, SV2, SV3 and SV4) can be found online at: https://doi.org/10.1016/j.jembe.2020.151321

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