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Ambient habitat noise and vibration at the Georgia Aquarium

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Abstract: Underwater and in-air noise evaluations were completed in performance pool systems at Georgia Aquarium under normal operating conditions and with performance sound tracks playing. Ambient sound pressure levels at in-pool locations, with corresponding vibration measures from life support system (LSS) pumps, were measured in operating configurations, from shut down to full operation. Results indicate noise levels in the low frequency ranges below 100 Hz were the highest produced by the LSS relative to species hearing thresholds. The LSS had an acoustic impact of about 10 dB at frequencies up to 700 Hz, with a 20 dB re 1 μPa impact above 1000 Hz.

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1. Introduction

The importance of hearing to marine mammals for producing and receiving sound for navigation, for locating food sources, and for communication among pods or clusters is well established (Ketten, 2000; Scheifele *et al.*, 2005). The keeping of marine mammals and fish in captivity presents some difficulties in terms of habitat size and the provision of acoustically suitable facilities. In aquaria, circulating water systems produce the most significant levels of background noise due to pumps and motors. This noise, together with pool architecture, choice of structural material, and bottom type determines the ambient noise level of these captive habitats. Animal welfare considerations for captive habitats include space requirements, water quality, light, ventilation, and ambient temperature, but rarely include acoustic properties of the habitat. To date only limited published research has been undertaken on the acoustics of aquarium habitats (O'Neal, 1998) although efforts are being made to monitor noise in marine environments (NOAA, 2004; Andrew *et al.*, 2002).

To quantify acoustic properties in aquaria in more detail, measurements were conducted at the Georgia Aquarium, one of the largest aquaria in the world, as a part of the construction process for their new Atlantic Bottlenose dolphin (*Tursiops truncatus Montagu*) exhibit. The objectives were to quantify the ambient noise levels in the water from machine vibration and from in-air performance speaker systems and sound tracks, and to examine the relationship between the ambient noise levels from these sources and the hearing thresholds of the dolphins to be kept in the habitat.

The bulk of background noise in aquaria is produced by mechanical systems and is relatively low frequency, consisting primarily of frequencies below 1000 Hz. Although marine mammal species such as dolphins can produce and perceive acoustic signals at frequencies up to 150 kHz, there are few anthropogenic noise sources or events in aquaria at these higher frequencies.

Measurements of the vibration levels of life support machinery were also made, focusing on energy in the infrasonic range of 0–20 Hz (Uchikune and Yoshida, 1997; Uchikune and Shirakawa, 1998). Life support pump machinery, including primary and secondary pump and filter systems, is the greatest contributor to structure-borne ambient noise in aquarium habitats, with intensity directly related to the exhibit's proximity to the machinery room. The life support system (LSS) for the habitat under study included four primary pumps, all of which were monitored for their vibratory characteristics. LSS pumps of this size primarily run at 1180 rpm, with a corresponding frequency coupled into the pool system of 19.7 Hz. Although dolphins and whales that are kept in aquaria cannot hear these frequencies acoustically, there is some indication that they may perceive low frequency vibrotactile signals (Au, 1993). Fully understanding the contributions of LSS to the acoustic environment necessarily includes an analysis across a broad range of vibrotactile and acoustic frequency ranges (Beranek, 1993; Lang 1998; Pierce, 1981).

1.1 Acoustic analysis procedures

We deployed calibrated, synchronized hydrophones at specific positions and depths throughout the underwater environment. Once noise levels were determined for specific areas or quadrants of the exhibit, mean noise levels were calculated for each pool. Specific sound levels at individual frequencies related to the LSS were analyzed in 1/3-octave bands to determine power levels across the range of frequencies recorded. Overall sound levels were calculated (dB re 1 uPa) and these were compared to the dolphin hearing threshold.

2. Methods

2.1 Equipment

The schematic of the dolphinarium is shown in Fig. 1. Sound pressure levels were recorded in each pool area [performance pool (or top oval) and holding pools] using an ST1400ENV data acquisition system, one CR-1 hydrophone (center hydrophones) and two SQ26MT, 24-bit recording systems each with one SQ26-08 hydrophone from Cetacean Research Technology Inc. (Seattle, WA) The hydrophones were calibrated by Sensor Technology and NIST (Gaithersburg, MD) at their facility.

The ST1400ENV acquisition system is a single channel 24 bit/48 kHz recording system with sample rates of 96 kHz and 192 kHz providing time-domain and 1/3 octave analysis, as well as ultrasonic and multi-channel processing. The CR-1 hydrophone has a linear (flat) frequency response range (±3 dB) of 0.0002 to 48 kHz (Cetacean Research Technology, 2012). When used with the Reson (Goleta, CA) preamplifier with 100 MΩ input impedance and a useable frequency range of (+3/−12 dB) (kHz) 0.00005 to 68 kHz (Cetacean Research Technology, 2012). The SQ26-08 hydrophones have a linear frequency range of 0.020 to 50 kHz.

