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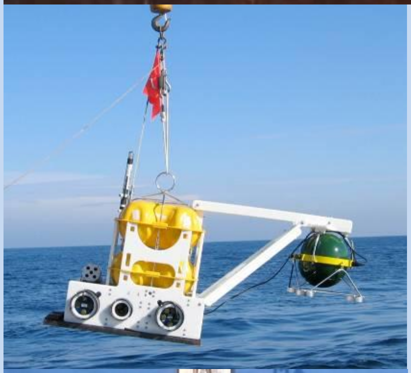
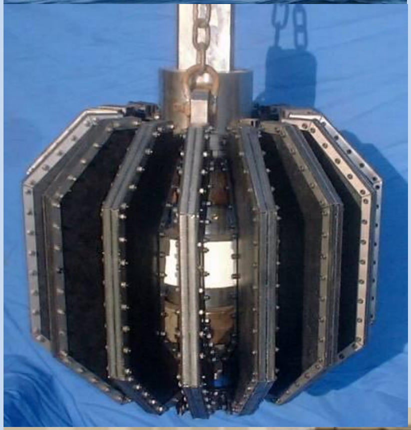
Bjørge Naxys

### REPORT OF THE WORKSHOP ON

# ALTERNATIVE TECHNOLOGIES TO SEISMIC AIRGUN SURVEYS FOR OIL AND GAS EXPLORATION AND THEIR POTENTIAL FOR REDUCING IMPACTS ON MARINE MAMMALS





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# Prologue

By Dieter Paulmann

As part of our continuing efforts to preserve the oceans and their inhabitants, we, Okeanos – Stiftung für das Meer (Foundation for the Sea), have focused on the issue of anthropogenic (human-made) underwater noise and its impact on marine mammals. Okeanos has held a number of international, multi-disciplinary workshops on various novel aspects of this issue, ranging from noise-induced stress effects, and noise management through spatial planning, to ship-quieting technologies, and techniques for assessing the cumulative impacts of underwater noise together with other anthropogenic stressors facing marine mammals. Fruitful, productive discussions and collaborations, especially between experts from diverse fields that don't commonly interact, have resulted from these workshops. Scientists from a diversity of disciplines and specialties (ranging from biologists to engineers) and policy makers, working together, have managed to merge their expertise to develop new ideas, techniques, and mechanisms for making progress on the science and management of ocean noise.

One such management mechanism to reduce ocean noise is source-based mitigation, i.e. making sound sources more benign to marine mammals. Seismic airgun surveys, including those used in the exploration of oil and gas deposits underneath the ocean floor, produce loud, sharp impulses that can raise noise levels substantially over large areas. These surveys can last for months and the noise they produce is virtually ubiquitous in the world's oceans. Though noise impacts on marine life (fish and even invertebrates, along with marine mammals) from seismic surveys are well documented, the biological relevance of these impacts on wild populations remains controversial among the various stakeholders. Rather than address the controversy or evaluate the evidence for or against impact, our purpose in this workshop was to examine quieter, potentially less harmful technologies that might be able to, at least partially, replace airguns. While airguns are excellent tools to image formations, structures, and deposits deep in the ocean substrate, they also have drawbacks from an engineering/industry point of view. They produce more noise than is needed for hydrocarbon exploration, the signal is not very repeatable or controllable, and the frequencies produced are not as low as are sometimes necessary for good penetration of the substrate. In the same way that, historically, airguns replaced explosives for oil and gas exploration because airguns were safer for humans, it is perhaps now time for airguns themselves to evolve into technologies that are more environmentally sensitive and perhaps even more effective in finding oil and gas deposits.

To this end, and supported by the Okeanos Foundation, an international, multi-disciplinary group of geophysical scientists, seismologists, biologists, and regulators met in Monterey, California, 31 August-1 September, 2009, to seek alternatives and/or modifications to airguns and airgun array configurations in order to minimize their potential impacts. Participants were asked to evaluate the strengths and limitations of various alternative/supplementary technologies, consider the conditions under which each could be applied, and discuss aspects such as the timeframes over which they would be commercially available, if not in use presently. Only participants with expertise in a particular alternative technology or airgun array configuration were invited, along with marine mammal biologists. The goal was to preferentially eliminate the use of sound for hydrocarbon exploration, or to reduce the amount or type of potentially harmful acoustic energy introduced, or the total area ensonified.

On the first day, each participant gave a presentation, generally about the technology in which they specialize. These technologies were then discussed on the second day, and a consensus summary statement was formulated by the group. This report consists of that summary statement, along with some supplementary notes by various participants, and three tables on seismic survey characteristics, applications for airgun alternatives, and characteristics of airgun alternatives, respectively.

Discussions were extremely collegial, and there was little disagreement on the main points, namely that:

- airguns produce “waste sound” that is not used by the industry, yet has the potential to impact marine life;
- that this sound (mainly high frequencies and lateral propagation) could be eliminated without sacrificing any data quality for the hydrocarbon industry;
- that reducing peak sound levels is a worthwhile goal even at the expense of requiring a slightly longer signal;
- that technologies are available or emerging that do not introduce any anthropogenic sound, or introduce substantially less sound, into the environment;
- that less sound may be required to gather the same quality of data due to more sensitive receivers;
- and, finally, that regulatory pressure/incentives and more funding to develop these technologies will expedite their availability and broaden their applications.

As the ever-expanding search for petroleum deposits moves towards deeper water (possibly requiring a louder signal) and more sensitive habitats, such as the Arctic, the need for more benign alternatives to airguns will escalate. Nevertheless, in some particularly vulnerable, critical, and productive habitats, any addition of noise may be too much. Moreover, alternatives that are assumed to be more environmentally benign than airguns, may in fact not be. Quieter is almost always better, but all alternatives should be assessed for their environmental impact before being put to wide use. This report is not meant to advocate any alternatives without such essential prior testing.

Some of the information contained within this report is somewhat preliminary in nature. There is still much research and development that needs to be done on some alternatives to seismic airguns. However, this report should dispel any doubts that substantial improvements can be made, even in the near future. What is mainly lacking is regulatory pressure as well as funding. This report seeks to stimulate debate and interest from companies, which in some cases are already developing alternatives to airguns, and policymakers.

This report also includes lists of participants and their presentations, the latter with abstracts.

