LONG-RANGE EFFECTS OF AIRGUN NOISE ON MARINE MAMMALS: RESPONSES AS A FUNCTION OF RECEIVED SOUND LEVEL AND DISTANCE

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ABSTRACT

Effects of noise from seismic surveys on marine mammals need to be understood so that they can be appropriately mitigated. This study examined effects of large airgun arrays (79-110 l) on a variety of marine mammal species in the waters of British Columbia and Washington at long distances (1 to > 70 km). Received noise levels near marine mammals were measured to overcome difficulties in modeling long-range propagation in complex near-shore waters. Although airguns concentrate energy at low frequencies, noise was detectable to at least 100 kHz, providing a mechanism to affect marine mammals with good high-frequency hearing. Apparent behavioral responses varied by species. Species with similar hearing capabilities exhibited markedly different responses to airgun noise, and a high-frequency specialist, the harbor porpoise, appeared to be the species affected by the lowest level of noise (< 145 db re 1 µPa RMS at a distance > 70 km). The long distances at which behavioral changes were observed indicate that long ramp-up times (>1-5 hours depending on species) are likely to be needed to prevent strong behavioral changes. While infrared imaging and passive acoustic monitoring can complement visual detection, technical constraints limit their usefulness. Scheduling surveys around seasonal distribution of species of concern, limiting periods of exposure, and routing airguns to ensure that marine mammals are not driven ashore may be as important as monitoring safety zones in preventing injuries and death.

INTRODUCTION

In March, 1998, the United States Geological Survey (USGS), in collaboration with a number of other government and academic institutions, conducted seismic surveys in Juan de Fuca Strait, Georgia Strait, Puget Sound, Hood Canal, and other marine waters in British Columbia and Washington to investigate earthquake hazards. The project was named SHIPS (Seismic Hazards Investigations in Puget Sound) and employed an array of airguns with a total capacity of up to 110 l.

Prior to scheduling the survey, USGS consulted with marine biologists to evaluate the biological implications of alternative timings and routes to determine the one likely to result in the least impact. Baseline condition of the habitat was determined in the course of long-term projects in the region. Monitoring during the seismic survey, both from the seismic survey vessel and other platforms to allow monitoring distant (10's of km) from the airgun array, to ensure any unanticipated effects could be addressed immediately, were planned. Post-exposure monitoring to determine whether any effects occurred that were not apparent during the survey itself through continuation of long-term studies and consultation with the regional stranding network was also planned. This process was seen as a model that could be used to modify practices for subsequent studies.

Although seismic tests and other applications of loud low-frequency sound in marine waters have been used for many years, there has been a heightened concern in recent years about the impacts of these sounds on marine mammals. Richardson et al. (1995) reviewed the effects of noise on marine mammals. While noise has been shown to affect the behavior of many species (see also Kraus et al. 1997, Olesiuk et al. 2002), the effects of airguns have been studied only to a limited degree. Non-acoustic mechanisms for direct effects of noise have also been proposed (gas bubble formation due to abnormal diving behavior, stress, stranding).

In addition to direct effects on mammals, seismic noise is known to cause immediate injuries to fish (McCauley *et al.* 2003) that would impair their long-term survival. For fish that rely on acoustic communication, impaired hearing could disrupt the maintenance of territories and mating behavior. Maximum travel speeds for many fish and invertebrate species are far slower than the travel speeds of survey vessels, meaning escape responses will be inadequate to limit impact. This provides a mechanism for indirect effects on marine mammals.

Two vessels, the R.V. Thomas Thompson, which towed the airgun array, and the R.V. John P. Tully, which towed a receiving streamer, were involved in the seismic research and were platforms for the observation of marine mammal behavior. In addition, a smaller vessel served as a platform for some more detailed observations, and allowed measurement of actual received sound levels near marine mammals.

The study area is inhabited by a variety of marine mammal species, including pinnipeds (harbor seals, California sea lions, and northern sea lions), odontocetes (harbor and Dall's porpoises), and mysticetes (gray and minke whales). These different taxa have different auditory sensitivities, and thus were expected to have different sensitivities to low frequency noise (Richardson et al. 1995). The presence of this variety of species therefore presented the opportunity to conduct an unusually comprehensive study of the effects of airgun noise on marine mammals.

The topographic complexity of the inshore waters was expected to reduce the correlation between received level and distance. Therefore, received sound levels and spectra were measured where possible, and this allowed testing the predictive value of a distance-sound level relationship

METHODS

Seismic Survey

Approximately 33,000 airgun blasts were generated from 10 to 24 March 1998. The survey consisted of generating shots with a towed array of 13 or 16 air guns with a total volume of 79 or 110 l, respectively. Maximum theoretical source level for the larger array was calculated to be on the order of 260 dB (re 1 µPa at 1m), and signals could be recorded up to 370 km away. The seismic survey methods are described in detail in Brocher et al. (1999).

The seismic survey vessel that towed the array was a platform for observing marine mammals close to the airgun array. Methods and results of this research component are detailed in Calambokidis *et al.* (1998). Observers used binoculars to assist with observation by day and an AN/KAS-1A chemical weapons detector to observe thermal infrared images at night.

Acoustical Monitoring

Two sampling regimes were used. The first involved measuring ambient noise and received sound levels at selected distances and orientations from the airgun array, and at locations of interest in the study of sound propagation. The second involved measuring ambient noise and sound levels from locations near marine mammals to produce a best possible estimate of actual noise exposure. Due to complicated sound propagation in inshore waters, measurements of the actual sound field near marine mammals were used rather than modeled levels. Measurements were based on two minute recordings to allow both determination of received level and ambient noise. Further, these recordings provided an opportunity to try to detect marine mammals using passive acoustics.