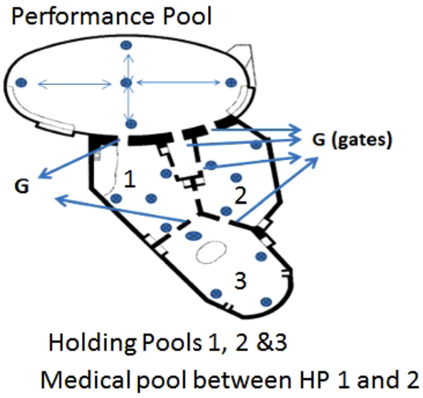

Fig. 1. (Color online) General geometry of the dolphinarium pool system at the Georgia Aquarium. The dots show horizontal hydrophone placements in each pool system and arrows pointing to the (*G*) indicating the position of gates within each interlocking pool system. Vertical measurements were taken as described in the text using these horizontal hydrophone placements. The CR-1 hydrophones were factory calibrated and re-calibrated at NIST prior to the project start.

2.2 Recording geometry

Synchronized recordings were made using an array of three hydrophones placed in three meter longitudinal increments across each pool at 1 m from the surface (air/water interface), at mid-depth and at 1 m from the bottom of the pool. Thirty-two sessions were recorded in total. Performance pool dimensions are 67.05 m long, 32.91 m wide, and 9.75 m deep. Hydrophone placement included two phones at the extremes (next to the pool walls) taken with the instruments at 1 m from the pool wall. Additional CR-1 hydrophone recordings were made in angular corners of all pools and in deep vertex areas of the main pool. In addition, single hydrophone samples were collected at all gates and along the skimmer sections for each exhibit pool. All recordings were 3 min in duration and repeated twice within each LSS or in-air performance sound track and water effects configuration.

2.3 LSS configuration and recording conditions

The entire LSS was initially shut down including all peripheral equipment, support pumps, feeder pumps, and ozone and protein towers (biological skimmers) with the exception of critical auxiliary pumps required to maintain the exhibits safely for animals in the aquarium. A three-minute recording was made in this configuration, forming an "all pumps off" baseline measurement of the pool system's acoustic environment. This procedure was repeated for mid-depth and at 1 m from the bottom of the pool system. During preliminary real-time analysis, the recordings were individually assessed and compared to ensure that an accurate surface baseline was available for later analysis. Next, the first main pump of the LSS was brought online and the measurement protocol was repeated. In addition to the hydrophone array pool measurement, each pump was assessed by taking accelerometer measurements during the recording session (Microstrain, 2011). All these measurements were repeated until all four main pumps were running. Finally all remaining peripheral equipment (support pumps, filters, ozone and protein towers—biological skimmers) were activated and the LSS was configured to its normal operating arrangement, the "all pumps on" condition. On the first day of these measurements, one of the main pumps showed excessive vibration and was subsequently shut down for repairs. An internal mechanical issue was discovered and repaired, and measurement data were collected with the repaired unit.

The same recording procedure was accomplished at all gates for the two habitat, non-performance and medical pool as well. This procedure was repeated in the performance pool with a range of special effects and performance music tracks playing through the in-air audio system. The audio tracks consisted of those targeted for use during future performances, including effects such as rain curtains and water fountains, as well as music and narrative soundtracks. Audio levels were varied from 85 to 100 dBA, corresponding to expected performance levels. Each recording set (surface, mid-depth, and bottom) for each LSS configuration, as well as vibration measurements for each configuration were analyzed separately. The all pumps off condition was compared with the all pumps on condition to determine the total contribution of the LSS to the noise level of the performance pool acoustic environment.

Recordings were generally collected using a sampling rate of 96 k samples per second, allowing for analysis up to a maximum of 48 kHz and averaged 3 min in duration. Both 1/3 octave and high resolution analyses were performed by averaging the frequency spectra of one-second analysis windows spaced across the entire recording length. This approach provides an accurate estimate of the true long-term sound level while allowing for analysis of shorter-term temporal variation in the power spectrum through calculation of the variance in the spectrum across windows. Overall sound levels re 1 μPa were used to compare with hearing thresholds of Atlantic Bottlenose dolphins as taken from Fay (1988), Au (1993), Finneran *et al.* (2008), and Finneran and Schlundt (2010).