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# Consensus Summary

# of the
Workshop on Alternative Technologies to Seismic Airgun Surveys
for Oil and Gas Exploration and
their Potential for Reducing Impacts on Marine Mammals

Lindy Weilgart (ed. and co-organizer of the workshop), Andrew Wright (co-organizer of the workshop), Leila Hatch (chair)

Participants (alphabetically): Ron Brinkman, MMS; Chris Clark, Cornell University; John Diebold, LDEO; Peter Duncan, Microseismic Inc.; Rob Habiger, Spectraseis AG; Leila Hatch, NOAA; John Hildebrand, Scripps Institution of Oceanography; Phil Nash, Stingray Geophysical Ltd.; Jeremy Nedwell, Subacoustech; Dave Ridyard, EMGS; Rune Tenghamn, PGS; Peter van der Sman, Shell; Lindy Weilgart, Dalhousie University; Warren Wood, NRL; John Young, ExxonMobil

## Abstract

Past experience shows us that a fraction of the airgun sound that has potential to impact marine mammals (either physically or behaviorally) comes from "waste sound" that is either too high frequency and filtered out before recording or propagates laterally away from receivers and is also never recorded. The Okeanos Seismic Airgun Alternatives workshop panelists identified several ways in which unwanted sound or noise from seismic airguns might be reduced with little or no effect on the quality of data acquired. In addition to eliminating this noise or unused signal, peak sound levels required for exploration might also be reduced by spreading the source energy out over time, and/or moving sources and receivers closer to the seafloor. Panelists also discussed promising new imaging technologies that are either completely silent (e.g. controlled source electromagnetics) or that can lessen the amount of seismic sound required to gather seismic data (e.g. increasing the density of more sensitive receivers, such as fiber optics or through the use of passive seismic technology) thereby still allowing for a reduction of the economic risk of hydrocarbon recovery. Workshop panelists acknowledged that these technologies are purpose driven and do not work in all circumstances. Many of these technologies may be either available now or in the next 1-5 years, depending on funding and technology advancements.

## Introduction

Supported by Okeanos, a multi-disciplinary group of geophysical scientists, seismologists, biologists, and regulators met to seek ways to reduce noise from seismic airgun surveys, specifically the large airgun arrays used for oil and gas operations in the ocean. We, the participants of this unique gathering, agree that marine life would benefit from a quieter ocean. With the introduction of new technologies and techniques, turning the tide on rising levels of noise in the oceans now seems feasible. The following findings and recommendations represent the key results of our discussions at the workshop.

## Findings and Recommendations

The most effective acoustic mitigation remains not exposing marine life (i.e., through avoidance) to additional anthropogenic noise.

- Government agencies responsible for regulating offshore seismic data acquisition activities (hereafter: 'Regulators') should collect or fund collection of baseline data on the distribution of marine mammals in space and time in areas where seismic data acquisition is being planned. These data should be collected as far in advance of the seismic data acquisition as is practicable (especially where species distribution is poorly understood or in areas where seismic data acquisition is new).
- In areas where seismic data acquisition will take place and is likely to expose marine animals to noise, efforts should be made by regulators in conjunction with the operator of the seismic data acquisition activity to reduce sound levels to the lowest practicable and/or integrate the use of alternative technologies into planned activities to reduce noise exposure.
- Impulsive sources like airguns have the potential to physically impact marine life because of the sharp rise times and high peak pressures of airguns. Behavioural effects are also possible due to exposure to sound at distances away from the airguns.
- A multi-dimensional metric or scoring system to quantify the impacts of airguns or alternatives on various marine animals would be very helpful, though difficult.

## Airguns

- Airgun design can be optimized to reduce unwanted energy.
  - Imaging deep geological targets requires an acoustic source outputting relatively low frequency content (<200Hz). The lower frequencies provide the deep energy penetration into the earth. Currently seismic airguns produce broad-band acoustic energy (>200Hz) and in directions (both inline and horizontal to the plane of interest) that are not of use. During collection of seismic data for deep imaging purposes one should strive to reduce unnecessary acoustic energy (noise) through array, source, and receiver design optimization. A more general statement can be made that regardless of the imaging target, anyone collecting seismic data should strive to reduce unwanted energy or noise. It should be noted that even if unwanted frequencies (> 200 Hz) are removed, there will still be frequency overlap with several marine animals (including most baleen whales) that can and should be minimized.
- Lower source levels could be achieved through better system optimization, i.e. a better pairing of source and receiver characteristics, and better system gain(s). For example, new receiver technologies, such as fibre optic receivers, may allow the use of lower amplitude sources through a higher receiver density and/or a lower system noise floor.
- Some evidence exists which indicates that re-engineered air guns with "mufflers" can be used to attenuate unwanted high frequency energy without affecting frequencies of interest.
- Bubble curtains may be used to optimize the directivity of the source, but they can be difficult to use, produce some noise themselves, and cannot fully eliminate horizontal propagation.

Use of alternative technologies with airguns and/or instead of airguns

Controlled sources generally put the same level of geophysically useable energy into the water as impulsive sources like airguns, but over a longer period of time, and a resulting lower peak sound level, i.e. they are quieter. For example, for a rough calculation in the near-field, a one-second oscillatory/vibrator/projector pulse puts the same level of geophysically useful energy into the water as an airgun's ten millisecond pulse, but is one-hundred times quieter, resulting in a ten-thousand fold reduction in the area of ensonification. These sources include technologies such as the electro-mechanical modern marine vibrator, low frequency acoustic projector (driving cylinder, e.g. LISA, a low frequency electromagnetic transducer system), the solid state piezo-ceramic Helmholz resonator (e.g. The Naval Research Laboratory's DTAGS), and other non-impulsive, oscillating sound sources. Furthermore, controlled sources can produce sound over the frequency range desired, generating signals that can be specifically designed to minimize the impact on marine mammals and maximize geological interpretability (e.g. pseudo-random sequences).

It has been suggested that masking, or the obscuring of signals important to marine life, may worsen over this smaller ensonified area, because of the more continuous nature of the vibratory source. However, airguns at distance, especially in a reverberant environment, permanently raise the noise floor, as the previous pulse does not decay fully to background noise levels before the next shot is fired. Thus, airgun shots do not represent truly intermittent signals, with gaps of silence between shots. To better understand the environmental advantages or disadvantages of the use of controlled acoustic sources will require further research.

Controlled sources, such as marine vibrators (e.g., hydraulic, electric, etc.), offer the opportunity to reduce the peak amplitudes introduced into the water column and to tune the frequencies transmitted to exactly the band-width required for operations. By using a sweep instead of an impulse source, one can reduce the amplitude (peak levels) by 30 dB. This is done by spreading out the energy over time. A sweep that is 10 s has the same amplitude after correlation that a short 40 ms pulse generated by the airgun has. The use of pseudo noise (PN) sequences could reduce the acoustic footprint further (perhaps by an additional 20 dB/Hz by spreading out frequencies over time), but more research is needed to fully understand how to implement these sequences in an effective and optimized way.

- There is some evidence that a swept signal with lower peak amplitude would have less impact on marine animals than a higher peak impulsive signal. It is possible that pseudonoise sequences would reduce impacts further than normal up or down sweeps as they would sound broadly similar to natural background noise--noise to which such animals would presumably be adapted. More research is needed to assess this.
- In certain situations and with certain non-airgun source types, placing the sources and/or receivers near or on to the sea floor can reduce the required source level, as well as the amount of sound that needs to travel through the water column. For example, marine vibrators can operate close to the sea-bed and accomplish increased penetration relative to shallow towing.
- A controlled source offers improved receiver optimization possibilities compared to airguns. For instance, a combination of fiber optic sensors with a reduced bandwidth seismic source, such as a marine vibrator, may make the most optimal use of these technologies.
- Marine vibrators also have the advantage of being more vertically directional in deeper water.