Observations from acoustics vessel

The acoustics vessel was a launch carried aboard the *Tully*. The launch was placed in the water and a sound level measurement was performed. The launch then traveled along a line at approximately 20 km/h until either marine mammals were closely approached, or the launch had traveled 10 km. Then the next acoustic measurement was made. When marine mammals were sighted, behavioral observations were made in as much detail as possible. In many cases, this was minimal. In others, what appeared to be the same individuals were followed for tens of minutes, and multiple sound level measurements were obtained in their vicinity.

Signals were received on a B&K 8105 hydrophone and amplified with a B&K 2635 charge amplifier. The signals were filtered using an SKL 302 variable electronic filter. Signals were digitized using a Tucker-Davis

Technologies AD2 and recorded on a personal computer using a TDT AP1. Blasts were reviewed aurally and in time-frequency amplitude mode to identify the most intense portion. Then a 10.24 msec segment was selected to be Fourier transformed to determine the frequency spectrum, and for calculation of peak-peak and RMS sound levels.

Position of the recording vessel was determined using Differential GPS. Position of the airguns was approximated by the DGPS position of the Thomas Thompson. The distance between these two locations was calculated to determine the distance between the source and the recording vessel. When possible, the recording vessel was positioned near marine mammals, to determine actual noise exposure.

A regression line for received level as a function of distance was calculated. Points which deviated from this line by about 6 dB or more were analyzed for possible propagation anomalies.

RESULTS AND DISCUSSION

Received sound level as a function of distance

Approximately one-third of the sound level measurements deviated by 6 dB or more from values predicted by simple spreading loss models. Values lower than expected could be attributed to shadow zones. Shallow water was sufficient to reduce sound levels, and land formed an effective barrier to direct propagation. Most cases of higher than expected levels might be attributed to upslope enhancement. In addition, long range propagation through Juan de Fuca Strait was better than expected, resulting in the airguns being clearly audible at ranges of 60-70 km, the longest distances at which signal measurement was attempted in the biological component of the study (Figure 1).

The airguns produced energy above ambient levels at all frequencies up to 100 kHz (the highest frequency measured), although the peak frequency was quite low. Low frequencies were filtered out by propagation through shallow water, and high frequencies attenuated faster with distance. Sample spectra are shown in Figure 2.

Marine mammals sighted from the recording vessel

Sighting locations and recording locations for the San Juan Islands and Northern Puget Sound are shown in Figure 3. Sightings in Western Juan de Fuca Strait are shown in Figure 4. Sightings in the Strait of Georgia are shown in Figure 5.

Responses of six species of marine mammals for which received sound levels were measured are summarized in Table 1 and Figure 6. As the study was designed to minimize the number of marine mammals exposed to noise, insufficient numbers of individuals were observed to merit statistical analysis. However, qualitative trends in responses for each species are summarized below. Sound levels are peak-to-peak levels referenced to 1 μPa (RMS levels were measured at 9-14 dB lower).

Harbor Seal *(Phoca vitulina).* Although this species was recorded within the 190 dB contour, it was generally moving away from the airguns at exposure levels above 170 dB. A common behavioral change observed was floating at the surface and visually orienting toward the airguns. Individuals were sometimes observed closer together in the water than is typically observed.

California Sea Lion *(Zalophus californianus).* This species was only recorded within the 180 dB contour. It was moving away from the airguns at the lowest exposure levels.

Steller (Northern) Sea Lion *(Eumetopias jubata).* This species was recorded at levels up to about 170 dB, but was moving away from the airguns at this level. One appeared to be looking for a place to haul out as the airguns passed by, but steep cliffs along the shore precluded this.

Gray Whale *(Eschrichtius robustus).* This species was recorded at levels up to about 170 dB, but did not appear to be disturbed at this level, and although moving away from the airguns, was moving to higher exposure levels (moving into deeper water where sound propagated more efficiently).

Dall's Porpoise *(Phocoenoides dalli).* This species was recorded outside the 181 dB contour. It was moving away from the airguns at the highest exposure levels. This species initially responded by moving away while traveling in the same direction as the seismic survey vessel, but as the airguns got closer (the towing speed exceeded the sustained swimming speed), individuals changed direction to move at right angles to the path of the airguns. Once the airguns passed the porpoises, they turned again and moved in the opposite direction to the seismic survey vessel's path. Travel speed was higher during the orthogonal and reverse movements than during the initial avoidance response.

Harbor Porpoise *(Phocoena phocoena).* This species was recorded at levels up to 155 dB, and was moving away at this level. Apparent avoidance responses were observed over 70 km from the airguns.

General Comments

It needs to be emphasized that this summary is based on a small number of observations (typically about 5 groups of each species were approached closely enough to get sound level measurements), so orientation of movement could be due to chance, and differences between species could actually reflect individual differences or chance correlations rather than responces to noise. We present these data because mitigation protocols, if successful, will result in small samples in each study, and meta-analysis involving several studies is likely to be required to rigorously address the issues.

California sea lions and Dall's porpoises are known for their tolerance of human activities. California sea lions haul out in urban areas, and Dall's porpoises commonly bow ride on power vessels. Although these two species were observed at higher noise levels than the others, they did appear to be responding to the airguns. Steller sea lions and harbor porpoises are generally considered more shy, so it is not surprising that they were only observed at lower sound levels, and appeared to be responding to the airguns at moderate exposure levels. Harbor seals were the most commonly seen species, so it was to be expected that they would show the widest range of exposure levels. While many appeared to be responding to the airguns, some seemed to be at least equally concerned with the acoustic monitoring vessel, and those observed at low exposure levels did not show a detectable response to the airguns.

