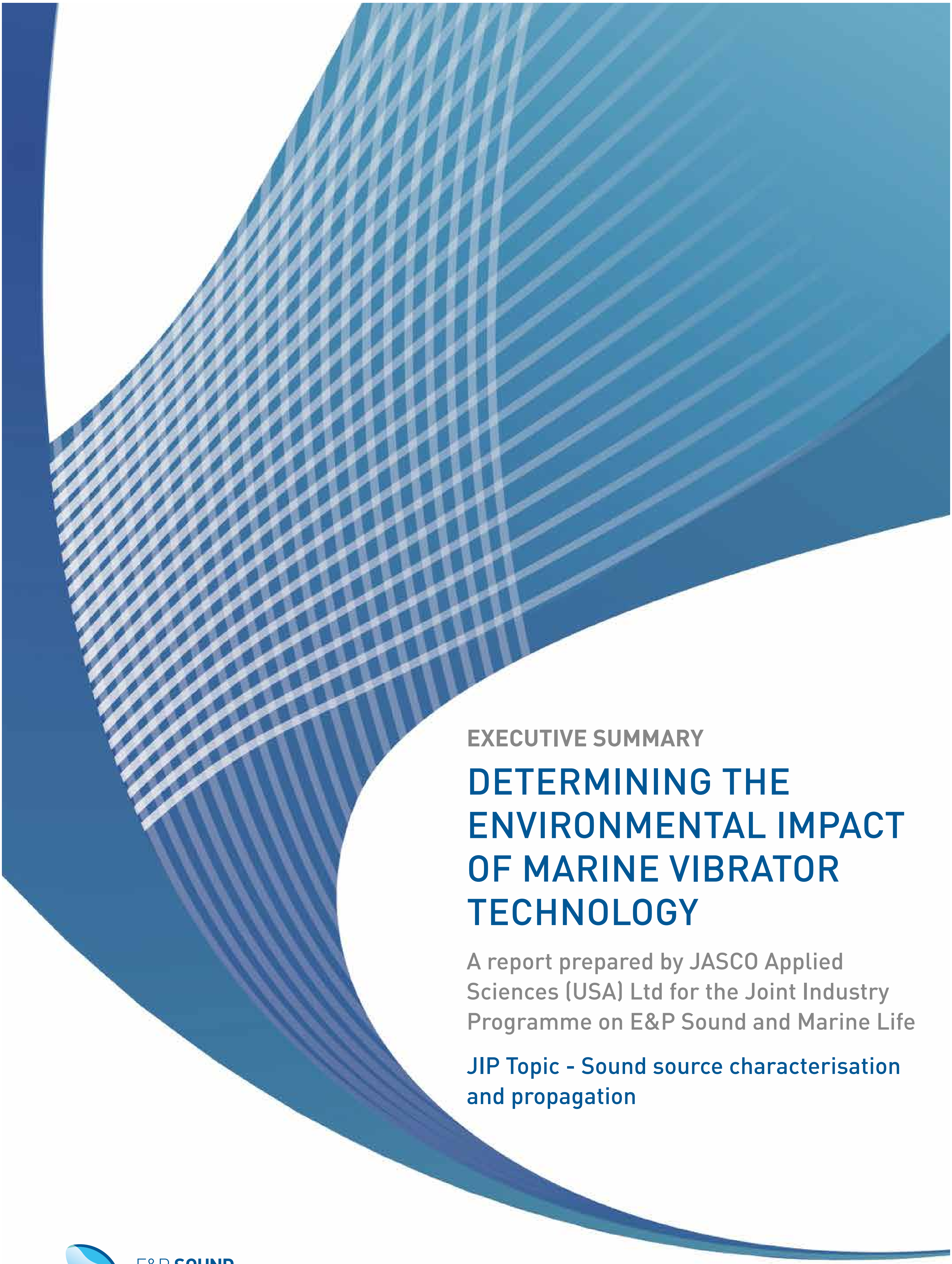

EXECUTIVE SUMMARY

DETERMINING THE ENVIRONMENTAL IMPACT OF MARINE VIBRATOR TECHNOLOGY

A report prepared by JASCO Applied Sciences (USA) Ltd for the Joint Industry Programme on E&P Sound and Marine Life

JIP Topic - Sound source characterisation and propagation

E&P SOUND
& MARINE LIFE
PROGRAMME

June 2018

About the E&P Sound & Marine Life Programme

The ocean is filled with a wide variety of natural and man-made sounds. Since the [early 1990s], there has been increasing environmental and regulatory focus on man-made sounds in the sea and on the effects these sounds may have on marine life. There are now many national and international regimes that regulate how we introduce sound to the marine environment. We believe that effective policies and regulations should be firmly rooted in sound independent science. This allows regulators to make consistent and reasonable regulations while also allowing industries that use or introduce sound to develop effective mitigation strategies.