- Front-loading the exploration workflow with the use of silent technologies (e.g., CSEM / 3D EM, gravity, gravity gradiometry, etc.) has potential to optimize the exploration process and require less sound to be injected into the environment. For instance, if 2D airgun surveys followed by quieter technologies (e.g. 3D CSEM) do not show promising targets, proceeding with 3D seismic surveys may not be worthwhile. Conversely, one may optimize 3D seismic activities based on the results from 2D seismic and 3D CSEM.
- Technologies such as marine vibrators, microseismic monitoring (passive seismic), and fiber optics have potential to reduce the need for 4D airgun surveys, used to monitor the movement of oil or gas in an exploited reservoir over time.
- Regulators and/or the geological and geophysical industry (including oil and gas exploration and production companies) should fund or undertake research into impacts on marine animals of alternative technologies such as marine vibrators and CSEM / 3D EM surveys. Companies developing these technologies need to work together with marine biologists to better understand, design, and carry out research needs in this area.
- While some airgun alternative technologies are available now or in the next 1-5 years (see Table 1), an increase in R&D funding for alternative exploration technologies (e.g., CSEM / 3D EM, marine vibrators, passive seismic, fibre optics receivers, etc.) will accelerate development and expand the application window. Governments should encourage the development and use of alternative technologies in an environmentally sensitive manner through both regulatory changes as well as additional funding to regulatory bodies, scientists, and engineers.

Coordination / Incentives

- Regulators should fund or undertake efforts to produce higher quality, accessible, and well-managed databases for marine animal distribution in space and time, which are needed to inform environmental impact assessments. Note: The Minerals Management Service (MMS) is data basing all current marine mammal observer sighting records and, although presently not a requirement, is encouraging the use of Passive Acoustic Monitoring (PAM) for future surveys.
- Efforts should be made to characterize the current (snap-shot in time) spatial distribution and other characteristics of noise exposure from airgun use in worldwide waters (centralize data on incidence of different uses and locations/regional use). Good measurements of the frequency content of seismic airgun pulses at various depths and ranges should be made.
- Holders of geological and geophysical data should mine their data to more fully characterize what is known about where airguns were used, what their output characteristics were, and any related propagation information that is available. Additionally, marine mammal observer databases, along with passive acoustic monitoring data, should be maintained for information on the distribution and behavior of marine mammals. Radiated acoustic energy from airguns should be related to marine mammal observer reports and other marine mammal data.
- Oil and gas industry associations could play a role in facilitating the collaboration between oil and gas operators, contractors, regulators, and scientists so that all parties can jointly exploit currently missed opportunities to share and/or obtain useful, multi-disciplinary information about the potential impacts of the various exploration methods and make the results available.
- Some countries have inherent incentives for airgun surveys within their work programs and in doing so, have implied disincentives for alternative technologies. Governments should discontinue programs that discourage the utilization of non-airgun technologies. Governments

should develop incentives for any alternative technologies that are found to have clear environmental benefits over current airgun technology.

- The academic geophysical community should also be encouraged to research quieter alternatives to airguns, with the aid of government and/or industry funding.
- Regulators should encourage and help fund research and development of quieter, alternative sources and their impact assessments.
- Governments and regulators should produce, domestically and internationally, clear, consistent environmental compliance laws, regulations, and standards, as well as apply them in a similarly consistent manner across different geographical areas. This would facilitate the development of more environmentally benign technologies.

## Additional Notes/Information

While proponents of LACS and gravity gradiometry, two technologies we mention in our tables, were unable to attend our workshop, we nevertheless supply information about these technologies in the interest of being more complete.

From:

http://www.bjorge.no/modules/module_123/proxy.asp?D=2&C=233&I=1691&mid=-1&sid=-1&pid=766

LACS (patented) Low-frequency Acoustic Source

LACS can be used for seismic acquisition. It is a digital source, is small in size, and does not need high pressure air to operate. It can control the spectral contents of single pulses, is repeatable with precise timing, and has a high pulse rate yet no interaction between pulses. In contrast, the interaction between airgun pulses which are close together in time (gas bubbles) is less predictable and weakens the pulses. Several LACS units may operate together to provide an increased pulse pressure. The system also allows accurate simulation of shipping noise, since it is similar both in the time and frequency domain, without a sweeping fingerprint.

Bjørn Askeland, a developer of LACS, adds: "…The important issue now is to get an overview of the potential of time-coded sequences for marine seismics. LACS is a digital high fire rate marine source. In telecommunications signals used to be analog, but now most of them are digital."

"… new sources [could] replace airguns for borehole seismic applications within 5 years if research money is made available and access to offshore wells is regulated. Taxation of borehole airgun surveys may be a way of speeding up the technological development and also for providing the necessary research money…".

Gravity Gradiometry

The following is supplied by Duncan Bate, ARKeX Inc.:

Unlike air guns, both gravity and gradiometry are passive; no energy is put into the earth or water. Variations in the naturally occurring gravity field are measured. Both technologies are fairly well developed and have been used by both mining and oil and gas industries for decades.
The major difference between gravity and gravity gradiometry is the way the field is measured. To measure the gradient of the field, a much more complex piece of equipment is needed, which is newer and more expensive than traditional gravity meters. The benefit of gravity gradiometry is the increase in resolution. The resolution is now more on the same scale as seismic data. Also, there has been a big step forward in the processing and interpretation of gravity gradient data. Gravity and gravity gradiometry are not applicable in all geological settings, and seismic data will always be preferred. However, in the correct setting, working with an integrated data set of seismic and gravity gradiometry, a better picture of the subsurface can be delivered which may also reduce the amount of seismic needed.

Additional Notes/Information from Participants:

Christopher Clark:

Past research has shown that bowhead and gray whales respond to seismic airgun arrays by moving away from and avoiding the area of the seismic survey (*Malme, C.I., Miles, P.R., Clark, C.W., Tyack, P., and Bird, J.E. 1984. Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Phase II: January 1984 migration. Report of Bolt Beranek & Newman, Inc., Cambridge, MA, to U.S. Minerals Management Service, Anchorage, AK. NTIS PB86-218377.*; *Richardson, W.J., Greene, C.R., Jr., Malme, C.I., and Thomson, D.H. 1995. Marine mammals and noise. Academic Press, New York, 576 pp.* ). There is also evidence that baleen whales change their vocal behavior in response to seismic exploration sounds. For example, blue whales summering in the Gulf of St. Lawrence increased the rates at which they produced mid-frequency (30-90Hz), social calls when a seismic sparker was operating (*Di Iorio, L., and Clark, C.W. 2009.* doi: *Exposure to seismic survey alters blue whale acoustic communication. Biol. Lett., doi: 10.1098/rsbl.2009.0651, 4 pp.*), while fin whales wintering in the area to the west of the British Isles stop singing in the presence of seismic airgun surveys *(Gagnon and Clark*, *unpublished data*). Di Iorio and Clark (2009) suggested that the blue whales increased their call rates as a way of compensating for the increased amount of background noise from the sparker. The fin whale response of song cessation is similar to that of humpback whale singers when disturbed by loud sounds or noises. In sum, none of the observed responses by large whales to geophysical exploration sounds is surprising, and we should expect continuing evidence to accumulate demonstrating that these low-frequency specialists respond to seismic impulses and seismic surveys in ways that are biologically sensible.