The gray whale data are ambiguous. Since the gray whales were observed in bays in which moving away from the airguns resulted in higher noise exposure, it is unclear whether their movements reflected a response to noise. Gray whales were expected to be the most sensitive to airgun noise, because they are believed to be the most sensitive to low frequency sound among the species studied. However, gray whales seemed more tolerant of airgun noise than harbor porpoises and northern sea lions. That is, behavioral responses to noise did not correlate well with expectations based on estimated hearing sensitivity to low frequency sound for the species studied.

Implications for management

Proposals have been made to use smaller safety zones for species believed to have poor low frequency hearing. This does not appear to be well founded, as airguns have strong high frequency components, and pairs of species likely to have similar hearing ability (e.g., harbour vs Dall's porpoise; Steller vs California sea lions) showed marked differences in responses to airguns.

The occurrence of strong behavioral changes at long range (> 70 km in harbor porpoises), along with the potential for behaviorally mediated injury or death, suggests that safety zones need to be larger than the size needed to prevent hearing loss, and for some species the safety zone may need to be larger than the range at which they could be seen from seismic survey vessels. Even with a 180 dB safety zone, this could require observing marine mammals on the order of 10 km from the seismic vessel.

The long range at which some species appeared to show avoidance behavior suggests that displacement from habitat and the duration of that displacement need to be considered when considering cumulative effects. Further, habitat can be significantly degraded before marine mammals will leave it for alternate habitat that is poorer in quality. That is, population-level effects could occur in the absence of displacement, and displacement to poorer quality alternate habitat could result in population-level effects in the absence of immediate injury or death.

It takes more than one observer to watch an area around an airgun array. Further, biologically significant effects can occur at distances where affected marine mammals are over the horizon so cannot be seen by observers stationed on the survey vessel. The value of having observers is reduced if airguns are allowed to operate while the safety zone is obscured by weather or darkness.

None of the marine mammals observed visually were detected acoustically, even at close range, indicating that passive acoustic monitoring will be of limited value. Although the hydrophone was only monitored for a few minutes at a time rather than continuously, it was monitored cumulatively for hours over the course of the study when marine mammals were known to be present.

The AN/KAS-1A (a thermal imager that yields a video image) used in this study was capable of detecting marine mammals at long distances. However, the magnification needed for long-range detection limited the field of view to less than 0.5% of the area around the array. Further, many species spend less than 10% of the time at the surface where they might be detected with a thermal imager. This limits the probability that the detector would be pointed in the right direction at the right time. Larger cetaceans (killer whales) were easier to detect with infrared than smaller species (porpoises) due to size, time at the surface, and thermal differences between the skin and blow and the water.

Many species are capable of remaining submerged for over 30 minutes. As a result, even with observation by multiple observers of the safety zone in good conditions, it won't be possible to ensure absence of species of concern. As marine mammal census surveys show, even with the best available technology and ideal sighting conditions, a high proportion of marine mammals can be missed along a vessel's track.

The long range at which strong behavioral changes were observed indicates that common ramp-up procedures are inadequate, since marine mammals cannot sustain swimming speeds adequate to leave the area. The fjord habitat where this study took place restricted movements perpendicular to the array, and prevented individuals from moving as far away as conspecifics in more open water. Arrays can produce complicated sound fields rather than smooth gradients, so moving toward a quieter area may not increase the distance from the source.

Although behavioral changes were observed, the precautions utilized in the SHIPS survey did not result in any detectable marine mammal mortalities during the survey, nor were any reported subsequently by the regional marine mammal stranding network.

ACKNOWLEDGMENTS

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Table 1. Behavior of Marine Mammals as a Function of Received Sound Level.