In 2005, a broad group of international oil and gas companies and the International Association of Geophysical Contractors (IAGC) committed to form a Joint Industry Programme under the auspices of the International Association of Oil and Gas Producers (IOGP) to identify and conduct a research programme that improves understanding of the potential impact of exploration and production sound on marine life. The Objectives of the programme were (and remain):

1. To support planning of E&P operations and risk assessments
2. To provide the basis for appropriate operational measures that are protective of marine life
3. To inform policy and regulation.

The members of the JIP are committed to ensuring that wherever possible the results of the studies it commissions are submitted for scrutiny through publication in peer-reviewed journals. The research papers are drawn from data and information in the contract research report series. Both Contract reports and research paper abstracts (and in many cases full papers) are available from the Programme's web site at www.soundandmarinelife.org.

Determining the Environmental Impact of Marine Vibrator Technology

Report v1.0

Prepared for:
Sound & Marine Life
Joint Industry Programme

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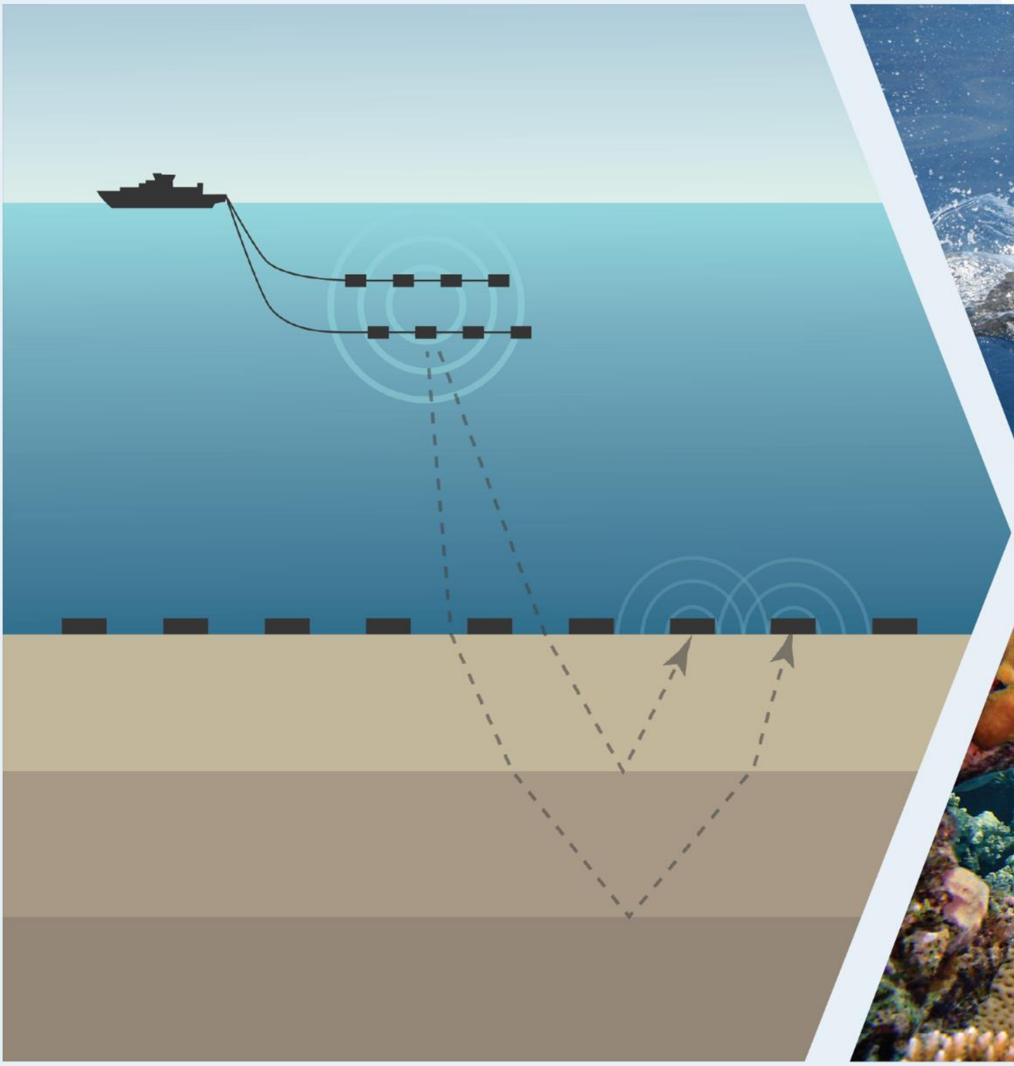

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Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made available to the recipients in integral and unedited form.