John Diebold:

A larger number of smaller airguns can be more effective when it comes to focusing the energy downwards, especially at higher frequencies. In theory, increasing receiver density can have a similar effect, and the proprietary "Q" streamers do this in the along-track direction. But with the current approach of individual streamers, it's dangerous to increase the across-track density very much.

With Wide Azimuth acquisition, there are more sources (typically 3 or 4) but the total number of shots is about the same, although they are more greatly distributed in space. If the number of receivers was doubled, the same result could (in principle) be achieved with half the shots. This certainly is what happens with multi-streamer vs. single-streamer 3D acquisition.

There are a couple of things going on simultaneously with tow depth of the array. Deeper towing enhances low frequencies in all directions, but it also limits the useful upper frequency boundary, and thus the resolution in travel time. A secondary effect is that shallow towing decreases the horizontal sound propagation, due to the Lloyd's mirror cancellation effects.

John Young:

Typical offshore 2D seismic surveys can cost in the millions to tens of millions of dollars, 3D seismic can cost in the tens to hundreds of millions, and deep water wells would also be in the tens to hundreds of millions. Field production facilities can be in the hundreds of millions to billions of dollars.

To image the geological target requires a certain degree of signal to noise ratio. This can be obtained by either reducing the noise or increasing the signal or a bit of both. For example, additional receivers can provide both additional signal and/or reduced noise through beam steering. Futhermore, finer receiver spatial sampling allows one to sample the noise better which, in turn, allows it to be removed more easily and optimally when the data are processed.

As an example (not an endorsement), WesternGeco's Q streamer acquisition technology has three distinct components. 1) It has finer receiver sampling in the inline direction or along a given seismic cable; 2) It has the ability to measure each source signature and then extrapolate to a far-field signature; 3) It has both lateral and vertical cable position control. Improvements to the data come from additional inline receiver sampling which allows one to sample the noise for better noise removal and/or sum adjacent receiver channels for increased signal. By measuring each source for each shot of the airgun, one can use individual signatures to deconvolve the data (in other words, remove the source signature on a shot-by-shot basis leaving only a spike for each acoustical interface). This in effect improves the signal-to-noise ratio (S/N). By controlling the positions of receivers more precisely one can minimize smear (most data processing algorithms like straight cables) which again is a form of increased S/N.

Another example (again, not an endorsement) so called across-track or cross-line density has increased to the point that the PGS Ramform Sovereign (2008) provides 22 streamer capability. PGS has since gone a step further with the development of "GeoStreamer" technology which allows streamers to be equipped with both a pressure and velocity phone. The dual sensor capability allows suppression of the surface ghost. Suppression of the surface ghost provides improved data quality via broad bandwidth/higher resolution and lower noise from being able to tow the streamers deeper. The deeper tow also allows one to work in higher sea states which provides greater operating efficiencies i.e., less time footprint in a given geographic area. On the other hand, operating in higher sea states means mitigation through visual detections of marine mammals in the safety zone is less effective.

Peter van der Sman:

Improvements in reducing high frequency noise could be made in airguns by altering the port/throat design. Some work has been done in the past to illustrate this. While the ideas are published, the results are not available in the open literature. However, a patent has been filed on this concept in 2005 proposing such changes and suggesting an attendant reduction in high frequency noise.

Noise can be added in or convoluted with the actual data at all stages of the exploration process, and the actual design and implementation of this whole chain of events (design, acquisition, processing, interpretation, etc.) will decide if the final objective can be met. For instance, self-noise from the streamer can be an important consideration. Increasing the output power at the source may not help, and indeed even hinder, the signal to noise ratio, if the source power is not the weakest link. "Shot-generated noise," for instance, is source energy that cannot be interpreted. If the sound decay of the previous shot has not yet reached ambient levels, increasing the source power may in fact raise the noise level for the subsequent shot. Though difficult, ideally, all components in the exploration process must be matched and designed to work optimally together. The source level should be lowered to the point just before it becomes the weakest link.

Warren Wood:

Deep Towed Acoustic Geophysical Systems (DTAGS) can detect areas missed by surface-towed airguns, but there is less penetration than from surface-towed airguns. This is mostly due to frequency content. DTAGS operates at higher frequencies (220-850 Hz) thus providing greater resolution at a cost of reduced penetration (100-200m in sand, 1000 m in soft mud). The vertical resolution is better because of the higher frequency content, and the horizontal resolution is better because of the proximity to the target (i.e. deep).

Any deep-towed instrument, of which DTAGS is one, limits the speed of the towing vessel. DTAGS is towed at 2.0 to 2.5 knots, whereas a surface towed seismic system may be towed up to 3 times faster, thus covering a greater number of kilometers per day of ship time. For surface or deep-tow, traversing from site to site requires pulling in all the gear and traveling at full speed (15-20 knots) to the next site and re-deploying the source and receivers. Deployment and recovery of DTAGS requires 2-3 hours. This is perhaps slightly more than required for a small surface seismic system, but much less than for a large 3-D system.

With the DTAGS system in its present form, there is also an issue of navigating the source and receivers. Right now, the system is simply towed, with knowledge of its location but without having complete control over where it goes (on the sub-wavelength scale). However, technology exists to solve this problem, so this could be accomplished with adequate funding.

Dave Ridyard:

The EM source is towed deep, 10-50 m above the seabed. As the depth of investigation of the EM method increases in the future, the power of the technology to de-risk further exploration efforts will increase accordingly.

Rune Tenghamn:

The latest version of PGS's Electrical Marine Vibrator will probably have an efficiency which is 4-6 times higher than for an airgun, though this needs to be tested before it can be confirmed. The Marine Vibrator is as reliable as an airgun.

Vibrators could have multi-azimuth applications. With coded output, several vibrators can be used at the same time with a different azimuth.

Vibrators have been used at a water depth of 100 m, but from an operational perspective, it is difficult to operate them at great depth (>1,000 m). They are pressure compensated and can therefore be used at different depths. The limitation is the length of the umbilical (electrical losses) and the change of air density. At some depth, the air will become a liquid or have such a high density that the performance will be affected.

To have mainly vertical propagation, the vibrator has to be at the right depth. For 20 Hz, the source would have to be at 18.75 m (a quarter of a wavelength). This is not possible if one is operating in shallower water. Seafloor reflections will spread the energy more in shallow water.

