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Categorizing Alternative Seismic Sources Based on Their Potential to Affect Marine Mammals

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Abstract

Seismic airguns generate high intensity noise that can affect marine life. Emerging alternative seismic sources offer promising opportunities to reduce acoustic impacts, yet their performance and integration into regulatory processes remain poorly quantified. We evaluated four recently developed alternative seismic sources to characterize their acoustic outputs, assess their relative impacts on marine mammals, and classify them within the tiered framework of the Operational National Mitigation Protocol for Geophysical Surveys—developed collaboratively by the National Marine Fisheries Service (NMFS), Bureau of Ocean Energy Management (BOEM), and Bureau of Safety and Environmental Enforcement (BSEE). The assessment included three ultra low-frequency (ULF) pneumatic sources (Tuned Pulse Source™ [TPS™], Gemini Source™, and Harmony™) and a representative marine vibroseis (MV) system. Using NMFS auditory injury and behavioral disturbance thresholds alongside a new (60 s M-weighted sound exposure level) metric, we found that all alternatives produced lower 60 s energy and smaller auditory injury zones than conventional high impact airgun arrays. ULF pneumatic sources concentrate energy below 10 Hz, contributing to reduced exposure at ecologically relevant frequencies. TPS™ and the Gemini Source™ align with moderate impact tiers, while Harmony™ is more similar to higher impact sources. For MV systems, single and dual element configurations are placed in a lower impact tier, though an 18-element array requires further characterization before classification. Remaining uncertainties, including limited behavioral data and incomplete source characterization, highlight the need for continued empirical research. By offering a science-based framework, this work contributes to regulatory modernization, advances efforts to reduce ocean noise, and enables the responsible adoption of emerging "quieter" seismic technologies within a more consistent and streamlined approach.

Keywords: acoustics; airguns; seismic surveys; geophysical sources; marine life; ocean energy; ocean quieting

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1. Introduction

Marine seismic surveys are essential tools for imaging subsurface geology, supporting applications ranging from hydrocarbon exploration to geohazard assessment, seafloor mapping, and marine research. Conventional seismic surveys, which have been the industry standard since their introduction in the 1960s, typically rely on compressed air chambers (i.e., airguns) that are towed behind a ship and are programmed to release high-energy pulses of sound at prescribed time intervals. The acoustic energy that is refracted and reflected off the seafloor and geologic features is received by arrays of tens to thousands of hydrophone receivers, either towed behind the ship or deployed on the seafloor. Despite advances in receiver technology and data processing, the fundamental design and operation of seismic sources have changed little over the past several decades [1,2]. Airguns and airgun arrays produce energetic broadband pulses spanning a few hertz to more than 10 kHz [3,4], though the frequencies that are most usable for geophysical imaging are concentrated below ~100 Hz [2]. The extraneous energy at high frequencies (>100 Hz) is substantial and represents an opportunity for quieting and reducing environmental impacts while retaining imaging performance. This extraneous energy, while not useful for geophysical imaging, is within the frequency bands where many marine mammals have their greatest hearing sensitivity.

Marine mammals are highly dependent on acoustic cues as a means of navigating through their environment, foraging, and communicating with conspecifics. The importance of sound to marine mammals means that unwanted anthropogenic noise could lead to a range of potential effects including auditory injury (e.g., permanent threshold shift [PTS]), temporary threshold shift (TTS), behavioral disturbance, acoustic masking, and physiological stress [5,6]. A large body of research has shown that exposure to impulsive sounds such as those produced by airgun arrays can negatively impact marine mammals [7], with effects ranging from avoidance [8], to changing vocalization behaviors [9,10], to reducing foraging effort [11]. Baleen whales are especially vulnerable to noise from oil- and gas-related activities because their hearing and communication range overlaps with many commonly used sound sources. Given the complexity of the science and the influential positions of the various stakeholders involved in this issue, regulating noise from seismic surveys has become a “wicked environmental problem” [12]. Presently, there is increasing scrutiny for regulatory bodies around the world to find better solutions to the growing problem of ocean noise [13].

In U.S. waters, geophysical surveys used for hydrocarbon exploration are regulated primarily by the Bureau of Ocean Energy Management (BOEM), Bureau of Safety and Environmental Enforcement (BSEE), and National Oceanic Atmospheric Administration’s National Marine Fisheries Service (NOAA-NMFS; hereafter referred to as NMFS), which regulates the impacts of noise to protected species and implements mitigation and monitoring requirements under the Marine Mammal Protection Act (MMPA, 16 U.S.C. § 1371) and Endangered Species Act (ESA, 16 U.S.C. § 1531 et seq.). NMFS, BOEM, and BSEE have recently collaborated to develop a standard set of protocols that apply to geophysical surveys across U.S. waters. These protocols include the Operational National Mitigation Protocol (ONMP) for geophysical surveys, which formalizes a tiering system for categorizing geophysical sound sources based on their relative potential to affect marine mammals (https://www.boem.gov/environment/center-marine-acoustics/regulatory-policy accessed on 30 June 2026). The ONMP is grounded in statutory requirements under the Outer Continental Shelf Lands Act (OCSLA) to ensure that geophysical data are collected in an environmentally sound manner and is implemented as part of BOEM’s project-approval criteria.

The scientific underpinning of this tiering protocol was developed by Ruppel et al. [4], which conducted a comprehensive review of active marine acoustic sources used for geophysical imaging (e.g., airguns, sparkers), high-resolution seafloor mapping (e.g., multibeam echosounders, side scan sonars, sub-bottom profilers), oceanographic measurements (e.g., acoustic Doppler current profilers [ADCPs], split beam sonars), and communication or tracking applications (e.g., acoustic releases, navigational transponders). Rather than relying solely on source level (i.e., how "loud" a source is), Ruppel et al. [4] introduced additional factors to describe physical qualities of the sound source. Those include transmission frequency, directionality, beamwidth, pulse repetition rate, and duty cycle—which are attributes that influence both the spatial footprint and biological relevance of acoustic exposures.

Using these physical attributes and typical operational configurations, Ruppel et al. [4] proposed a four-tier classification scheme that groups acoustic sources according to their relative risk to marine animals. Tier 1 represents the highest potential risk and includes high-energy airgun arrays (>1500 in^3 total volume or >12 airguns). Tier 2 includes lower energy airgun configurations ($\leq$1500 in^3 or $\leq$12 airguns). The distinction between Tier 1 and Tier 2 was inferred by [4] based on a compilation of peak source levels and an observed change in relationship between volume and peak source level near 1500 in^3 and generally serves to provide a useful delineation separating the broad gamut of airgun sources utilized and their associated acoustic energy. Tier 3 encompasses non-airgun impulsive seismic sources such as sparkers and certain boomers, and Tier 4 includes de minimis sources considered unlikely to result in auditory injury or behavioral disturbance of marine mammals. Tier 3 sources are expected to be less impactful than Tier 2 sources, but their effects are still not minimal enough to be considered de minimis.

U.S. federal agencies adopted this tiering scheme nearly wholesale and folded it into the ONMP (https://www.boem.gov/environment/center-marine-acoustics/regulatory-policy accessed on 30 June 2026), underscoring its utility as a scientific foundation for regulatory mitigation frameworks. By grounding source categorization in physical, measurable attributes rather than species-specific biological characteristics and behavioral responses, the approach supports consistent and transparent regulation and emphasizes that the framework is adaptable: i.e., it could be modified with new data on source characteristics or if thresholds change, and it could be adapted by jurisdictions with different environmental laws and/or thresholds.

Importantly, the source-based tiering approach provides a pathway for evaluating emerging technologies. For sources not explicitly addressed in the original analysis, Ruppel et al. [4] recommend applying the same physical criteria (i.e., frequency, source level [SL], pulse rate, pulse duration, duty cycle, and directionality) to estimate likely risk. This method enables regulators to integrate the tiering framework and reduce the effect of uncertainty on regulatory processes. In cases where empirical data are limited, Ruppel et al. [4] recommend a case-by-case evaluation until sufficient information becomes available. This paper uses and expands upon the Ruppel et al. [4] framework to assess alternative seismic technologies, many of which differ substantially from traditional airguns in frequency content, temporal characteristics, air chamber volume size, and operational mode.

Earlier work attempted to demonstrate the potential impacts of some alternative seismic technologies through modeling approaches [14,15]; however, empirical data were needed to verify model outputs. Several alternative seismic sources have now reached a level of technical and operational maturity that allows their acoustic characteristics, deployment approaches, and potential environmental impacts to be clearly defined and reliably measured. Improved source characterization and expanded operational experience support empirical comparisons with conventional technologies. Together, these advances enable alternative seismic sources to be assessed in a manner that aligns technological innovation with adaptive management and the use of best available science.

As governmental agencies around the world aim to integrate lower impact technologies into their regulatory frameworks, a quantitative tiering framework can offer a consistent basis for evaluating and comparing emerging "quieter" seismic sources. The term "quieter" can indicate reduced source levels, reduced signal energy at frequencies within marine mammal hearing ranges, or both. Establishing a science-based approach supports regulatory modernization, advances efforts to reduce ocean noise, and enables the responsible adoption of lower impact seismic technologies within a more streamlined approach.

The goal of this work is not to define a new tiering framework for conventional seismic sources but to position emerging alternative technologies within the existing framework as defined by Ruppel et al. [4] and adopted in the ONMP, commensurate with their acoustic characteristics. To do this, relevant source parameters were compiled and analyzed for several emerging technologies and conventional seismic sources that were classified as either Tier 1, 2, or 3. Each source's characteristics (i.e., SLs, temporal properties, and spectral content) were used to estimate distances to auditory injury and behavioral disturbance, calculate values for a new metric (60 s M-weighted sound exposure level [$SEL_{60s,M}$]; see Section 2.2), and compare emerging technologies with conventional sources. The results were then leveraged to understand the relative impact of the alternative technologies considered herein and categorize them within the existing tiering framework. An extensive Supplementary File S1 provides the general methodology for deriving acoustic metrics and weighting factor adjustments for each source, as well as figures detailing the array layout, spectra, and waveforms associated with each source.

2. Materials and Methods

2.1. Evaluated Seismic Sources

This analysis focused on four emerging alternative seismic technologies: Tuned Pulse Source (TPS™), Gemini Source™, Harmony™, and a representative marine vibroseis (MV) system (Marine Vibrator Joint Industry Project Integrated Projector Node [MV JIP IPN]). These sources were selected based on operational maturity and data availability. For each technology, the best available acoustic characterizations were compiled from the public literature, direct industry communication, and information submitted in federal petitions and authorization applications (File S1). Comparable information was also assembled for representative Tier 1–3 conventional sources, including medium volume Tier 1 airgun arrays, smaller airgun arrays consistent with the upper end of Tier 2, small airguns consistent with the lower end of Tier 2, and sparkers (File S1). A summary of all sources and their assumed source levels is provided in Table 1.

2.1.1. Conventional Seismic Sources

Conventional airguns are high-pressure pneumatic sources that generate repeatable, broadband, impulsive acoustic pulses for marine seismic exploration. Each gun releases compressed air into the water, producing a primary pressure pulse and a subsequent bubble oscillation. Airguns are deployed in arrays combining different chamber volumes and firing delays to increase source energy, enhance directivity, broaden bandwidth, and reduce bubble effects. Conventional seismic airguns and airgun arrays radiate most of their acoustic energy at low frequencies, with peak energy typically occurring between approximately 10 Hz and 40 Hz depending on airgun volume, operating pressure, and array design. However, detectable energy exists at frequencies above 10 kHz in field measurements. As an example, Martin et al. [3] measured energy in the 16 kHz decidecade band which was 20 dB above background sound levels at a range of 6 km.

The Tier 1 arrays considered are 5380 in^3 (42 airguns), 5110 in^3 (32 airguns), 4130 in^3 (31 airguns), 1680 in^3 (20 airguns), and 1500 in^3 (six airguns; 3000 psi) arrays, while Tier 2 is represented by 1500 in^3 (six airguns; 2000 psi), 1000 in^3 (12 airguns), and 30 in^3 (2 airguns) arrays, as well as 90 in^3 and 10 in^3 single airguns. These arrays span the range of source configurations commonly deployed in contemporary geophysical operations—from the large multi-element arrays used in full-scale 2D and 3D industrial surveys to the smaller arrays and single-gun systems typically employed in site-specific investigations, hazard surveys, or down-hole applications. As such, they are representative of real, currently used sources in global commercial practice. Importantly, the two larger Tier 2 arrays are each at the upper limit of Tier 2 as defined in Ruppel et al. [4] and the ONMP: the 6-element, 1500 in^3 array is at the upper end in terms of total volume, and the 12-element 1000 in^3 array is at the upper end in terms of number of elements. Similarly, the 90 in^3 and 10 in^3 single airguns and the 30 in^3 2-element array are representative of the lower end of Tier 2.

All conventional sources were modeled with a firing pressure of 2000 psi, which is generally considered "standard" in the field, with the exception of the data obtained for a 1500 in^3 array that was operated at 3000 psi [16]. Since 3000 psi is rather unusual for a 1500 in^3 array, a 2000 psi version was also included as a scaled hypothetical source to obtain an equal pressure comparison across sources. Notably, the 1500 in^3 3000 psi array has been evaluated as Tier 1 herein due to higher source levels compared to the 1500 in^3 2000 psi array, which was the intended uppermost limit of Tier 2 in Ruppel et al. [4] and the ONMP. Detailed descriptions of all conventional airgun sources are provided in File S1.

In addition to airguns, this analysis incorporates sparkers for comparative purposes. Sparkers are high-resolution, impulsive seismic sources that convert electrical, rather than pneumatic, energy into acoustic output. During operation, a high-voltage discharge is released across multiple electrodes, or "tips," which vaporizes the surrounding seawater, leading to the creation and collapse of bubbles [17]. Consequently, the key predictors of total acoustic energy for sparkers are electrical energy and the number of tips, rather than air volume or array size as in airgun systems. Sparker energy may range from 0.2 to 30 kJ, which produces overall energy comparable to single airguns with volumes greater than 1 in^3 and approximately 15 in^3, respectively [17]. Relative to airguns, sparkers have faster repetition rates, they have generally lower source levels, and their primary energy is at higher frequencies [4]. Ruppel et al. [4] classifies most sparkers as Tier 3 sources, with some low energy sparkers in Tier 4. This study included three sparker systems, each evaluated in two configurations (i.e., low and high power), with source levels taken from Crocker et al. [18]. The evaluated sparkers are the SIG ELC 820, Applied Acoustics (AA) Dura-Spark, and AA Delta sparker; further details are provided in File S1.

2.1.2. Ultra Low-Frequency (ULF) Seismic Sources

ULF pneumatic sources have emerged in recent years to address the need for improved low-frequency bandwidth for sub-salt and sub-basalt imaging, as well as to reduce potential environmental impacts [1,19]. These systems include the TPS™, Gemini Source™, and Harmony™, which are characterized by bubble resonance frequencies below 7 Hz and are engineered to generate enhanced energy in the 1–10 Hz band. These sources typically contain peak energy below 10 Hz, with reduced signal amplitude above ~60–90 Hz. The TPS™ (Sercel, Houston, TX, USA) is a low pressure (~1000 psi), high volume (28,000 in^3) pneumatic source that releases a large, controlled air volume to produce an impulsive, long rise-time signal with low-frequency bubble oscillation, yielding a 2.6–2.8 Hz peak frequency and a broad (1–60 Hz) spectrum with reduced high-frequency energy. The Gemini Source™ (TGS, Houston, TX, USA) is a high volume (8000 in^3), single element source that produces a peak frequency of 3.4 Hz with a broad spectrum (~2–80 Hz) and has reduced high-frequency output relative to conventional arrays. The Harmony™ source (Shearwater Geoservices, Houston, TX, USA) is a 6000 in^3 modified hypercluster array of six 1000 in^3 airguns that uses frequency locking among closely spaced bubbles to enhance low-frequency output—producing a ~4.2 Hz peak frequency and a broadband spectrum while reducing high-frequency energy.

ULF technologies are considered impulsive, intermittent sources; however, they are designed to provide two primary advantages over conventional airguns. First, they provide deeper subsurface penetration and improved imaging of complex geologies due to the concentrated low-frequency energy. Second, the reduced signal amplitude at higher frequencies may lower sound exposure for marine mammals whose hearing ranges overlap with the higher frequency components of conventional airgun pulses. Descriptions and images of representative ULF systems are provided in File S1.

2.1.3. Marine Vibroseis (MV)

MV systems differ significantly from pneumatic sources because they generate controlled, continuous, or swept acoustic signals using electromechanical or hydraulic actuators that may be towed behind a vessel or deployed on the seafloor. Unlike impulsive airgun sources, MV systems produce non-impulsive signals with operator-defined frequency content and duration, resulting in lower peak sound pressure levels and a smoother temporal envelope. MV systems can be tuned for specific geological targets and survey objectives, supporting applications such as high-resolution imaging and full waveform inversion modeling. These characteristics may also reduce the potential for disturbance to marine mammals relative to impulsive sources. Operational details and acoustic source characteristics for an empirical survey using small-scale representative MV systems and a modeled large-scale MV system (i.e., the Marine Vibrator Joint Industry Project Integrated Projector Node [MV JIP IPN]) are summarized in File S1.

Table 1. Source levels for conventional airguns, airgun arrays, sparkers, and alternative seismic sources considered in this analysis. Source levels were derived from horizontal surface-affected waveforms, except for MV and sparkers. Horizontal surface-corrected spectra were used for MV. Source levels for all sparkers were taken directly from the primary reference. Where azimuthally dependent data were available, the broadside angle was assumed to reduce that directionality (see File S1 for details). Metrics are per-pulse sound exposure level (SEL_{ss}), zero-to-peak sound pressure level (PK SPL), and 90% energy-windowed RMS SPL. SEL is given for the entire pulse duration for all sources, which is typically less than 1 s for pneumatic sources and 5 s for MV JIP IPN sources.

Source Category	Source	Configuration	Tow Depth (m)	Pulse Interval (s)	SEL_{ss} (dB re 1 μPa^2 m^2 s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)	Primary Reference
Tier 1	5380 in^3	42 airguns	12	10	233.9	256.0	248.0	CMA Gundalf analysis
	5110 in^3	32 airguns	9	10	232.4	254.3	248.3	CMA Gundalf analysis
	4130 in^3	31 airguns	8	10	229.3	251.8	245.8	CMA Gundalf analysis
	1680 in^3	20 airguns	7	10	227.3	252.1	246.3	CMA Gundalf analysis
	1500 in^3 (3K psi)	6 airguns	10	10	225.7	251.2	244.1	CMA Gundalf analysis
Tier 2	1500 in^3 (2K psi)	6 airguns	10	10	222.1	248.2	240.1	CMA Gundalf analysis
	1000 in^3	12 airguns	12	10	222.9	247.3	239.3	CMA Gundalf analysis, Frankel and Ozanich [20]
	90 in^3	1 airgun	4	10	205.2	232.4	222.0	CMA Gundalf analysis, Zeddies et al. [21]
	30 in^3	2 airguns	4	10	206.4	235.5	230.2	CMA Gundalf analysis, Austin et al. [22]
	10 in^3	1 airgun	2	10	197.6	228.0	223.6	CMA Gundalf analysis
Tier 3	AA Dura-Spark	2400 J, 400 tip sparker	<1	0.5	188	225	214	Crocker and Fratantonio [18]
	AA Delta Sparker	2400 J sparker	1	0.5	185	221	205	Crocker and Fratantonio [18]
	SIG ELC 820	750 J sparker	1	0.5	182	214	206	Crocker and Fratantonio [18]
	AA Dura-Spark	100 J, 80 tip sparker	<1	0.5	173	207	200	Crocker and Fratantonio [18]
	AA Delta Sparker	500 J sparker	1	0.5	167	206	190	Crocker and Fratantonio [18]
	SIG ELC 820	300 J sparker	1	0.5	174	207	198	Crocker and Fratantonio [18]

Table 1. *Cont.*

Source Category	Source	Configuration	Tow Depth (m)	Pulse Interval (s)	SEL_{ss} (dB re 1 μPa^2 m^2 s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)	Primary Reference
Alternatives	TPS™	1–28,000 in^3	8	12	216.3	237.6	219.7	Sercel Pers. Comm., analysis per this study
	Gemini Source™	1–8000 in^3	8	5.5	216.9	240.0	231.0	TGS Nucleus analysis
	Harmony™	1–6000 in^3	8	10	226.2	249.1	244.0	Shearwater Geoservices Gundalf analysis
	MV JIP IPN	18 elements	6	5 on/5 off	217.2	218.6	210.6	Matthews et al. [23]; dynamic
	MV JIP IPN	1 element	6	5 on/5 off	196.5	199.0	193.1	Li and Martin [24]; dynamic—PILOT-19-B-1-09
	MV JIP IPN	2 elements	6	5 on/5 off	201.1	204.0	198.9	Li and Martin [24]; dynamic—PILOT-16-E-1-22
	MV JIP IPN	2 elements	6	5 on/5 off	200.1	203.4	197.9	Li and Martin [24]; stationary—PILOT-05-B-1-01

2.2. Marine Mammal Acoustic Criteria and Metrics

The MMPA protects all marine mammals, while the ESA provides additional protections for species listed as threatened or endangered. Although their definitions of "take" differ slightly, activities that may affect ESA-listed marine mammals must be considered under both statutes. Marine mammals are grouped into five functional hearing categories based on auditory anatomy and hearing sensitivity: low-frequency cetaceans, high-frequency cetaceans, very high-frequency cetaceans, phocid pinnipeds (in water and in air), and otariid pinnipeds (in water and in air) [25,26]. NMFS has regulatory authority over the protection of cetaceans and most pinnipeds, while the U.S. Fish and Wildlife Service has jurisdiction over sirenians, polar bears, walruses, and sea otters.

Under the MMPA, auditory injury equates to Level A harassment, while behavioral disturbance and TTS equate to Level B harassment[1]. NMFS [25] has defined auditory injury onset thresholds using dual criteria for whichever is exceeded first of the unweighted peak sound pressure level (PK SPL; $L_{p,0\text{-}pk}$ in dB re 1 μPa) and the auditory injury-weighted cumulative sound exposure level ($SEL_{Aud\ Inj}$; $L_{E,Aud\ Inj}$ in dB re 1 μPa^2 s) for impulsive sources and $SEL_{Aud\ Inj}$ for non-impulsive sources [25]. The auditory weighting functions for each hearing group are solely used for auditory injury onset and differ from the broader M-weighting functions used later in this analysis. For behavioral disturbance onset thresholds, NMFS currently uses a 90% energy-windowed root-mean-square sound pressure level (RMS SPL; $L_{p,rms,90\%}$) of 160 dB re 1 μPa for non-explosive impulsive sound sources (e.g., airguns and impact hammers) and intermittent sound sources (e.g., scientific and non-tactical sonar), and 120 dB re 1 μPa for continuous sounds [27]. Those are unweighted, non-cumulative (i.e., instantaneous) thresholds that are applicable for all marine mammal species, regardless of hearing group. Notably, the decision is made here to use the 160 dB re 1 μPa RMS SPL threshold as the criteria directly associated with behavioral disturbance for all sources. This choice was made to provide direct comparisons, but also because the operational timing assumed for the MV sources analyzed here is consistent with that of an intermittent sound source. These criteria, combined with source characteristics and propagation modeling, are used to estimate distances at which injury or disturbance may occur [28].

It should be noted that an inherent limitation of this work and generally of assessing acoustic impacts to marine mammals stems from the uncertainty in deriving acoustic criteria. Regarding auditory injury, the NMFS [25] criteria is based on the best available data for TTS and extrapolated to approximate auditory injury onset. However, in many instances data is only available for a limited number of species or a limited number of individuals for a given species [25]. Regarding behavioral disturbance, the authors recognize that behavioral response is complex and context-dependent [29], and further that it has been shown that dose–response functions more accurately predict behavioral response than single step function thresholds such as the 160 dB re 1 μPa RMS SPL threshold [30,31]. However, in this work we are focused on the acoustic properties of the sound sources considered here rather than accurate quantification of behavioral responses. Thus, it is deemed that the 160 dB re 1 μPa RMS SPL threshold is an appropriate means of a simplistic point of comparison.

Two approaches were used to determine the appropriate tiers for the alternative seismic sources. First, the current NMFS [25,32] auditory injury and behavioral disturbance onset thresholds were used to estimate approximate distances at which received levels may elicit auditory injury and behavioral disturbance for each source. These distances are used solely for cross-source comparison; they are not intended for take estimation. Therefore, the specific results herein (e.g., approximate distances to thresholds) likely will differ significantly from those that are more appropriate for estimating take from a more sophisticated modeling approach for a specific activity in a specific environment. It should further be noted that the risk of auditory injury from geophysical sources is reduced when standard mitigation and monitoring measures are implemented (Table 2).

Second, an audibility metric was incorporated that captures differences in spectral and temporal characteristics across seismic sources. We introduce a 60 s M-weighted SEL ($SEL_{60s,M}$; $L_{E,60s,M}$ in dB re 1 μPa^2 m^2 s) which is nicknamed the "Conrad metric." Sound exposure level (SEL) provides a consistent basis for comparing the acoustic energy of sources with differing durations or duty cycles [33], and a 60 s window exceeds the pulse interval of all sources considered, ensuring the temporal differences are fully captured. The older M-weighting functions introduced by Southall et al. [34] have been used to evaluate marine mammal behavioral responses [21,35]. M-weighting functions were used because they operate as frequency-dependent filters that emphasize broad audibility across each hearing group rather than the narrower weighting functions used for injury onset, offering a biologically relevant measure of audible energy. The $SEL_{60s,M}$ metric is a measure of the total acoustic energy produced by each source in 60 s and within a frequency range relevant to each hearing group. The 60 s M-weighted SEL is intended to compare seismic sources and is not intended as a metric to assess behavioral harassment. In all cases, the metric is represented herein as a source level (i.e., at 1 m distance).

Ranges to auditory impacts were assessed using NMFS [25,32] criteria alongside $SEL_{60s,M}$ values for each source and each marine mammal hearing group. While NMFS's thresholds provide a basis for estimating ranges to onset of auditory injury and behavioral disturbance, $SEL_{60s,M}$ adds a comparative measure of audibility that reflects spectral and temporal characteristics of the source. Although this approach diverges from the framework developed in Ruppel et al. [4], each of the factors examined in that study were incorporated to various degrees through a combination of the criteria and metrics that were analyzed. For example, $SEL_{60s,M}$ directly accounts for inaudible frequencies (Factor 1) and partially accounts for degree of exposure (Factor 5) by considering pulse duration and duration of pulse intervals, while distance to the 160 dB re 1 μPa behavioral threshold (Factor 2) is explicitly evaluated. Although directivity and beamwidth parameters (Factors 3 and 4) were not calculated, directional characteristics were considered by focusing on horizontal propagation (see Section 2.3 and File S1). Evaluation of PK SPL also was included, which informed airgun categorization in Ruppel et al. [4].

Together, these methods allow comparison of the potential for auditory injury and behavioral disturbance using NMFS [25,32] criteria while also characterizing relative audibility across hearing groups. This integrated framework supports consistent cross-source evaluation of potential auditory and behavioral impacts and builds upon the framework developed by Ruppel et al. [4].

