Assessment of Acoustic Exposures on Marine Mammals in Conjunction with *USS Shoup* Active Sonar Transmissions in the Eastern Strait of Juan de Fuca and Haro Strait, Washington ~ 5 May 2003 ~

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I. Introduction

On 5 May 2003 the *USS SHOUP* (DDG 86) participated in an active sonar training exercise in the eastern Strait of Juan de Fuca and Haro Strait in Washington State. This paper provides an assessment of the potential effects of transmitted sonar on the hearing and behavior of marine mammals known to be in the area, based on the estimated received noise at the animal's location. The National Marine Fisheries Service (NOAA Fisheries) received reports of similar military exercises during the winter of 2002 and spring 2003 in the inland waters of Washington. No information on the nature of those exercises, the source sound levels or vessel movements are available and this analysis is therefore restricted to the events of 5 May 2003.

II. Active Sonar Transmissions

The *USS SHOUP* is equipped with the AN/SQS-53C (V) 4 tactical mid-frequency sonar and Kingfisher mine avoidance system. This system is an array of multiple sound sources (transducer elements) mounted on the hull of the vessel that actively projects sonar signals into the environment. Reflected sonar signals are received by other transducers and processed in order to detect various submerged objects. The *USS SHOUP*'s active sonar system projects signals in three back-to-back 200-Hz constant bandwidths centered at 2.9 kHz (full frequency band: 2.6 to 3.3 kHz) at a source level of 235 dB_{RMS} re: 1µPa. These operational characteristics are within the nominal reported output parameters for 53C tactical sonar systems. The *USS SHOUP* projected signals in this frequency band in discrete directional sweeps across the array of projecting transducer elements. Each transmission includes a 1-s transmission to the port side of the vessel, followed by a 1-s transmission to the starboard, and then a 0.3-s omnidirectional signal (5 dB below 1-s transmissions). Thus, the total duration of each transmission is 2.3 s, but the extent to which direct path transmissions are received during this period depends on whether receivers are behind, in front of, or to either side of the vessel. (*i.e.*, direct path transmission may be less than or equal to 2.3 s). Relative positions of receivers and the vessel, and their orientation within variable environments, affect sound propagation characteristics, including reverberation levels (sound received by indirect propagation paths) and exposure from direct path transmission. These parameters of received sound fields have been extensively modeled and to some extent validated for a group of killer whales in the area whose position was known (NRL, 2004). They are unknown for other marine animals that may have been exposed, but whose position was not determined during sonar transmissions.

On 5 May 2003, the *USS SHOUP* departed the Naval Station in Everett Washington at 0855 (PST) and began participating in an active sonar training exercise (called a "Swept Channel Exercise") from 1040 to 1052 in Admiralty Inlet between Marrowstone and Whidbey Islands (U.S. Navy (PacFleet), 2004). During this period, and continuing for approximately another half-hour, the *USS SHOUP*'s sonar operated in a short-range mode and did not begin transmitting sonar signals over long distances or durations until long-range mode operations were initiated at 1123 (NRL, 2004). Frequency-modulated sonar signals (between 2.6 and 3.3 kHz) of approximately 235 dB_{RMS} re: 1µPa were emitted approximately once every 28 seconds from 1123 until 1438. While operating in the long-range mode, signals were beamformed and directionally focused to varying degrees azimuthally relative to the hull of the ship. During this period, the vessel transited from Admiralty Inlet on the west side of Whidbey Island, passed west-northwest through the Strait of Juan de Fuca (entering Canadian water at approximately 1220), turned back to the east at 1329 off Vancouver Island, and then traveled northward (approximately along the United States-Canadian border) through Haro Strait between Vancouver Island and San Juan Island.

The position, course, and speed of the vessel over this interval are available in Table 1 of the U.S. Pacific Fleet report (U.S. Navy (PacFleet), 2004). Over the approximately four hours of active sonar usage (including short and long-range transmissions) by the *USS SHOUP* on 5 May 2003 a total of approximately 575 individual sonar signals (estimated based on duration of sonar transmissions and stated duty cycle) were transmitted. As the ship passed through the Strait of Juan de Fuca and Haro Strait projecting active mid-frequency sonar, variations in its position, bearing, sonar operational mode, and the highly variable environmental factors affecting sound propagation and reverberation, combined to result in a large range of received sound characteristics at specific positions in the area.