In shallow water operations with 6-10 sources, one has the option to not only send out a signal once at each location, but to "stack" several signal sweeps or sequences, i.e. repeat the signal generation at the same source location until an adequate signal to noise ratio is achieved. By doing this, one can improve the signal to noise ratio even if the source itself is rather weak. The reason one can "stack" the signal with a marine vibrator (a controlled source) is that the signature of the signal can be made identical each time. For an airgun, the signature will change from shot to shot, which will make this process less effective.

Even if many vibrator sources are needed for deep-water operations, the peak signals will be much quieter than for an airgun array. This is due to three factors: 1) the energy is more spread out in time; 2) the frequency is more spread out in time; 3) only the energy in the seismic band of interest is sent out.

Rob Habiger:

Low Frequency (~1-10 Hz) measurements of the earth's passive seismic wave field are being studied by multiple academic and industry groups as a new technology for identifying and delineating hydrocarbon reservoirs. This technology has been predominately applied on land where acquisition instrumentation, survey design, and processing workflows/software are evolving fairly rapidly among a limited technical community. The technology is much less mature for marine applications, with only one offshore survey acquired to date. Additional experiments are required to fully test it offshore and advance its application to oil and gas exploration.

Peter Duncan:

Passive seismic (using earthquakes or interferometry) for structural imaging is a lot less costly than the acquisition of conventional seismic on land. However, it may not be in the marine environment (compared to streamer acquisition) as it requires the deployment of ocean bottom receivers, either cables or autonomous nodes.

Passive imaging techniques today offer a lower resolution imaging suitable for frontier exploration and to rank order a list of exploration opportunities to determine which are the most likely to be successful, and therefore pursued, but they are not sufficient for field development.

The frequency limit of 20 Hz achievable with interferometry means that the resolution is low. Conventional streamer data has signal content up to 60 Hz and sometimes higher, thus achieving higher resolution. Over the next years (perhaps 5), passive techniques might be able to achieve higher frequencies, hence higher resolution.

********************************************************************************

Note: The following tables contain values that are highly variable, e.g. from survey to survey, etc. We have attempted to give our best guess in the interest of giving the reader "ballpark" values only. Many thanks to Ron Brinkman, John Diebold, John Hildebrand, and Warren Wood, for filling in values for airguns and other acoustic sources used in seismic surveys.

## Table 1. Characteristics of various technologies used to image the ocean substrate for petroleum deposits.

| | Pings /Survey | J /Ping | Duty Cycle | Peak Frq | Frq Range | Watts | Peak Pres re 1 µPa | Pulse Duration | Directionality sr/4pi | Source Depth | Tow Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Added noise:** | | | | | | | | | | | |
| **Airgun Array &** | 100,000 | 2.5 x 10^5 | 20 s | 50 Hz | 5-200 Hz@ | 8.3 x 10^6 | 256 dB | .03 s | 0.25 | 3-12 m | 4 kts |
| **Silenced Airguns** | | | | | | | | | | 3-12 m | 4 kts |
| **Marine Vibrators** | Similar to airguns | | | 10 Hz | 6-100 Hz# | ? | 20-50 dB below airguns | 6-10 s | omni | 0-1000 m | 0-4 kts |
| **DTAGS** | c20k | | 30s | 650 Hz | 220-850Hz | | | 250ms | omni | 0-6 km | 2kts |
| **Para-metrics** | ? | ? | ? | ? | ? | ? | ? | ? | 10 deg. | 0-6 km | ? |
| **LISA** | | | 100% | 10 | 5-500 | 20-200K | 210@1m | continuous | variable | 0-100m | 0-4kts |
| **Sparkers +** | c20k | 300 | 1 s | 500 Hz | 480-520 Hz | 1.5 x 10^5 | 233 dB | 2 ms | omni | 0-6 m | |
| **Boomers** | c20k | 280 | | 600Hz | 0.1-15 kHz | | | 2-3 ms | omni | 0-6 m | 4 kts |
| **LACS**** | | | | 50 Hz | 10-150 Hz | | 212 dB | 8-100 ms | | | |
| **No added noise:** | | | | | | | | | | | |
| **Gravity*** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| **Gravity Gradiometry*** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| **Passive Seismics** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| **EM** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | Near seabed | 1.5 kts |
| **Micro-seismics** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| **Receivers:** | | | | | | | | | | | |
| **Fibre Optics** | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | | | | | | | | | | | |

*Added by Duncan Bate, ARKeX Inc., a supplier of gravity gradiometry

**Added by Bjørn Askeland, a developer of LACS

***LACS increases its signal energy by transmitting many pulses at a rapid rate.

#  Any harmonic attenuated, practically no energy above 100Hz

@ - Frequencies extend to at least 10,000 Hz, but typically, the industry will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded, regardless of what

& - Turner et al. 2006. Preliminary acoustic level measurements of airgun sources from ConocoPhillips' 2006 seismic survey in Alaskan Chukchi Sea. JASCO Research Ltd. Report, July 27, 2006.

+ -  Cannelli, G.B. and D'Ottavi, E. 1994. Optimization of marine sparker source efficiency by electroacoustic method. IEEE I-750-755.

## Table 1 (cont'd.).

| | Days /Survey Area | Water Depth | Burial Depth | Vert. Resol. | Horiz. Res. | Deployment | Receiver Density | Signal Process. Maturity | Est. Time to Commer. Avail. | EIA Maturity | Max. fire rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Added noise:** | | | | | | | | | | | |
| **Airgun Array &** | 30 | all | | 30 m | 20-200 | surface tow | variable | mature | available | medium | 10 s |
| **Silenced Airguns** | | all | | 30 m | 20-200 | surface tow | variable | mature | 1 yr | medium | 10 s |
| **Marine Vibrators** | | all | | 3 m | 20-200 | 8 - 15m | variable | medium | 3-5 yrs | young | continuous |
| **DTAGS** | | all | 1km | 1.5 | 20m | Deep tow (full ocean) | variable | medium | 1 yr | young | 30 s |
| **Para-metrics** | ? | all | ? | ? | ? | | variable | young | 5-10 yrs | infant | 10 pings/s |
| **LISA** | | all | | 30 m | 30m | surface tow | variable | young | 5-10 yrs | young | |
| **Sparkers +** | | <1000 | | 1 m | 20-200 | surface tow | variable | mature | available | young | 5 s? |
| **Boomers** | 1-14 days | <1000 | | 1.5 m | 20-200 | surface tow | variable | mature | available | young | 5 s? |
| **LACS**** | | | | | | | | medium | 2 yrs. | available | 15 shots/s*** |
| **No added noise:** | | | | | | | | | | | |
| **Gravity*** | ~200 sq mi/mo. | all | all | depth dep. | 2000m | boat/air/water bottom | N/A | mature | available | | |
| **Gravity Gradiometry*** | ~200 sq mi/mo. | all | all | depth dep. | 200m | boat/air | N/A | medium | available | | |
| **Passive Seismics** | 365 | all | water bottom | 300m | 150m | water bottom | 4/sq mi | mature | 5 yrs | young | N/A |
| **EM** | 5-100 | >20 m | <6 km | 1-200 m | 1-200 m | seabed | 500-5,000m | medium | available | emerging | |
| **Micro-seismics** | life of field | all | water bottom | 100m | 50m | water bottom | 4/sq mi | medium | 2 yrs | young | |
| **Receivers:** | | | | | | | | | | | |
| **Fibre Optics** | life of field | all | water bottom | 100 m | 50 m | seabed | 150/sq m | mature | available | emerging | |

*Added by Duncan Bate, ARKeX Inc., a supplier of gravity gradiometry

**Added by Bjørn Askeland, a developer of LACS

***LACS increases its signal energy by transmitting many pulses at a rapid rate.

# Any harmonic attenuated, practically no energy above 100Hz

@ - Frequencies extend to at least 10,000 Hz, but typically, the industry will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded,

& - Turner et al. 2006. Preliminary acoustic level measurements of airgun sources from ConocoPhillips' 2006 seismic survey in Alaskan Chukchi Sea. JASCO Research Ltd. Report, July 27, 2006.