Date	Time	Species	Group Size	Latitude Deg. (N)	Latitude Minutes	Longitude Deg. (W)	Longitude Minutes	RMS Level	P-P Level	Comment
3/19/1998	1117	Harbor seal	41	48	50.319	123	12.795	121.3	135.5	hauled out
3/13/1998	1421	Harbor seal	1	47	34.954	122	59.511	129.8	142.8	moving west
3/14/1998	1349	Harbor seal	1	48	10.523	122	50.396	131	143.5	
3/21/1998	1711	Harbor seal	2	47	35.563	122	28.569	136	149.5	
3/19/1998	1111	Harbor seal	41	48	50.425	123	12.882	137.3	151.3	hauled out
3/15/1998	751	Harbor seal	1	48	11.529	123	51.543	143.2	155.3	orient > JT
3/21/1998	1659	Harbor seal	1	47	35.652	122	28.623	145	159.3	moving >Blakely Rock
3/18/1998	1717	Harbor seal	1	49	36.289	124	37.406	149.5	162.9	orient
3/17/1998	1027	Harbor seal	1	49	28.428	124	4.616	153.1	165.9	slow trav, orienting > TT
3/21/1998	1624	Harbor seal	1	47	40.852	122	25.169	155.6	166.9	
3/19/1998	1457	Harbor seal	43	48	43.575	122	53.384	156.1	169.1	orient >TT
3/17/1998	1204	Harbor seal	2	49	37.943	124	9.585	157.5	169.3	moving toward TT
3/17/1998	1131	Harbor seal	2	49	37.913	124	10.231	157.8	170.7	move toward shore
3/13/1998	1510	Harbor seal	1	47	38.592	122	53.788	159.5	172.1	mill
3/17/1998	1150	Harbor seal	1	49	38.004	124	9.769	160	172.4	moving away
3/20/1998	1645	Harbor seal	1	48	22.266	124	30.216	163.5	175.4	orient >TT
3/18/1998	1643	Harbor seal	2	49	40.533	124	42.474	177.5	187.4	moving away
3/21/1998	956	Harbor seal	2	48	5.325	122	39.84	183.2	192.7	
3/21/1998	1441	Harbor seal	1	47	49.402	122	28.718	185.8	194.9	
3/19/1998	1726	California sea lion	1	48	32.405	122	44.492	170	181.8	moving North
3/21/1998	1435	California sea lion	1	47	49.328	122	28.688	172.8	182.9	moving away
3/21/1998	1452	California sea lion	1	47	49.222	122	28.741	176.4	186.1	
3/21/1998	956	California sea lion	1	48	5.325	122	39.84	183.2	192.7	
3/19/1998	1117	Northern sea lion	100	48	50.319	123	12.795	121.3	135.5	hauled out
3/14/1998	1349	Northern sea lion	1	48	10.523	122	50.396	131	143.5	
3/19/1998	1111	Northern sea lion	100	48	50.425	123	12.882	137.3	151.3	hauled out
3/22/1998	1707	Northern sea lion	1	48	30.863	123	9.193	155.6	170.2	looking around
3/19/1998	1039	Northern sea lion	3	48	52.336	123	12.538	160.1	171.9	moving away
3/21/1998	1210	Gray whale	1	47	58.645	122	29.634	139.3	154.3	
3/14/1998	1012	Gray whale	1	48	12.647	122	46.407	137.7	155	
3/14/1998	1039	Gray whale	1	48	13.091	122	47.719	160.3	170.3	
3/21/1998	1257	Gray whale	1	47	58.572	122	29.691	163.4	172.5	
3/14/1998	1349	Dall's porpoise	3	48	10.523	122	50.396	131	143.5	
3/22/1998	1649	Dall's porpoise	2	48	32.089	123	12.409	157.4	168.3	
3/22/1998	1340	Dall's porpoise	4	48	19.461	122	57.938	156.6	172.2	
3/22/1998	1311	Dall's porpoise	4	48	18.178	122	55.455	165.4	176.5	
3/22/1998	1445	Dall's porpoise	4	48	23.083	123	1.624	169.5	179.8	slow roll away
3/22/1998	1314	Dall's porpoise	4	48	18.182	122	55.474	171.3	180.8	
3/14/1998	1349	Harbor porpoise	3	48	10.523	122	50.396	131	143.5	
3/15/1998	726	Harbor porpoise	7	48	10.878	123	47.821	142.5	155.2	moving away
3/15/1998	734	Harbor porpoise	7	48	10.839	123	48.018	142	155.2	moving away
3/15/1998	702	Harbor porpoise	1	48	10.907	123	41.887	142.4	155.3	moving away
3/20/1998	758	Unidentified porpoise	3	48	24.331	124	2.868	167.9	177.8	
3/19/1998	1305	Unidentified porpoise	3	48	48.769	122	54.613	165.6	178.4	slow roll >TT

Figure 1.

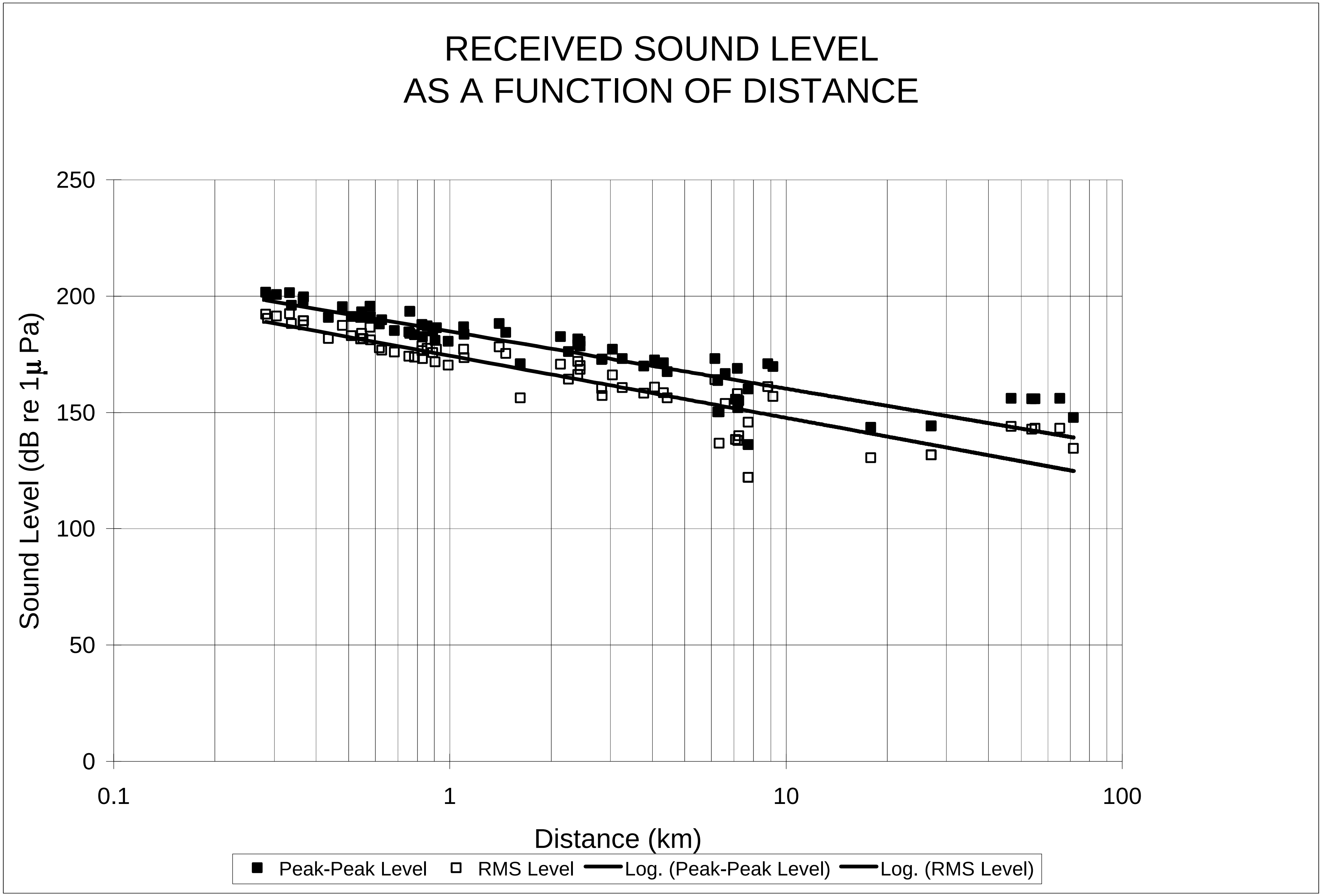
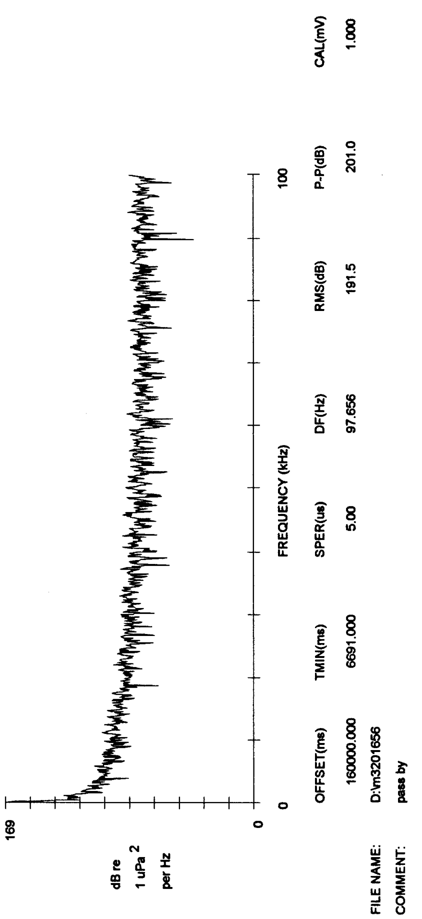