2.3. Acoustic Analysis

A complete discussion of the source modeling methodology and associated rationale is presented in File S1. Briefly, source waveforms and spectra were derived from modeling via Gundalf [36] for all conventional sources and Harmony™, from Nucleus+ [37] for the Gemini Source™, and via the notional waveform as derived from far-field signatures for TPS™. Waveforms and spectra included surface reflections or ghost notches, and the effective horizontal characteristics were approximated from dip angles of 15°, 30°, and 45°, following techniques for measurement of noise from vessels [38] and recommendations for measuring seismic sources [39]. This represents the authors' best attempts to capture the likely horizontal down-range characteristics without conducting site-specific numerical propagation modeling. Notably, it is standard to define source levels as the theoretical or notional level at 1 m corresponding to an equivalent monopole source in a uniform medium [40]. In this case, metrics were derived from the approximate horizontal surface-affected source waveforms (i.e., PK SPL, SEL, RMS SPL) and do not meet this strict source level definition but are rather closer to what may be referred to as dipole source levels. Regardless, these metrics are simply referred to herein as "source levels," though caution should be exercised when applying them in other contexts. In this manuscript, source levels are denoted as such based on the inclusion of meters in the units (e.g., dB re 1 μPa m), following ISO 18405 [40].

In the case of MV, the authors did not have access to models or data associated with surface-affected (i.e., with ghost) characteristics and therefore used reported surface-corrected (i.e., without ghost) waveforms, spectra, and metrics from Matthews et al. [23] and Li and Martin [24]. Source level metrics for sparkers were taken from Crocker and Fratantonio [18], and a representative spectrum from McQueen et al. [41] was used for all sparkers.

2.3.1. Source Characterization

NMFS characterizes non-explosive sound sources as impulsive or non-impulsive for the purpose of selecting the appropriate auditory injury criteria and as intermittent or continuous for behavioral harassment thresholds. In this analysis, these distinctions were made categorically and based solely on source-specific, at-source characteristics; propagation-dependent factors that could cause an impulsive signal to become non-impulsive were not incorporated. For MV, the signal is non-impulsive, emitting sound at an approximate 50% duty cycle. It is recognized that there are very few sound sources that are truly continuous temporally. However, a key distinction between continuous and intermittent sound sources is that intermittent sounds have a more regular (i.e., predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle), which continuous sounds do not [28]. Therefore, the representative MV source is considered an intermittent source with respect to the behavioral disturbance thresholds. All other sources in this document are impulsive, intermittent sources.

2.3.2. Calculation of Auditory Injury Onset Ranges

Horizontal source spectra were weighted using the NMFS [25] auditory weighting functions. For each hearing group, weighting factor adjustments were calculated as the difference between the unweighted and hearing-group-specific weighted broadband levels. The associated adjustment factors, SEL source level (Table 1, as calculated from horizontal source waveforms, hereafter simply referred to as the SEL source level), pulse intervals, and uniform assumptions of vessel speed (2.0 m/s for sparkers and 2.315 m/s for all other sources) were entered into the NMFS Optional User Spreadsheet tool (Version 3.1, 2024) to estimate ranges to auditory injury thresholds (Table 2). Impulsive sources were evaluated using the mobile impulsive source tab; MV was evaluated using the non-impulsive intermittent mobile source tab [25]. This method assumes constant source velocity and direction, a stationary receiver, consistent pulse spacing, and propagation loss using spherical spreading [28,42]. For mobile sources, the NMFS Optional User Spreadsheet tool applies the "safe distance" concept from Sivle et al. [42], defined as the distance from the source beyond which the SEL-based threshold is not exceeded. Notably, the non-impulsive acoustic thresholds are higher than the thresholds for impulsive sources based on the reduced potential for auditory injury.

For estimating auditory injury ranges (impulsive sources only) to the PK SPL thresholds, PK SPL source levels were calculated from surface-affected source waveforms. Each source level was then propagated to the appropriate thresholds assuming spherical spreading, without considering absorption (Table 2). The simplifying assumption was made that range dependence follows spherical spreading for all sources and all metrics.

2.3.3. Calculation of Behavioral Disturbance Onset Ranges

Ranges associated with the onset of behavioral disturbance were estimated by determining the distance at which the received RMS SPL decayed to the 160 dB re 1 µPa threshold [32], assuming spherical spreading in the absence of absorption. The distances to the threshold were based on surface-affected source waveforms, except for MV, which used surface-corrected source waveforms. Frequency-dependent auditory weighting was not used when estimating behavioral disturbance ranges. It is important to note that the RMS SPL metric in practice depends strongly on the environment and has range dependence that requires time domain propagation modeling or empirical data to accurately estimate. For this effort, the RMS SPL was computed from source waveforms; therefore, the simplifying assumption was made that range dependence follows spherical spreading for all sources.

2.3.4. Calculation of 60 s M-Weighted SEL

For analysis of the 60 s M-weighted SEL, each spectrum was weighted according to the Southall et al. [34] M-weighting functions for each marine mammal hearing group (Table 3) to produce weighting factor adjustments. Weighting factor adjustments were calculated as the difference between the unweighted broadband level and the M-weighted broadband level using the horizontal source spectra. Single-shot SEL source levels (SEL_{ss}; $L_{E,ss}$ in dB re 1 µPa^2 m^2 s) were also used, as they represent a per-pulse source level that accounts for pulse duration. SELs were reduced by the weighting factor adjustment for each hearing group and adjusted according to the source-specific pulse interval (i.e., the time between pulses) to account for all energy within a 60 s time period. This method is represented in Equation (1):

$$L_{E,\,60s,\,M,\,hg} \;=\; L_{E,\,ss} - Adj_{M,\,hg} + 10Log_{10}(60\;s\;/t_{int})\;, \quad (1)$$

where $L_{E,\,60s,\,M,\,hg}$ is the hearing-group-specific 60 s M-weighted SEL, $L_{E,ss}$ is the SEL_{ss}, $Adj_{M,\,hg}$ is the hearing-group-specific weighting factor adjustment, and t_{int} is the pulse interval in seconds.

2.3.5. Tier Classification

Ruppel et al. [4] relied on multiple factors to ascribe sources into each tier, as described in Section 2.2 above. Because of this, it is not possible to draw a line between tiers based on a single metric. The somewhat qualitative definitions of tiers that emerged from [4] are a result of the multi-faceted and complex nature of the problem. Similarly, defining quantitative thresholds for tiers is outside the scope of this manuscript. Instead, this work aims to provide a general, science-based relative-risk arrangement of sources to support policy frameworks such as the referenced tiering system. Most importantly, we seek to clarify the relative risk associated with emerging sources compared with those previously placed within the existing framework.

Tiering determinations for this work are made as follows: when an alternative seismic source produced acoustic parameters comparable to those of a previously evaluated source assigned to Tiers 1–3, the alternative source was placed in the corresponding tier. Sources exhibiting characteristics consistent with those already classified as de minimis in the ONMP or with negligible estimated ranges for auditory injury and behavioral disturbance would likewise potentially be considered de minimis. However, none of the sources evaluated in this analysis met the criteria for de minimis classification.

3. Results

The auditory injury and behavioral disturbance onset ranges provided in this analysis are approximate estimates using simplified methods and intended for comparison across sources rather than for estimating take. Results likely will vary significantly from those generated by more sophisticated techniques, including location-specific propagation and animat exposure modeling. Thus, while useful for tiering sources, these ranges are not synonymous with location-specific estimates and are not recommended for use in assessing take or exposure.

3.1. Spectral Characteristics

One of the primary distinctions among the various sources considered is their relative energy distribution in the frequency domain. Many of the criteria considered depend strongly on this input, as the overlap of source spectra with marine mammal weighting functions dictates the portion of each signal that may contribute to weighted SEL metrics (i.e., auditory injury and the Conrad metric). Spectra for each source were converted to decidecade band SELs where necessary (i.e., unless the source data were taken from the literature in decidecade band SELs) and are shown in Figure 1, which provides a comparison of the analyzed alternative technologies and conventional sources in Tiers 1–3.

Figure 1 demonstrates that the alternative sources have a different distribution of energy at frequencies < 100 Hz compared to conventional airgun sources. Specifically, ULF pneumatic alternatives (i.e., Gemini Source™, Harmony™, and TPS™) exhibit greater energy than all conventional sources for some frequency bands below 10 Hz. Energy in frequency bands above approximately 10 Hz is lower for alternative technologies than the highest amplitude analyzed Tier 1 source (Figure 1). In the case of both the Gemini Source™ and TPS™, frequency band levels are within or below the range of levels associated with Tier 2 sources for all frequencies above approximately 5 Hz. For Harmony™, frequency band levels remain near the lower limit of Tier 1, from approximately 8 Hz to 200 Hz, and generally remain bounded by the Tier 2 sources for higher frequencies. The MV source is based on spectra from 1, 2, and 18 elements, and frequency band levels below 100 Hz are consistently within the range of Tier 2 sources. Beyond 100 Hz, the frequency band levels are significantly lower for the MV sources (Figure 1). The MV upper bounds above 100 Hz shown as solid green lines are based on measurements from Li et al. [24] and contain background noise contamination, while the dashed green line indicates the lower bound above 100 Hz based on the modeled results from Matthews et al. [23].

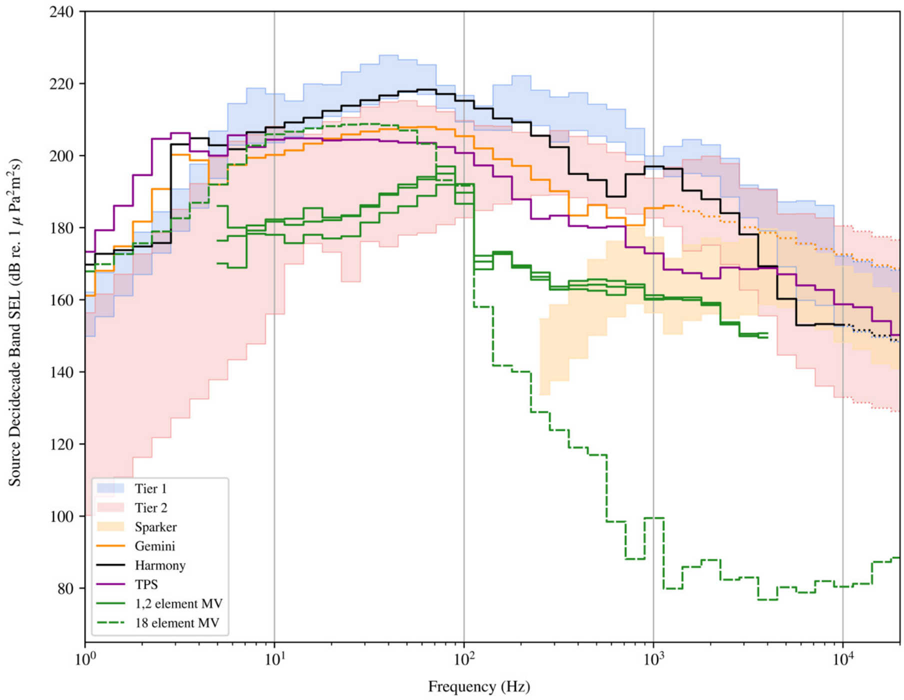

Figure 1. Decidecade unweighted SEL source level spectra for the Gemini Source™, Harmony™, TPS™, and MV JIP IPN (1, 2, and 18 elements) compared to the Tier 1–3 conventional sources considered in this analysis. The range of levels analyzed for each tier is shown by their respective shaded-colored regions. For simplicity, only two sparkers are included, representing the lowest and highest amplitude sources. The spectra for sparkers only extend down to approximately 250 Hz, and while they capture most of the total expected energy, it should be assumed that additional energy extends to lower frequencies. All four configurations of MV sources are shown: single-element MV (dynamic), dual-element MV (stationary and dynamic), and modeled data from a dynamic 18-element MV array (see Table 1 and File S1 for source details). Finely dotted lines for pneumatic sources indicate applied high-frequency extrapolation (i.e., 15 dB per decade for decidecade bands).

3.2. Auditory Injury Ranges

Application of the NMFS [25] auditory weighting functions revealed substantial differences in predicted auditory injury ranges across source types (Table 2). Auditory injury has the potential to occur when either the $SEL_{Aud\ Inj}$ threshold or the unweighted PK SPL threshold is exceeded. To be conservative, the criterion that results in the largest injury range is generally used. For all sources, either the $SEL_{Aud\ Inj}$ thresholds for low-frequency cetaceans or the unweighted PK SPL thresholds for very high-frequency cetaceans result in the largest injury ranges (Table 2). The auditory injury onset ranges (Table 2) for HF cetaceans and pinnipeds are generally small for all sources (i.e., ≤20 m for HF cetaceans and OW pinnipeds, and a maximum of 165 m for PW pinnipeds). For VHF cetaceans, the PK SPL threshold results in auditory injury onset ranges of hundreds of meters for all airgun arrays with volumes of >1000 in^3, as well as Harmony™. Auditory injury onset ranges for $SEL_{Aud\ Inj}$ for LF cetaceans are significant for Tier 1 airgun arrays generally, approaching 3 km for the 5380 in^3 airgun array but decreasing to tens of meters or less for small volume airguns, sparkers, MV, TPS™ and the Gemini Source™.

ULF pneumatic sources produced smaller $SEL_{Aud\ Inj}$ ranges for pinnipeds and high- and very high-frequency cetaceans due to their reduced high-frequency energy content compared to Tier 1 and the larger Tier 2 conventional airgun arrays (Table 2). Some alternative sources (TPS™, Gemini Source™, and MV) have smaller or similar expected auditory injury onset ranges compared to the Tier 2 conventional sources and have substantially smaller ranges compared to Tier 1 conventional airgun arrays (Table 2). Thus, considering the expected likelihood of auditory injury and based on the configurations presented, two pneumatic ULF alternative sources (i.e., TPS^{TM} and Gemini Source^{TM}) can be placed in Tier 2. For the Harmony^{TM} source, expected auditory injury onset ranges were similar to the 1500 in^3 3000 psi airgun array, which is the lower bound of Tier 1 (Table 2). The small-scale MV systems, which were analyzed using the higher non-impulsive $SEL_{Aud\ Inj}$ thresholds rather than the impulsive thresholds, have null SEL ranges for all hearing groups (Table 2). The likelihood of auditory injury is sufficiently less than Tier 2 sources, such that expected impacts are at the most commensurate with Tier 3 for the smaller configurations of MV based on auditory injury onset ranges alone. MV sources operated continuously were not analyzed and should be treated on a case-by-case basis.

3.3. Behavioral Disturbance Onset Ranges

Conventional Tier 1 airgun arrays generated the largest behavioral disturbance zones. In this analysis, the TPS^{TM} and Gemini Source^{TM} produced behavioral ranges comparable to or smaller than those of Tier 2 conventional sources (Table 2). For the Harmony^{TM} source, expected behavioral disturbance ranges were similar to the 1500 in^3 3000 psi airgun array, which is the lower bound of Tier 1 (Table 2). MV systems, evaluated using the 160 dB re 1 µPa threshold for non-explosive impulsive or intermittent sources, exhibited behavioral disturbance onset ranges similar to sparkers due to their comparable RMS SPLs (Table 2).

Table 2. NMFS auditory injury (AUD INJ) "safe distances" (m) calculated for auditory-weighted cumulative SEL (dB re 1 µPa^2 s) and PK SPL (dB re 1 µPa) and the spherical spreading distance (m) to the 160 dB threshold based on RMS SPL (dB re 1 µPa). PK SPL was calculated only for impulsive sources. MV signals are non-impulsive, thus the non-impulsive auditory injury criteria were used. Marine mammal hearing group abbreviations are low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), phocid pinnipeds in water (PW), and otariid pinnipeds in water (OW) [25].

Source Category	Source	Configuration	SEL AUD INJ Safe Distance					PK SPL AUD INJ Safe Distance					160 dB Distance
			LF	HF	VHF	PW	OW	LF	HF	VHF	PW	OW	
Tier 1	5380 in^3	42 airguns	2910	4	92	165	13	50	20	502	45	20	25,214
	5110 in^3	32 airguns	1674	2	38	71	5	41	16	411	37	16	26,062
	4130 in^3	31 airguns	1230	1	14	53	3	31	12	308	27	12	19,389
	1680 in^3	20 airguns	1087	1	20	55	3	32	13	320	28	13	20,694
	1500 in^3 (3K psi)	6 airguns	486	2	153	43	7	29	11	287	26	11	16,040
Tier 2	1500 in^3 (2K psi)	6 airguns	224	1	69	21	3	20	8	203	18	8	10,155
	1000 in^3	12 airguns	205	1	118	23	4	18	7	183	16	7	9189
	90 in^3	1 airgun	10	0	0	1	0	3	1	33	3	1	1258
	30 in^3	2 airguns	17	0	1	2	0	5	2	47	4	2	3252
	10 in^3	1 airgun	3	0	0	0	0	2	1	20	2	1	1511
Tier 3	AA Dura-Spark	2400 J, 400 tip sparker	9	0	213	7	3	1	1	14	1	1	501
	AA Delta Sparker	2400 J sparker	5	0	107	4	1	1	0	9	1	0	178
	SIG ELC 820	750 J sparker	2	0	54	2	1	0	0	4	0	0	200
	AA Dura-Spark	100 J, 80 tip sparker	0	0	7	0	0	0	0	2	0	0	100
	AA Delta Sparker	500 J sparker	0	0	2	0	0	0	0	2	0	0	32
	SIG ELC 820	300 J sparker	0	0	8	0	0	0	0	2	0	0	79

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Table 2. *Cont.*

Source Category	Source	Configuration	SEL AUD INJ Safe Distance LF	HF	VHF	PW	OW	PK SPL AUD INJ Safe Distance LF	HF	VHF	PW	OW	160 dB Distance
Alternatives	TPS™	1–28,000 in^3	11	0	1	0	0	6	2	60	5	2	962
	Gemini Source™	1–8000 in^3	70	0	25	2	0	8	3	79	7	3	3541
	Harmony™	1–6000 in^3	415	0	4	8	1	23	9	227	20	9	15,774
	MV JIP IPN	18 elements	0	0	0	0	0	n/a	n/a	n/a	n/a	n/a	339
	MV JIP IPN	1 element	0	0	0	0	0	n/a	n/a	n/a	n/a	n/a	45
	MV JIP IPN	2 elements	0	0	0	0	0	n/a	n/a	n/a	n/a	n/a	88
	MV JIP IPN	2 elements	0	0	0	0	0	n/a	n/a	n/a	n/a	n/a	79

3.4. 60 s M-Weighted SEL

The $SEL_{60s,M}$ source level metric provided additional insight into broad audibility across hearing groups, while also capturing important temporal characteristics of the sound source (i.e., pulse duration and pulse interval). For low-frequency cetaceans, the TPS™ and Gemini Source™ produced $SEL_{60s,M}$ values within the range of those calculated for Tier 2 conventional sources (Table 3), reflecting strong overlap with low-frequency cetacean hearing sensitivity. As shown in Figure 2, the low-frequency cetacean $SEL_{60s,M}$ values are approximately the same (i.e., within 1 dB) as the unweighted SEL_{60s} values for all evaluated sources, except the 18-element MV and TPS™, which were reduced by ~1 and 2.6 dB, respectively. Notably, recent evidence suggests mysticetes may be more reasonably represented by two hearing groups (very low frequency and low frequency) [43]. In this case, the differences between the sources in Figure 2 may be understated for those species which would be placed into the updated low-frequency hearing group. For pinnipeds and high- and very high-frequency cetaceans, $SEL_{60s,M}$ values for TPS™ and Gemini Source™ were lower than those of Tier 1 and 2 airgun arrays ≥1000 in^3 (Figure 2; Table 3), consistent with their reduced high-frequency output. For all hearing groups, $SEL_{60s,M}$ values for Harmony™ were similar to the 1500 in^3 airgun arrays (Figure 2; Table 3). The single and dual-element MV sources produced lower $SEL_{60s,M}$ values across all hearing groups relative to ULF sources, conventional airguns, and high-energy sparkers (Figure 2; Table 3), with the exception of the single 10 in^3 airgun. Additionally, the 18-element MV $SEL_{60s,M}$ is lower for all hearing groups than that of conventional airgun arrays and ULF sources, with the exception of the 30 in^3 airgun array. Together, these results indicate a general and significant reduced audibility of MV sources compared to other technologies.

In categorizing airguns, Ruppel et al. [4] compiled peak source levels as a function of total air volume in order to visualize a break point between Tier 1 and Tier 2, derived based on separate known relationships between air volume and peak pressure for single airguns and airgun arrays. A similar visualization is presented in Figure 3. Rather than examining the relationship between air volume and peak pressure, Figure 3 shows the relationship between PK SPL and $SEL_{60s,M}$ for low-frequency cetaceans using surface-affected source levels, except for MV, which used surface-corrected source levels. According to NMFS [25], it is recognized that PK SPL is not an evaluated metric for non-impulsive sources. However, PK SPL can be computed for any acoustic signal, and it is often reported for these sources. Further, because impulsive sources typically have high relative PK SPL, inclusion of this metric allows consideration of relative impulsivity across sources. Because the $SEL_{60s,M}$ encompasses information about both frequency composition and temporal characteristics, the relative position of each source on this plot provides a meaningful comparison across sources (Figure 3). The low-frequency cetacean hearing group was chosen since this group may be the most sensitive to exposures from these low-frequency sources.

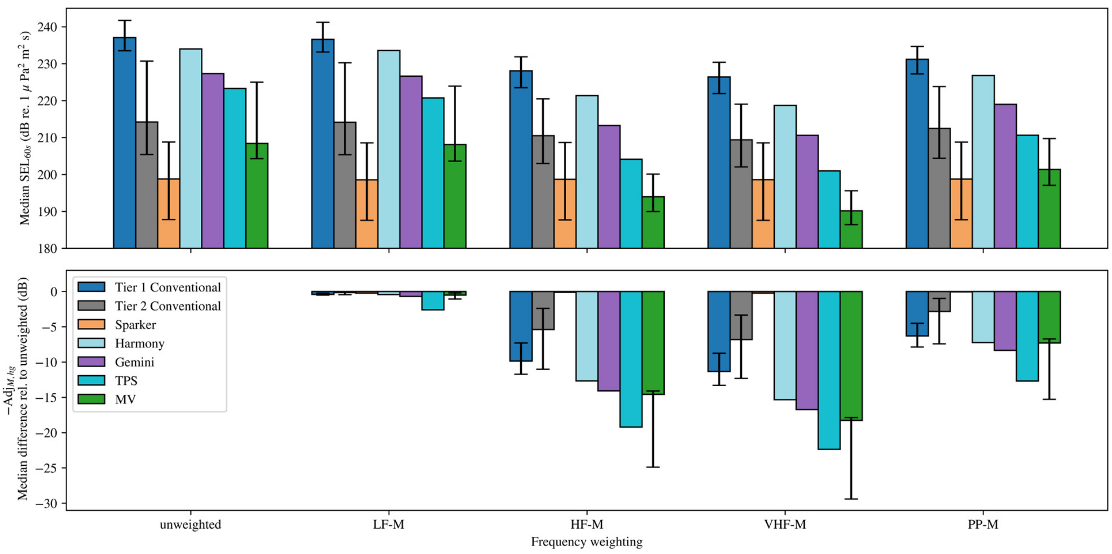

Figure 2. Comparison of unweighted SEL_{60s} and M-weighted SEL_{60s} for all evaluated sources (**top panel**), and the relative differences in decibels between the unweighted SEL_{60s} and marine mammal hearing-group-specific M-weighted SEL_{60s} (**bottom panel**). For Tier 1, Tier 2, sparkers, and MV, multiple sources were evaluated per category. For these categories, the bar amplitudes are their associated median value. The error bars indicate the minimum and maximum values in each case. M-weighted marine mammal hearing group abbreviations are low-frequency cetaceans (LF-M), high-frequency cetaceans (HF-M), very high-frequency cetaceans (VHF-M), and pinnipeds in water (PP-M).

Table 3. The 60 s M-weighted SEL ($SEL_{60s,M}$; dB re 1 μPa^2 m^2 s) source levels for marine mammal hearing groups. Pinnipeds are in a single hearing group following the methods and hearing ranges from Southall et al. [34]. The terms high- and very high-frequency cetaceans [25] correspond to mid- and high-frequency cetaceans, respectively, in Southall et al. [34]. Marine mammal hearing group abbreviations are low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and pinnipeds in water (PP).

Source Category	Source	Configuration	$SEL_{60s,M}$			
			LF	HF	VHF	PP
Tier 1	5380 in^3	42 airguns	241.2	231.9	230.4	234.7
	5110 in^3	32 airguns	239.8	228.5	226.9	232.3
	4130 in^3	31 airguns	236.6	228.1	226.3	231.2
	1680 in^3	20 airguns	234.9	227.8	226.4	230.6
	1500 in^3 (3K psi)	6 airguns	233.2	223.5	221.9	227.2
Tier 2	1500 in^3 (2K psi)	6 airguns	229.5	220.5	219.0	223.8
	1000 in^3	12 airguns	230.3	219.7	218.4	223.3
	90 in^3	1 airgun	212.8	207.6	206.2	210.1
	30 in^3	2 airguns	214.1	210.5	209.4	212.4
	10 in^3	1 airgun	205.3	203.0	202.0	204.4
Tier 3	AA Dura-Spark	2400 J, 400 tip sparker	208.6	208.7	208.6	208.7
	AA Delta Sparker	2400 J sparker	205.6	205.7	205.6	205.7
	SIG ELC 820	750 J sparker	202.6	202.7	202.6	202.7
	AA Dura-Spark	100 J, 80 tip sparker	193.6	193.7	193.6	193.7
	AA Delta Sparker	500 J sparker	187.6	187.7	187.6	187.7
	SIG ELC 820	300 J sparker	194.6	194.7	194.6	194.7

Table 3. *Cont.*

Source Category	Source	Configuration	$SEL_{60s,M}$			
			LF	HF	VHF	PP
Alternatives	TPS™	1–28,000 in^3	220.7	204.1	201.0	210.6
	Gemini Source™	1–8000 in^3	226.6	213.2	210.6	219.0
	Harmony™	1–6000 in^3	233.6	221.3	218.7	226.8
	MV JIP IPN	18 elements	223.9	200.1	195.6	209.7
	MV JIP IPN	1 element	203.6	190.0	186.4	197.1
	MV JIP IPN	2 elements	208.7	194.8	191.0	202.2
	MV JIP IPN	2 elements	207.5	193.0	189.3	200.5

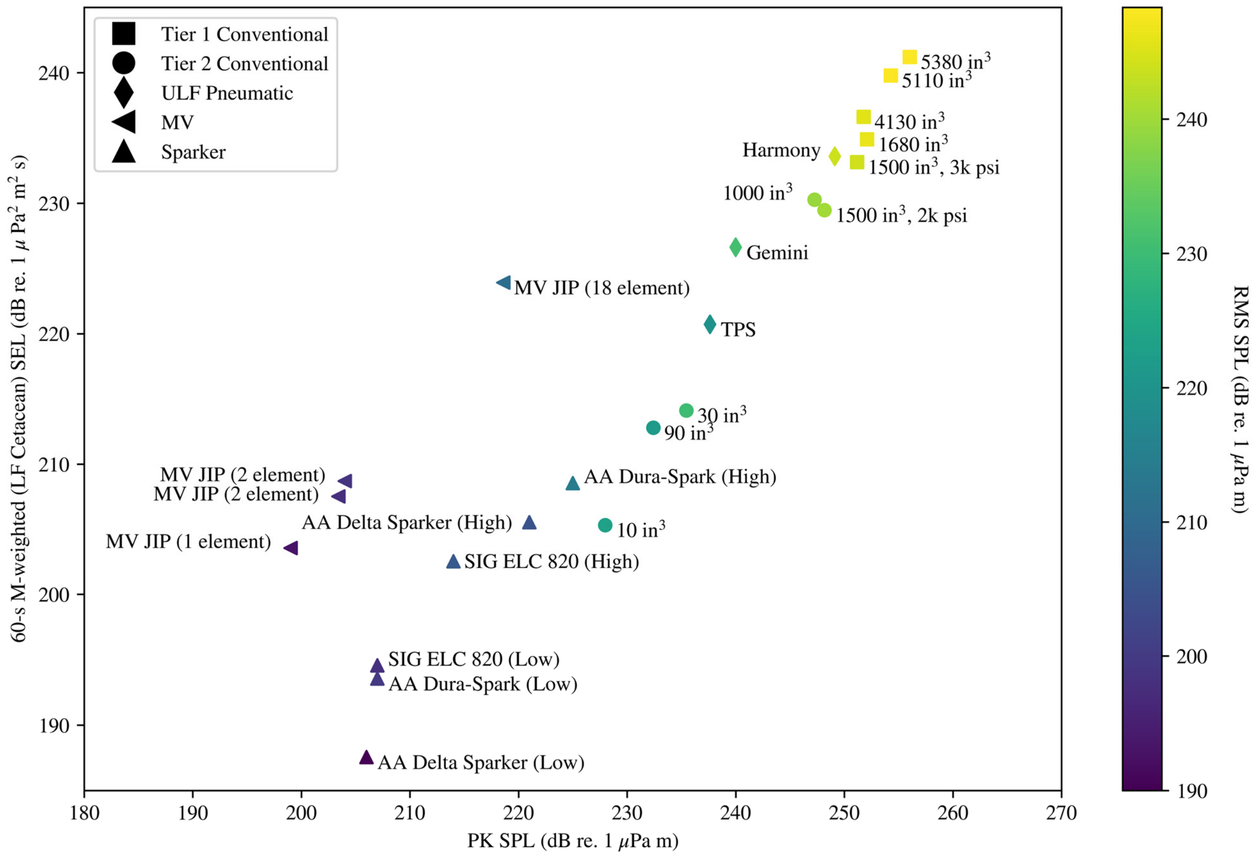

Figure 3. Visual comparison of PK SPL and $SEL_{60s,M}$ source levels for all sources. The low-frequency cetacean hearing group was selected for the representative 60 s M-weighted SEL ($SEL_{60s,M,LF}$) values. Sources are colored based on RMS SPL source levels shown on the secondary y-axis.