+ - Cannelli, G.B. and D'Ottavi, E. 1994. Optimization of marine sparker source efficiency by electroacoustic method. IEEE I-750-755.

### Table 2. Applications of various technologies used to image the ocean substrate for petroleum deposits.

**Applications**

| | | | | | | | | | Penetration | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Added noise:** | Site Survey | 2D | 3D | 4D | Refraction | High Res | WAZ | Other | Shallow | Deep |
| **Airguns** | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| **Silenced Airguns** | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| **Marine Vibrators** | P | P | P | P | P | Y | P | P | Y | Y |
| **DTAGS** | Y | P | P | P | P | Y | P | P | Y | N |
| **Para-metrics** | N | N | N | N | N | P | N | N | P | N |
| **LISA** | P | P | P | P | P | Y | P | P | Y | Y |
| **Sparkers** | Y | N | N | N | N | Y | N | N | Y | N |
| **Boomers** | Y | N | N | N | N | Y | N | N | Y | N |
| **LACS** | P | P | P | P | P | P | P | P | P | P |
| **LACS**** | Y | Y | Y | Y | P | P | P | P | Y | P |
| **No added noise:** | | | | | | | | | | |
| **Gravity** | - | + | + | + | + | - | + | | - | + |
| **Gravity*** | - | ++ | ++ | - | N/A | - | N/A | | + | ++ |
| **Gravity Gradiometry*** | + | ++ | ++ | + | N/A | + | N/A | | ++ | ++ |
| **LF Passive Seismics** | - | + | + | + | + | - | + | | + | + |
| **CSEM / 3D EM** | + | ++ | ++ | ++ | + | + | + | | ++ | + |
| **Magneto** | - | + | + | + | + | - | + | | - | + |
| **Heatflow** | - | + | + | + | + | ? | - | | - | + |
| **Micro-seismics** | - | + | + | ++ | - | - | + | | - | + |
| **PSTT** | - | + | + | + | + | - | + | | - | + |
| **Daylight Seismic** | - | + | + | + | - | - | + | | - | + |
| **Receivers:** | | | | | | | | | | |
| **Fibre Optics** | + | + | + | ++ | + | + | + | | + | + |
| | | | | | | | | | | |

"P" = possibly

*Added by Duncan Bate, ARKeX Inc., a supplier of gravity gradiometry

**Added by Bjørn Askeland, a developer of LACS

## Table 3. Characteristics of various types of seismic surveys and imaging technologies.

| **Uses** | **Area Covered** | **Survey Time** | **Sound Intensity** | **Power** | **Incidence** | **Peak Pressure** | **Frequencies** |
|---|---|---|---|---|---|---|---|
| | **(typically)** | | **(dB re 1µpa)**** | **(Watts)*** | **(Shots / Day)** | **(PSI)** | **(Hz)** |
| **Shallow** | | | | | | | |
| 2D | 100-5,000 miles | 28 days-6 mos. | 215-230 dB | 150 - 270 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| 3D | 9-1,000 sq. miles | 2 mos.-1 year | 240-255 dB | 150 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| 4D | 9 sq. miles | 2 weeks-1 mo. | 240-255 dB | 150 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| **Deep** | | | | | | | |
| Site Spec. Survey | 60-600 miles | 5 days-2 mos. | 200-230 dB | 1,500 | 17,280 | 2,000 | 10-10,000 # |
| 2D | 100-10,000 miles | 28 days-1 year | 215-230 dB | 150-270 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| 3D (including WAZ) | 9-25,000 sq. miles | 2 mos.-3 years | 240-255 dB | 150 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| 4D | 9-27 sq. miles | 2 weeks-1 mo. | 240-255 dB | 150 KW | 4,320 - 8,640 | 2,000 | 10-10,000 # |
| **Shallow and Deep** | | | | | | | |
| Refraction | Linear | 1 day | | 270 KW | 1,440 | 2,000 | 6 - 60 |
| Bathymetry (@) | 60-120 miles | varies | 210 dB | 100 - 2,000 KW | 8,640 - 86,400 | N/A | 3,500 - 12,000 |
| High Res | | varies | | 500 KW | 17,280 | 2,000 | 30 - 300 |
| Sidescan Sonar | 9-90 sq. miles | 5 days- 2 weeks | | | 1,440 - 7,200 | N/A | 50-600 kHz |
| Site Spec.Survey | 60-120 miles | 5 days- 2 weeks | 200-230 dB | 1,500 KW | 17,280 | 2,000 | 10-10,000 # |
| Sub-Bottom Profile | 60-120 miles | 5 days- 2 weeks | 200-230 dB | | 1,440 - 7,200 | N/A | 10-10,000 # |
| VSP | near well | 1-2 days | 200-230 dB | | 4,320 - 8,640 | 2,000 | 10-10,000 # |

Note: several instruments are often used concurrently, such as bathymetry and high res for site surveys

* - note: actual units are total energy, Joule/square meter-Hz; one Joule = one Watt-second

** - note: an airgun signal is an energy signal (not power), therefore intensity @ 1 µPa makes more sense

# - typically, the industry will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded, regardless of what is generated.

@ - time, area, and power values vary a lot for swath bathymetry surveys.

In deep water, power is high, pings are further spaced apart, swaths are wide, so more area is covered in a given time.

In shallow water, power is low, pings are frequent, swaths are narrow.