Executive Summary

Overview

Marine seismic surveys are conducted to study the geologic structure of the earth's crust under bodies of water. These surveys are performed by projecting sound energy through the water column into the underlying geological layers, where the sound reflects and refracts off different rock and sediment types. Sound returning to the surface is measured and interpreted for a variety of purposes, including identifying potential hydrocarbon resources, detecting fault lines and earthquake risk zones, understanding plate tectonics, and siting renewable energy infrastructure on the seabed.

Compressed air sources, referred to as seismic air guns, are the most commonly-used sound sources for marine geophysical surveys (Parkes and Hatton 1986); however, the geophysics industry has been interested in alternative seismic energy sources for many years. The adoption of vibroseis technology, used extensively on land, for marine environments was explored as early as the 1970s with limited success. In more recent years, concern about the potential impacts of seismic air gun sources on marine fauna and their habitats, and significant technology and geophysical data processing advancements, prompted the industry to re-invest in research and development of commercial marine vibroseis (MV) technology. In 2011, the Exploration and Production (E&P) Sound & Marine Life Joint Industry Programme commissioned an initial assessment of the potential effects of MV sources on marine fauna (LGL and MAI 2011). Since then, both the design and equipment testing of MV sources, and our understanding of the effects of underwater sounds on marine life have progressed. Although many uncertainties remain, advancements since 2011 warranted an updated analysis.

This study builds on the previous assessment (LGL and MAI 2011) by evaluating current MV technology in the context of best available scientific knowledge of acoustic effects on marine life. JASCO Applied Sciences (JASCO), LGL Ecological Research Associates (LGL), and Robert Brune, LLC, conducted an extensive desktop study involving source signal, sound propagation, and animal movement and sound exposure modeling of a variety of MV and air gun array configurations in multiple operating environments. Operational scenarios were intentionally developed to enable the calculation and direct comparison of the modeled levels of the various sound signals received by animals (including acoustic particle motion in very shallow water), and distances to marine mammal, fish, sea turtle, and invertebrate effects thresholds. Several established guidelines for injury and behavioral exposure criteria were used to allow comparisons between criteria. The available injury criteria are directly applicable to the two sound sources and were used as prescribed by the authors. Behavioral exposure criteria directly applicable to low-frequency, non-impulsive MV sounds were not available. Therefore, behavioral response thresholds derived for low-frequency active sonar (LFAS), the most similar source for which guidelines have previously been developed, were used in this study. Using these criteria, this study employs models to quantitatively predict the relative potential exposure levels of two different seismic sources (MV versus air guns) in multiple configurations and operational environments, for a variety of marine species.

Key Study Assumptions

Unlike air guns, which have been the subject of extensive research and animal exposure experiments, MV is a new technology that has yet to be widely field tested or studied for potential effects to marine fauna. Therefore, several assumptions were made in this study. Two key study assumptions relate to the modeled signal characteristics and the acoustic effects criteria used to calculate exposure levels.

Signal Characteristics

It is assumed that the modeled synthetic signatures for the MV arrays represent realistic output signatures.

Recorded output signals from existing marine vibrators were not available for use in this study, so input parameters for the various MV array elements were developed in consultation with JIP industry experts involved in the design and verification of commercial systems currently in development. The synthetic signatures for the MV arrays utilized general frequency bandwidth and timing considerations, which are deemed operationally realistic for the scenarios assessed. The model used a synthetic source signal for each element in the MV arrays, and the far-field source signature of each array was computed by summing the element's signatures with the appropriate phase delays for the array layout.

Effects criteria

When effects criteria are source-specific, low-frequency active sonar (LFAS) is assumed to be the best proxy for a MV array in terms of the temporal structure of the signal from the two source types. It is recognized, however, that the two sources differ in some significant aspects, such as the typical upper frequency limit of LFAS being substantially higher than that of MV arrays.

Air gun arrays produce impulsive sounds (typically <<1-s long) while MV arrays produce non-impulsive sounds (typically >>1-s long). This inherent difference between the sources required the application of separate threshold criteria when predicting and comparing their potential impacts. While some effects criteria guidelines for in-water sounds are source-specific, most guidelines use these same two broad categories based on the temporal characteristics of the sound. Currently published guidelines for fishes and sea turtles present threshold criteria specific to air gun arrays, but not for MV arrays. Similarly, behavioral response criteria applicable to air gun arrays are available, but not for MV arrays. Therefore, guidelines for LFAS were used as a proxy to estimate effects from MV arrays on marine life.

The underwater sound source most similar to MV arrays, for which criteria have been developed, is the LFAS. While sonar is often assumed to be continuous, it is not, and like MV, it is a non-impulsive source. For comparison, the survey scenarios developed for this study included MV array sounds that are 5–30 s long, repeated every 11–40 s, meaning sound is produced 45–77% of the time over each duty cycle. LFAS, such as SURTASS LFA, transmit series of sweeps and tones for ~100 s, followed by a quiet period of 6–15 min, resulting in sound produced ~10–22% of the time over each duty cycle. Both sources primarily produce sounds below 500 Hz.