4. Discussion

This analysis evaluated four emerging alternative seismic sources within the tiered source classification framework established by Ruppel et al. [4] and the ONMP (https://www.boem.gov/environment/center-marine-acoustics/regulatory-policy accessed on 30 June 2026). By applying the NMFS [25,32] auditory injury and behavioral disturbance onset thresholds alongside a new metric that allows for comparisons across geophysical source types ($SEL_{60s,M}$), the analysis demonstrated that ULF pneumatic sources and a representative MV system differ meaningfully from conventional airgun arrays in their acoustic characteristics and their potential to affect marine mammals. Compared to Tier 1 airgun arrays, this analysis indicates that the TPS™, Gemini Source™, and MV arrays have lower energy over a 60 s window, smaller auditory injury ranges, and smaller behavioral disturbance ranges for all marine mammal hearing groups (Tables 2 and 3). Taken together, this assessment indicates that sources evaluated in Tiers 2 and 3 could justifiably warrant less restrictive mitigation requirements than Tier 1 arrays, thereby supporting their broader use and providing a foundation for the more detailed discussion that follows.

ULF pneumatic sources concentrate peak spectral energy below 10 Hz and exhibit steep decay above roughly 60–90 Hz, resulting in reduced audibility for pinnipeds, and high- and very high-frequency cetaceans compared to conventional airgun arrays. Additionally, peak energy for the analyzed ULF pneumatic sources is below the cut-off for presumed low-frequency cetacean hearing range (i.e., 7 Hz–36 kHz) [25], which is not the case for conventional airgun sources.

When considered collectively, TPS™, Gemini Source™, and Harmony™ all demonstrate reduced high-frequency output above 200 Hz and overall acoustic energy consistent with or less than the lower boundary of Tier 1 conventional airgun arrays; however, their relative acoustic footprints differ, with TPS™ exhibiting the lowest impact, followed by Gemini Source™ and then Harmony™ (Figure 3; Tables 1–3). These differences underscore the need to evaluate emerging technologies based on their measured acoustic characteristics when assigning mitigation tiers. Based on the configurations considered, TPS™ and Gemini Source™ align well with Tier 2 (Figures 1–3). The acoustic profile of the Harmony™ source is comparable to the 1500 in^3 array operated at 3000 psi, which represents the lower boundary of Tier 1 and is therefore provisionally placed in Tier 1. The distinction between Tiers 1 and 2 in Ruppel et al. [4] did not consider a source's operational pressure in psi, but our work shows that this factor should be considered in future iterations. At this time, tier placement has not been determined for a survey configuration that uses multiple ULF sources fired simultaneously, fired nearly simultaneously (e.g., as used in seismic apparition), or operated in conjunction with conventional airguns. For example, Gemini Source™ as evaluated (i.e., single 8000 in^3 unit fired with a 5.5 s dither) is categorized as Tier 2. However, significant variations of this configuration (e.g., higher pressure, higher volume, simultaneous firing of multiple units, or shorter pulse intervals) may warrant a Tier 1 categorization and should be evaluated on a case-by-case basis.

For MV, tier placement currently depends on the deployment scale. The MV source operated with single- and dual-elements aligned with Tier 3 due to its non-impulsive characteristics, lower source levels, reduced high-frequency output compared to the smallest conventional airgun sources, and <100 m spherical spreading ranges to 160 dB RMS SPL, which are comparable to the three evaluated lower energy sparkers (Figures 1–3; Tables 1–3). There is potential for small MV arrays such as those examined to be grouped as Tier 4 (de minimis) sources as more field data are collected. At the time of writing, data analysis is underway for a behavioral response study of tagged foraging blue (*Balaenoptera musculus*) and fin whales (*B. physalus*) exposed to a single-element MV JIP IPN system [44]. However, it will likely take several years before sufficient behavioral response studies or other science can support such a distinction for these relatively powerful geophysical sources.

For this analysis, empirical data were lacking for the 18-element MV array, and we relied instead on modeled data [23]; therefore, there is uncertainty as to whether this MV belongs in Tier 2 or Tier 3. Empirical data will be essential to determine the appropriate mitigation tier for full-scale MV arrays. As additional MV technologies emerge, their classification similarly will require case-by-case assessment. The tiering framework is designed to accommodate such developments, providing a flexible, source-based, quantitative approach. Notably, Austin et al. [45] recently conducted measurements of the SAExploration MV source in shallow water (2 Triton elements in a single tow body at a depth of 5 m). The estimated source levels were 183 and 192 dB re 1 μPa^2 m^2 s, for low- and high-frequency sweeps, respectively. If converted to a 5 s SEL for comparison to the MV JIP sources in this analysis, the high-frequency sweep would yield approximately 199 dB re 1 μPa^2 m^2 s. Due to similarities in source level and the spectrum presented in Austin et al. [45] for the high-frequency sweep, the SAExploration MV source is expected to have similar results to the single- and dual-element MV JIP sources.

The results indicate that these four alternative seismic source technologies occupy an intermediate space, where they are quieter and emit lower frequency sound than conventional airgun arrays, yet none currently fall within the Tier 4 (de minimis) classification under the ONMP due to their acoustic footprint. Tier 4 sources are described as "unlikely to result in incidental take of marine mammals," even without implementation of mitigation measures. In this analysis, the MV sources are unlikely to result in take for some marine mammal species based on the sources' frequencies primarily being outside the hearing range of those species, with the exception of low-frequency cetaceans and pinnipeds. Therefore, we cannot deem the analyzed MV sources as de minimis. This analysis did not evaluate modified airgun technologies such as Bluepulse™ and eSource™. It is possible that some configurations of these and similar sources marginally above 1500 in^3 in total volume or with 12 or more airguns have acoustic characteristics commensurate with Tier 2 and therefore should be evaluated in the future.

Although the present assessment relies on the best available early measurement data for emerging alternative seismic sources, several uncertainties remain. We have applied the most robust source modeling approaches currently available to account for known variability amongst the sources, and we have worked closely with technology developers to understand and predict the acoustic characteristics of these systems and their potential implications for marine mammals. Even with these efforts, alternative seismic sources cannot yet be classified with the same confidence as conventional airguns. General marine animal behavioral response data for ULF and MV systems remain sparse, and source characterization across many operational modes and environmental conditions is still incomplete. Reported source levels can vary depending on assumptions made associated with directionality and tow depth, and due to the inclusion or removal of the surface reflections. The authors have taken care to compare sources equally when possible, and this approach will need to be included in future analyses of alternative sources. Further, significant uncertainty remains regarding the high-frequency characteristics of airguns [46]. This is a challenging problem to solve numerically [47] and is complicated by the potential for high-frequency byproduct sounds [48], which may also exist for the alternative sources considered here. While most of the energy for all sources is at lower frequencies, energy at high frequencies can have a strong influence on $SEL_{Aud\ Inj}$ for higher frequency hearing groups. Our focus on low-frequency cetacean M-weighted SEL in Figure 3 mitigates this to some degree, but future work is needed to resolve true differences in high-frequency content. Additionally, a full-scale MV system capable of deep-penetration seismic imaging has yet to be developed. Addressing these gaps would improve the precision of tier placement and may ultimately support broader adoption of lower impact technologies, including potential future consideration of some systems for Tier 4 classification.

This analysis demonstrates that the evaluated ULF pneumatic sources and a representative MV system generally potentially have lower effects on marine mammals compared to Tier 1 conventional airgun arrays. These findings extend the source-based framework of Ruppel et al. [4] and provide a science-based foundation for integrating alternative technologies into the current U.S. regulatory context, while also offering an approach applicable internationally in jurisdictions where the evaluated sound sources are used. This approach supports innovation of lower impact technologies by ascribing mitigations that are commensurate with impacts, which will advance efforts to reduce anthropogenic sound in the ocean.

Source-based classification can be incredibly useful as regulators aim to provide predictability to industry but should be treated as an iterative process that is periodically updated as new information on marine mammal biology and source characteristics emerge. It is important that industry continues to simultaneously develop new sources and conduct measurements in realistic field conditions using the best available measurement standards so that these classifications can be updated. The scientific community should focus on behavioral response studies and opportunistic field measurements to aid regulators in their assessments. In turn, regulators should continually assess new information and use it to ascribe mitigations that are commensurate with impacts. This comprehensive approach offers a path to quieting while maintaining or even advancing industry geophysical capabilities.

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Note

[1] See 16 U.S.C. 1362(18) for definitions of "harassment" under the MMPA.

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Supplementary Data Appendix to *Categorizing Alternative Seismic Sources Based on Their Potential to Affect Marine Mammals*

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This data appendix contains information, figures, and tables regarding the acoustic sources evaluated in this paper and the methods we used.

Source Characteristics Analysis

The goal of this analysis was to compare the relative source characteristics as they are likely to be received at range. The analysis was designed for the specific purpose of providing fair comparisons between a variety of sources with respect to their expected far-field horizontal characteristics. Importantly, the analysis was not designed for prediction of take for a specific activity or location.

To simplify the analysis and attain environmentally agnostic and source-neutral results, the analysis conducted was simplified with respect to propagation modeling (i.e., simple spreading laws). In contrast to common numerical propagation models, this analysis does not inherently include boundary effects such as surface reflections. Importantly, surface-corrected source levels (i.e., true hypothetical source levels absent surface effects) are theoretical in nature unless propagated through an appropriate propagation model in a particular environment and are therefore not as meaningful for direct comparison. For these reasons, sound level metrics (sound exposure level [SEL], root-mean-square sound pressure level [RMS SPL], and peak sound pressure level [PK SPL]) and spectra are derived from surface-affected waveforms that include 'ghost' reflections from the surface, where possible. Unless stated otherwise in the following sections, for all sources analyzed, surface-affected waveforms and spectra were calculated using Gundalf [1] or Nucleus[1] [2], and by including a surface reflection coefficient of -1.

Reducing Directionality

Airgun arrays are inherently complex acoustic sources with frequency-dependent directionality, making it difficult to characterize them using a single waveform or spectrum, regardless of whether surface reflections are included. Unlike for a theoretical point source, source characteristics for airgun arrays result from the combined acoustic energy of several distributed sources. Their output varies with both downward directivity (i.e., dip angle, measured in the plane perpendicular to the sea

[1] Raw output files from Nucleus+ software run for the Gemini Source™ were provided by TGS.

surface) and azimuthal angle (i.e., in the plane parallel to the sea surface). Therefore, directionality must be reduced carefully to obtain results that are characteristic of down-range sound levels and spectrum for all azimuths. Figure S1 shows the general coordinate system used and defines dip and azimuthal angles.

For azimuthal directionality, the broadside angle (90 degrees clockwise relative to vessel heading) was selected since the broadside sound fields have a stronger influence on the overall ensonified area of a mobile source as it moves along track-lines. Additionally, while there is considerable azimuthal directionality at higher frequencies, broadband levels for many arrays are relatively uniform with azimuth. For example, the 5,110 in^3 array examined exhibits only minor azimuthal variation in broadband SEL (approximately 1–2 dB). Conventional arrays considered here generally exhibited slightly higher broadband levels in the broadside direction relative to other azimuths.

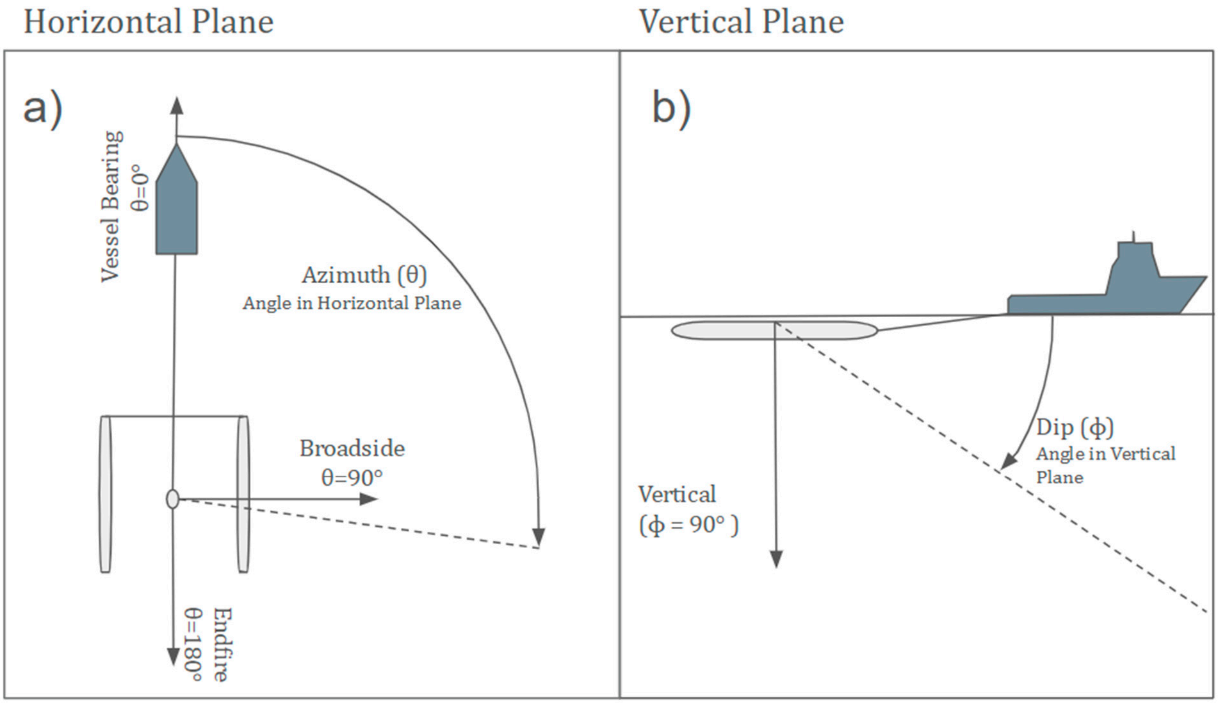

Figure S1. General coordinate system used for source directionality: (a) definition of azimuthal angle, as well as broadside and endfire aspects in the horizontal plane, (b) definition of dip angle in the vertical plane.

In reducing vertical directionality, source levels referenced to the horizontal plane are often used to represent monopole point source equivalent source levels [e.g., 3]. This is practical given the sound field at long ranges is dominated by sound propagating close to horizontal [4]. In those cases [e.g., 3], the true horizontal direction is used, and surface effects are included by way of the propagation model. However, when using surface-affected data, sound levels very near horizontal are not appropriate to represent down-range sound fields due to significant cancellation of energy via the Lloyd's Mirror effect. To resolve this, effective 'horizontal' surface-affected source levels and spectra are computed from the linear arithmetic mean taken over dip angles of 15, 30, and 45 degrees [5,6], unless stated otherwise in the following sections due to data availability. This approach provides a more realistic representation of what a distant receiver would encounter without relying on a propagation model and therefore allows comparisons that are independent of geographic location. Similarly, narrowband spectra were computed by taking the arithmetic mean over the same angles in each frequency bin. We applied this method to all of the following analyzed sources: conventional airguns and airgun arrays (i.e., 5,380 in^3, 5,110 in^3, 1,500 in^3, 1,000 in^3, 90 in^3, 30 in^3), Harmony™, Tuned Pulse Source (TPS)™, and Gemini Source™. The following sections provide the resulting waveforms, spectra, and derived metrics. Data for these sources were modeled using Gundalf [7], except in the case of Gemini Source™ (in which Nucleus+ provided surface-affected waveforms) and TPS (in which notional waveforms were leveraged). For marine vibroseis (MV), surface-affected data were not available, and thus horizontal surface-corrected data were used. Each source's waveforms, spectra, and acoustic metrics also are discussed.

High-Frequency Extrapolation

For some sources, the available or computed spectrum extends to 20 kHz, while others are truncated near 1 kHz. To account for potentially missing energy from approximately 1 to 20 kHz, a log-linear roll-off of 25 dB per decade was applied for narrowband spectra of pneumatic sources (airguns, airgun arrays, TPS™, Gemini Source™, and Harmony™) for which the data did not extend to 20 kHz. This assumption is based on several datasets that support a decay rate of roughly 20–26 dB per decade in this band for surface-affected airgun signatures [8-11]. There is a fair amount of uncertainty generally regarding the magnitude of the high-frequency content in airgun signals [e.g., 9,12], and we discuss the implications of this assumption, particularly for M-weighted levels, in the manuscript. For MV, no extrapolation was assumed, and therefore the data for those sources do not extend to 20 kHz. However, the modeled signatures from Matthews *et al.* [13] had insignificant energy above approximately 200 Hz, and Li and Martin [14] only attributed sound levels at and below 100 Hz to the MV sources. Thus, it was deemed unnecessary to approximate spectral characteristics to 20 kHz for MV.

Root-mean-square Sound Pressure Level

Regarding RMS SPL, the acoustic metric associated with behavioral harassment for impulsive or intermittent sources, is defined as the RMS SPL calculated over the time window that contains 90% of the acoustic energy. This is true for all sources considered, including MV when operated intermittently. For methodology associated with this windowing technique, see Madsen [15]. As this metric is range and environment dependent, it can be challenging to represent it in a generic sense (i.e., as a source level). One option is to assume a standard relative offset between SEL and RMS SPL (e.g., 6–8 dB) based on empirical data and anchor the values to the less variable sound exposure level. However, because this analysis consists of a variety of sources with different temporal characteristics, a single standard relative offset is likely not applicable for all sources, and determining an appropriate standard far-field relative offset is beyond the scope of this work. In lieu of time domain propagation modeling in representative environments, the RMS SPL used was calculated from the surface-affected source waveform at 1 m. This results in the overall assumption that, for all sources RMS SPL decays with range proportionally. Therefore, values provided for RMS SPL should be used with caution, and associated spherical spreading ranges to the threshold of 160 dB re 1 μPa carry significant uncertainty. This situation is similar to the frequently repeated cautionary statement that PK SPL source levels for airguns: though they may be useful for approximating far-field levels, they are theoretical in nature, and corresponding values of pressure near the source are typically much lower [16].

Conventional Seismic Sources

5,380 in^3 Array

The 5,380 in^3 airgun array used in this analysis was modeled as an example of the upper volume end of 'medium' sized seismic arrays (i.e., 1,500 to 5,400 in^3). The array configuration is shown in Figure S2. The array consisted of 42 1900 LLXT airguns, ranging in size from 70 to 230 in^3. Each airgun had an operating pressure of 2,000 psi and a tow depth of 12 m. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S3, along with derived metrics). Final horizontal surface-affected source levels are given in Table S1. The decidecade band SEL spectrum is provided in Figure S4.

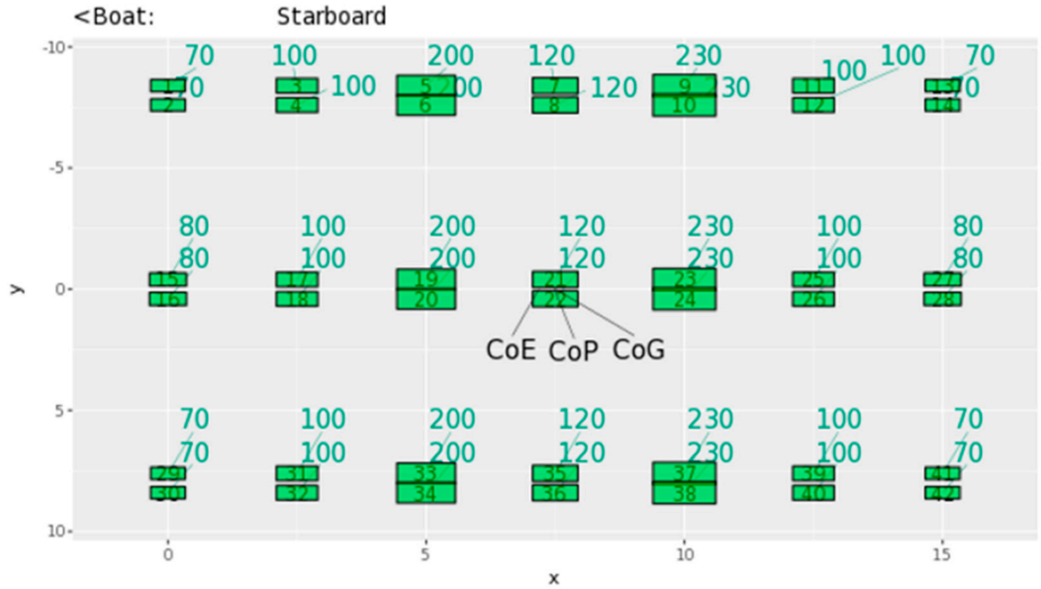

Figure S2. The 5,380 in³ airgun array configuration for Gundalf simulation. Individual gun volumes are provided in green text in in³; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and the geometric center, respectively.

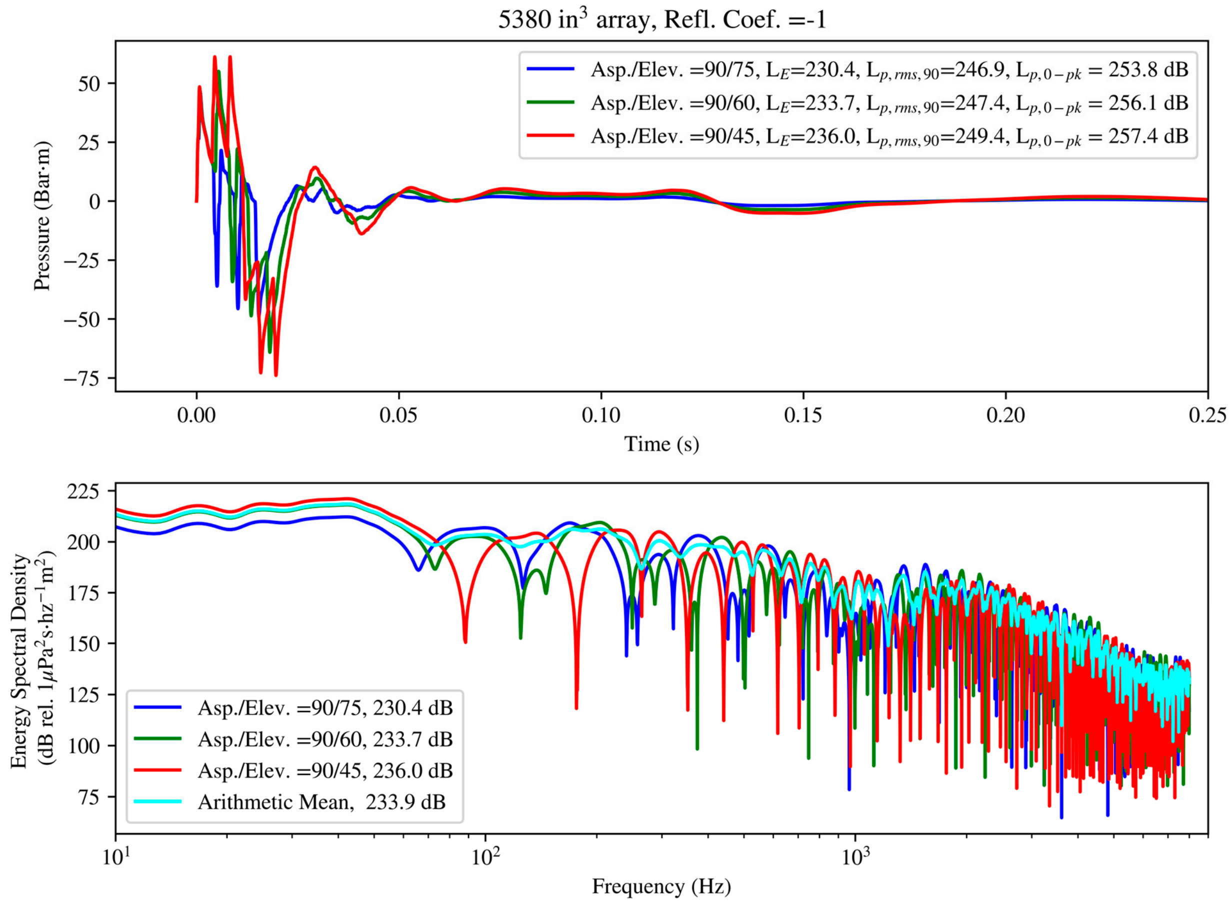

Figure S3. Surface-affected waveforms, spectra, and associated metrics for the 5,380 in³ array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

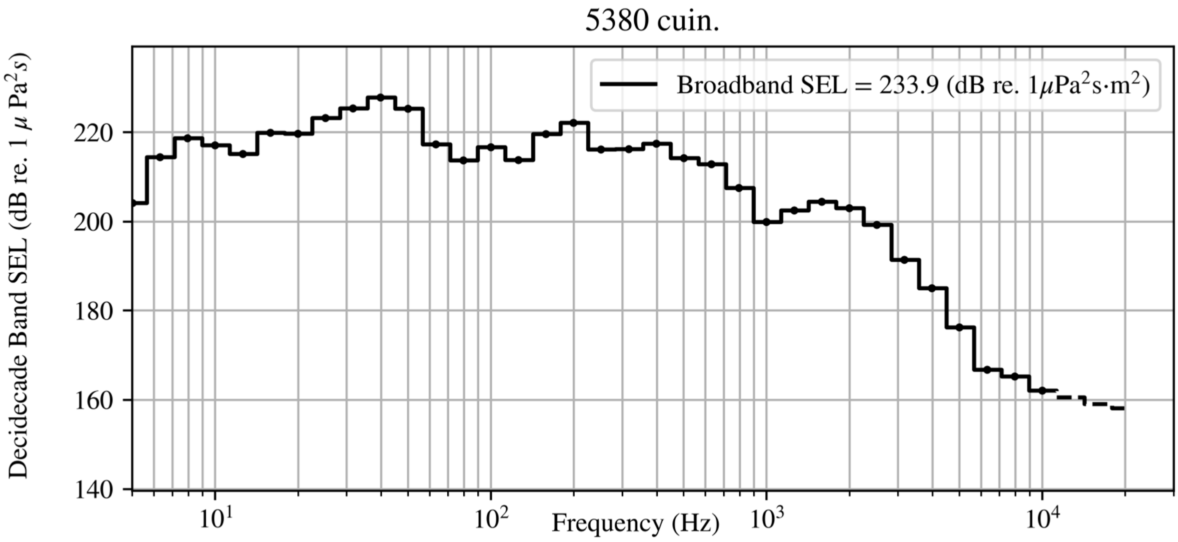

Figure S4. Decidecade SEL spectrum for the 5,380 in³ airgun array, associated with the arithmetic mean, with extrapolation above 10 kHz shown with the dashed line.