Personal accounts from divers, including a video with audio recordings given to NOAA Fisheries (Martin, pers com, 2003), indicate that sonar signals were audible underwater on the date and time of the *USS SHOUP*'s sonar transmissions. Additionally, there were reports of sonar signals detected through the hulls of vessels in the area (Bain, 2003) and by people on shore (in air). A statement provided to NOAA Fisheries (Osborne, 2003), indicated that aerial sounds presumably resulting from sonar transmissions were audible at estimated received levels of 40-80 dB_{RMS} re: 20μPa. These underwater and aerial observations from humans in the area indicate that mid-frequency sonar signals were detectable over background ambient noise at various locations on 5 May. However, these observations are subjective and are not accompanied with calibrated measurements of received sound characteristics. Calibrated recordings of some of the 5 May *USS SHOUP* sonar transmissions were obtained by Dr. Val Viers of Colorado College, while working on a sound monitoring project for The Whale Museum. Four hydrophones were positioned at approximately 5-19 m depths and located on the eastern (U.S.) side of Haro Strait off San Juan Island. Over 370 individual sonar transmissions recorded on each hydrophone were made available for analysis. The recordings made indicated the presence of significant reverberation (in some cases lasting up to 19 s from the 1-2 s duration transmissions) in addition to sounds received along a direct propagation path. The extensive reverberation, and variation of it across transmissions, is the result of the extremely complex bathymetry in the environment the vessel was moving through. The hydrophones were designed to receive relatively low-level sounds and were unable to respond reliably for received levels above 140 dB_{RMS} re: 1uPa. Various modeling exercises were used to estimate received levels for higher exposures (closest vessel approaches) where the calibrated recordings exceeded the functional dynamic recording range of the recording hydrophones.

The Navy Undersea Warfare Center, Newport estimated received sound levels at various ranges from the *USS SHOUP* at specific points along her track. The U. S. Navy Pacific Fleet conducted a more comprehensive analysis based on acoustic modeling using known transmission characteristics. Scientists at the Naval Research Laboratory (NRL) analyzed these recordings and compared them with sound propagation modeling done to estimate received sound levels at known positions of killer whales (*Orcinus orca*) (J-pod) in the area (discussed below). In all of the modeling exercises, environmental conditions relevant to sound propagation were estimated; *in situ* sound speed profile data from 5 May were obtained but not retained by the *USS SHOUP*. The analyses conducted by NRL were the most detailed and the only ones based on empirical measurements of received sound characteristics. For this reason, and the fact that estimates of received levels for J-pod were conducted, these analyses were used in assessing acoustic exposures of sonar on marine mammals during the event. It should be noted that the NRL analyses consistently overestimated (by 1-10 dB) empirical measurements of received levels, where such measurements did not exceed the dynamic range of recorders. Thus, the estimates of received levels by marine mammals relatively close to the vessel based on the NRL models should be considered worst-case estimates.

III. Acoustic Exposure on Marine Mammals

A. Killer whales (J-pod)

A number of local researchers observed the movements and behavior of a pod of Southern Resident killer whales (J-Pod) during the period of time the *USS SHOUP* was projecting mid-frequency sonar on 5 May. Dr. David Bain observed the position, movements and behavioral patterns of J-pod from 1047-1557, a period including all long-range mode transmissions of the *USS SHOUPs'* tactical mid-frequency sonar (Bain, 2003). At the time of initial observation, J-Pod was located on the southwest side of San Juan Island, approximately 47 km from the vessel as it moved through Admiralty Inlet. After reversing their course from southward to northward at 1134, J-pod moved to the northwest along the western side of San Juan Island throughout the morning and mid-day, as the *USS SHOUP* steamed through the Strait of Juan de Fuca and ultimately up Haro Strait. The *USS SHOUP* moved considerably faster up Haro Strait than did J-Pod, which slowed and several times reversed course as the vessel approached from the south. The closest approach of the ship to J-pod (approximately 2.5 km) occurred at approximately 1434, when the animals were located in Haro Strait on the west coast of San Juan Island, approximately 15 km from their location some four hours earlier.