# Participants

## Participants (Chair, then in alphabetical order) and their specialty

Chair: Leila Hatch, Ph.D., NOAA, Scituate, Mass., USA; marine mammals, marine ecologist

Ronald Brinkman, Senior Staff Geophysicist, Minerals Management Service, New Orleans, LA, USA; regulations and R&D

Christopher W. Clark, Ph.D., Director Bioacoustics Research Program, Cornell Laboratory of Ornithology, Ithaca, NY, USA; marine mammals, bioacoustics

John Diebold, Ph.D., Chief Scientist for Marine Operations, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA; seismic surveys for science

Peter Duncan, Ph.D., President, Microseismic, Inc., Houston, TX, USA; passive seismic tomography

Rob Habiger, Ph.D., CTO, Spectraseis AG, Zürich, Switzerland; passive seismic

John Hildebrand, Ph.D., Professor of Oceanography, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA; marine mammals, bioacoustics, seismic surveys for science

Phil Nash, CTO, Stingray Geophysical Limited, Guildford, UK; fiber optic sensors

Jeremy Nedwell, Ph.D., Founder, Subacoustech Ltd., Southhampton, UK; low frequency projector arrays and airgun "silencers"

Dave Ridyard, President, EMGS, Houston, TX, USA; electromagnetic survey techniques

Rune Tenghamn, Vice President, Innovation and Business Development, PGS Data Processing and Technology, Houston, TX, USA; marine vibrator technology

Peter van der Sman, Shell, Amsterdam, Netherlands; airguns

Lindy Weilgart, Ph.D., Department of Biology, Dalhousie University, Halifax, NS, Canada; marine mammals, bioacoustics

Warren Wood, Ph.D., Naval Research Laboratory, Stennis Space Center, MS, USA; deep water seismic source

John Young, Marine Sound Issue, Mgmt. Team Coordinator, ExxonMobil Exploration Co., Houston, TX, USA; petroleum industry use of seismic data

# Presentation Abstracts

## An Overview of the Uses of Sound by Marine Mammals and the Impacts from Anthropogenic Underwater Noise Sources

Lindy Weilgart, Dalhousie University

Marine mammals, particularly cetaceans (dolphins, porpoises, and whales), use sound for all aspects of their life, including reproduction, feeding, communication, navigation, hazard avoidance, and otherwise sensing their environment. Hearing is their primary sense, as sound travels very efficiently underwater (hundreds of kilometers), whereas vision is limited to only tens of meters. Some cetacean species are primarily solitary and widely scattered, so that sound could be particularly important in uniting them. In blue and fin whales, for instance, females probably must rely on finding mates by the loud, low frequency sounds males make. Such calls can theoretically travel almost across ocean basins, at least in the absence of appreciable human-made noise. Cetacean vocalizations are thought to be used for purposes such as to coordinate movements and maintain contact between group members, to repel mating competitors and attract mates, to identify group membership, etc. Mating songs probably also allow females to assess the quality of potential mates. Echoes from the ice may help whales found in polar waters navigate through open leads safely (Ellison et al. 1987). Similarly, whales likely use acoustic cues, such as echoes from ocean bottom features or surf noise, to find their way during long migrations.

Some of the observed effects of anthropogenic underwater noise on marine mammals include: changes in vocalizations (increases in call duration, falling silent, etc.), displacement or avoidance, changes in diving or feeding behavior, changes in swim speed or breathing rate, shifts in migration path, stress, hearing damage (from captive animal studies), and strandings and deaths at sea. Specifically, some of the more concerning impacts from noise are: noise causing hemorrhaging and death in beaked whales (Jepson et al. 2003, Fernández et al. 2005), the displacement of gray whales from their breeding lagoons for about 10 yrs. (Bryant et al. 1984), the avoidance of noise by killer whales for 6 yrs. (Morton and Symonds 2002), belugas fleeing from noise at distances of 35-50 km and staying away for 1-2 days (Finley et al. 1990, Cosens and Dueck 1993), increased stress hormones in a captive beluga whale with exposure to noise (Romano et al. 2004), indications of a reduction in feeding in sperm whales (Miller et al. 2009), and a greater fatal entanglement rate in fishing gear by humpbacks exposed to noise (Todd et al. 1996). Given that we know cetaceans use sound for so many life functions, the consequences of noise might be to decrease their feeding efficiency, place higher energetic demands on them, interfere with their group cohesion and social behavior, cause mother-calf separations, increase predation pressure, produce more navigational errors (e.g. strandings, entanglements in fishing gear, etc.), and lower calving rates. Thus, the welfare of cetacean populations could be impacted. Indeed, noise is thought to contribute to some species' population declines or their lack of recovery (e.g. killer whales, western gray whales; NMFS 2002, IWC 2007).

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## Biological Implications of Chronic Exposure from over Large Spatial Scales: Seismic Surveys

Christopher W. Clark, Cornell University

There is little to no precedent as to the scientific processes for quantifying and evaluating the potential impacts of chronic exposure from anthropogenic sources of sound on marine animals. This statement certainly applies to the situation when a seismic airgun array is the sound source, and to a lesser extent when another mechanism is the source of the intense, impulsive survey signal (e.g., sparkers). Although shipping noise is undoubtedly the largest contributor to chronic ocean noise on an ocean basin scale, noise from a seismic airgun array survey can change the acoustic environment on a seasonal timescale and for a region much larger than the region within which the survey is conducted. It is noteworthy that a seismic survey generates sound intentionally, while a ship produces noise as a bi-product of its propulsion system. Thus, although one could say that the seismic sound is a signal and the ship sound is noise, from the perspective of a marine mammal both activities introduce sounds that have the potential to interfere with and mask bioacoustically important activities (e.g., communication, finding food, navigating, detecting predators). Under sound propagation conditions which promote frequency and time dispersion, a seismic signal can be transformed from an impulsive, reasonably broadband sound into a much longer sound with biologically salient features. Under such circumstances the original, *ca*. 100ms seismic signal can last for many seconds and/or have distinctive frequency-modulation characteristics such that the original seismic sound is no longer impulsive and simply noise, but acquires structure and becomes bioacoustical clutter. Present regulations do not yet recognize this acoustic phenomenon as representing a shift from the impulsive into the non-impulsive behavioural response regulatory paradigm. Overall, these seismic survey situations can result in complex acoustic scenes that infuse large ocean areas with varied mixtures of impulsive noise and frequency-modulated sounds, often convolved with high levels of reverberation. As a result, for situations in which multiple seismic sources are operating concurrently in the same region, the active bioacoustic space for a given species can be dominated by seismic sounds for periods of many months.

## Impacts of Airguns on Marine Animals: Thresholds for Injury and Behavioral Alterations

John Hildebrand, Scripps Institution of Oceanography

The sound pressure fields created by airguns have been shown to create both injuries and behavioral disturbances to marine animals such as cetaceans and fish.  This presentation provides background information on relevant acoustic metrics, and examples of injuries and behavioral disturbances following exposure to operating airguns.

Decibel sound pressure level (dB re: µPa RMS) is the standard metric for describing an acoustic field, but may not be the best criterion for judging the impact of sound exposure.  Acoustic peak pressure (dB re: µPa peak) and sound exposure level (dB re: µPa – s) are alternate metrics with appeal for impulsive sources such as airguns.  Using acoustic peak pressure accounts for the potential for sound impact, independent of duration. Alternately, sound exposure level is a metric that takes into account the signal duration by integration of the sound pressure level over the duration of the signal, a proxy for acoustic energy.  A dual exposure criteria for tissue injury and behavioral disturbance from noise exposure has been proposed, based on these two metrics.