Table S1. Resulting source level metrics for the 5,380 in³ airgun array.

5,380 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa² m)**
Surface-Affected Horizontal (15/30/45 degree dip)	233.9	256.0	248.0

5,110 in³ Array

The 5,110 in³ airgun array considered in this analysis is a common configuration that has been suggested to be representative of typical arrays used for deep-penetration surveys in the Gulf of America. Data for this source are available from several sources, including in-house Gundalf modeling, Frankel and Ozanich [17], and the EnerGeo Alliance [18]. The source configuration as initially presented by Weirathmueller *et al.* [19] was the starting point for the in-house Gundalf modeling and is given in Figure S5. The array consists of 32 1900 LLXT airguns towed at a depth of 9 m and with air chamber volumes ranging from 90 to 250 in³. Each airgun had an operating pressure of 2,000 psi. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S6, along with derived metrics). Final horizontal surface-affected source levels are given in Table S2, as well as surface-corrected source levels which were also available for this source. The decidecade band SEL spectrum is provided in Figure S7.

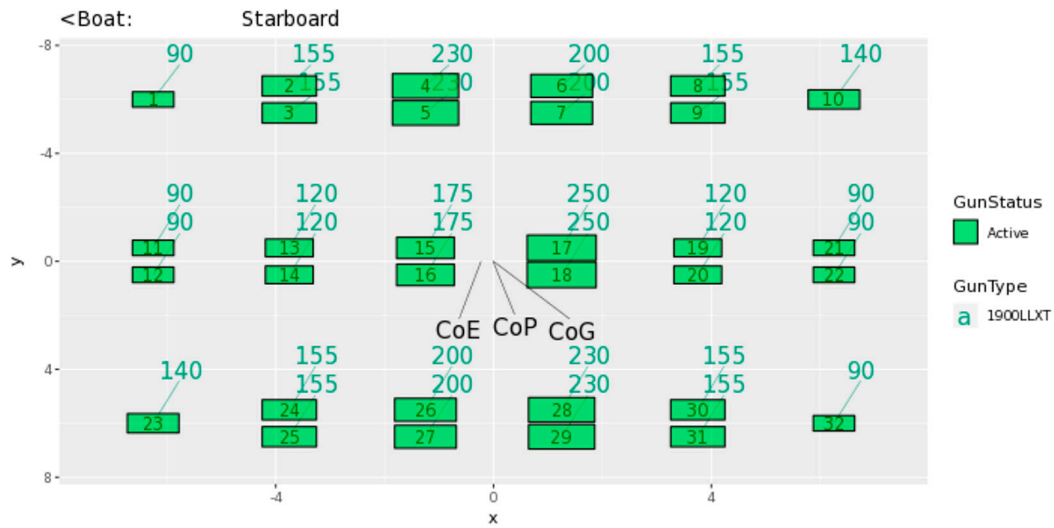

Figure S5. The 5,110 in³ airgun array configuration for Gundalf simulation. Individual airgun volumes are provided in green text in in³; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and geometric center, respectively.

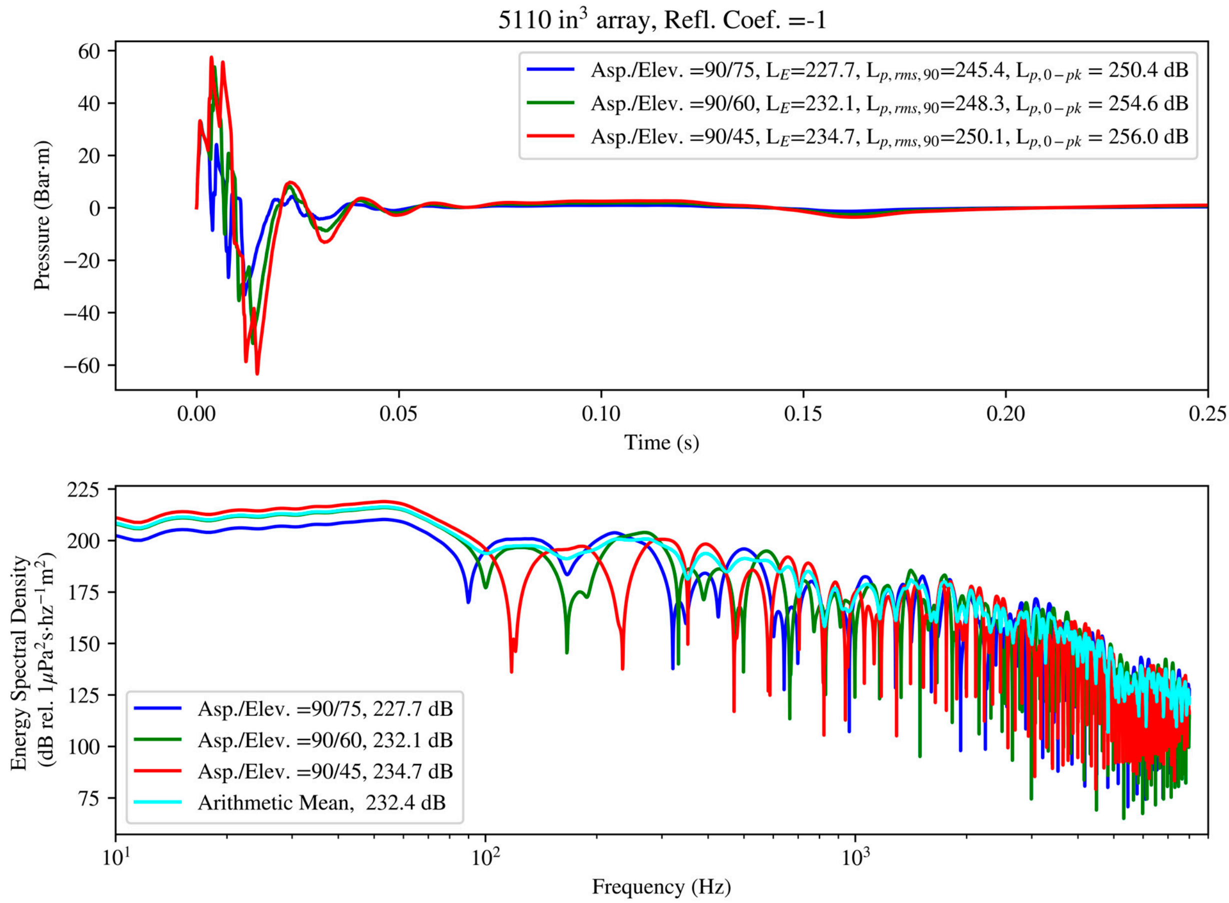

Figure S6. Surface-affected waveforms, spectra, and associated metrics for the 5,110 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

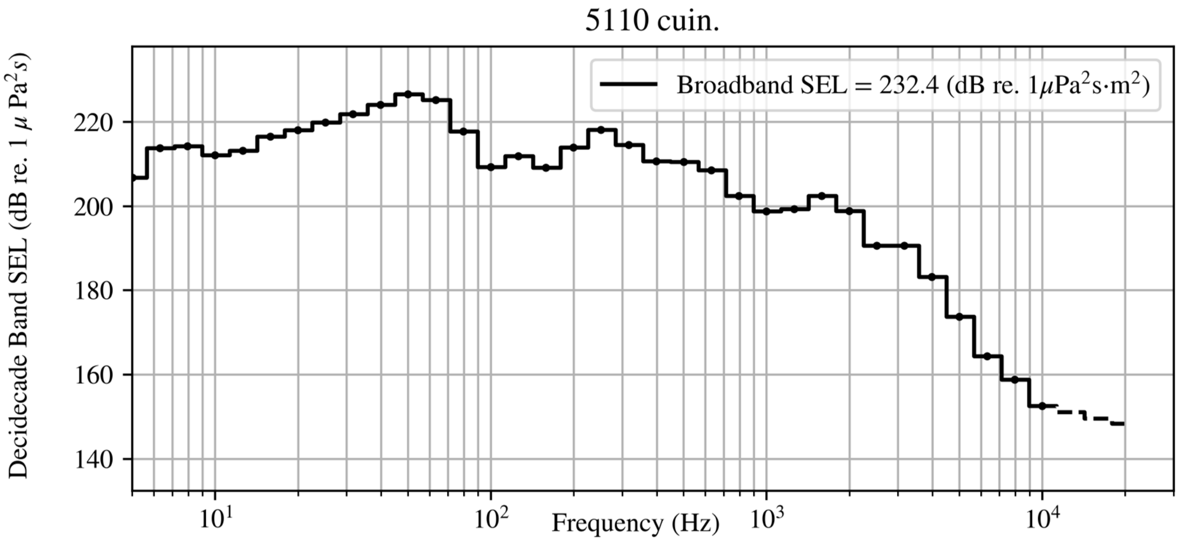

Figure S7. Decidecade SEL spectrum for the 5,110 in³ array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S2. Resulting source level metrics for the 5,110 in³ airgun array. Surface-affected horizontal metrics were carried forward in the analysis, the surface-corrected levels are provided for comparison as they were also computed during initial phases of this analysis.

5,110 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	232.4	254.3	248.3
Surface-corrected Horizontal (0 degree dip)	231.4	252.5	-

4,130 in³ Array

The 4,130 in³ array configuration was taken from Matthews *et al.* [13] and was modeled in Gundalf using the layout provided in Figure S8 below. The array consists of 31 airguns towed at a depth of 8 m and with air chamber volumes ranging from 40 to 250 in³. Each airgun had an operating pressure of 2,000 psi. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S9, along with derived metrics). Final horizontal surface-affected source levels are given in Table S3, as well as surface-corrected source levels which were also available for this source. The decidecade band SEL spectrum is provided in Figure S10.

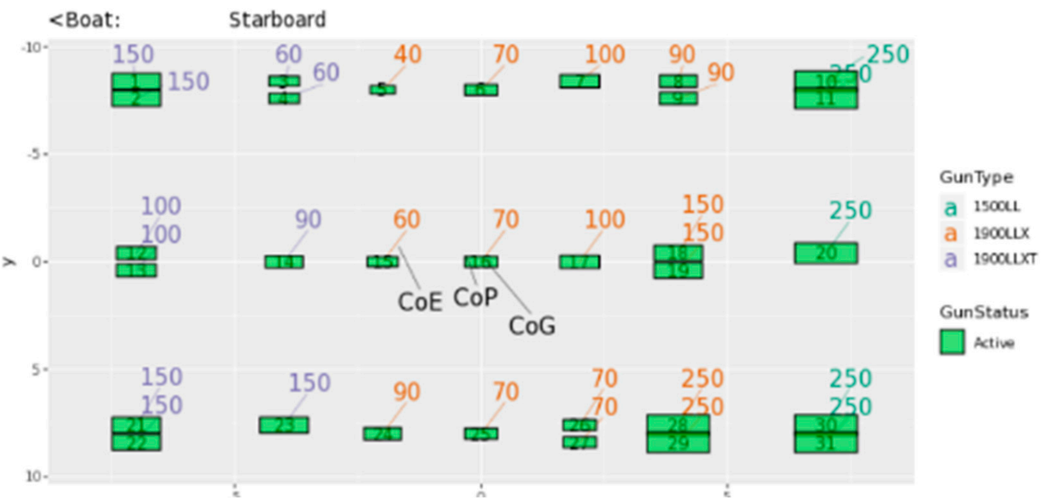

Figure S8. The 4,130 in³ airgun array configuration for Gundalf simulation. Individual airgun volumes are provided in green text in in³; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and geometric center, respectively.

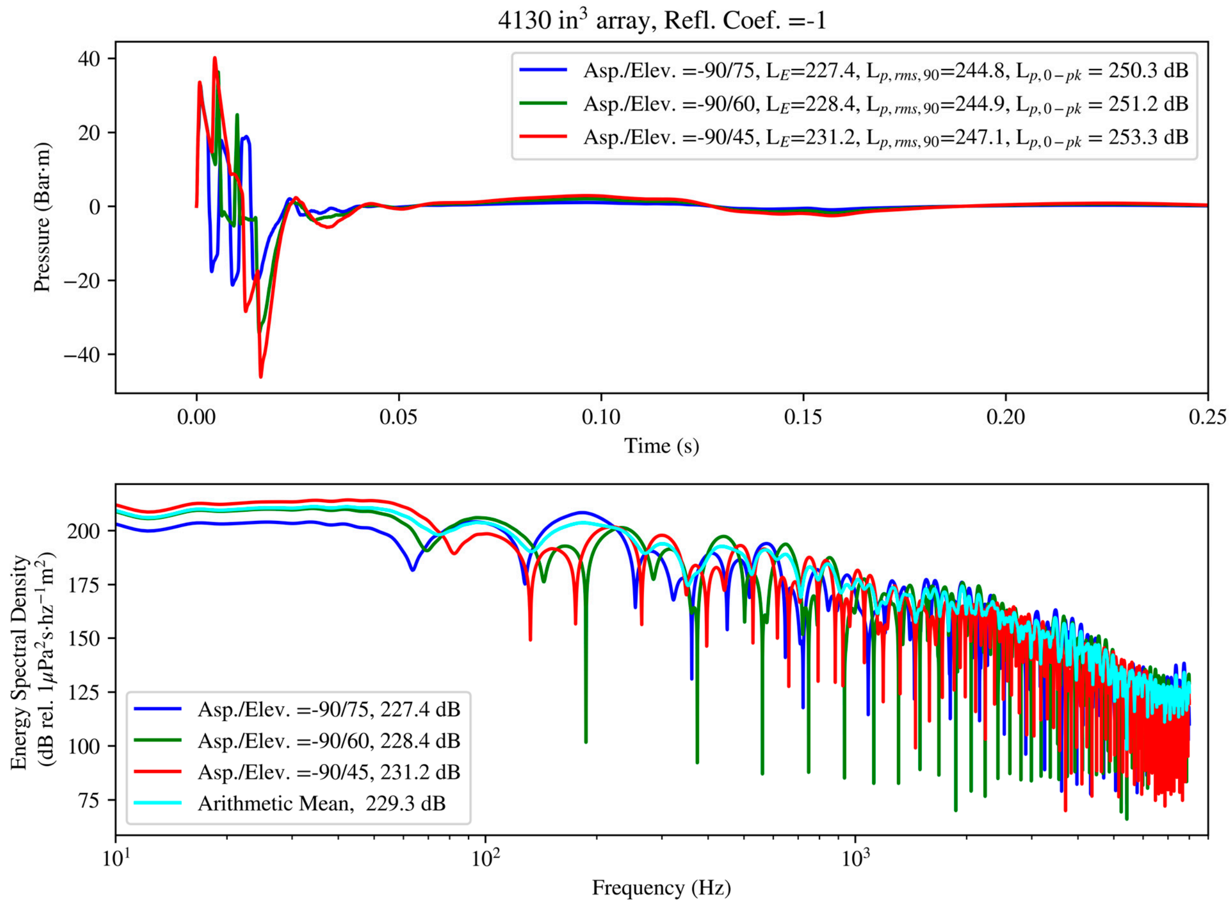

Figure S9. Surface-affected waveforms, spectra, and associated metrics for the 4,120 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

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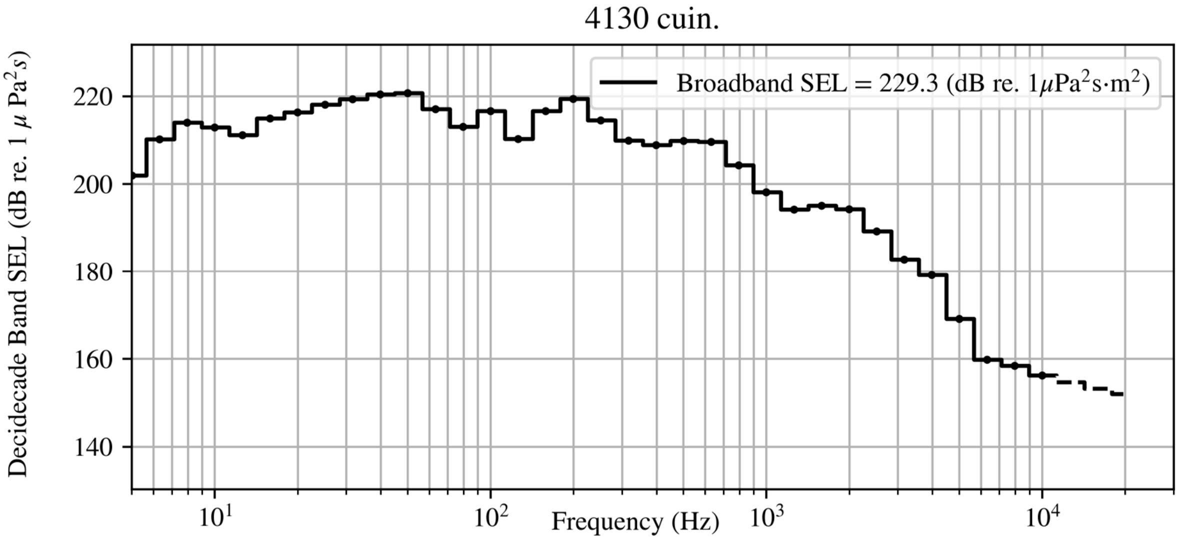

Figure S10. Decidecade SEL spectrum for the 4,130 in³ array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line

Table S3. Resulting source level metrics for the 4,130 in³ airgun array. Surface-affected horizontal metrics were carried forward in the analysis, the surface-corrected levels are provided for comparison as they were also computed during initial phases of this analysis.

4,130 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	229.3	251.8	245.8

1,680 in³ Array

The array layout for the 1,680 in³ is based on the array presented in Jochens and Biggs [20] and was modeled in Gundalf with the configuration shown in Figure S11 below. The array has a tow depth 7 m and is composed of 20 1900LLXT airguns ranging in volume from 40 in³ to 120 in³. The surface-affected waveforms and spectrum are shown in Figure S12, along with derived metrics. Final horizontal surface-affected source levels are given in Table S4, as well as surface-corrected source levels which were also available for this source. The decidecade band SEL spectrum is provided in Figure S13.

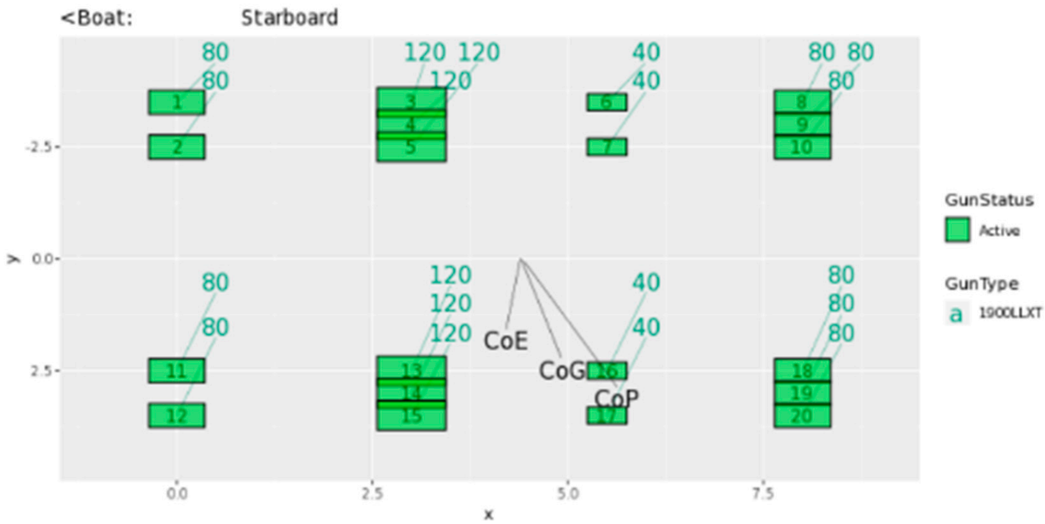

Figure S11. The 1,680 in³ airgun array configuration for Gundalf simulation. Individual airgun volumes are provided in green text in in³; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and geometric center, respectively.

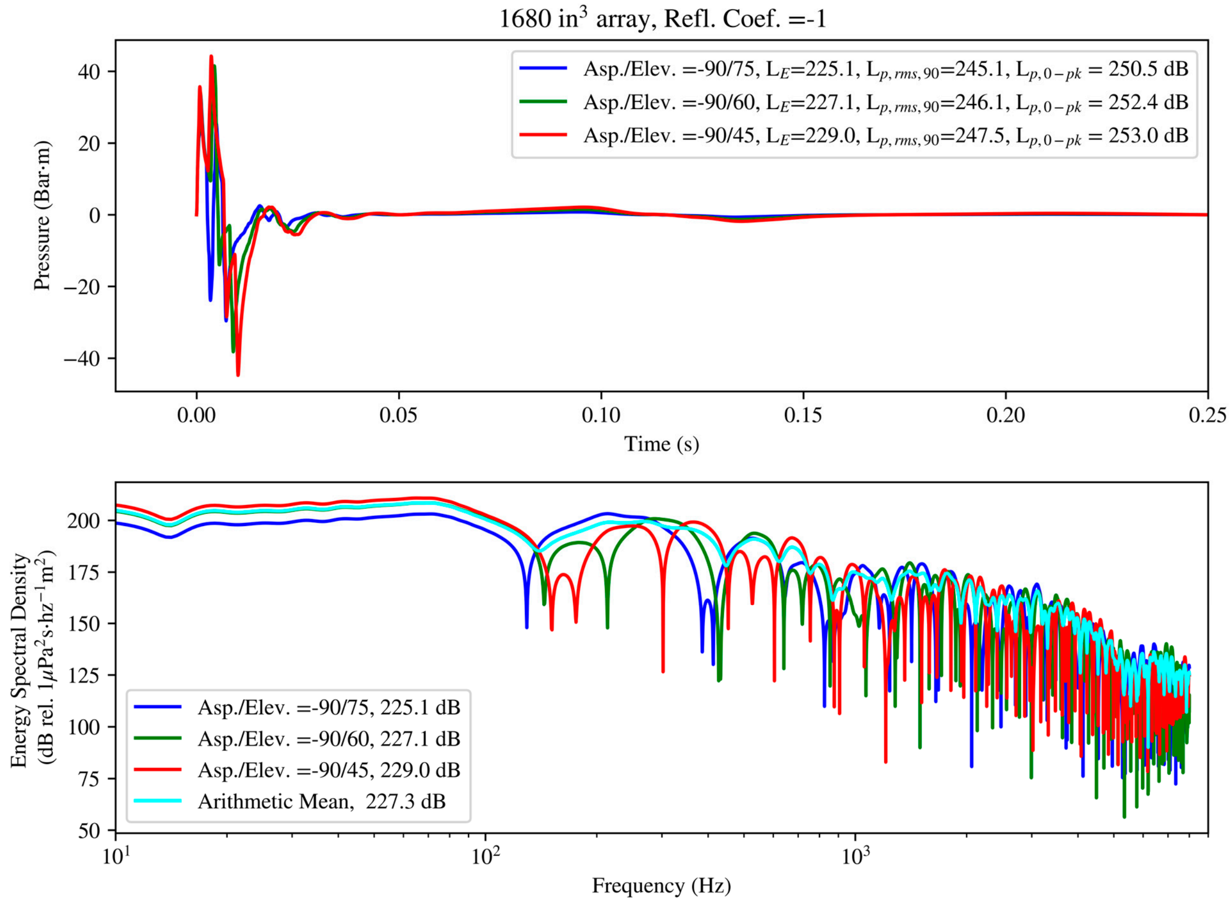

Figure S12. Surface-affected waveforms, spectra, and associated metrics for the 1,680 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

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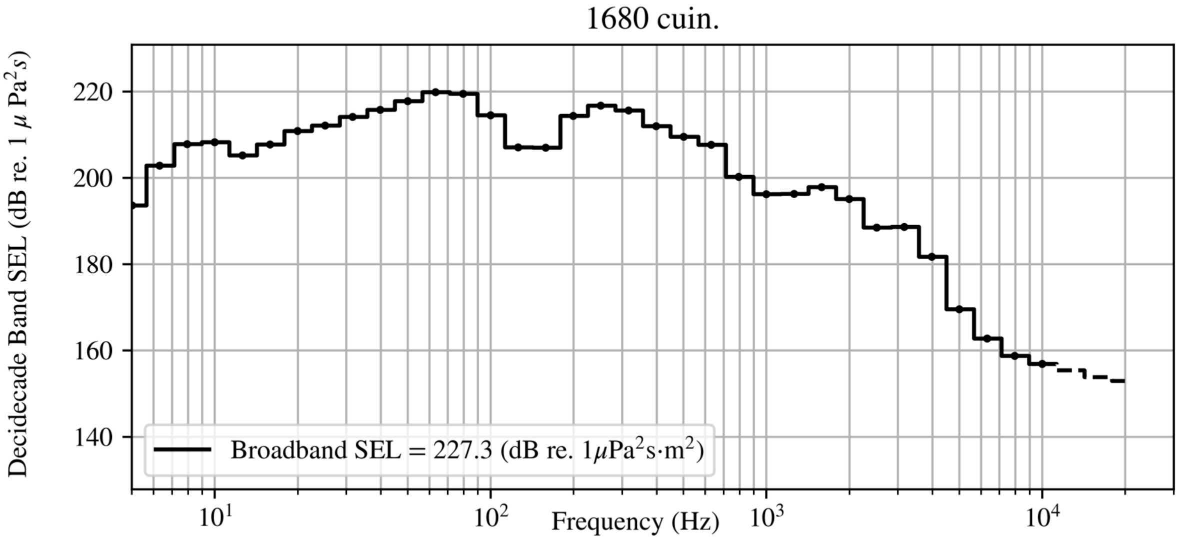

Figure S13. Decidecade SEL spectrum for the 1,680 in³ array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S4. Resulting source level metrics for the 1,680 in³ airgun array. Surface-affected horizontal metrics were carried forward in the analysis, the surface-corrected levels are provided for comparison as they were also computed during initial phases of this analysis.

1,680 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	227.3	252.0	246.3

1,500 in³ High-Pressure Array

The hypercluster 1,500 in³ airgun array consists of six G-Gun airguns with air chamber volumes of 250 in³ and towed at a depth of 10.1 m. Each airgun has an operating pressure of 3,000 psi [21]. The array configuration is given in Figure S14. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S15, along with derived metrics). Final horizontal surface-affected source levels are given in Table S5. The decidecade band SEL spectrum is provided in Figure S16.