The extremely thorough and detailed initial NRL analyses, presented in part in the U.S. Navy (PacFleet) (2004) report, included both received sound characteristics at the position of the hydrophones (relatively near the position of J-pod during the closest approach of the vessel) and estimated received levels at J-pod for each sonar transmission of the *USS SHOUP*. For received levels above the recording range of the receiving hydrophones, the NRL analysis bound possible direct-path received levels by assuming a 500m wide area and depth regime (0-20 m) within which the animals were exposed and calculated a mean received level within this area (see U.S. Navy (PacFleet), 2004). For this area, which differs for each exposure based on the documented movement patterns of J-pod, a mean predicted sound level (in dB_{RMS} re: 1µPa) was calculated from acoustic modeling to estimate transmission loss. This is the average received level within the specified area for each sonar ping; points of lower and higher estimated received level exist as well. The estimated mean sonar levels received by J-pod killer whales ranged from approximately 121 to 175 dB_{RMS} re: 1µPa. The lower received levels occurred when the vessel was furthest from the animals and/or environmental features affected direct path propagation of sonar pings. The maximum received levels occurred as the vessel approached, and during the time period of closest proximity between the vessel and the animals. The vast majority of sonar pings were likely received by J-pod at levels below 160 dB_{RMS} re: 1µPa. For the point of closest vessel approach (1434), the NRL analysis estimates the mean direct path received level within the specified area to be 169.3 dB_{RMS} re: 1µPa (U.S. Navy (PacFleet), 2004). Within this area, the estimated received levels range from approximately 150 to 180 dB_{RMS} re: 1µPa. The upper value represents the highest possible estimated single exposure of J-pod killer whales at any point during the event.

Following the initial analysis conducted by NRL for the Navy report, NOAA Fisheries requested additional analyses from NRL on the exposures of killer whales using “sound exposure level” (SEL). Quantifying exposure with this metric, the units of which are dB re: 1µPa^2-s), it was possible to incorporate the cumulative effects of multiple exposures as well as duration of each direct path and reverberation exposure. The expanded analysis (NRL, 2004) integrated the modeled exposure conditions across the duration of long-range sonar transmissions to estimate a range of likely received SEL values for J-pod individuals. Variability in the estimated SEL values resulted from the use of several integration procedures (based on exposure duty cycle – provided by NOAA Fisheries), as well as assumptions about the relationship between *in situ* measurements and their relation to modeled mean and maximum received noise estimates. The most probable received SEL values for J-pod were from 169.1 to 187.4 dB re: 1µPa^2-s; worst-case estimates ranged from 177.7 to 195.8 dB re: 1µPa^2-s.

Several scientists with extensive field experience observing and studying killer whales in Washington, reported behavioral reactions of animals to the sonar on 5 May (Bain, 2003; Baird, 2003; Osborne, 2003; Balcomb, 2003). Dr. Bain was on the water observing the animals during the time of the event and noted that the animals displayed "abnormal" behaviors consistent with avoidance. Dr. Osborne reported observing the animals bunched closely together near shore, and Mr. Balcomb videotaped the behavior of the animals near shore. Dr. Baird, after viewing the videotape of J-pod during the event (provided by Mr. Balcomb), similarly concluded that the behavioral patterns exhibited by the killer whales was "not typical for southern resident killer whales." In contrast, the U.S. Navy (PacFleet) (2004) report summarizes behavioral assessments from four marine mammal researchers not on the water with the animals, but with considerable expertise with marine mammals at the Naval Warfare Systems (SPAWAR) laboratory. The Navy report indicated that their scientists interpreted the behaviors recorded on video as "within the species normal range of behaviors of the orca and there were no immediate or general overt behavioral reactions depicted." The present analysis does not attempt to add to these opposing interpretations, but rather provides NOAA Fisheries' assessment of the potential effects of received sonar sounds (described above) on the hearing and behavior of the killer whales based solely on the estimated received noise conditions at the animal's location.