We note that the use of certain criteria in this report does not reflect an opinion on which criteria are "better" or more appropriate. Rather, this study utilized the most similar criteria when considering signals from both source types. This allowed for more realistic comparisons that were more easily interpreted. The inherent differences between impulsive air gun sounds and non-impulsive MV sounds mean that it is not appropriate to use the exact same criteria for both sources.

Scenarios Evaluated

Five representative combinations of locations and survey types were chosen for comparing air gun and MV arrays. The scenarios were as follows:

1. Transition zone (offshore Indonesia, water depth 2–10 m), where a stationary survey with narrow (100 m) spacing between survey lines was modeled.
2. Transition zone (offshore Indonesia, water depth 10–25 m), where a towed survey with narrow (100 m) spacing between survey lines was modeled.
3. Shallow water zone (northern North Sea, water depth 110–130 m), where a towed survey with narrow (100 m) spacing between survey lines was modeled.
4. Shallow water zone (northern North Sea, water depth 110–130 m), where a towed survey with broad (500 m) spacing between survey lines was modeled.
5. Deep water zone (north central Gulf of Mexico, water depth >1000 m), where a towed survey with broad (500 m) spacing between survey lines was modeled.

The array layouts modeled in each scenario were based on typical operational requirements for the given survey type and location. For example, smaller arrays (with fewer elements) were modeled in the transition zone environment relative to those modeled in the shallow and deep environments.

Methods

Marine Mammals Effects criteria

To assess the potential injurious impacts of MV and air gun sounds on marine mammals, we applied the methods and criteria recommended by Southall et al. (2007) and U.S. National Marine Fisheries Service (NMFS 2016), the latter incorporating work by Finneran (2016). Both guidelines recommend assessing injury using dual criteria based on: frequency-weighted cumulative sound exposure level (L_{E})[1] and unweighted peak sound pressure level (L_{pk})[2]. The associated L_{E} and L_{pk} thresholds are based on the predicted onset of a permanent threshold shift (PTS) in hearing. Frequency-weighted cumulative L_{E} is evaluated using the provided frequency weighting functions to discount the received level of sound according to the frequency-dependent hearing sensitivity of different marine mammal groups.

The sound pressure level (L_{p})[3] metric is used to evaluate potential behavioral disruption of marine mammals. We applied two different approaches to estimate exposure to sound above behavioral thresholds: the first used the unweighted L_{p} threshold values of 160 and 120 dB re μPa applied by U.S. and other regulators to assess the number of exposures to impulsive (air gun) and non-impulsive (MV array) sources, respectively. It bears noting that a threshold basen on an unweighted metric ignores the spectral range of hearing ability of a given species and assumes that all frequency components of a signal contribute equally to its effect. Because there is lack of consensus on these behavioral thresholds, and it is uncertain whether the 120 dB re μPa would be appropriate for MV sources with variable and/or irregular signal sweeps, an alternative criterion was also used to estimate exposures resulting in potential behavioral disruption. The second approach used a multiple-step probability of response approach based on frequency-weighted L_{p} values proposed to NMFS by a permit applicant (Wood et al. 2012) for impulsive sources and proposed by the U.S. Department of the Navy (DoN 2008, DoN 2012) for non-impulsive LFAS (the most similar source for which behavior exposure guidelines were available; see Key Study Assumptions).

Fish, Sea Turtles, and Invertebrates Effects Criteria

The most recent comprehensive assessment of exposure criteria for fishes and sea turtles is from an ANSI-accredited standards committee report by Popper et al. (2014). The approaches and criteria suggested by Popper et al. (2014) are similar to those for marine mammals in that a dual criterion, based on L_{E} and L_{pk} metrics, are used for assessing potential injury for impulsive sound sources, and the L_{p} metric is used for assessing potential behavioral disruption. The L_{p} metric is also used for assessing potential injury for non-impulsive sound sources (LFAS). No frequency weighting functions are suggested and, in some cases, the lack of available data lead Popper et al. (2014) to provide qualitative assessment criteria instead of quantitative thresholds. Popper et al. (2014) did categorize sounds as impulsive or non-impulsive, but more specifically provided exposure criteria based on the type of source producing the sounds (explosion, pile driving, seismic air gun, sonar, and shipping). Few data exist to evaluate exposure to sounds produced by air guns for fishes and sea turtles, so the criteria developed by Popper et al. (2014) for seismic air gun sources were based on predictions derived from the effects of pile-driving sounds (Halvorsen et al. 2011b, 2012a, 2012b). Because there are no data for exposure to MV sounds, we used the criteria and thresholds provided by Popper et al. (2014) for LFAS (the most similar source for which behavior exposure guidelines were available; see Key Study Assumptions).