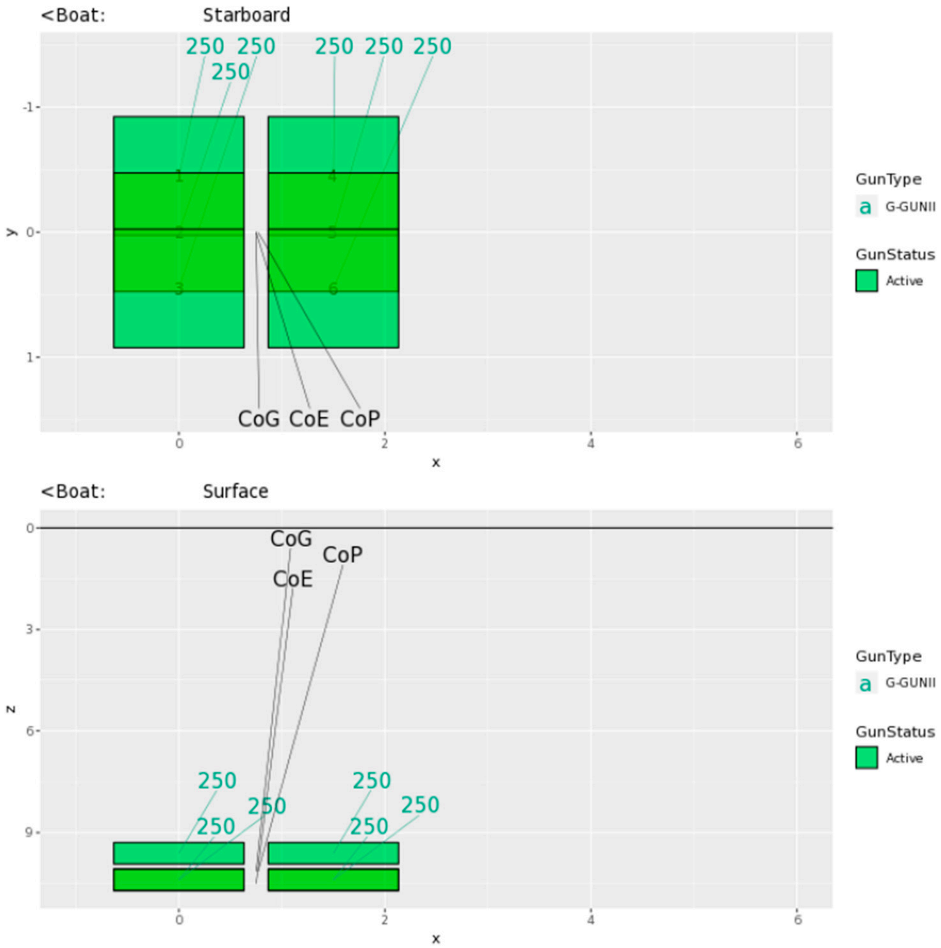

Figure S14. The 1,500 in^3 airgun array configuration for Gundalf simulation. Individual airgun volumes are provided in the green text in in^3; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and geometric center, respectively.

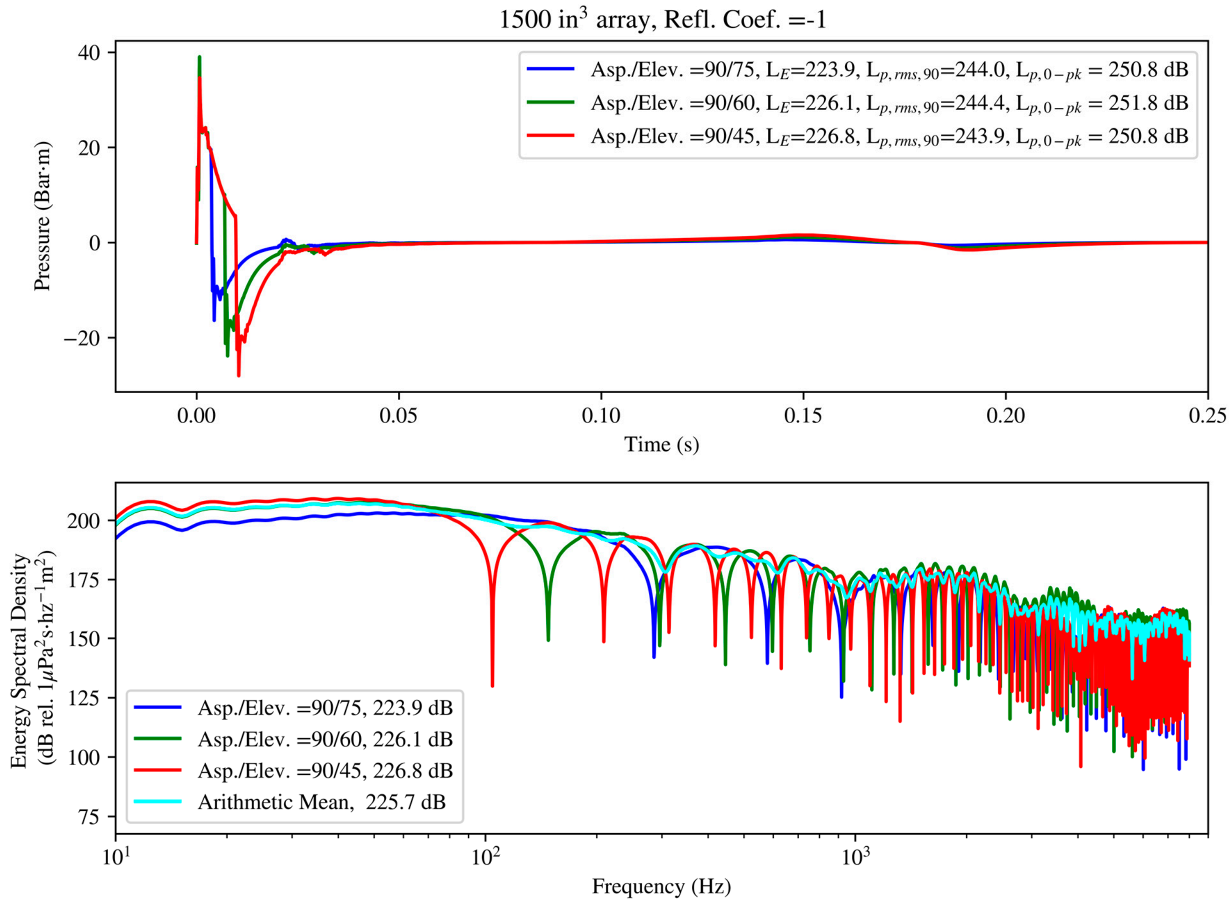

Figure S15. Surface-affected waveforms, spectra, and associated metrics for the high-pressure 1,500 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

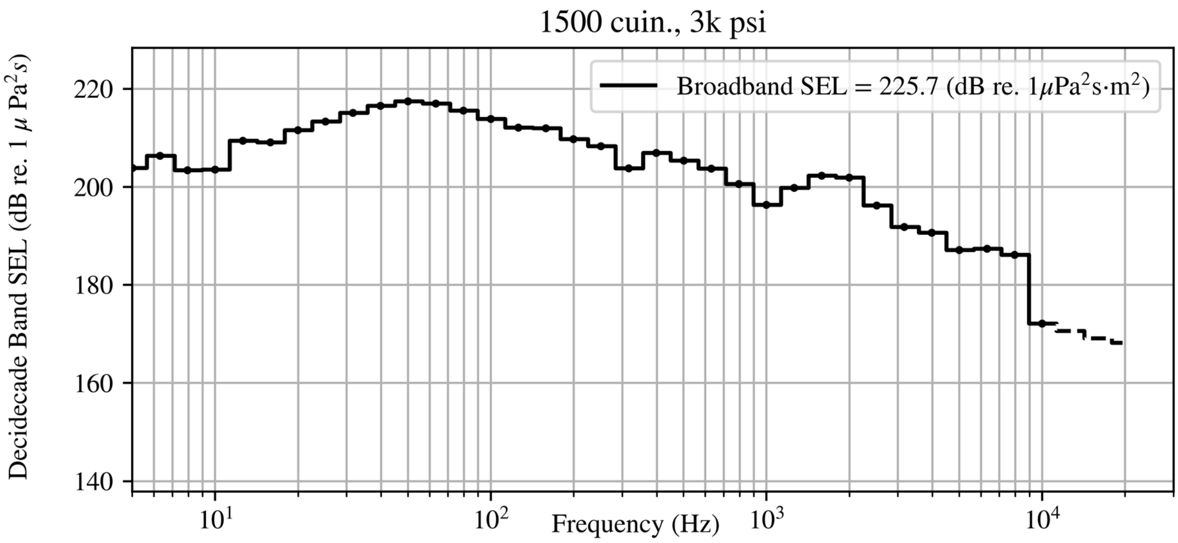

Figure S16. Decidecade SEL spectrum for the high-pressure 1,500 in³ airgun array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S5. Resulting source level metrics for the high-pressure 1,500 in³ airgun array.

1,500 in³ (3,000 psi)	SEL (dB re 1 µPa² m² s)	PK SPL (dB re 1 µPa m)	RMS SPL (dB re 1 µPa m)
Surface-affected Horizontal (15/30/45 degree dip)	225.7	251.2	244.1

1,500 in³ Array

The hypercluster 1,500 in³ airgun array is identical to the higher-pressure variant above, except that, in this case, each airgun has an operating pressure of 2,000 psi [21]. The average source depth was 10.1 m. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S17, along with derived metrics). Final horizontal surface-affected source levels are given in Table S6. The decidecade band SEL spectrum is provided in Figure S18.

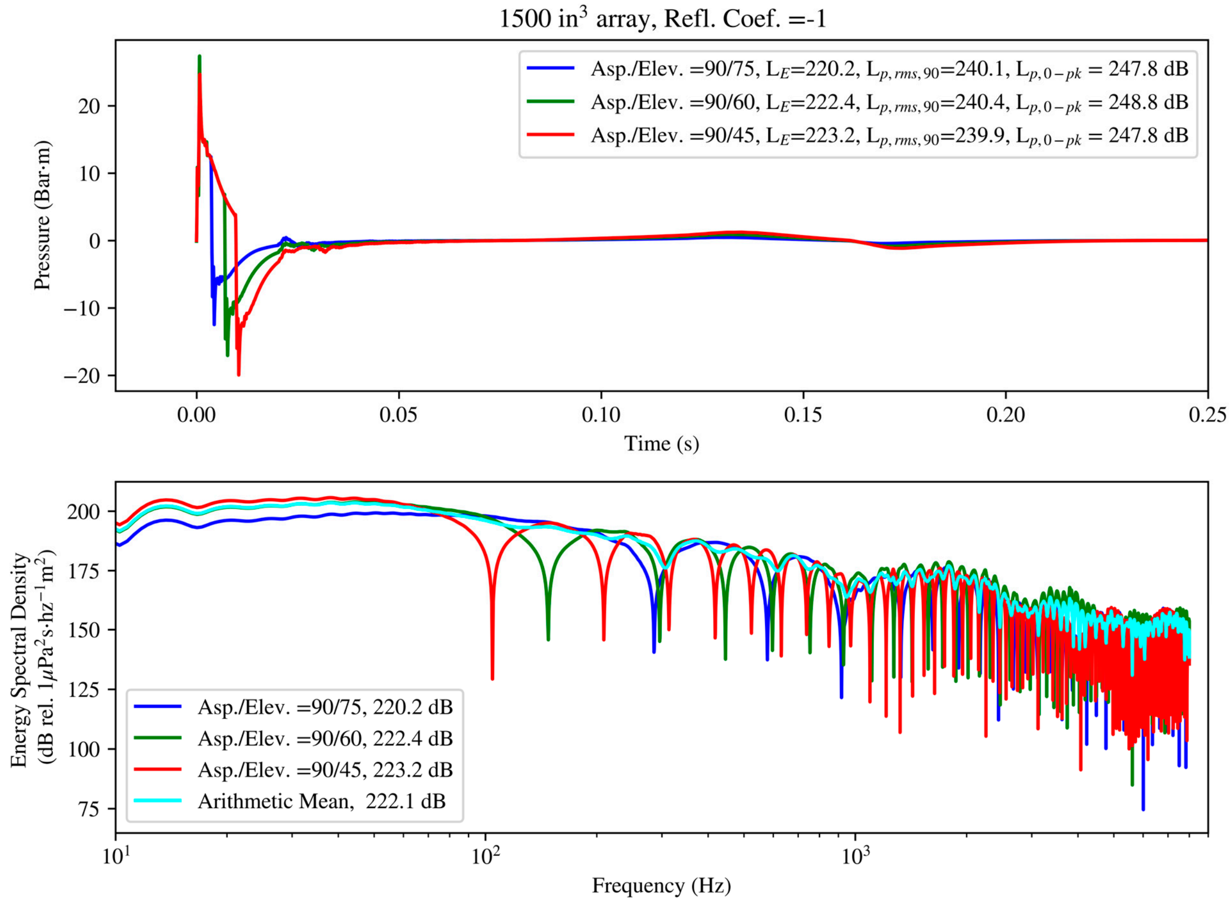

Figure S17. Surface-affected waveforms, spectra, and associated metrics for the 2,000 psi variant of the 1,500 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

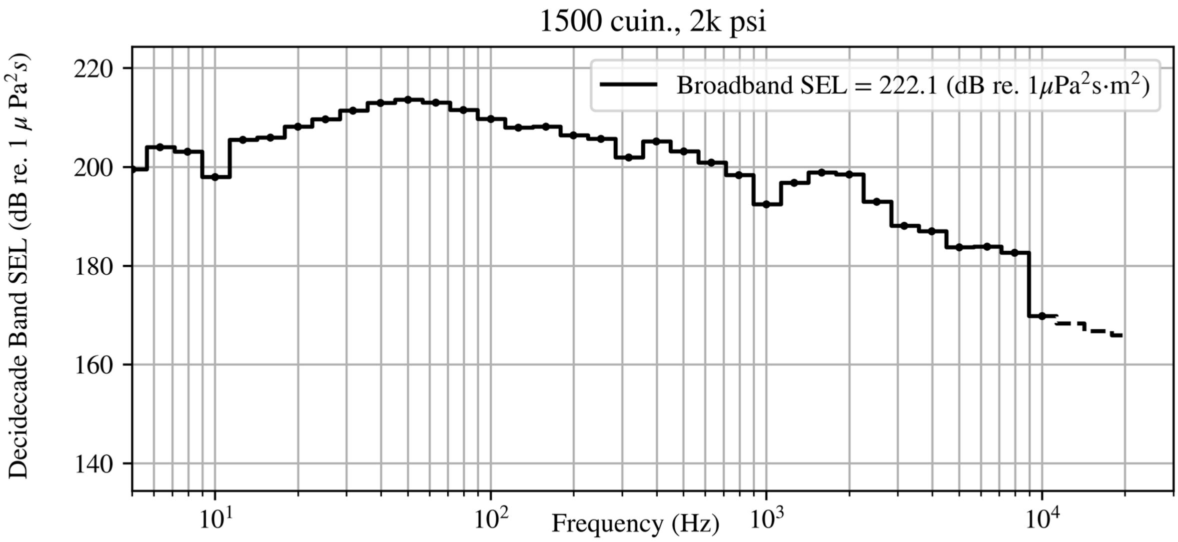

Figure S18. Decidecade SEL spectrum for the 2,000 psi variant of the 1,500 in³ airgun array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S6. Resulting source level metrics for the 2,000 psi variant of the 1,500 in³ airgun array.

1,500 in³ (2,000 psi)	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	222.1	248.2	240.1

1,000 in³ Array

Data for the 1,000 in³ airgun array considered in this analysis are available from in-house Gundalf modeling and Frankel and Ozanich [17], which used JASCO's Airgun Array Source Model. The source configuration as initially presented by Frankel and Ozanich [17] was the starting point for the Gundalf modeling and is provided in Figure S19. The array consists of 12 G-Gun airguns with air volumes ranging from 50 to 150 in³ and was modeled at a tow depth of 12 m. Each airgun had an operating pressure of 2,000 psi. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S20, along with derived metrics). Final horizontal surface-affected source levels are given in Table S7. The decidecade band SEL spectrum is provided in Figure S21.

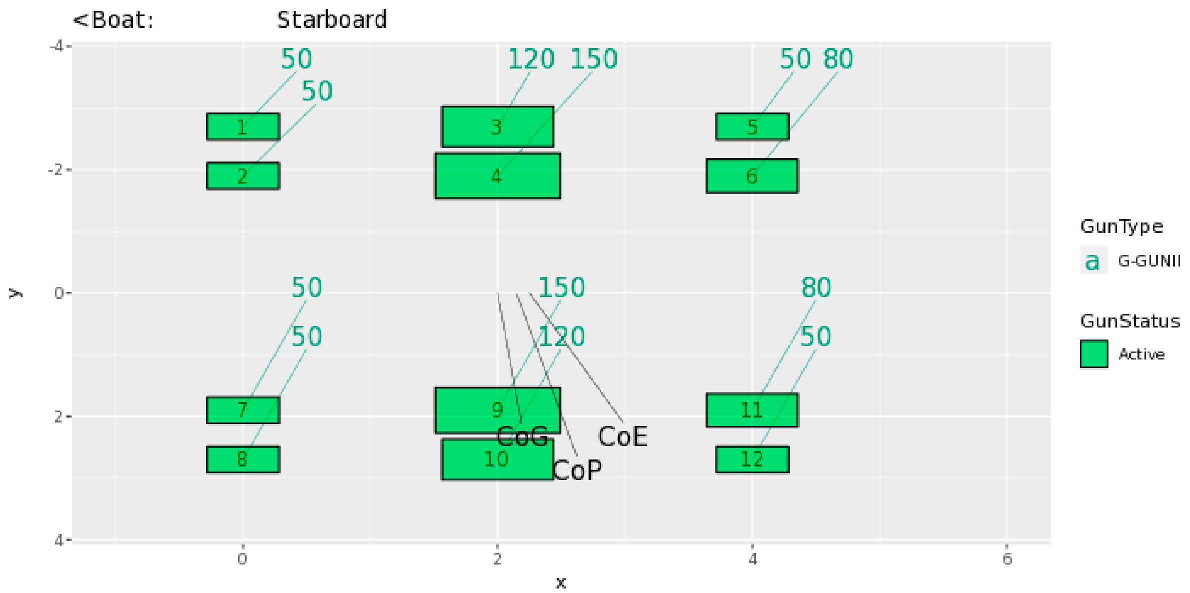

Figure S19. The 1,000 in³ airgun array configuration for Gundalf simulation. Individual airgun volumes are provided in the green text in in³; x and y dimensions have units of meters. CoE, CoP, and CoG correspond to the center of energy, pressure, and geometric center, respectively.

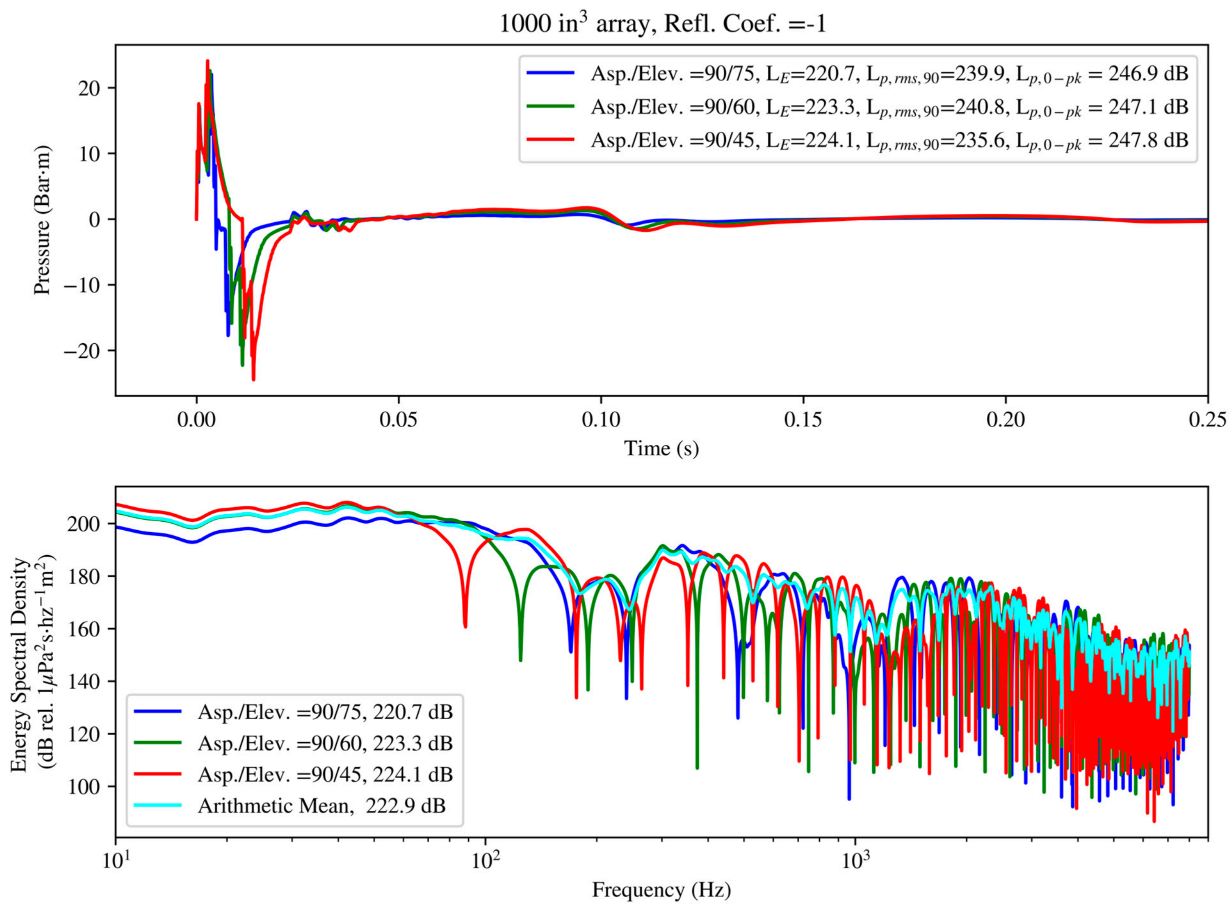

Figure S20. Surface-affected waveforms, spectra, and associated metrics for the 1,000 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

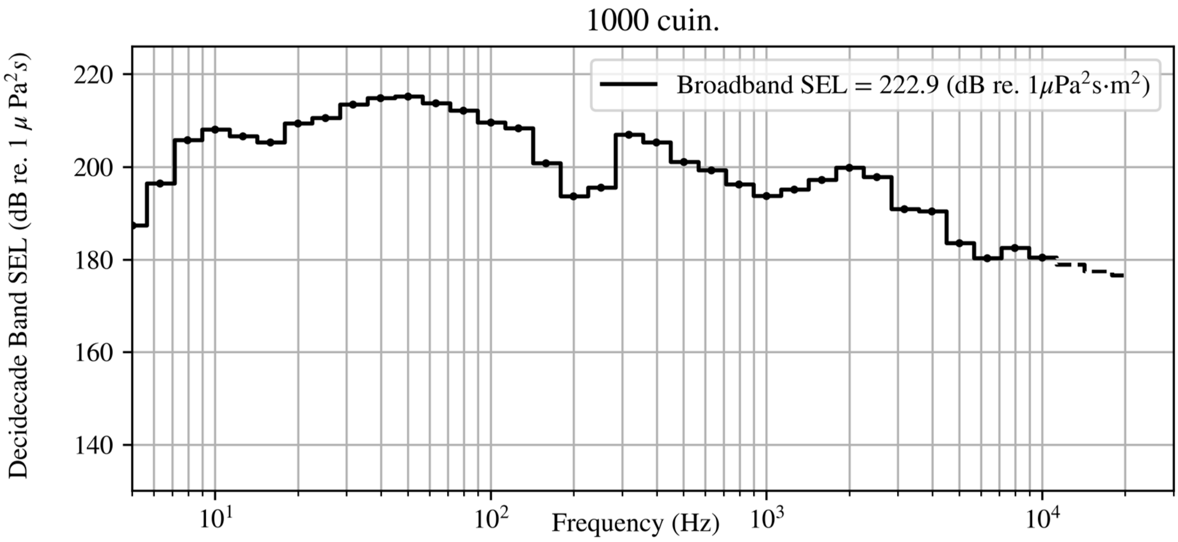

Figure S21. Decidecade SEL spectrum for the 1,000 in³ airgun array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S7. Resulting source level metrics for the 1,000 in³ airgun array. Surface-affected horizontal metrics were carried forward in the analysis, the surface-corrected levels are provided for comparison as they were also computed during this analysis.

1,000 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	222.9	247.3	239.3
Surface-corrected Horizontal (0 degree dip) [17]	219.4	243.1	-

90 in³ Airgun

Data for the 90 in³ single 1900LLXT airgun was modeled at a tow depth of 4 m. The 90 in³ airgun source presented by Zeddies *et al.* [3] was the starting point for the in-house Gundalf modeling. The model assumed an airgun operating pressure of 2,000 psi. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S22, along with derived metrics). Final horizontal surface-affected source levels are given in Table S8. The decidecade band SEL spectrum is provided in Figure S23.

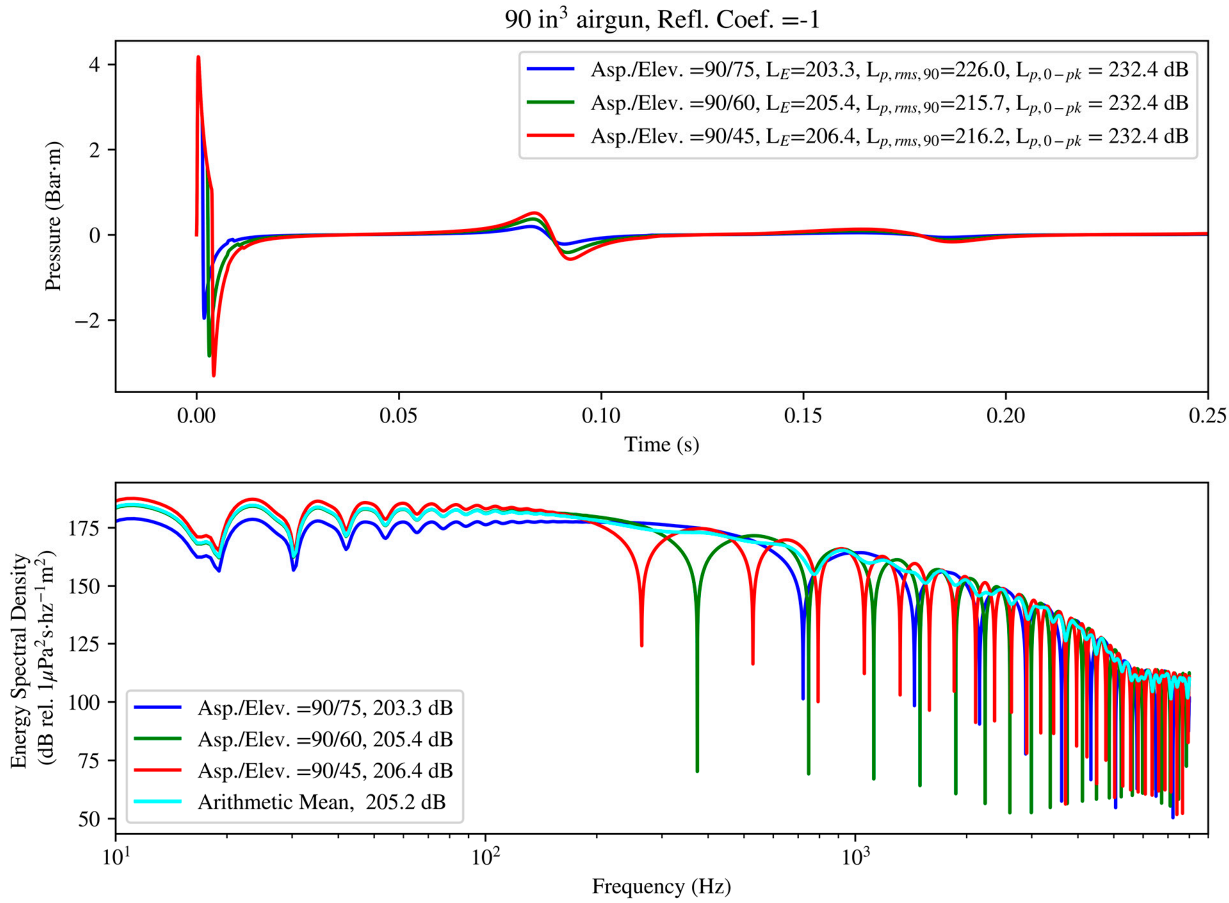

Figure S22. Surface-affected waveforms, spectra, and associated metrics for the 90 in³ airgun for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees). For the 60 and 45 degree elevation angles, the secondary pulse near 0.09 seconds has enough energy to drive the 90% duration to that time, resulting in significantly lower SPL RMS for those angles. The 90% duration for the 75 degree elevation angle is approximately 5 ms.