In assessing whether the sonar was audible to the whales and could have negatively affected their hearing, some direct data are available and some extrapolations are required from related species. It is very likely that many, if not most, of the 5 May 2003 sonar transmissions from the *USS SHOUP* were audible to the members of J-pod. This statement is based on the frequency band of the sonar, estimated received levels described above, and empirical measurements of hearing in killer whales (Hall and Johnson, 1972; Bain *et al*., 1993) and other odontocete cetaceans (see Richardson *et al*., 1995). It is also likely that the considerable reverberation of sonar transmissions known to have existed during the event (NRL, 2004) compromised to some extent the ability of animals to determine the location and movement of the vessel. In terms of the sonar sounds interfering with the whales' ability to hear biologically meaningful signals, there are several considerations. These include whether the received noise from the sonar interfered with the ability to simultaneously detect meaningful signals (called auditory masking) and whether the noise exposure resulted in either temporary or permanent changes in hearing sensitivity (called temporary threshold shift (TTS) and permanent threshold shift (PTS)).

During the period of time when each sonar signal was received by whales in J-pod, auditory masking within the fairly narrow frequency band occupied by the sonar signals likely occurred to some degree. Masking of killer whale hearing occurs when noise and biological signals overlap in frequency (Bain and Dahlheim, 1994). The extent of noise interference with signal detection depends on the received levels, frequency and temporal relationships, and directional nature of both the sonar field and any natural, or other, signals to which the animals were listening. The video tape provided by Mr. Balcomb showed several other vessels in the area of J-pod that were certainly generating noise of some level covering a wider band frequency band than the *USS SHOUP*'s sonar. These noises also had the potential to cause some degree of auditory masking, depending on the above considerations. However, based on the calibrated recordings, within the frequency band of the *USS Shoup*'s sonar transmissions (2.6 – 3.3 kHz), the sonar signals were the dominant noise event or much of the duration of sonar transmissions that morning. The long-term biological significance of auditory masking resulting from sonar exposure was likely minimal, considering the relatively brief duration (just over three hours) of exposure.

Measurements of TTS in killer whales are unavailable, but TTS has been investigated in related odontocete cetaceans (bottlenose dolphins and belugas) and received levels estimated for TTS onset (defined as 6 dB of TTS) (Schlundt *et al*., 2000; Finneran *et al*., 2000; 2002; Nachtigall *et al*., 2003). Based on our current knowledge of basic hearing capacities and auditory morphology for a number of odontocete cetaceans, we assume that the fatiguing effects of noise exposure in killer whales are comparable to those documented in related species. Finneran *et al*. (2002) presented all of the available cetacean TTS data comparatively using both sound pressure level (dB_{peak} re: 1µPa) and SEL (dB: re: 1µPa^2-s)). Most of the received (direct path) sonar exposures were 1 s in duration, due to the operational nature of the source and the vessel's position relative to the whales. Based on this exposure pattern, and using Finneran's comparative analyses, received levels at J-pod whales would have likely needed to exceed 192 dB_{RMS} (195 dB_{peak} for non-impulse sounds) re: 1µPa to cause even TTS onset (Schlundt *et al*., 2000). As described above, none of the individual exposures were estimated to exceed 180 dB_{RMS} re: 1µPa. Reverberation levels were much lower than direct path exposure. Therefore, in terms of individual exposures, it appears unlikely that the whales experienced TTS from sonar exposures.

However, the animals received multiple sound exposures of varying levels, the potential cumulative effects of which were considered using the SEL summation procedure described in the NRL (2004) analysis. From the Finneran *et al*. (2002) comparative analyses, it is estimated that sound exposures of approximately 195 dB: re: 1µPa^2-s are needed to cause TTS onset in cetaceans. Research on TTS following multiple exposures is currently being conducted. However, the precise relationship between TTS onset for comparable SEL values from either single or multiple exposures is unknown. The integration procedures provided by NOAA Fisheries for use in the NRL (2004) analysis bounded the anticipated variability by making different assumptions about the recovery of hearing sensitivity between multiple exposures. As indicated, other than for the absolute worst-case estimate of received noise conditions, SEL levels from multiple exposures were below the estimated TTS onset value in water for cetaceans (based on single exposures). Therefore, it is unlikely that the animals experienced TTS from the cumulative effects of multiple exposures.