RECEIVED SOUND LEVEL
AS A FUNCTION OF DISTANCE
Sound Level (dB re 1µ Pa)
250
200
150
100
50
0
0.1
1
10
100
Distance (km)
Peak-Peak Level
RMS Level
Log. (Peak-Peak Level)
Log. (RMS Level)

Figure 2.



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0
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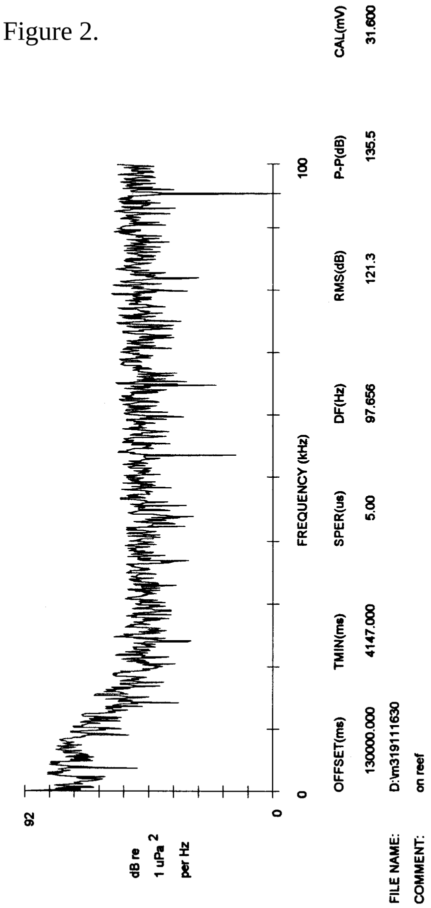

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0
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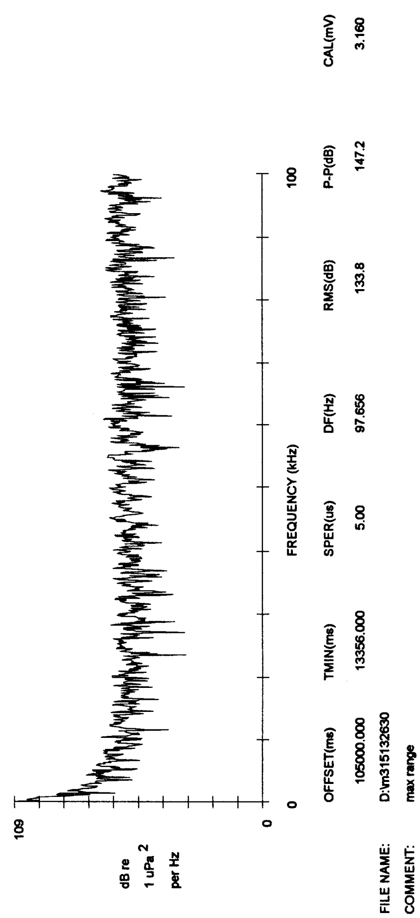