Once the overall sound levels were computed, these data were plotted relative to the hearing threshold of the species of interest, so that the aquarium signal intensity relative to hearing thresholds could be easily visualized across frequency in Fig. 2. Individual analyses as well as averages were examined to identify locations in the habitat region that might have greater susceptibility to either vibration-coupled or in-air coupled noise sources.

3. Results

3.1 Auditory results

Figure 2 also displays average all pumps off and all pumps on sound pressure levels across frequency ranges from the third octave filterbank analysis.

Relative to the dolphin hearing threshold these particular data show intensity levels that are above the hearing threshold in the frequencies above 1000 Hz; however, this is likely to be a result of the overall effects of the intense low frequency levels recorded below 1000 Hz per Richardson *et al.* (1995) and refined by Finneran and Schlundt (2010). With regard to hearing threshold at 20 kHz, Finneran and Schlundt (2010) have recently shown that the actual threshold level is probably higher at 10 kHz as previously reported and grows at a faster rate based on 3 kHz and 20 kHz exposures. However, specific thresholds have not been determined with certainty. Nevertheless, we were conscious of the likelihood of increased vulnerability to lower noise levels. Comparison between the all pumps off and all pumps on curves indicate that the LSS system primarily impacts frequencies below 1000 Hz, with the LSS all pumps on configuration increasing ambient sound level by about 10 dB up to 700 Hz. Ambient levels above the 1000 Hz range were roughly the same in the all on and all off conditions and were above the frequency range of best hearing for dolphins most likely due to the contribution of the lower frequencies based on the 1/3-octave power analysis shown in Fig. 3. Even with all pumps on, the peak acoustic level in the 0–200 Hz range due to pump vibration coupling is only slightly likely above the species hearing threshold.

3.2 Impact of in-air theatrical effects on in-water environment

Ambient conditions produced by in-air special effects and performance sound tracks were also investigated. The special effects consisted of wind machine, rain curtain, water cannons, and fountains and were all intermittent or transient surface events. There was no measureable impact underwater due to these special effects.

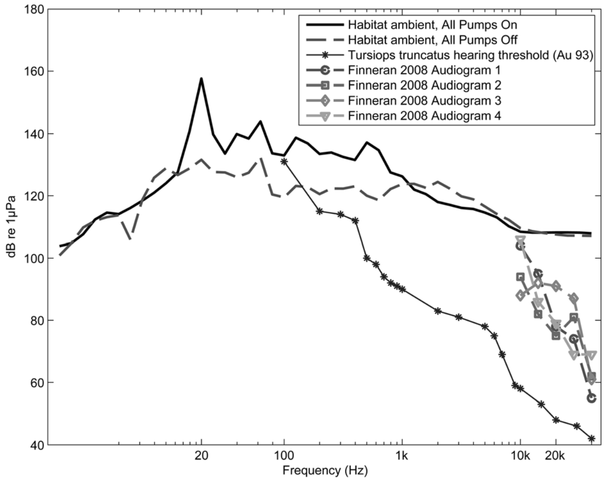

Fig. 2. Third-octave range sound pressure level for the all LSS pumps on and all LSS pumps off conditions. In order to compare directly against established hearing thresholds, ambient noise levels are calculated in dB re 1 uPa rather than the conventional units of dB re $1\mu\text{Pa}/\sqrt{\text{Hz}}$. Superimposed reference comparisons include Atlantic Bottlenose (*Tursiops truncatus*) hearing thresholds per Au (1993) along with audiograms from the four individuals in Finneran *et al.* (2008).

The underwater translational effects of the performance sound track were then measured at 85, 90, 95, and 100 dBA in-air levels in the theater. These measurements indicated that the levels of narration or music playing in the theater did not elevate the underwater noise level beyond what the LSS already contributed, regardless of sound-track volume level. It should be noted that care should still be taken not to locate public address speakers (those used for the demonstrations and shows in aquaria) over the water, since the coupling of sound pressure is significant in the vertical plane.

Analysis of the individual recording positions for these same ranges of LSS and in-air noise conditions indicated that although there was some spatial variation in ambient levels. As can be seen from Fig. 2, there are two primary frequency ranges of concern, the 0 to 200 Hz range where coupled LSS vibrational noise is significant, and the range from 600 to 1000 Hz, which is at the low frequency end of the Atlantic Bottlenose dolphin hearing range. In this frequency range there were still some remnants of LSS influenced ambient noise existing above the hearing threshold, but impact was very low. In the most sensitive part of the species hearing range near 15 000 Hz the ambient noise levels were minimally perceptible but with no discernible impact due to LSS operating conditions in the habitat.