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[1] ISO 18405 standard notation; replaces SEL

[2] ISO 18405 standard notation; replaces SPL peak

[3] ISO 18405 standard notation; replaces SPL rms

There are currently no recommended criteria for evaluating potential impacts for invertebrates. Invertebrates appear to have particle motion sensitivity; therefore, we used the criteria suggested by Popper et al. (2014) for fishes without swim bladders (i.e., fishes that are only sensitive to particle motion) to evaluate invertebrate exposure levels. While received sound levels used in assessing effects for fishes and sea turtles were based on maximum levels over the entire water column, sound levels used to evaluate effect for invertebrates were based on levels received at the seabed. Popper at al. (2014) provides only qualitative relative risk ratings at varying distances from a sound source to evaluate potential sound-induced behavioral disruption of fishes. The exception is for LFAS, where Popper et al. (2014) provide an L_{p} of >197 dB re 1 µPa for potential behavioral disruption for some types of fishes. This threshold is used in this study for MV sources.

While all fishes, and likely all invertebrates, are sensitive to the particle motion aspect of sound, there are no exposure criteria based on this metric. Therefore, particle acceleration levels were modeled for both air gun and MV sources, but not compared to any thresholds.

Source Signature, Sound Propagation, and Animal Exposure

The MV array's signatures were modeled using synthetic signals, and the air gun array signatures with JASCO's Air gun Array Source Model (AASM; MacGillivray 2006). 3-D underwater sound fields and particle motion were calculated using JASCO's Marine Operations Noise Model (MONM), full-wave propagation model (FWRAM), and wavenumber integration model (VSTACK).

The 3-D sound fields were used to calculate distances to threshold criteria for marine mammals, fishes, sea turtles, and invertebrates, and as input to JASCO's Animal Simulation Model Including Noise Exposure (JASMINE) to estimate the number of marine mammals and sea turtles potentially exposed to the various sound level thresholds. For each scenario, the number of exposed animals in a 24-h period was calculated as the number of above-threshold exposures for 24 h intervals averaged over 7 days of simulation.

For each scenario, the received sound signals were modeled at set points along a grid. These received signals were characterized by several metrics, which may be used to estimate potential masking of biologically important signals:

1. Peak pressure (L_{pk}) and sound exposure level (L_{E}),
2. Duration of the signal above ambient levels,
3. Bandwidth of the signal above ambient levels,
4. Pressure rise time, and
5. First and second derivatives of pressure with respect to time.

Ambient sound levels were based on the best available published data for each region. These levels were used for defining the duration and bandwidth at receiver locations away from the sources. The pressure rise time and the first and second derivatives of the pressure with respect to time are related to particle acceleration and changes in particle acceleration, which may be used as indicators of potential tissue damage.

In the Transition Zone, where the water is shallowest, particle motion was modeled using VSTACK at 1 cm above the seabed. Because of the lack of particle motion exposure criteria for fishes and invertebrates, the particle motion model results are qualitatively discussed.

Results

Source Signatures

For comparative purposes, the modeled air gun and MV arrays produce similar acoustic energy (broadband L_E of 218–233 dB re 1 µPa^2·s m for the air gun arrays, and 215–233 dB re 1 µPa^2·s m for the MV arrays, in the vertical direction). Despite having similar energy outputs, the L_{pk} of the air gun arrays are 8 to 55 dB higher than that of the MV arrays. Outside of the main frequency bands relevant to seismic surveys, the spectral levels for the air gun arrays generally decrease by ~30 dB per decade while spectral levels for the MV arrays decrease by >50 dB per decade. Thus, the frequency content and bandwidth of the signals differ significantly, with the MV arrays producing substantially less energy outside the useful spectral range for seismic exploration. For example, L_E at frequencies between 1-2 kHz for the modeled air gun arrays is 181.3–199.9 dB re 1 µPa^2·s m (in the vertical direction), L_E at frequencies between 1-2 kHz for the modeled MV arrays is 97.7–160.5 dB re 1 µPa^2·s m (in the vertical direction). Because MV sounds have less energy in the best hearing range of most marine mammals, frequency weighting reduces the effective sound levels for MV more than for air gun sounds.

Effects on Marine Mammals

Injury

Although the air gun and idealized MV signals in this study produced similar broadband acoustic energy in the seismic bandwidth (up to 100 Hz), MV arrays emitted less high-frequency energy than the air gun sources. As the same frequency weighting is applied to the sound fields generated by both technologies, and L_E thresholds are higher for non-impulsive than impulsive sources, the modeled distances to L_E thresholds were generally shorter for MV arrays relative to the air gun arrays. This is especially evident for mid- and high-frequency cetaceans, for which the frequency-weighting functions discount a large portion of the acoustic energy at frequencies below a few hundred Hertz. L_{pk} at the source is lower for MV than for air gun arrays. Since L_{pk} thresholds are the same for impulsive and non-impulsive sources the distances to injury thresholds based on the L_{pk} metric are also shorter for MV arrays compared to air gun arrays. Thus, regardless of which metric is used and in all modeled operational scenarios, distances to injurious exposure thresholds are expected to be shorter for MV arrays than for air gun arrays of similar broadband acoustic energy. It is essential to note that any distances to L_E injury thresholds presented in this study cannot be interpreted as estimates of range to injury, since the results are based on single pulses or sweeps and not on cumulative exposure to multiple events on which the criteria are based. Only relative comparisons between the two types of sources can be drawn from those ranges.