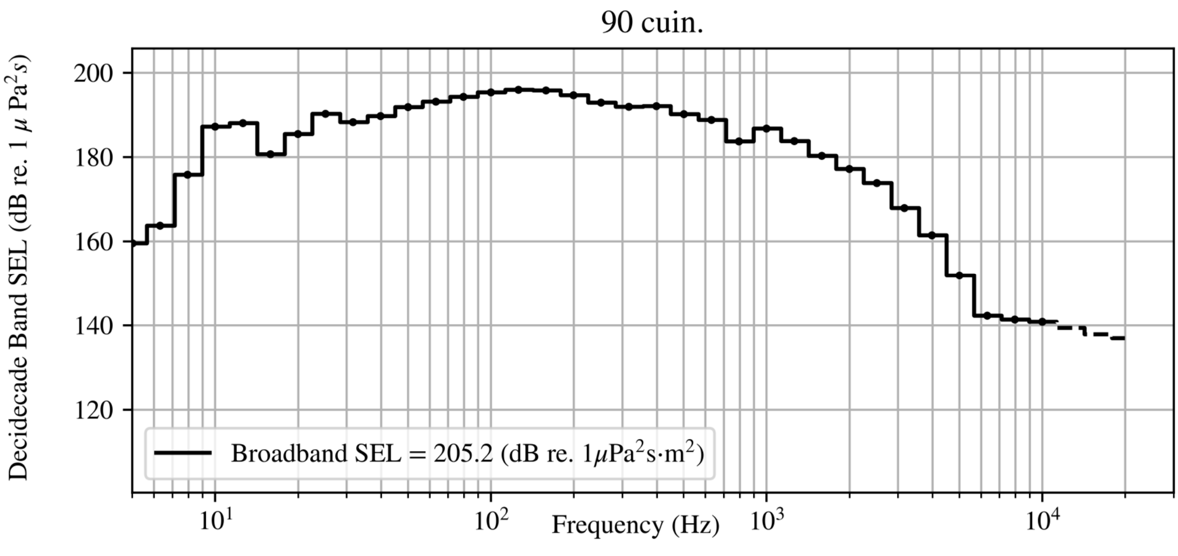

Figure S23. Decidecade SEL spectrum for the 90 in³ airgun, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S8. Resulting source level metrics for the 90 in³ airgun. Surface-affected horizontal metrics were carried forward in the analysis, the surface-corrected levels in Zeddies *et al.* [3] are provided for comparison.

90 in³	SEL (dB re 1 μPa² m² s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)
Surface-affected Horizontal (15/30/45 degree dip)	205.2	232.4	222.0
Surface-corrected Horizontal (0 degree dip) [3]	207.8	227.7	-

30 in³ Array

Data for the 30 in³ array consisted of two 1900LLXT airguns with volumes of 10 in³ and 20 in³, mounted side by side with a 1-m separation distance. The array was modeled at a tow depth of 4 m. The 30 in³ array source configuration presented by Austin *et al.* [22] was the starting point for the in-house Gundalf modeling. Each airgun had an operating pressure of 2,000 psi. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S24, along with derived metrics). Final horizontal surface-affected source levels are given in Table S9. The decidecade band SEL spectrum is provided in Figure S25.

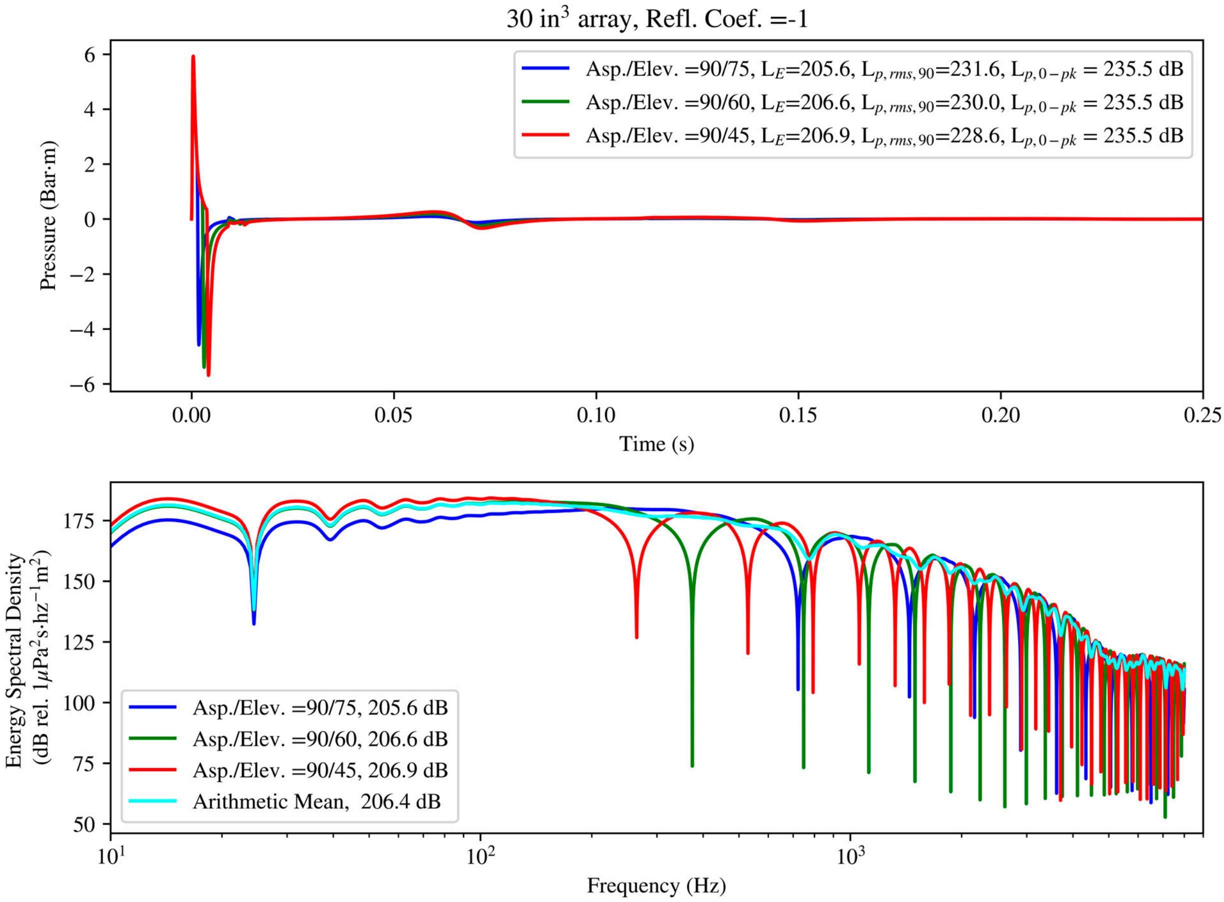

Figure S24. Surface-affected waveforms, spectra, and associated metrics for the 30 in³ airgun array for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

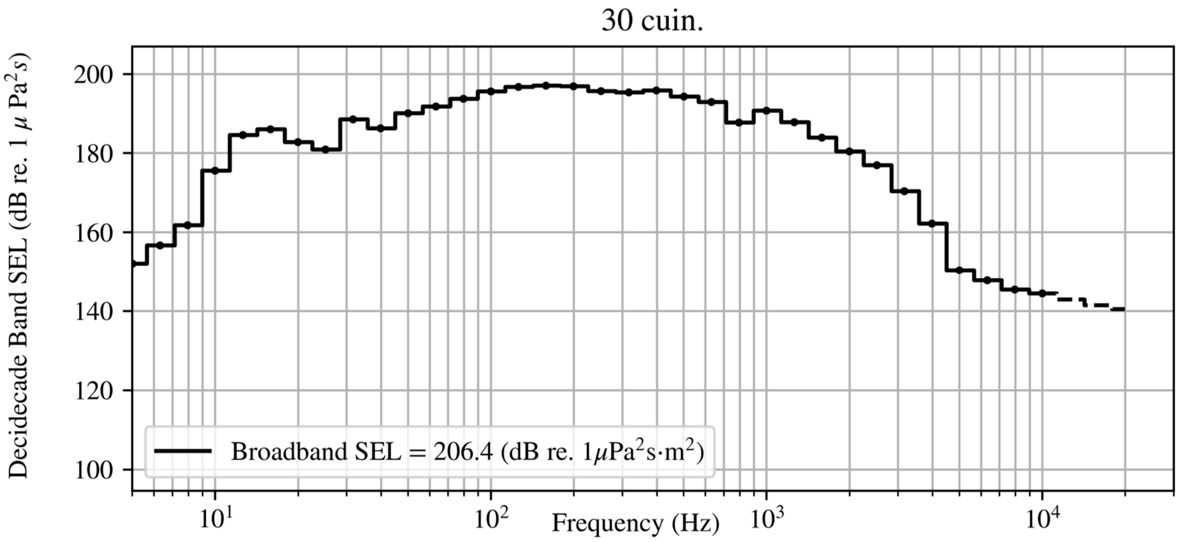

Figure S25. Decidecade SEL spectrum for the 30 in³ airgun array, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S9. Resulting source level metrics for the 30 in³ airgun array. Surface-affected horizontal metrics were carried forward in the analysis, the metrics from Austin *et al.* [22] are provided for comparison.

30 in³	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	206.4	235.5	230.2
Austin *et al.* [22]	206.1	231.5	214.5

10 in³ Airgun

Inclusion of a 10 in³ single airgun is based on proposed use of a 10 in³ single airgun for mitigation [23] and use of 10 in³ and other small volume single guns in directed environmental impact studies [24]. The 10 in³ modeled here had an operating pressure of 2,000 psi, and a 2-m tow depth was assumed. Gundalf was used to calculate the surface-affected waveforms and spectrum (shown in Figure S26, along with derived metrics). Final horizontal surface-affected source levels are given in Table S10. The decidecade band SEL spectrum is provided in Figure S27.

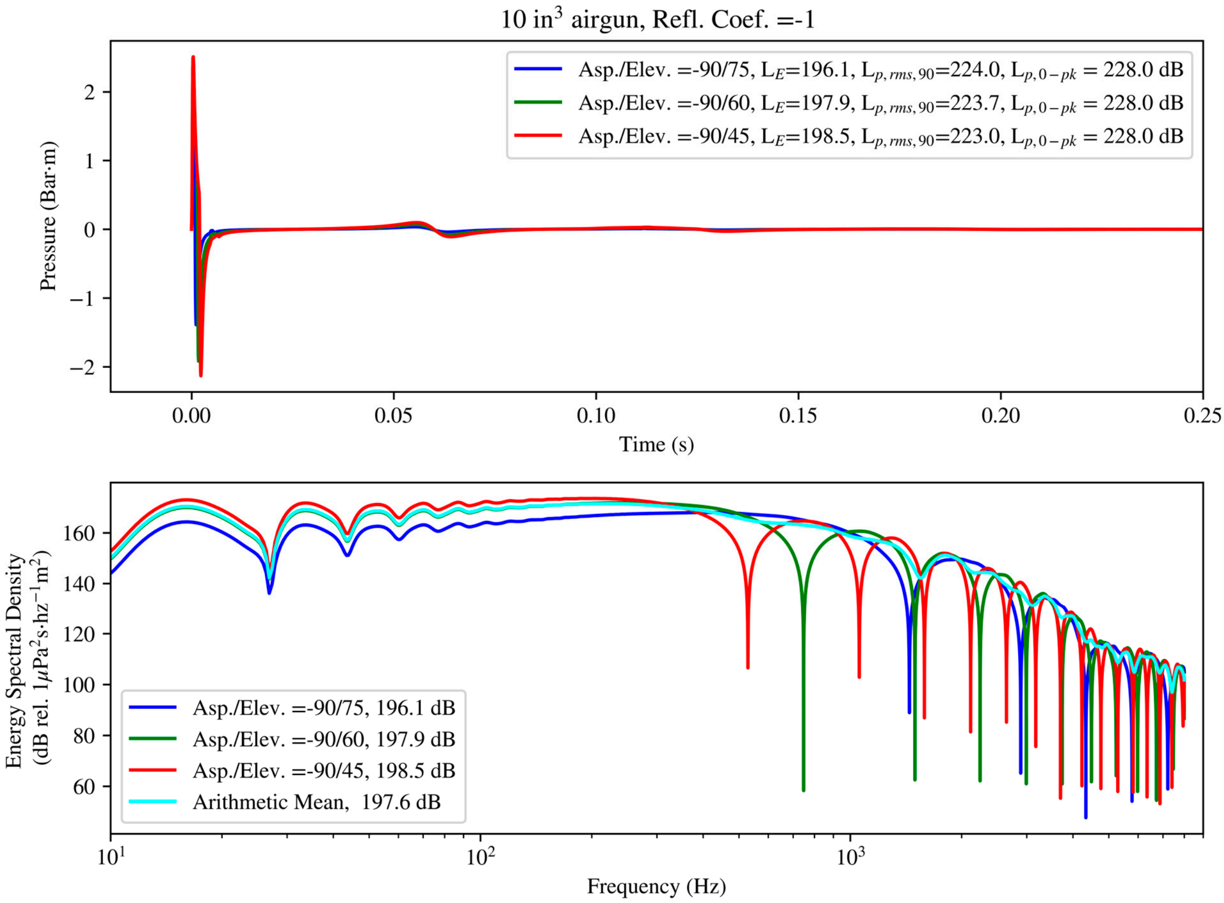

Figure S26. Surface-affected waveforms, spectra, and associated metrics for the 10 in³ airgun for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

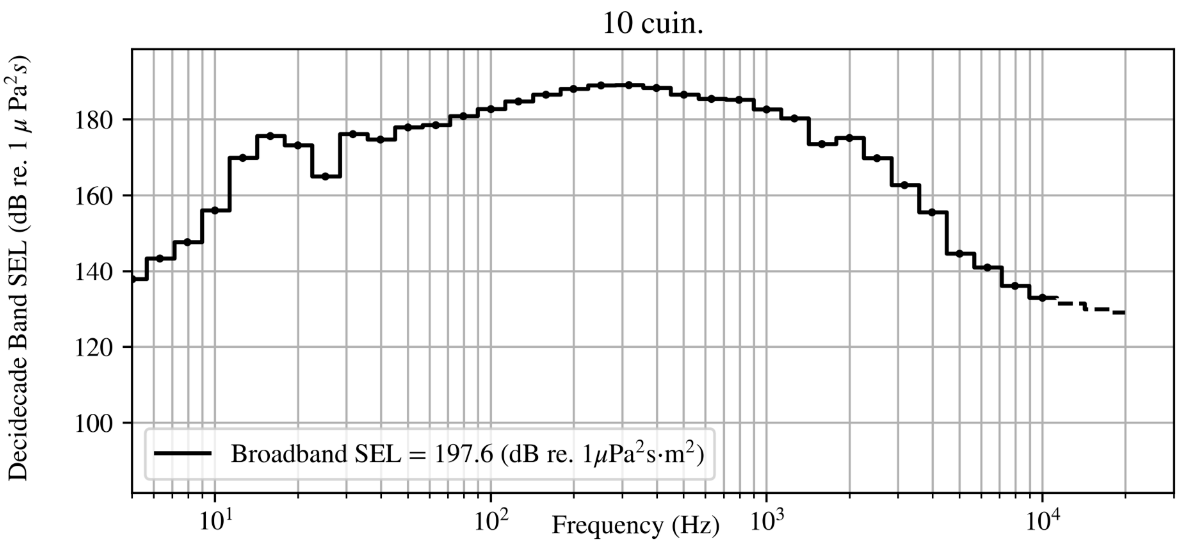

Figure S27. Decidecade SEL spectrum for the 10 in³ airgun, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S10. Resulting source level metrics for the 10 in³ airgun. Surface-affected horizontal metrics were carried forward in the analysis.

10 in³	SEL (dB re 1 μPa² m² s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)
Surface-affected Horizontal (15/30/45 degree dip)	197.6	228.0	223.6

Sparkers

Sparkers are high-resolution geophysical (HRG) seismic sources. Source levels for sparkers used in this analysis were taken from Crocker and Fratantonio [25], who conducted close-range controlled measurements of three sparker systems for a wide range of operational parameters. Crocker and Fratantonio [25] contains the largest and most rigorously documented dataset available for source levels and other characteristics of these HRG sources. We included all three sparker systems measured by Crocker and Fratantonio [25]: the Applied Acoustics (AA) Dura-Spark, the AA Delta Sparker, and the SIG ELC 820. The low and high-power configurations were analyzed for each source. Based on the presence of ghost reflections in the signals, as well as a lack of discussion regarding removing surface effects, it is assumed that source levels from Crocker and Fratantonio [25] are surface-affected. A representative spectrum was digitized from McQueen *et al.* [26], which was based on field measurements of an AA Dura-Spark operating at 800 J. The assumed vessel speed and pulse interval were 2 m/s and 0.5 seconds, based on Ruppel *et al.* [27] and McQueen *et al.* [26], respectively. The decidecade band SEL spectrum assumed for all sparkers is provided in Figure S28. Assumed source levels are provided in Table S11.

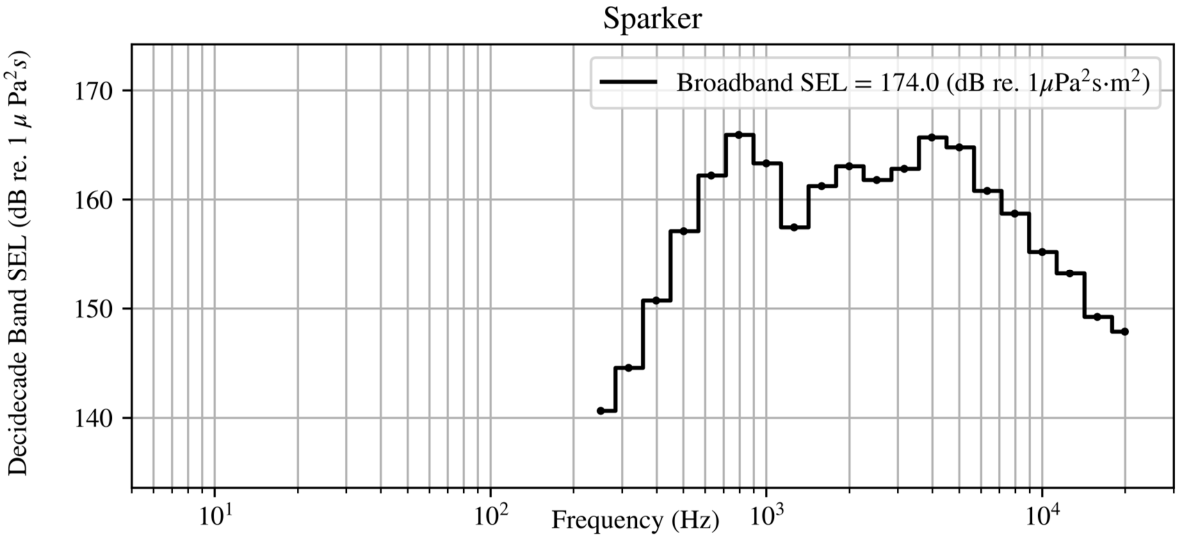

Figure S28. Decidecade SEL spectrum assumed for all sparkers from McQueen *et al.* [26]. The spectrum is normalized in this case to the SEL source level for the SIG ELC 820; however, in the analysis the appropriate broadband source levels were used for each sparker source and are provided in Table S11 below.

Table S11. Source level metrics for Sparkers from Crocker and Fratantonio [25].

Sparkers	SEL (dB re 1 μPa² m² s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)
AA Delta Sparker (High: 2,400 J)	185	221	205

AA Delta Sparker (Low: 500 J)	167	206	190
AA Dura-Spark (High: 2,400 J, 400 Tip)	188	224	214
AA Dura-Spark (Low: 100 J, 80 Tip)	173	207	200
SIG ELC 820 (High: 750 J)	182	214	206
SIG ELC 820 (Low: 300 J)	174	207	198

Ultra Low-frequency (ULF) Pneumatic Sources

In response to the need for improved low-frequency bandwidth (which is source limited for conventional airgun arrays) to improve sub-salt and sub-basalt imaging, as well as to address concerns related to conservation, novel pneumatic sources have emerged as viable options relative to conventional airguns [28,29]. ULF seismic sources (e.g., TPS™, Gemini Source™, Harmony™) are defined as pneumatic sources with bubble resonance frequencies below 7 Hz. These sources generally contain peak energy below 10 Hz, with reduced signal amplitude above approximately 60–90 Hz. Each one has a unique peak frequency based on the specific configurations of the hardware.

ULF seismic technologies aim to provide two benefits compared to conventional seismic airguns. First, the lower peak frequency penetrates farther into the seabed and thus yields improved imaging. Conventional airgun acoustic signals decay rapidly at these low frequencies, and ULF seismic sources are designed to fill this information gap. Second, the reduced signal amplitude at higher frequencies should reduce the sound exposure of marine mammals to seismic surveys that use these sources in lieu of conventional airgun arrays. Descriptions and images of some market-ready ULF seismic sources are provided herein.

Because ULF pneumatic sources typically involve only one or two elements, with the exception of the Harmony™ six-element source, they are significantly more omnidirectional than traditional airguns; thus understanding and reducing vertical directionality is not necessary.

TPS™

The TPS™ by Sercel is a broadband marine seismic source capable of generating energy below 2 Hz. TPS™ is a pneumatic source that operates at low pressure (~1,000 psi) and releases a large volume of air in a controlled manner (Figures A29 & A30). This generates an impulsive signal with a long rise time and a bubble oscillation at low frequencies. The design enables the TPS™ to produce a high-amplitude, low-frequency signal down to approximately 1 Hz, while emitting comparatively reduced high-frequency signal content relative to conventional airgun arrays. The system is currently available in a 28,000 in^3 volume chamber size, which produces a peak frequency of 2.6–2.8 Hz. TPS™ produces an effective frequency spectrum of approximately 1–60 Hz, enabling efficient seismic data acquisition across a broad depth range by providing both lower and higher frequency content in a single deployment.

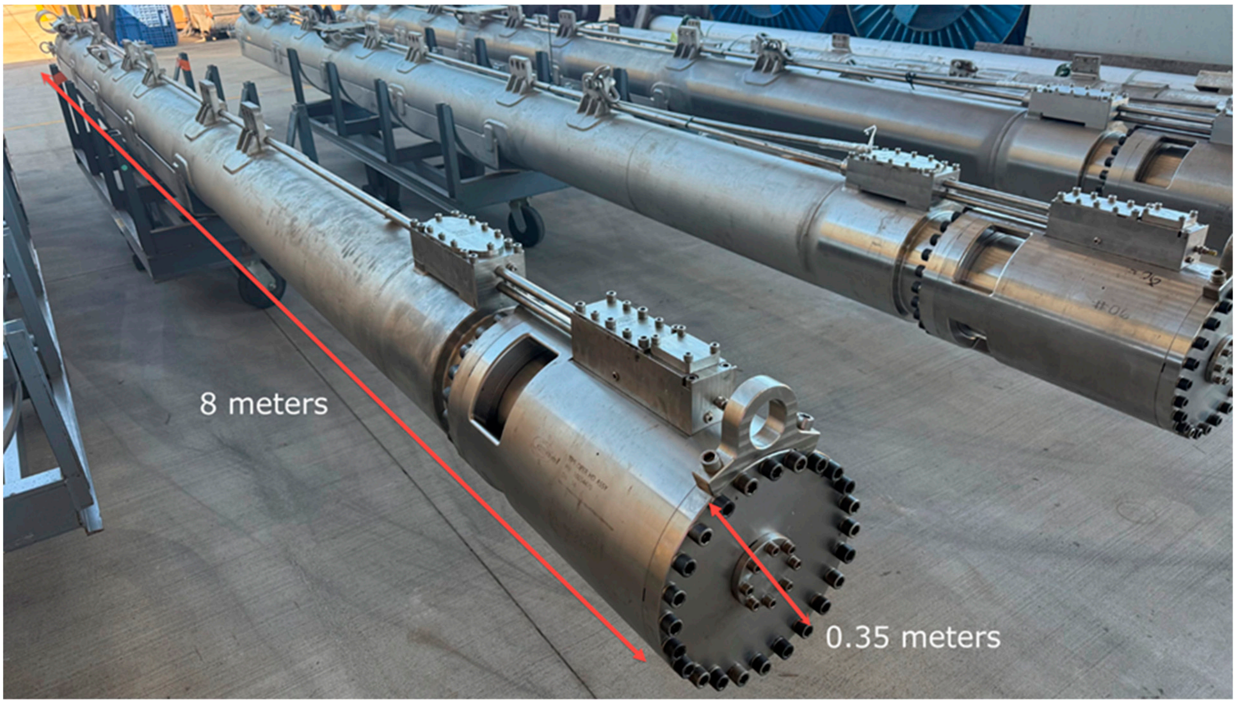

Figure S29. The TPS™ on a dry deck. Photo courtesy of Sercel.