All four main pumps were monitored for their vibratory behavior. In addition, there were four small auxiliary pumps which produced comparatively low levels of vibration. Acceleration was measured at the primary paths through which vibration can potentially couple into the habitat, including structural elements such as the floor at the pumps, at the frame, and at the pump inlet/outlet pipes. Acceleration levels in the all pumps on condition directly related to the peak acoustic levels in the 0–200 Hz range. The fundamental 19.7 Hz vibration frequency coupling and associated harmonics could be identified in the high resolution acoustic spectra; however, the net sound pressure levels due to this pump vibration coupling resulted in an increase of only about 10 dB re 1 μPa over the all pumps off condition in the 50–200 Hz range and were only marginally above the species hearing threshold due to the species relatively low sensitivity in the lower frequency range.

One contributing factor to the reduced acoustic coupling is that the main (and auxiliary) pumps are mounted on shock absorbing foundations, which were quite efficient in reducing the transmission of vibration energy to the floor and other parts of

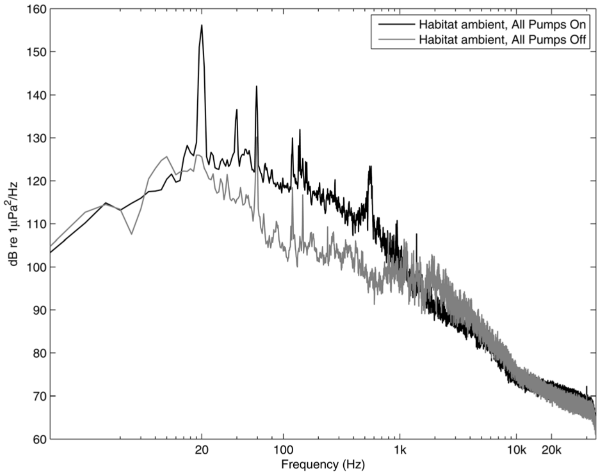

Fig. 3. High resolution habitat ambient spectrum plotted across full analysis range for all LSS pumps on and all LSS pumps Off conditions.

the structure. Measurements of acceleration on the floor near the main pumps confirmed that the shock absorbers were efficient in cutting down the vibration levels in the floor near the pumps.

4. Discussion

The primary results of interest for this particular acoustic mapping are the sound levels relative to the hearing threshold for Atlantic Bottlenose dolphins (*Tursiops truncatus Montagu*). These results indicate that all in-water and in-air overall noise levels were minimally above the hearing thresholds for this species at frequencies up to 1000 Hz, with an impact of about 10 dB due to the LSS system. Above 1000 Hz, ambient levels were above the hearing thresholds but not impacted directly by the LSS operation conditions, with levels not dissimilar to ambient ocean levels at those frequencies (Au, 1993). These noise levels at frequencies of 10 kHz and above appear to have no effects of significance to the dolphins in the habitat based on post-project observations. That is, no behavioral or husbandry symptoms were shown. With respect to 19.7 Hz and harmonic machinery related noise, the levels just reached the dolphin hearing thresholds at 20 Hz, but did not exceed likely threshold elsewhere in the infrasonic range. It is likely that the decreases in sensitivity with lowering frequencies continues on the same trajectory as the slope of the hearing threshold curve from 0.1 to 20 kHz, but this has not actually been measured. Noise spectrum levels at low frequencies appear to be high even when the main pumps for this exhibit are not on. We attribute this to the fact that although the primary components of the LSS for this exhibit were shut down, there were still some auxiliary pumps that were required to remain on during testing. It was necessary to keep these pumps on in order to maintain enough air flow to this and other adjacent exhibits for animal welfare. In addition, the LSS for adjacent exhibits were fully running. The noise from these adjacent systems as well as the auxiliary pumps appears to be masked by closer pump noise when the dolphinarium pumps are on.

In-air special effects had minimal coupling to underwater sound levels for performance sound tracks. Sound levels were well below the target for all tested volume levels in the theater. Overall, the impact of air-borne to water sound coupling appears primarily as a surface effect and was insignificant with respect to potential auditory concerns for animals in this habitat. This conclusion is based not only on the low sound levels measured below the water in the performance pool but also on the intermittency and short duration of the surface water and sound track effects.

As previously reported, the highest amplitude acoustic signal measured in the performance pool was at the fundamental vibrational frequency of 19.7 Hz. High resolution power spectra at 20 Hz showed sound pressure levels peaking at 156 dB re 1 μPa^2/Hz. Overall sound levels were also calculated using a high pass filter at 1000 Hz, giving a resulting overall level of 130 dB re 1 μPa. Although the low frequency impact is not large with respect to the dolphin hearing range it is possible that a vibrotactile effect exists. The consistency and magnitude of the coupling, both in the current study location and in other similar installations, suggests that these effects should be studied further. Overall, the acoustic and vibration measures indicated minimal impact of the aquarium LSS on ambient habitat levels.

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