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dB re 1 uPa 2 per Hz
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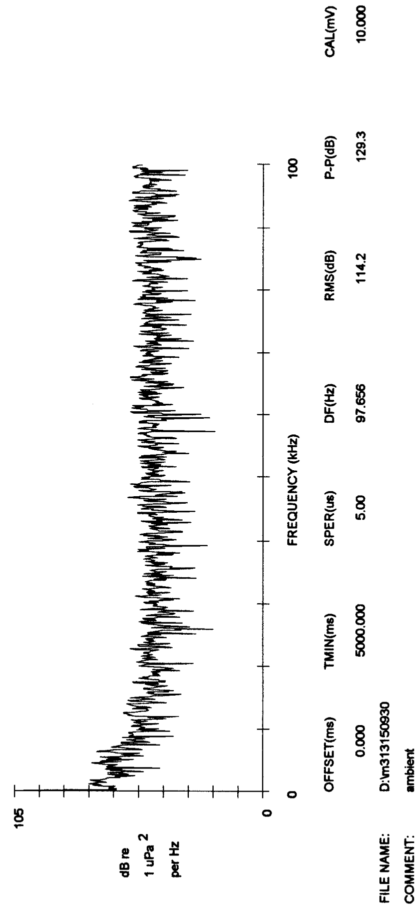

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dB re 1 uPa 2 per Hz
0
0
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100
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RMS(dB) 114.2
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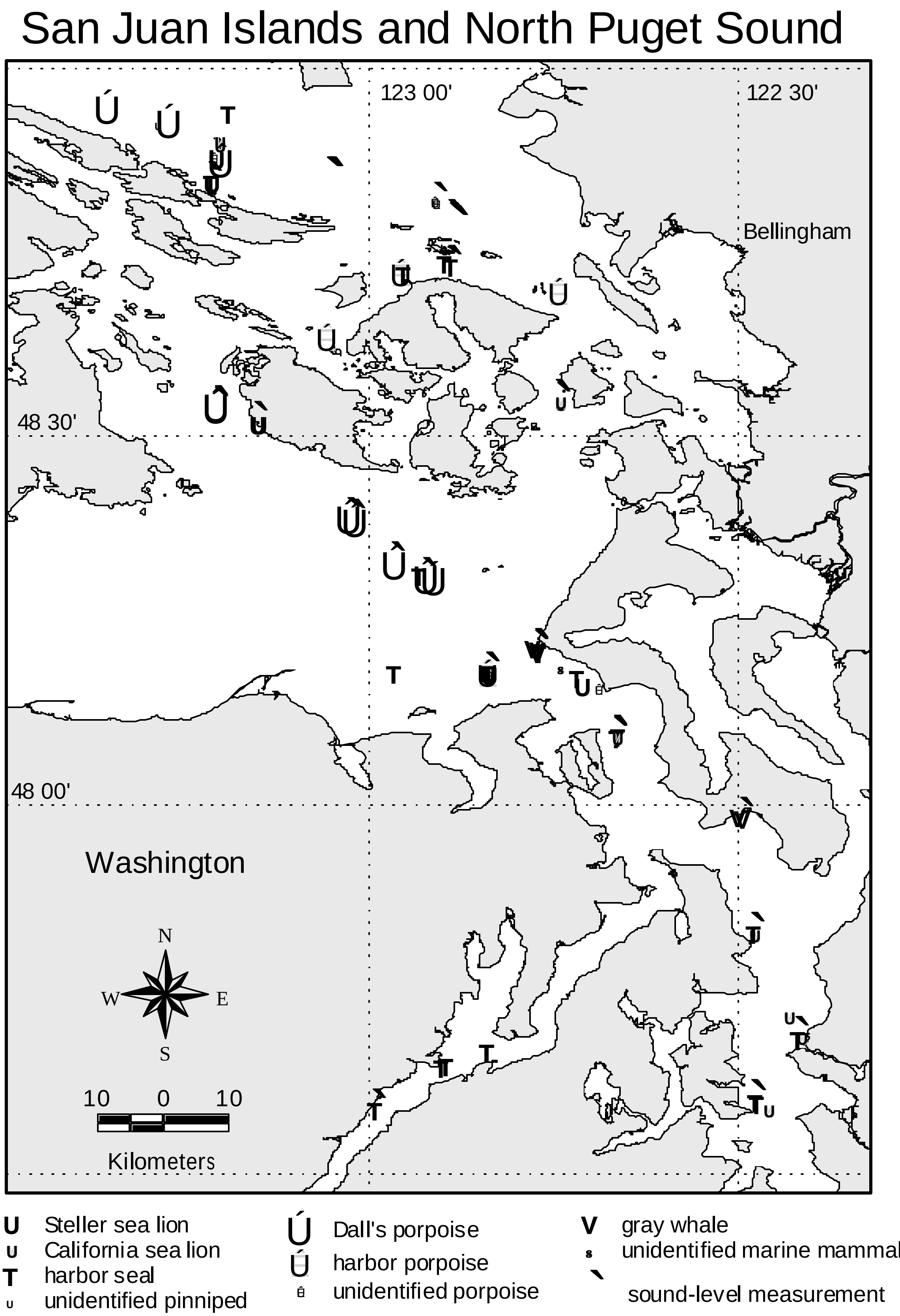


Figure 3. Locations of marine mammal sightings and sound level measurements.