The onset of PTS in killer whales or any marine mammals is unknown, but from the extensive literature on terrestrial mammals, it occurs at much higher exposure levels than the onset of TTS. Since the animals were unlikely to have experienced TTS from sonar exposures, it is almost certain that no PTS (injury) occurred.

Controlled exposure experiments involving killer whales and tactical mid-frequency sonar sounds have not been conducted. Thus, it is not possible to definitively state, based on empirical evidence, the received sound parameters that would be required to induce a behavioral reaction in this case. Observations of killer whales exposed to other sorts of acoustic stimuli indicate that behavioral patterns in these animals may be affected by the presence of human activity (*e.g.*, Foote *et al*., 2004). Other cetaceans exposed to human sound sources, such as seismic airgun sounds and low frequency sonar signals, have been shown to exhibit avoidance behavior when the animals are exposed to noise levels of 140-160 dB re: 1μPa in some conditions (Malme *et al*., 1983; 1984; 1988; Ljungblad *et al*., 1988; Tyack and Clark, 1998). While the relevance of these observations in quantifying avoidance behavior in killer whales is uncertain, based on the duration and received levels of exposures and known behavioral reactions in other cetaceans, J-pod killer whales experienced exposure levels likely to induce behavioral reaction as a result of the 5 May 2003 sonar transmissions. This conclusion is in accord with eyewitness accounts of behavioral changes and unusual behaviors reported during the event.

B. Harbor porpoise and other marine mammals

The locations of either individuals or groups of other marine mammals including harbor porpoise during the 5 May sonar transmissions were not documented or are unknown. Based on seasonal marine mammal distribution, sighting and stranding data, several species of cetaceans are known to have been, or were almost certainly, present in the eastern Strait of Juan de Fuca on that date. In addition to the aforementioned killer whales, witness accounts during the event documented sightings of a minke whale (*Baleanoptera acutotrostrata*) "porpoising" away from the oncoming ship following the initiation of the sonar exercise. Further, several harbor porpoise (*Phocoena phocoena*) carcasses were found stranded on area beaches before, on and after 5 May, indicating the presence of the species in the Strait of Juan de Fuca. While it is possible to estimate approximate areas of harbor porpoise distribution in the area at that time of year and how the animals may have moved during the event, doing so would be highly speculative.

Based on the NRL analyses (NRL, 2004; U.S. Navy (PacFleet), 2004) it is clear that direct path sonar transmissions and reverberation were highly variable as the *USS SHOUP* moved throughout the event. In the absence of reliable position data for species other than killer whales during the event, a precise reconstruction of received levels from sonar transmissions is not possible. It is also not possible to estimate with confidence whether harbor porpoise in the area experienced behavioral reaction, auditory masking, TTS, or PTS in the manner attempted above for J-pod killer whales. However, the NRL analyses predict that received levels from sonar transmissions of at least 140 dB_{RMS} re: 1µPa intermittently occurred across large areas (most) of the eastern Strait of Juan de Fuca and Haro Strait for multiple hours on 5 May 2003. Marine mammals present in the area during this time would have presumably received exposures of 140 dB_{RMS} re: 1µPa or more, levels known to cause avoidance behaviors in some cetaceans. Harbor porpoise tend to display fairly strong behavioral reactions to some anthropogenic sounds at received levels well below 140 dB_{RMS} re: 1µPa (Kastelein *et al.*, 2000; Olesiuk *et al.*, 2002) and there is a body of direct and anecdotal evidence that this species appears to be relatively sensitive to acoustic exposure in some conditions.

NOAA Fisheries conducted an extensive forensic examination to determine the causes of death for the stranded harbor porpoises found in the area. None of the necropsies indicated the presence of acoustic trauma (Norman et al, 2004 in press) although post mortem decomposition hampered the analysis. Whether behavioral reaction to the 5 May 2003 sonar transmissions was responsible for strandings of harbor porpoise in the area over the following days is unknown.

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