For both air gun and MV arrays, animal exposure modeling predicted very few animals would be exposed to such levels. This was true even without the model incorporating the implementation of mitigation measures or aversive behavioral responses, both of which are applicable to most seismic surveys and would further reduce the likelihood of potentially injurious effects.

Behavioral response

The two source types were evaluated for potential behavioral response using the current NMFS criteria (NOAA 2005), which prescribe a L_p threshold of 160 dB re 1 µPa for air guns and 120 dB re 1 µPa for non-impulsive sources, among which the MV is included. The difference in L_p levels between the two source types (29.5 dB on average) is generally less than the difference between the behavioral thresholds (40 dB). Consequently, longer distances to the behavioral thresholds were found for the MV source than the air gun source, and more animals were predicted to be exposed to sound levels above behavioral thresholds for the MV than the air gun. However, these criteria do not incorporate known differences in the frequency-dependent hearing sensitivity of different marine mammal species or individual variation in the likelihood of behavioral response, nor is there agreement that the 120 dB re 1 µPa is an appropriate threshold for MV sources.

When the more realistic, frequency-weighted, multiple-step functions proposed by Wood et al. (2012) and DoN (2012) are used for comparative purposes, the result is reversed and fewer animals (by about an order of magnitude) are predicted to be exposed to sound levels above behavioral thresholds for the MV than for air gun arrays. This is primarily caused by the higher source levels (i.e., sound pressure amplitude) of air gun arrays resulting in longer distances to behavioral response thresholds that are nearly equivalent for the two source types. However, these results do not directly incorporate context-dependent factors that may affect the likelihood of behavioral response, such as feeding, breeding, or migrating behaviors or the previous exposure history of individuals.

Masking

Acoustic masking reduces the ability of animals to detect biologically-relevant sounds, potentially affecting their fitness. Masking is assumed to occur when noise levels exceed the signal of interest levels within a critical hearing band or bands. The importance of masking effects is not yet fully understood, and no masking criteria for assessment currently exist. While this study does not directly address the potential impacts of acoustic masking, it compares aspects of the air gun and MV signals that are known to contribute to masking, such as signal level, duration, and bandwidth.

The longer duration of MV sounds, relative to air gun pulses, increases the potential for MV sounds to mask signals of interest to marine mammals. The survey scenarios developed for this study included MV array sounds of 5, 17, or 30 second duration and repeated every 11, 22, or 40 seconds, meaning sound could be perceived 45–77% of the time over each duty cycle. Received air gun pulses lasted up to 1-s each, and they were repeated every 10–11 seconds. Thus, air gun sounds were present 9–10% of the time over each duty cycle. In general, for the scenarios in this study, the MV array ensonified the marine environment for periods 36–67% longer than the air gun arrays.

Despite longer signal durations, MV arrays are less likely than air gun arrays to result in masking for most species because: (1) the distances within which the sound may be perceived are smaller, and (2) the main frequencies produced by the MV source do not overlap with the hearing ranges of most marine mammals. The higher L_{pk}, L_E, and L_p of air gun sounds means that the distances within which masking might occur were 2 to more than 5 times greater for the air gun arrays than the MV arrays. Analysis of signal bandwidth at increasing distances from the sources showed that the bandwidths of MV array sounds begin to narrow from their maximum width at distances 10 to 20 times shorter than that of air gun sounds. This means that the potential extent of masking from frequency overlap with marine mammal hearing is reduced at shorter distances for MV sounds than for air gun sounds. The lack of acoustic energy at frequencies outside of those of seismic interest (greater than ~200 Hz) for MV sources means that only mysticete whales are likely to experience masking from MV sounds, and within a shorter ensonified distance relative to air guns.

The difference in bandwidth and distances to potential masking depend on the harmonic content of MV sounds. The intent of marine vibroseis sources is to produce only the sounds needed for seismic exploration; however, real-world systems have some distortion, which adds acoustic energy outside of the intended frequency band. Measurements from MV arrays were not available at the time of this study, so the harmonic content of the modeled signals were estimated based on provided descriptions, and thus have a high level of uncertainty around them. Nonetheless, the modeling results show that marine fauna using frequencies above several hundred Hertz will experience less masking from MV arrays than from air guns.