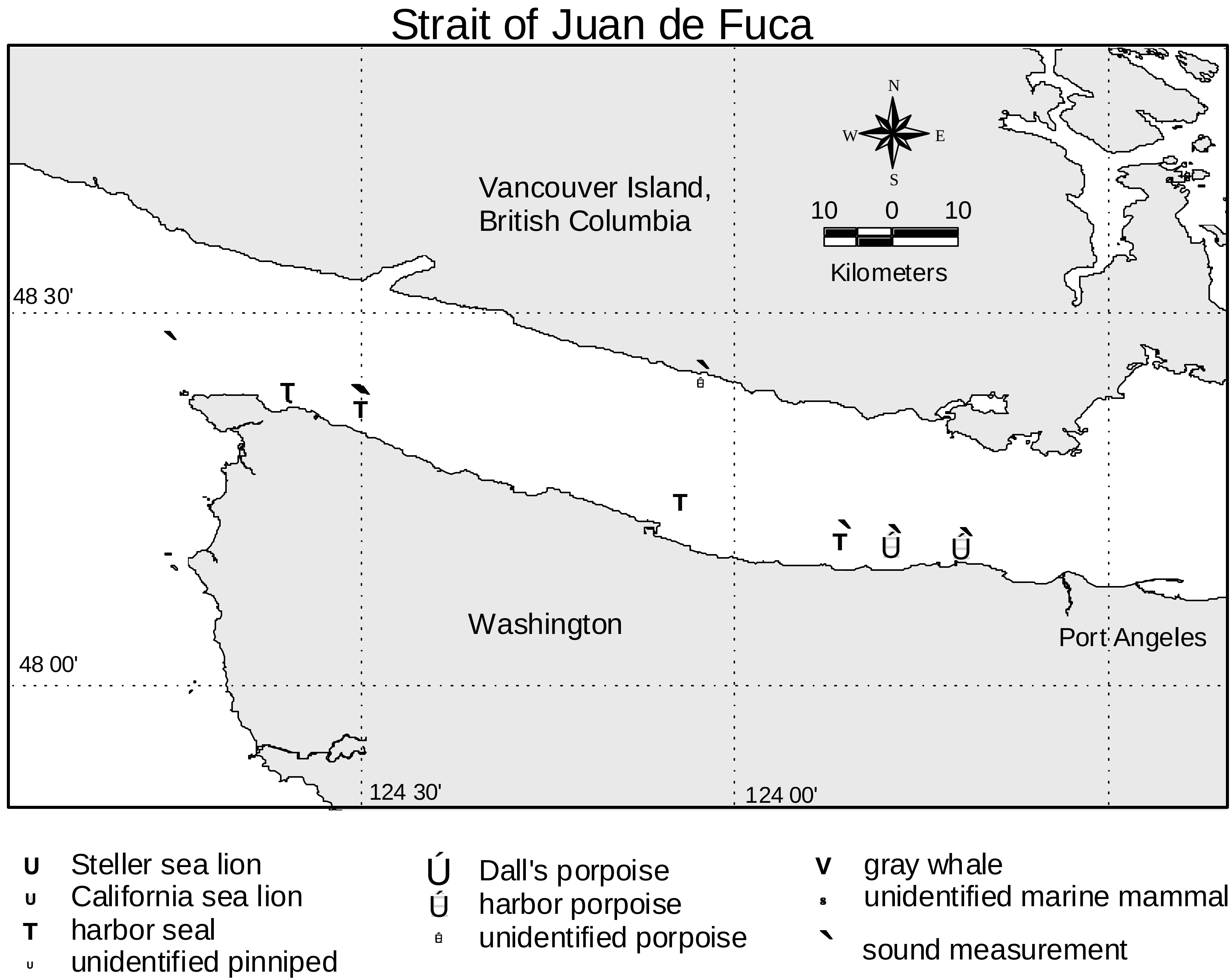


Figure 4. Locations of marine mammal sightings and sound level measurements.