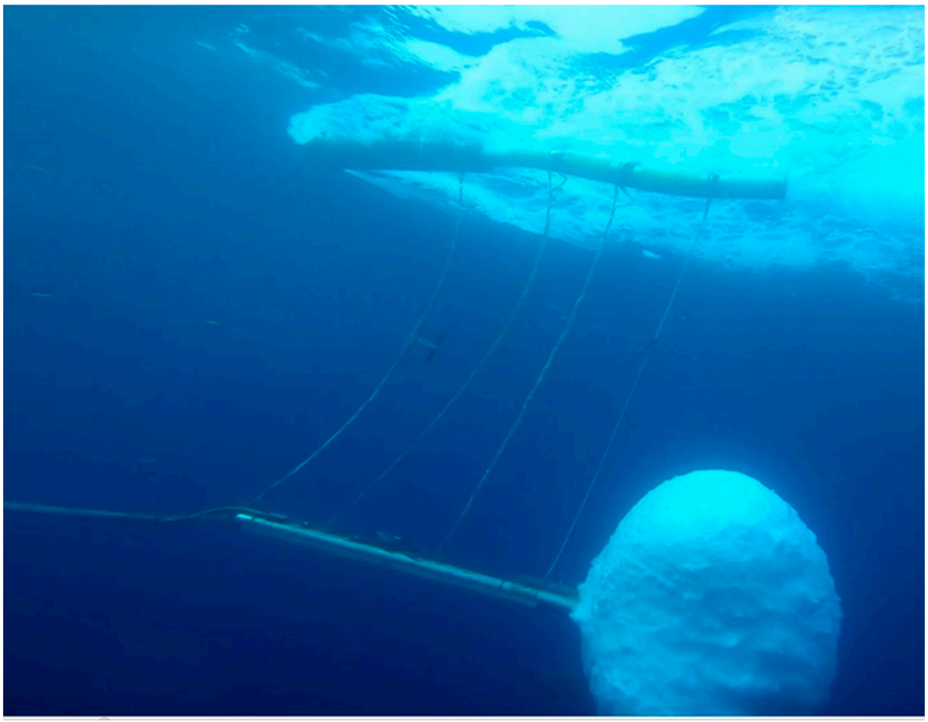

Figure S30. The TPS™ suspended from a surface float after firing. Photo courtesy of Sercel.

Data for the 28,000 in^3 TPS™, typically operated at 1,000 psi, is available from Martin *et al.* [30], Large *et al.* [29], and Large *et al.* [31]; it also was acquired via personal communication with Sercel. Sercel provided far-field power spectral density (PSD) and time signatures recorded on ocean bottom nodes (OBNs) representing both the notional (de-ghosted) and vertical far field. The vertical far field was an average of several measured shots from an ocean bottom node at a depth of approximately 3 km (S. Ronen, personal communication, July 18, 2025). The signatures were analyzed by the authors to calculate PK SPL and 90% RMS SPL, while SEL was estimated by summing the PSDs. As the far-field signature was provided as a keel aspect (i.e., directly down, dip = 90 degrees), it would not be a fair comparison with the 'horizontal' surface-affected characteristics computed for other sources. Additionally, the notional signature is de-ghosted or equivalently surface-corrected and also does not provide a fair comparison. Thus, the notional was summed with an appropriate time-delayed surface reflection to produce far-field signatures as a function of dip angle. Time delays were computed as [32]:

$$\tau = 2d\cos(\phi)/1500\ m/s, \tag{S1}$$

where d is the depth of the source (m), and ϕ is the elevation angle relative to vertical. The final signal is then approximated as:

$$p(t) = p_{notional}(t) - p_{notional}(t-\tau). \tag{S2}$$

Figure S31 shows the notional and vertical far-field signatures, along with a synthetic vertical far-field signature (notional sum) calculated using the method described above. This reconstructed vertical far field signal offers a rough check of this methodology for one angle, and, while it is not an identical match to the vertical far-field signature, its derived metrics are within 1 dB of the actual values in all cases (Figure S31). The disagreement that does exist is likely due to the de-ghosting procedure, which is designed for traditional airguns and is not optimized for sources that are not monopole, like TPS™.

Surface-affected waveforms were computed from the notionals, using the methodology described above for 15, 30, and 45 degree dip angles. Corresponding power spectral densities were computed from the waveforms using the periodogram function from the Python package SciPy [33]. Waveforms and spectra are provided in Figure S32 based on a source depth of 8 m. Final horizontal surface-affected source levels are given in Table S12. The decidecade band SEL spectrum is provided in Figure S33.

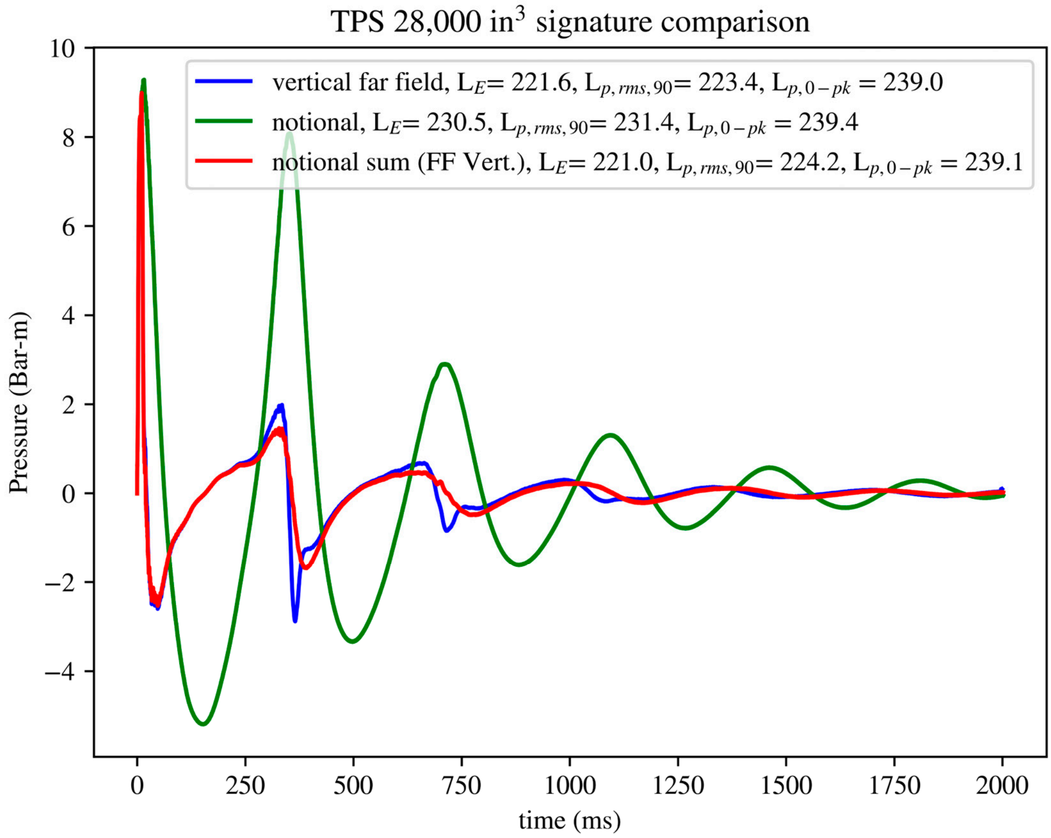

Figure S31. Vertical far field (i.e., surface-affected), notional (i.e. surface-corrected), and 'notional sum', using equations (1) and (2) with $\phi = 0$ (i.e., the reconstructed vertical far field) signatures of a TPS™ signal from OBN measurements provided by Sercel. Legend includes acoustic metrics calculated by the authors.

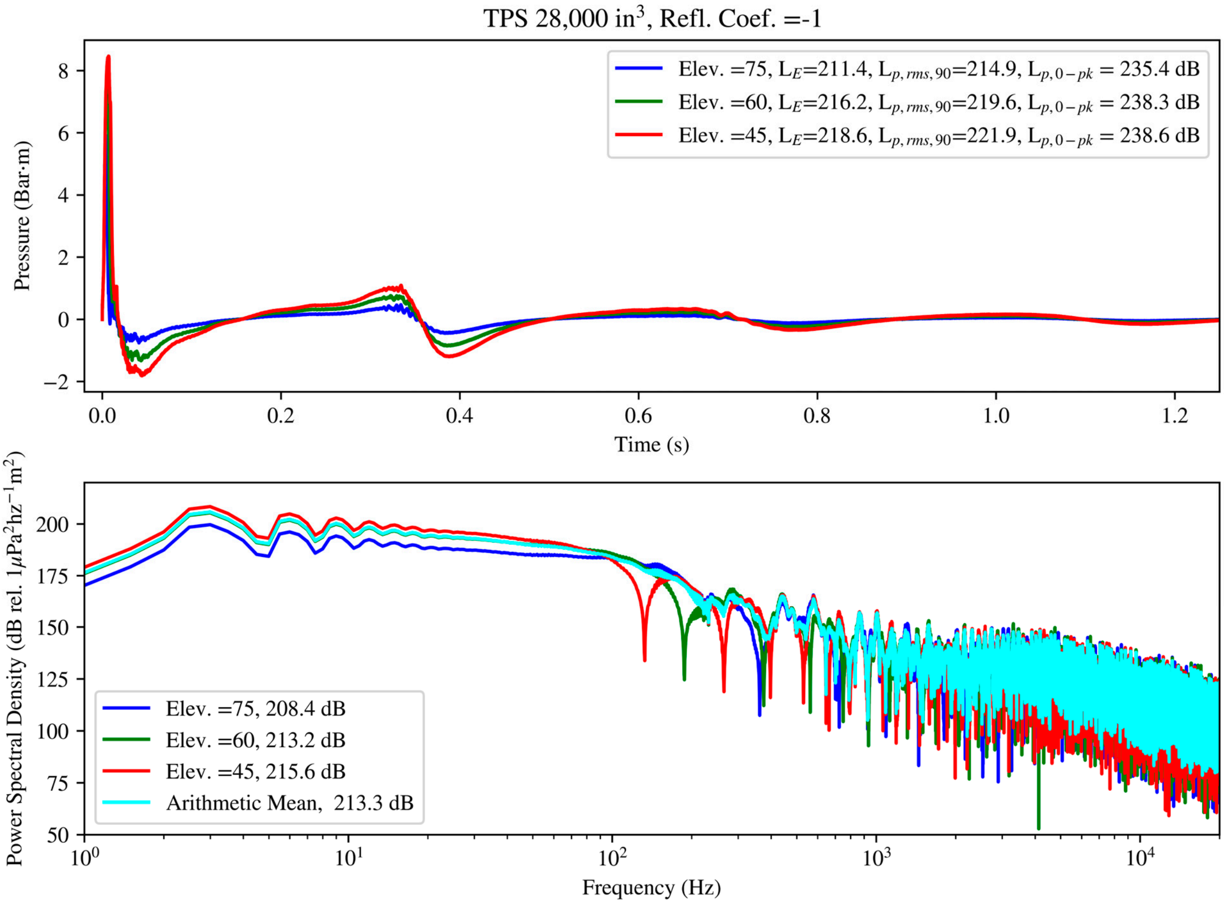

Figure S32. Surface-affected waveforms, spectra, and associated metrics for the TPS™ for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees). Note that the spectrum is in units of PSD rather than energy spectral density, and there the broadband level is lower than the SEL source level.

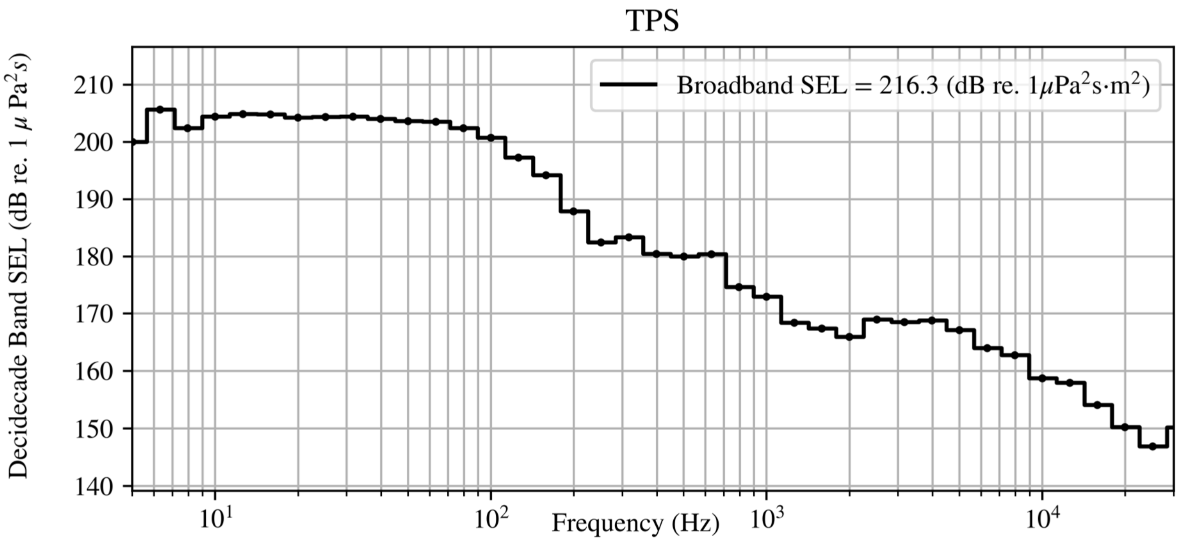

Figure S33. Decidecade SEL spectrum for TPS™, associated with the arithmetic mean in Figure S32. No extrapolation was necessary for high frequencies due to the high temporal resolution time signatures used.

Table S12. Resulting source level metrics for the TPS™. Surface-affected horizontal metrics were carried forward in the analysis, the metrics analyzed from notional and far-field signatures are included for comparison.

TPS™	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	216.3	237.6	219.7
Surface-affected Vertical	221.2	239.0	223.4
Surface-corrected Monopole (notional)	230.5	239.4	231.4

Gemini Source™

The Gemini Source™ by TGS is a broadband marine seismic source capable of generating energy below 4 Hz. It uses a pneumatic, airgun-based mechanism compatible with standard seismic vessels and operates as a high volume single point source, giving it a compact configuration that simplifies deployment and handling (Figures A34 & A35). The system is available in 4,000 in^3 and 8,000 in^3 volume chambers, with the 8,000 in^3 size most common. The 8,000 in^3 size produces a peak frequency of 3.4 Hz. The Gemini Source™ produces an effective frequency spectrum of approximately 2 to 80 Hz, enabling efficient seismic data acquisition across a broad depth range by providing both low and higher frequency content in a single deployment. Although the Gemini Source™ emits across this broad range, its higher frequency amplitudes are generally lower than those of conventional airgun arrays (e.g. approximately 15 dB lower at 1 kHz than the 5,110 in^3 source analyzed), contributing to a reduced high-frequency acoustic footprint.

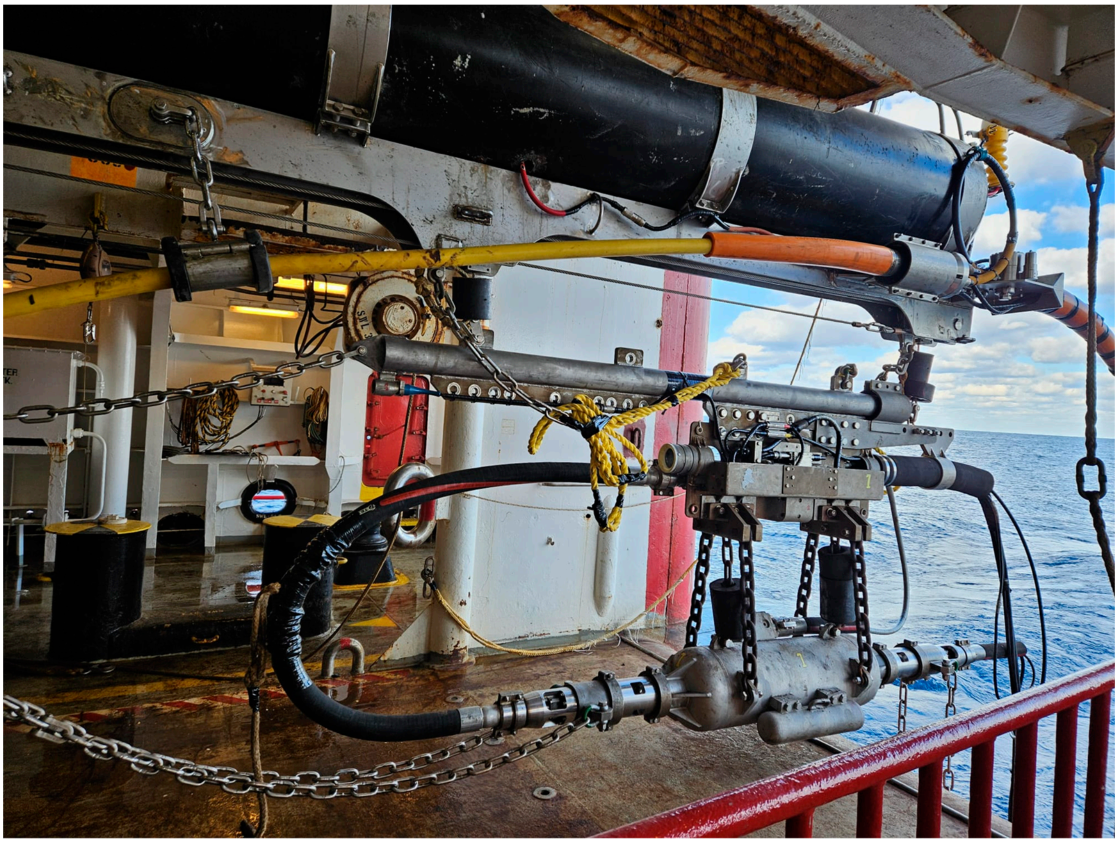

Figure S34. The Gemini Source™ 8,000 in^3 on a dry deck. Photo courtesy of TGS.

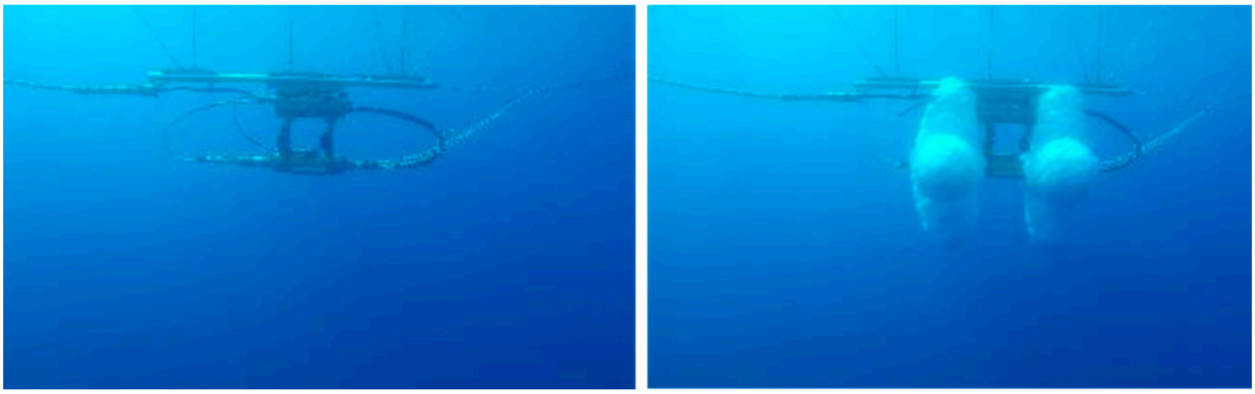

Figure S35. The Gemini Source™ 8,000 in^3 before firing (left) and after firing (right). Photo courtesy of TGS.

Data regarding the 8,000 in^3 configuration of the Gemini Source™ is available from EnerGeo Alliance [18] and Li *et al.* [34]. For this effort, the surface-affected waveforms were modeled by TGS using Nucleus+, which was recently calibrated based on the measurements of Li *et al.* [34]. Corresponding power spectral densities were computed from the waveforms using the periodogram function from the Python package SciPy [33]. Both waveforms and spectra are provided in Figure S36 based on a source depth of 8 m. Final horizontal surface-affected source levels are given in Table S13. The decidecade band SEL spectrum is provided in Figure S37.

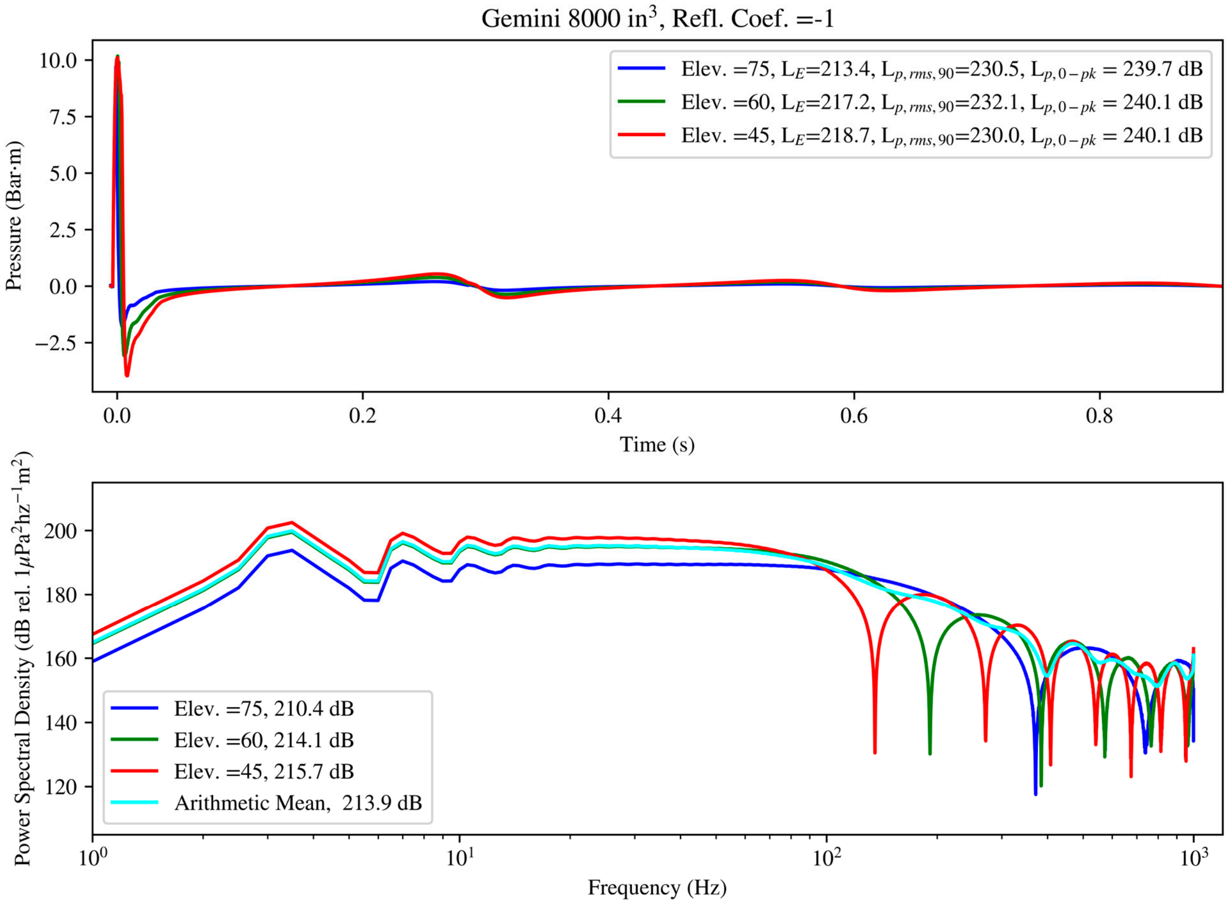

Figure S36. Surface-affected waveforms, spectra, and associated metrics for the 8,000 in³ Gemini Source™ for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees). Note that the spectrum is in units of PSD rather than energy spectral density, and the broadband level is lower than the SEL source level.

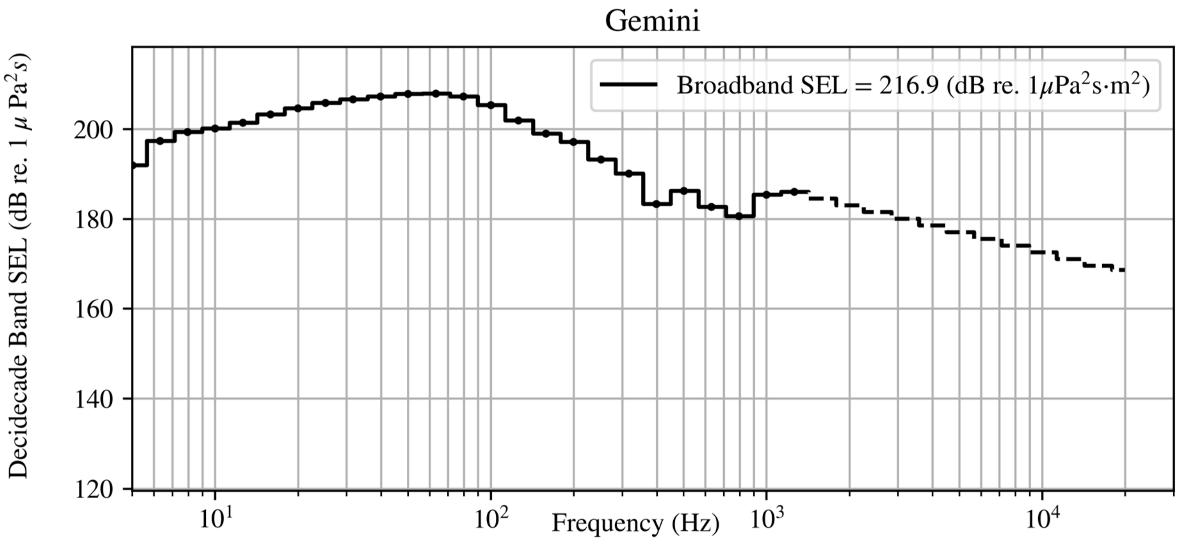

Figure S37. Decidecade SEL spectrum for the 8,000 in³ Gemini Source™, associated with the arithmetic mean, with extrapolation beyond approximately 1 kHz shown with the dashed line.

Table S13. Resulting source level metrics for the 8,000 in^3 Gemini Source™. Surface-affected horizontal metrics were carried forward in the analysis, and the metrics analyzed from notional and far-field signatures are included for comparison.

Gemini Source™	**SEL (dB re 1 μPa^2 m^2 s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Surface-affected Horizontal (15/30/45 degree dip)	216.9	240.0	231.0
Surface-corrected Measurement Li *et al.* [34]	219.1-221.9	239.5	-

Harmony™

The Harmony™ source by Shearwater Geoservices is a modified hypercluster airgun array consisting of six 1,000 in^3 airguns (6,000 in^3 in total volume) with a peak frequency of approximately 4.2 Hz (Figures A38 & A39). It is a broadband marine seismic source that produces a frequency spectrum of approximately 2 to 90 Hz, enabling efficient seismic data acquisition across a broad depth range by providing both low and higher frequency content in a single deployment. Unlike the TPS™ and the Gemini Source™, the Harmony™ source enhances low-frequency output through frequency locking, a physical process in which pressure fields from closely spaced airgun bubbles interact. Because the source utilizes six elements, it may have more directionality than TPS™ and the Gemini Source™. When the airguns are fired simultaneously in a tight hypercluster, the bubbles partially coalesce and interact, effectively behaving as a larger bubble that shifts the dominant frequency downward by roughly one half to one full octave compared with a conventional airgun array. This configuration increases low-frequency energy while reducing comparatively high-frequency output and improving the peak-to-bubble ratio relative to a single airgun of equivalent volume. By achieving increased low-frequency content using existing airgun technology, the Harmony™ source likely offers some of the associated benefits in reducing marine life exposure, but to a lesser extent than the TPS™ and the Gemini Source™.