Effects on Fishes, Sea Turtles, and Invertebrates

The research on the impact of anthropogenic sounds on fishes, sea turtles, and invertebrates is not as extensive as that for marine mammals. Where assessments of these effects have been conducted, the results indicate that impulsive sounds with rapid rise times appear to be more injurious than non-impulsive sounds (Popper et al. 2014). Therefore, injurious impacts on fishes, sea turtles, and invertebrates are expected to be generally lower for the MV source than the air gun.

In this study, results show that distances to injury thresholds for fishes with swim bladders (involved or not involved in hearing) are shorter for MV than air gun arrays. Distances to injury thresholds for other fishes without a swim bladder, sea turtles, and invertebrates exposed to air gun sound, are generally similar or shorter than for fishes with swim bladders. These distances, however, could not be compared to that for MV sound since no quantitative thresholds are available for the MV or a comparable source.

The absence of quantitative criteria for use in the assessment of behavioral effects for fishes, sea turtles, and invertebrates complicates source comparisons. The qualitative risk data (Popper et al. 2014) relating to behavioral exposure thresholds for fishes, sea turtles, and invertebrates, suggest high risk for all animals near (tens of meters) an impulsive sound source. This probability of behavioral response decreases with increasing distance from the source. For non-impulsive sound, Popper et al. (2014) indicate a low risk to most animals (Fish I and II species, sea turtles, and invertebrates), regardless of distance between the sound source and receiver. These criteria suggest that behavioral disturbance to fishes, sea turtles, and invertebrates is expected to be generally lower for the MV source than the air gun.

The only quantitative behavioral disturbance criteria described by Popper et al. (2014) is for low- and mid-frequency naval sonar. The criterion for low-frequency sonar, used in this study as a proxy criterion for MV sources, applies to one category of animal (Fish III species). Calculated distances to this behavioral threshold were all <50 m in this study. The comparable qualitative risk data for the same species are high risk at both near (tens of meters) and intermediate (hundreds of meters) distances from the air gun array, suggesting that the distance to the behavioral threshold for these species is greater for the air gun array than MV.

Effects in Different Water Depth Regimes

Every operational area will have specific physical environmental conditions and biological species that necessitate a project specific analysis to determine which seismic source is most appropriate. Nonetheless, the three different scenario locations used in this study allow comparison of the different source types, and also MV sweep types, among different water depths.

Distances to injury and behavioral response thresholds from both source types were shortest in very shallow water (Transition Zone – Scenarios 1 and 2). This is a result of the lower-energy sources used in the Transition Zone, and the higher sound propagation attenuation due to increased interactions with the seabed in very shallow water. There was very little difference between the distances to injury and behavioral response thresholds in shallow water (North Sea – Scenarios 3 and 4) and deep water (Gulf of Mexico – Scenario 5) locations for each sound sources. Although, as described above, the distances to injury thresholds were shorter for MV arrays than for air gun arrays in all Scenarios.

Conclusions

The largest difference between air guns and MV is that air guns produce high-amplitude impulsive sounds while marine vibrators produce lower-amplitude, non-impulsive sounds. While the sounds produced by the sources modeled in this study had roughly equal energy, impulsive air gun sounds concentrate the sound energy in time, and have high amplitudes spread over many frequencies. Non-impulsive MV sounds are typically limited in frequency content (e.g., tonal or swept frequency), have lower amplitudes, and last over longer durations. The distinction between impulsive and non-impulsive sounds is made because the two are perceived differently by animal hearing (Southall et al. 2007; Popper et al. 2014) and are therefore subject to different threshold criteria. Due to a rapid rise time and high peak pressures, impulsive sounds at close range are more likely to cause tissue or mechanical damage, whereas the longer duration of non-impulsive sounds may result in greater temporal potential for behavioral disturbance through mechanisms like masking.

For all the scenarios modeled in this study, distances to injury thresholds for marine mammals are shorter for the MV than the air gun array. This is especially true for mid- and high-frequency cetaceans when frequency-weighting functions are applied, which results in the discounting of a large portion of the energy emitted at frequencies below a few hundred Hertz. MV and air guns are both low-frequency sources with greater potential for injury to low-frequency cetaceans compared to mid- and high-frequency cetaceans. Nonetheless, modeled distances to potentially injurious levels from both sources were short and exposure modeling predicted very few animals may be exposed above such levels from either source.

Using current NMFS behavioral criteria (NOAA 2005) that have a much lower threshold for non-impulsive sources (L_p 120 dB re 1 µPa) than impulsive sources (L_p 160 dB re 1 µPa), models predicted longer distances to the behavioral thresholds for the MV source than the air gun source. Owing to the larger ensonified area, exposure modeling results predicted that more animals could be exposed to sound levels above behavioral thresholds from MV arrays than from air gun arrays. While there is no scientific consensus on these behavioral criteria in general, use of the non-impulsive NMFS criterion for MV sources in particular may not be appropriate to the temporal structure of their signal. An alternative approach to calculate numbers of potential behavioral response exposures is to employ frequency-weighted step-functions (DoN 2012, Wood et al. 2012). When these criteria were applied to the scenarios in this study, there are lower estimated numbers (by about one order of magnitude) for the MV source than the air gun source.