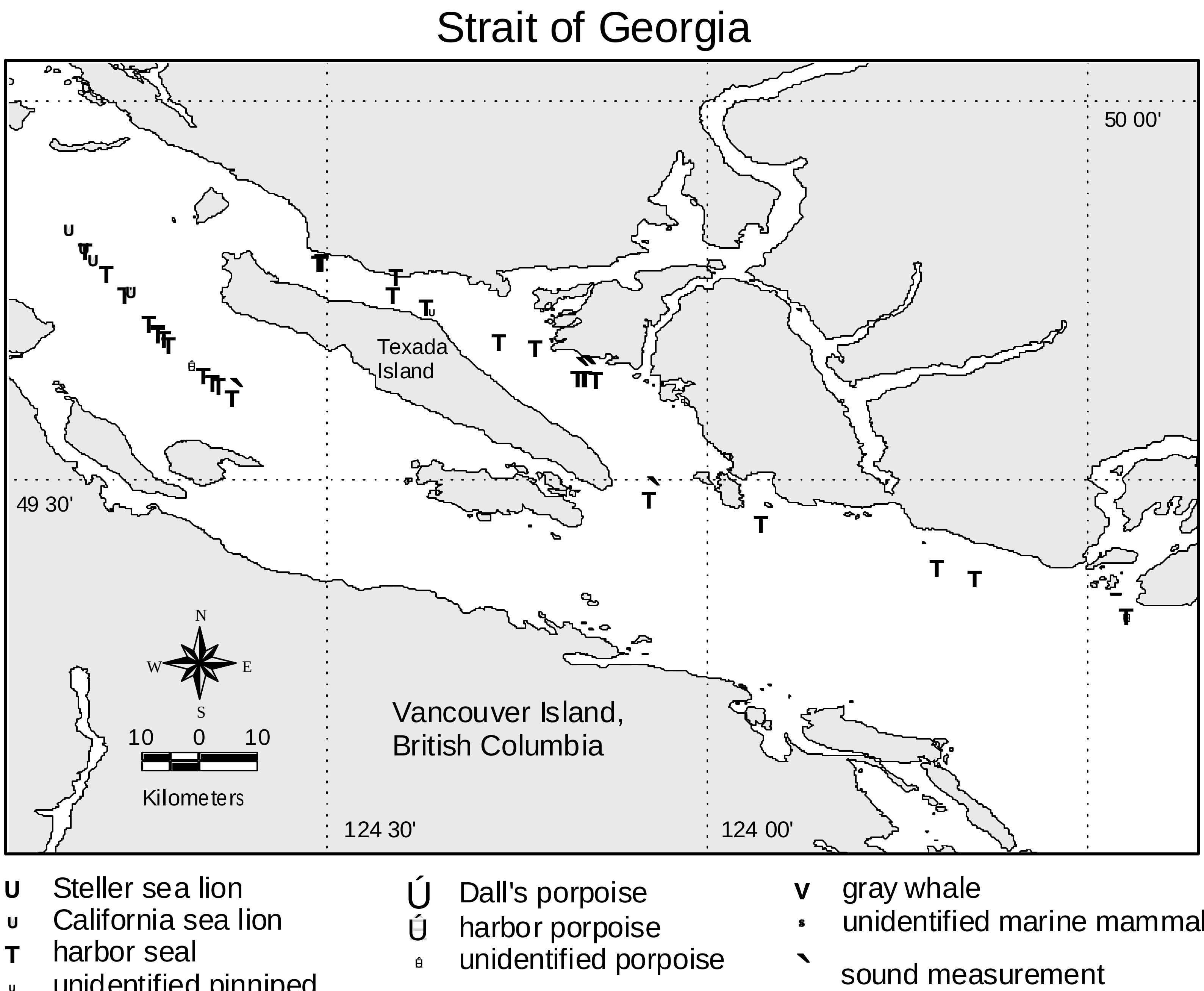
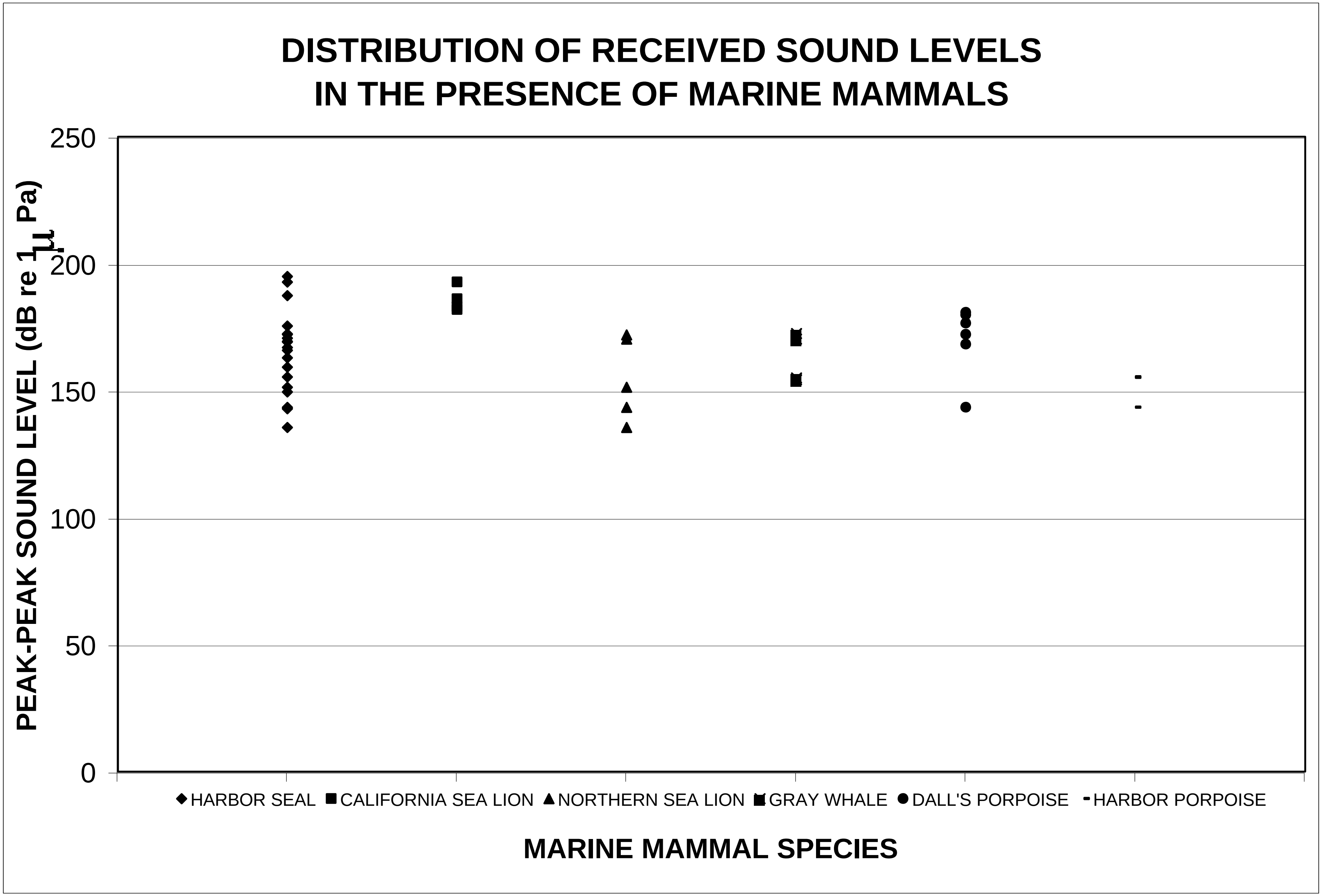


Figure 5. Locations of marine mammal sightings and sound level measurements.

Figure 6.



DISTRIBUTION OF RECEIVED SOUND LEVELS
IN THE PRESENCE OF MARINE MAMMALS
PEAK-PEAK SOUND LEVEL (dB re 1 μ Pa)
250
200
150
100
50
0
HARBOR SEAL
CALIFORNIA SEA LION
NORTHERN SEA LION
GRAY WHALE
DALL'S PORPOISE
HARBOR PORPOISE
MARINE MAMMAL SPECIES