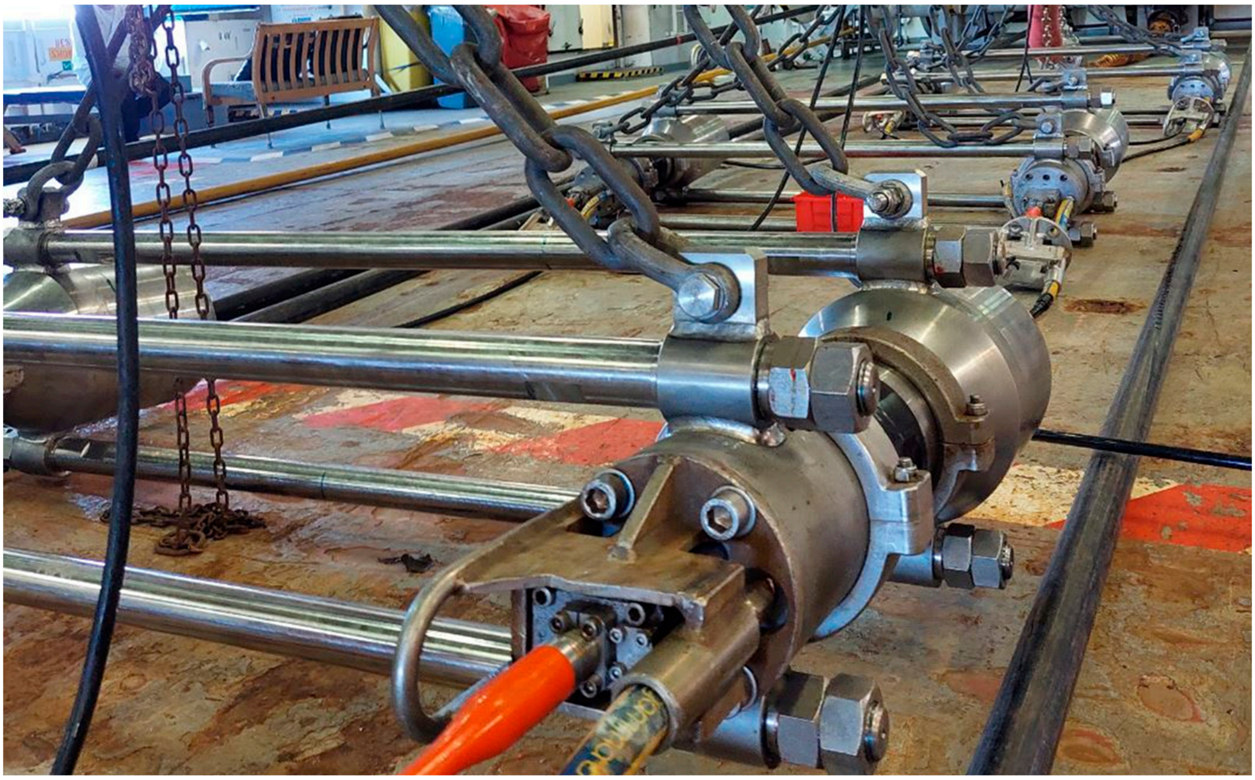

Figure S38. The Harmony™ source on a dry deck. Photo is courtesy of Shearwater Geoservices.

Figure S39. The Harmony™ source after firing. Photo is courtesy of Shearwater Geoservices.

As with all the conventional sources considered, data for Harmony™ were modeled using Gundalf and were provided by Shearwater Geoservices. Results were provided for various depths, and for consistency with the other ULF sources considered, a source depth of 8 m was carried forward. Surface-affected waveforms and spectrum are shown in Figure S40, along with derived metrics. Final horizontal surface-affected source levels are given in Table S14. The decidecade band SEL spectrum is provided in Figure S41.

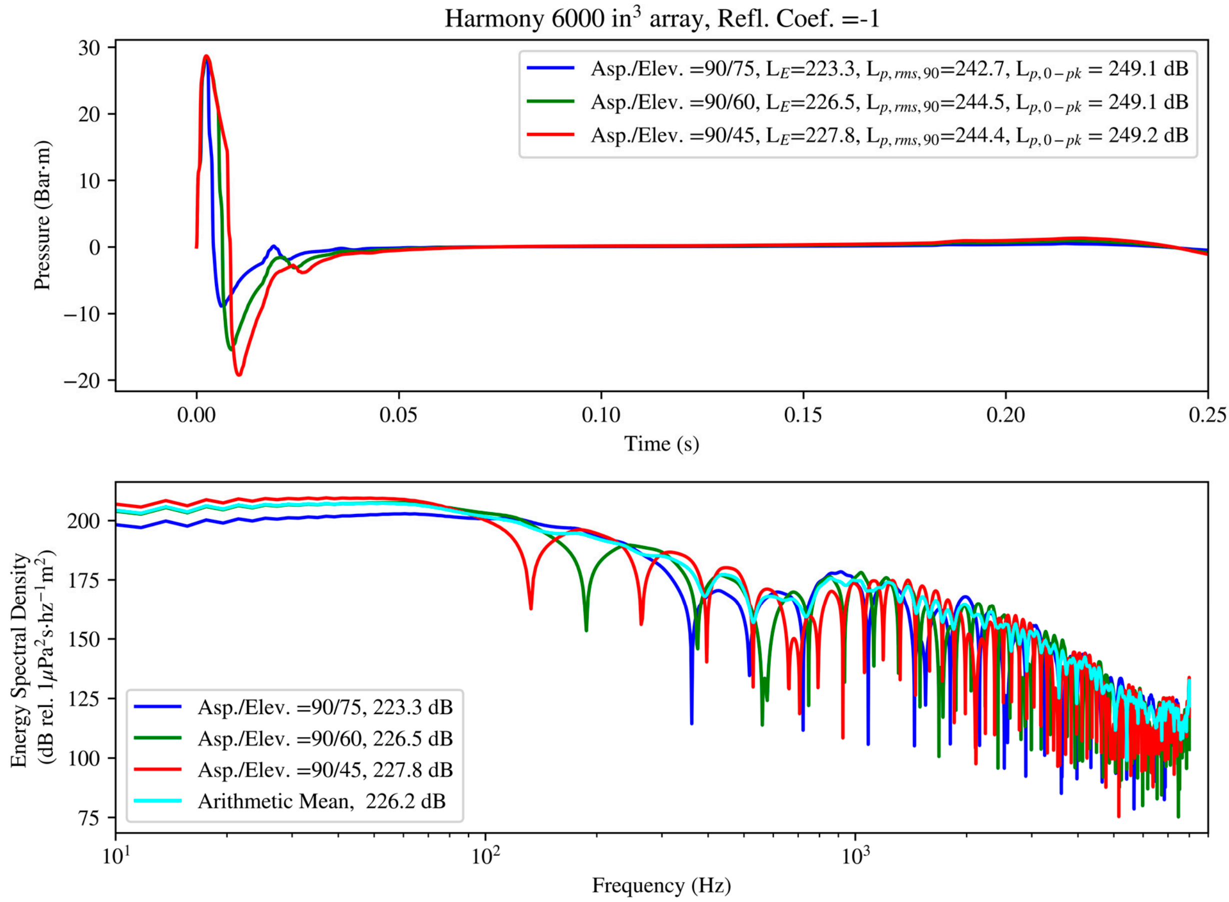

Figure S40. Surface-affected waveforms, spectra, and associated metrics for the 6,000 in³ Harmony™ source for dip angles of 15, 30, and 45 degrees (or equivalent, elevation angles of 75, 60, and 45 degrees).

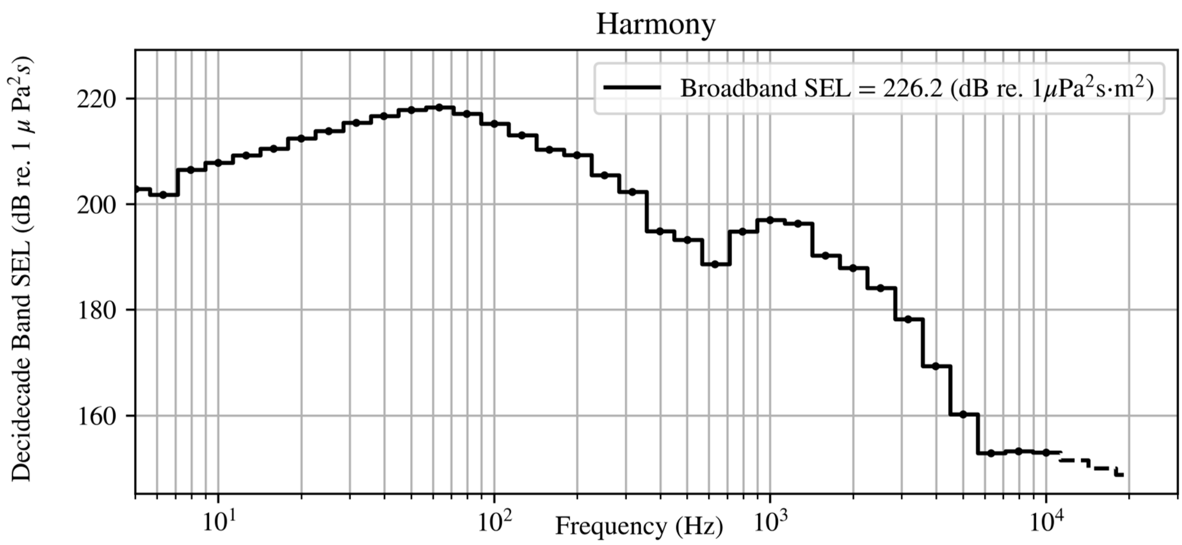

Figure S41. Decidecade SEL spectrum for the 6,000 in³ Harmony™ source, associated with the arithmetic mean, with extrapolation beyond 10 kHz shown with the dashed line.

Table S14. Resulting source level metrics for the 6,000 in³ Harmony™ source.

Harmony™	SEL (dB re 1 μPa² m² s)	PK SPL (dB re 1 μPa m)	RMS SPL (dB re 1 μPa m)
Surface-affected Horizontal (15/30/45 degree dip)	226.2	249.1	244.0

Marine Vibroseis (MV)

MV is an alternative to conventional airgun sources used in marine seismic surveys. Instead of releasing high-pressure pulses of air, marine vibrators use electromechanical or hydraulic actuators towed from a vessel or mounted on the seafloor to produce controlled, continuous, or swept acoustic signals. This allows MV systems to emit energy over a broader range of frequencies with a more gradual onset and lower peak SPLs, which can improve subsurface imaging (especially for high-resolution and full-waveform inversion applications) and potentially reduce disturbance to marine life compared to impulsive sources like conventional airguns. MV systems also offer precise control over signal characteristics, including frequency content and signal duration, which enables optimization for specific geological targets and survey objectives. However, their deployment and operational logistics differ from conventional towed arrays.

There have been 2D field trials of different MV technologies tested with limited output frequency ranges typically below 100 Hz. Currently, an array of several MV systems is needed to achieve the amplitudes that are necessary for deep-penetration seismic data acquisition. A large-scale MV array does not currently exist; however, single- or dual-element MV systems appear to be capable of acquiring usable seismic data for shallower targets. The Marine Vibrator Joint Industry Project (MV JIP) sponsored by TotalEnergies, Shell, and ExxonMobil through the Texas A&M Engineering Experimentation Station continues to support the development of the Integrated Projector Node (IPN) marine vibrator developed by General Dynamics Applied Physical Sciences since 2013 [35]. The MV JIP's IPN system was selected as a representative technology (Figure S42). Field trials which used single- and dual-element IPN systems deployed at a depth of 6 m were included in the analysis [14]. In addition, a modeling study by Matthews *et al.* [13], which included a large-scale array of 18 MV JIP IPN systems towed at a depth of 6 m, was also included in the analysis. The IPN system can produce frequency sweeps with different durations. This analysis considered a continuous 5 s duration sweep from 5–100 Hz with a 50% duty cycle (i.e., 5 s on / 5 s off). Additional MV technologies will be evaluated as data become available.

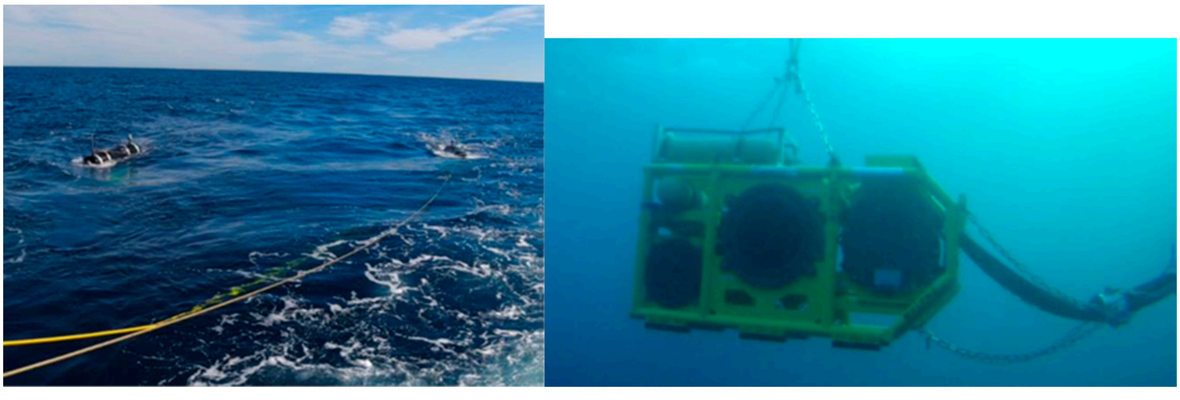

Figure S42. Photos depicting the deployment of two MV JIP IPN systems under tow. On the left, the black bodies are the floats that keep the IPNs floating in the water column where the yellow rope attaches from the floats to the A-frame. On the right, a photograph from one of these IPNs in stationary mode illustrates how towing is performed. The umbilical which is attached to the front of the IPN is what provides the towing force when under tow. The chains on top of the IPN are attached to the float providing buoyancy to the IPN. Photos and description used with permission from Alfaro *et al.* [35].

MV JIP (18-element)

Modeled source characteristics are available in Matthews *et al.* [13] for an 18-element MV JIP IPN array. Each element was modeled as a linear frequency upsweep, based on MV JIP guidelines, with a source waveform amplitude of 5 kPa. The total array source waveform was established by summing the waveforms from each individual element. As ghost or surface reflection contributions were not discussed, and because the authors were developing source waveforms and spectra for use in propagation models that would inherently include boundary effects, it is assumed that the source waveforms, spectra, and source levels are surface corrected (i.e., de-ghosted). Spectra were digitized from the energy source spectral density for the endfire orientation. Although the broadside source levels as reported in Matthews *et al.* [13] were used for consistency with other sources, the endfire spectrum was used as the broadside spectrum was obscured in the figure by other traces. The endfire digitized energy source spectral density was converted to decidecade band SEL, normalized to the reported energy source level (ESL) in Matthews *et al.* [13], and used in this analysis (as shown in Figure S43). Though it was not explicitly stated in [13], we assume that the reported SPL was calculated over a 90% energy window. The associated source levels are provided in Table S15 and were taken from Matthews *et al.* [13].

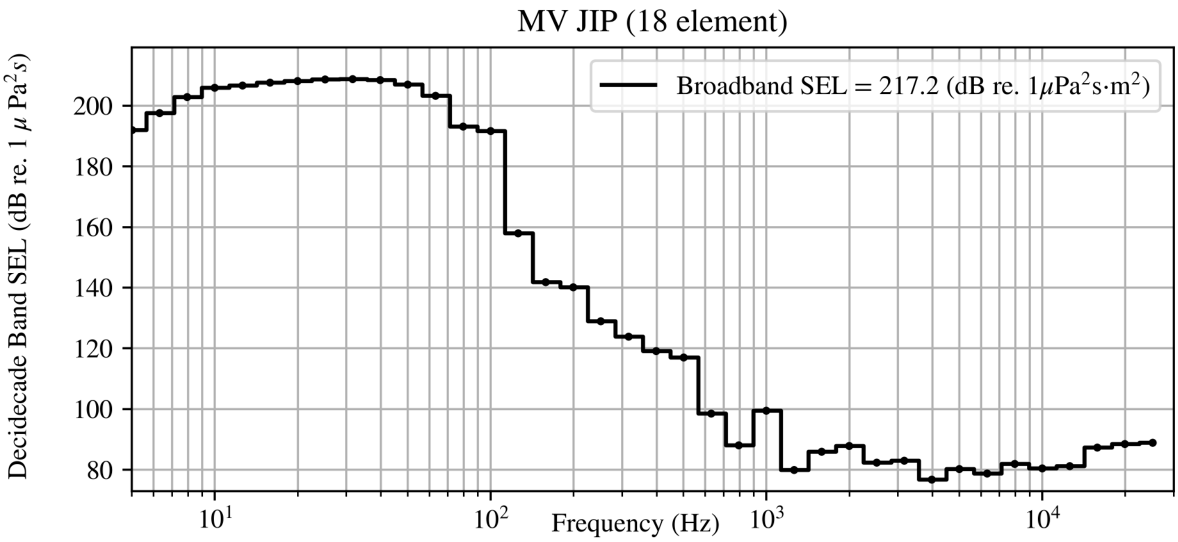

Figure S43. Decidecade SEL spectrum for the modeled 18-element MV JIP IPN.

Table S15. Source level metrics for the 18-element MV JIP IPN, as taken from Matthews *et al.* [13].

MV JIP (18-element)	**SEL (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
Modeled Matthews *et al.* [13]	217.2	218.6	210.6

MV JIP (1- and 2-element)

Sound field measurements were conducted by Li and Martin [14] of single- and dual-element MV JIP IPN sources. Measurements were back propagated and surface corrected, and tables of decidecade band source levels were provided for a variety of measurements. For this effort, we selected three sets of results as representative of this measurement campaign, namely the dual-element dynamic MV JIP (PILOT-16-E-1-22), single-element dynamic MV JIP (PILOT-19-B-1-09), and dual-element static MV JIP (PILOT-05-B-1-01). These results were presented in Li and Martin [14] as decidecade band figures for the different MV configurations tested at sea. In all cases, the results for the seabed critical angle back-propagation method were used. Decidecade band SEL is shown for each in Figures A44–A46. PK SPL and RMS SPL were not back propagated in Li and Martin [14] but instead were given in various figures as a function of range. It was confirmed with the authors that RMS SPL was calculated using a 90% energy window (B. Martin, personal communication, February 27, 2026). To approximate the source levels for these metrics, values were estimated from the figures for the closest point of approach (CPA), which was approximately 170 m. Next, we assumed that the relative difference between SEL and RMS SPL (and SEL and PK SPL) was approximately the same at the CPA and at 1 m. Finally, the observed differences were used to adjust the SEL source level to produce approximate PK SPL and RMS SPL source levels. The observed differences at the CPA were approximately -7.5 dB for RMS SPL and -2 dB for PK SPL, relative to SEL. The pulse durations as reported in Li and Martin [14] were variable and ranged from 12 to 17 s. For this effort, we standardized MV sources to operate on a 50% duty cycle with 5-s durations and adjusted the SEL accordingly. SEL provided in the figures are as they were reported in Li and Martin [14]. The SEL given in the table is the adjusted value (duration of 5 s). Source levels carried forward in the analysis are provided in Table S16.

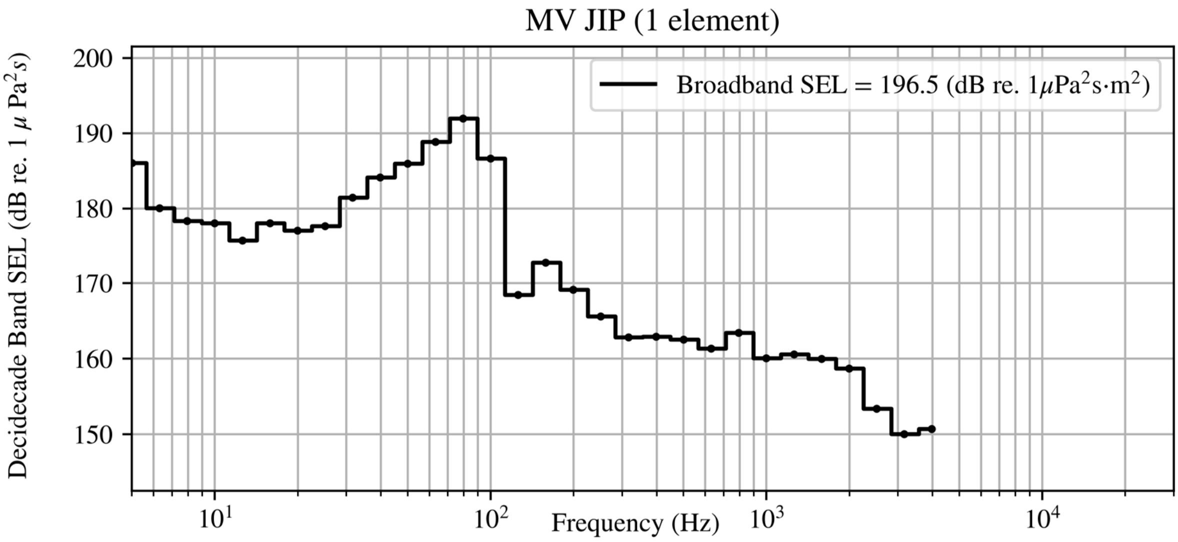

Figure S44. Decidecade SEL spectrum for the single-element dynamic MV JIP IPN (PILOT-19-B-1-09), taken from tabulated values in Li and Martin [14].

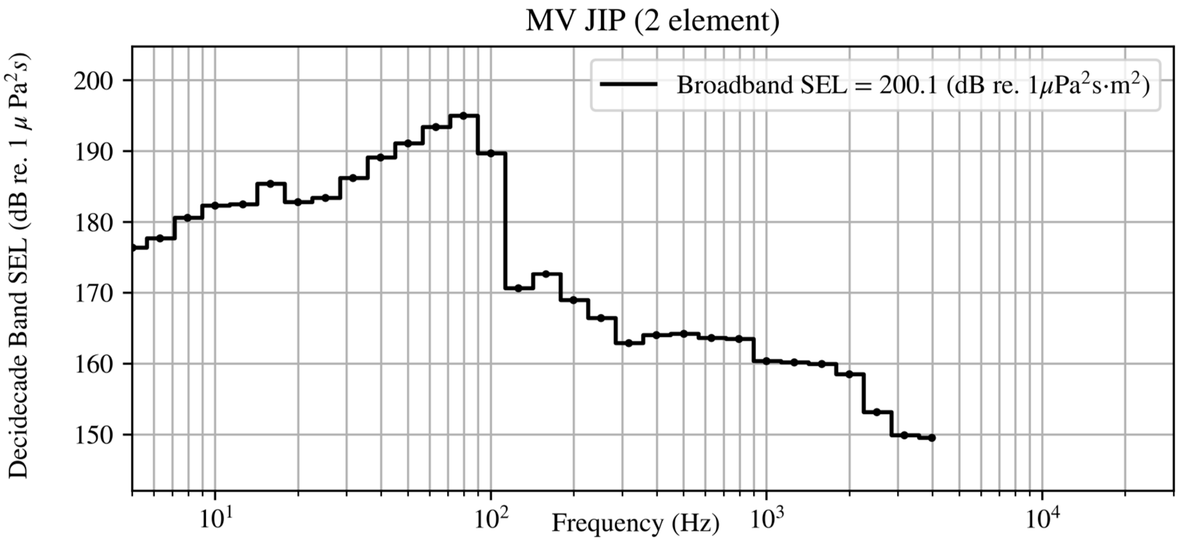

Figure S45. Decidecade SEL spectrum for the dual-element static MV JIP IPN (PILOT-05-B-1-01), taken from tabulated values in Li and Martin [14].

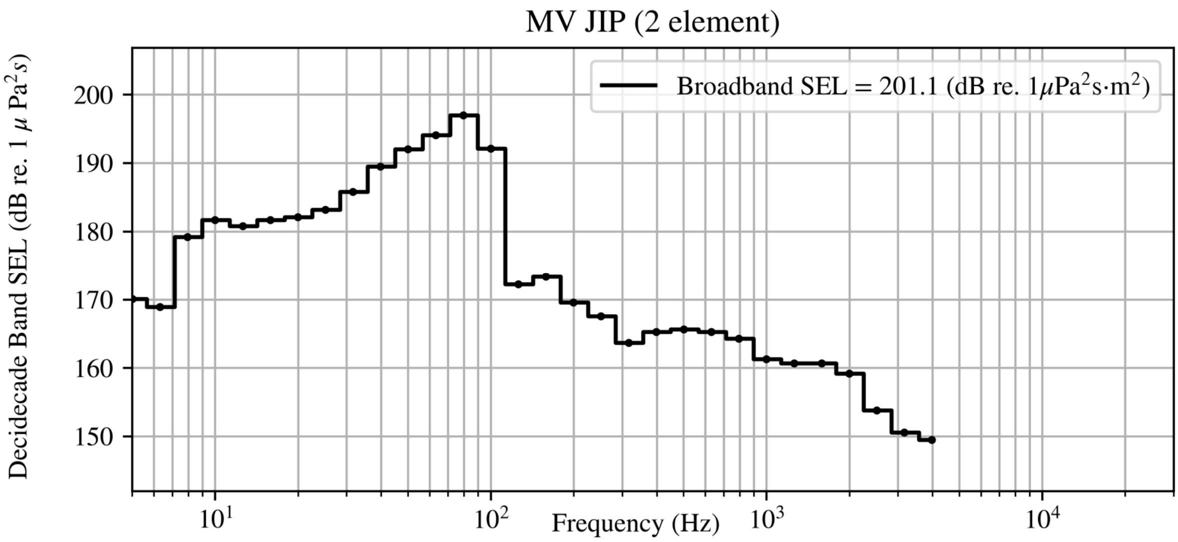

Figure S46. Decidecade SEL spectrum for the single-element dynamic 2-element MV JIP (PILOT-16-E-1-22), taken from tabulated values in Li and Martin [14].

Table S16. Source level metrics for the single- and dual-element dynamic MV JIP IPN systems. SEL is from tabulated values and adjusted to a 5-s pulse; PK SPL and RMS SPL are inferred from figures in Li and Martin [14].

MV JIP 1- & 2-element	**SEL (5 s) (dB re 1 μPa² m² s)**	**PK SPL (dB re 1 μPa m)**	**RMS SPL (dB re 1 μPa m)**
1-element MV JIP (PILOT-19-B-1-09)	196.5	199	193.1
2-element MV JIP (PILOT-05-B-1-01)	200.1	203.4	197.9
2-element MV JIP (PILOT-16-E-1-22)	201.1	204	198.9

Acoustic Metrics

Standardized Notation	Equivalent Terminology	Equivalent Acronym[1]
$L_{p,0-pk}$	Peak sound pressure level[2] [1 μPa or 1 μPa m]	PK SPL[3]
$L_{E,p}$	Sound exposure level [1 μPa² s or 1 μPa² m² s]	SEL[4]
$L_{E,ss}$	Single shot (per-pulse) sound exposure level [1 μPa² s or 1 μPa² m² s]	SEL_{ss}
$L_{E,AUD\ INJ}$	NMFS's auditory injury-weighted cumulative sound exposure level [1 μPa² s or 1 μPa² m² s]	$SEL_{Aud\ Inj}$
$L_{E,60s,M}$	60-second M-weighted sound exposure level [1 μPa² s or 1 μPa² m² s]	$SEL_{60s,M}$
$L_{p,rms,90\%}$	90% energy-windowed root-mean-square sound pressure level [1 μPa or 1 μPa m]	RMS SPL[5]

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[1] As presented in NMFS acoustic technical guidance documents.

[2] Sound pressure level is equivalent to the sound pressure source level when defined at 1 meter.

[3] Peak sound pressure level is also commonly abbreviated as SPL_{pk} or Lpk.

[4] Sound exposure level is equivalent to the energy source level when defined at 1 meter.

[5] Root-mean-square sound pressure level is synonymous with sound pressure level and therefore the SPL acronym is an accepted acronym for this metric.

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