A prevalent assumption is that the longer duration of MV sounds relative to air gun pulses greatly increases the potential for masking signals of interest to marine mammals. However, the lower amplitude of MV sounds results in calculated ranges of potential masking that are 2 to 5 times smaller than predicted for air gun arrays. In addition, the lower energy content of MV sounds at frequencies above 100 Hz means that few species other than low-frequency cetaceans are likely to experience significant masking from MV sounds. Thus, the potential masking effects for marine life that use frequencies above several hundred Hertz will be less for MV than for air gun arrays. For species using lower frequencies, there will be a tradeoff between the two sources in the duration of time over which masking could occur (longer for MV) and the area within which masking could occur (smaller for MV).

The maximum received L_{pk} and particle acceleration levels estimated from modeling are consistently lower for the MV sources compared to the airgun array sources. These results suggest that MV sources have less potential than air gun arrays to cause mortality, mortal injury, and recoverable injury effects on fishes, sea turtles, and invertebrates. The slower rise times associated with MV signals also supports the conclusion that these types of sources have less potential to cause mortality and injury to fishes and invertebrates than air guns. Based on the model results, MV sources are also estimated to produce a smaller area of exposure with the potential to cause behavioral effects on fishes, sea turtles, and invertebrates. The longer signal durations associated with MV arrays, however, means that this source type may result in more sustained masking for fishes and invertebrates at closer ranges.

Qualitative Summary

A qualitative summary of the results is provided in the table below. The symbols <, =, and > are used to indicate that we expect less, similar, or greater effects from the MV array than from the associated air gun array. The air gun array associated with Scenario 1 and 2 is the 750 in^3 array; the air gun array associated with Scenario 3–5 is the 4130 in^3 array. The qualitative results for potential injury and behavioral disturbance are based on the calculated distances to sound level thresholds and the number of exposed animals. The qualitative results for masking are based on comparison between received signal properties, up to 50 km from the sources.

Table 1. Summary of results. The symbols <, =, and > indicate that effect from the marine vibroseis signal is less than, equivalent, or greater than from the air gun array pulse. The 750 in^3 air gun array is used for comparison in scenarios 1 and 2; the 4130 in^3 air gun array is used for comparison in scenarios 3–5. The summarized injury and behavior results are based on distances to sound level thresholds and estimated numbers of exposed animals. The summarized masking results are based on signal properties up to 50 km from the source. MV: marine vibroseis; MM: marine mammals; LFC: low-frequency cetaceans; MFC: mid-frequency cetaceans; HFC: high-frequency cetaceans; OPW: otariid pinnipeds in water; PPW: phocid pinnipeds in water.

Scn	Operational zone (Region)	Water depth (m)	Source	Injury			Behavior			Masking		
				Southall et al. (2007)	NMFS (2016)	Popper et al. (2014)	NOAA (2005)	Wood et al (2012) or DoN (2012)	Popper et al. (2014)	Frequency range	Temporal	Spatial
1	Transition Zone	2–10	MV–A Linear upsweep	< LFC < PPW = MFC < OPW = HFC	< LFC < PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–A PRN signal	< LFC < PPW = MFC < OPW = HFC	< LFC < PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
2	Transition Zone	10–25	MV–B Linear upsweep	< LFC < PPW = MFC < OPW = HFC	< LFC = PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–B PRN signal	< LFC < PPW = MFC < OPW = HFC	< LFC = PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
3 & 4	Shallow Water (North Sea)	110–130	MV–B Linear upsweep	< for all MM	< for all MM	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–B PRN signal	< for all MM	< LFC < PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
5	Deep Water (Gulf of Mexico)	1500–1600	MV–B Linear upsweep (5–40 Hz)	< for all MM	< for all MM	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–B Linear upsweep (5–100 Hz)	< for all MM	< LFC < PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–B PRN signal	< for all MM	< LFC < PPW = MFC = OPW < HFC	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV-C Logarithmic upsweep	< for all MM	< for all MM	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–C PRN signal	< for all MM	< for all MM	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM
			MV–D Linear upsweep	< for all MM	< for all MM	< Fish II < Fish III *	> for all MM	< for all MM	n/a **	< for all MM	> LFC < other MM	< for all MM

* No comparison available for Fish I, sea turtles, and invertebrates: There are no quantitative criteria for Fish I, sea turtle, or invertebrate for MV.

** No comparison available: There are no quantitative criteria for the air gun array.

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