Studies with captive beluga whales and bottlenose dolphins have demonstrated that following exposure to sounds of sufficient intensity, these animals exhibit an increased hearing threshold, described as a temporary threshold shift (TTS).  The trade-off between sound intensity and duration that produces TTS, follows roughly an equal-energy curve; long duration signals produced TTS at lower signal intensities than short duration signals.

Field studies have demonstrated behavioral disturbance of cetaceans following exposure to airguns. Migrating gray whales deviate from their swim tracks to reduce received sound pressure levels from exposure to airguns.  Likewise, observations during seismic surveys demonstrate that small odontocetes show large lateral spatial avoidance, while mysticetes and killer whales show localized spatial avoidance.

Studies with caged fish suggest that the ears of fish exposed to airguns sustain severe damage to their sensory cells, with no evidence of repair or replacement of damaged cells after exposure. Likewise, acoustic mapping and fishing trawls before, during, and after airgun usage suggest severely affected fish distribution, local abundance, and catch rates.

## Marine seismic surveys for science: Purpose, operation and product

John Diebold, Lamont-Doherty Earth Observatory

Marine seismology using controlled sources began in the 1930's, producing fundamental new understanding of the extension of continental structures along continental shelves, and also that the deep ocean is floored by an entirely different kind of crust. By necessity, the sources used were explosives, sometimes in great quantity (many hundreds of pounds.)

The introduction of the airgun as a marine seismic source during the early 1960's represented a great increase in safety and resolution, though it took several decades of additional development to achieve the kinds of airgun arrays that are in use today. These arrays typically use a dozen or more small airguns, firing simultaneously, but spread out in space so as to deliver a short and repeatable pulse of acoustic energy in a generally downward direction.

Current developments in active-source marine seismology are increasing the resolution with which acoustic images can be made, and increasing the depths that can be imaged. Typically the latter effort requires longer arrays of passive receivers, though signal strength is a concern as well. Increased resolution typically requires smaller, specially designed sources and increased number and wider aerial disposition of receivers.

The resulting images and structural details are a critical data type, providing fundamental improvements in humankind's understanding of earth processes. This understanding in turn allows important progress to be made in a wide range of topics from the locations and mechanics of earthquakes to the history of climate change.

Airguns, explosives, and a number of other marine seismic sources depend upon the same basic principle – a bubble of gas, which, due to its internal pressure, expands. In the case of airguns, the pressure within the initial bubble is well constrained, and is far less than that produced by the rapid combustion of explosive solids. As a result the expansion of the air bubble is much slower, and comparatively few high frequencies are produced.

On board US academic research vessels environmental impact is reduced in a number of ways. Minimum source level is used in the first place, and timing of each survey is planned to avoid times of known seasonal breeding, feeding and migration for key marine mammal species. Track lines are often adjusted for local areas of sensitivity and principal investigators are encouraged to favor deeper water options whenever possible. A comprehensive program of visual observation is always carried out, most often supplemented with passive acoustic monitoring. Typically five experts, independent of other operations, are devoted to these tasks. A complete report of sighting and behavioral descriptions is filed with NMFS for every survey and these data are available for inclusion in larger database efforts.

## How Seismic Data Is Used By the Petroleum Industry

John Young, ExxonMobil

By 2030, it is widely estimated that global energy demand will increase approximately 30% from today's level. In order to address this need for energy, the petroleum industry explores for hydrocarbon deposits beneath the earth's surface including under oceans. Seismic surveys are the most accurate and efficient method currently available for hydrocarbon exploration.

Today, the most common marine seismic operations include acoustic sources and receiver streamers, towed behind a vessel. The sources are activated, releasing sound energy directed downward through the water column and into the earth. As a result of differences in acoustic impedance between geologic strata, seismic energy is reflected back to the streamers. The reflected energy is digitally recorded and processed to obtain a detailed image of the subsurface.

Sophisticated subsurface imaging, facilitated by increased computing power, allows for the identification of previously unknown hydrocarbon deposits and reduces the risks associated with drilling in water depths of up to two miles. Increased drilling success rates equate to increased hydrocarbon reserves for the world's energy needs.

## The potential for reducing unnecessary horizontal and high frequency components of sound produced by airguns

Peter van der Sman, Shell

Since the early sixties, the seismic industry started to move away from using dynamite as seismic energy source. The main reason for this move was safety, yet in the years to follow also the environmental impact started being used as a motivation. Being used to deal with impulsive sources, the first alternative the industry came up with was impulsive in nature; the airgun. Yet, it was soon follow with marine vibroseis in the mid sixties. Since then, a host of different sources have been proposed and used. Currently though, over 95 percent of the seismic operations is conducted using airguns. So what are the underlying reasons for the airgun to 'survive' in a Darwinian like sense?

As with any new technology, it takes time to develop it in all relevant aspects needed to realize the desired objectives. A typical timeframe in this sense is often in the range of 10 to 25 years. On the other side, one needs to realize that development is costly and that over the duration of such a development the industry tends to alternate several times through periods of prosperity where new technologies are nurtured and others where technologies are shelved or worse.

In the case of the airgun for instance, it took about 10 years before arrays of airguns emerged, tuning a range of volumes to collectively emit a signal suitable for seismic prospecting. Yet it took another 10 to 15 years or so to develop them into the high-fidelity source systems the industry needs. Marine vibroseis though did not do as well. In contrast to their onshore cousins, the marine version never really got of the ground. The fundamental reason for this may be the geophysical requirement to generate sufficient low-frequent energy (say 5 to 10 Hz) at typical surveying speeds. To do so, units become large and heavy which also prevents the use of fair sized arrays to circumvent this. Then again, the vibroseis technology offers a huge potential in that it can shape both the emitted signal and its frequency spectrum and this is exactly where the technology is believed to have merits in an environmental sense. So is marine vibroseis the way to go or can we still work the airgun system to accommodate both geophysical and environmental constraints.

In my presentation I will present a few concepts and ideas on airguns, aiming to complement the contributions by the other speakers such that we collectively present the whole spectrum and merits of all the technologies at our disposal in the context of the workshop.

## A Deep Water Resonator Seismic Source

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The Naval Research Laboratory's deep-towed acoustics/geophysics system (DTAGS), originally designed to characterize abyssal plain sediments, is an example of a seismic source technology capable of generating 220 Hz – 1 kHz swept frequency sound waves at levels up to 200 dB (re 1 µPa @ 1 m), and at full ocean depths. The source is composed of a series of five concentric rings each composed of pie-shaped piezo-ceramic material. The natural resonance of the ceramic transducers provides the high frequencies and the size and shape of the barrel-shaped resonator cavity boosts the low frequencies. This combination yields a broadband (over two octaves) signal with a relatively flat spectrum. The solid-state nature of the construction ensures not only that the source is extremely repeatable, but also that it is insensitive to changes in depth; yielding nearly identical signals from the sea surface to full ocean depth (6000 m). The source can be energized with almost any kind of waveform, and at almost any sound level below 200 dB, allowing significant flexibility to tune the source amplitude, frequency, and waveform for specific needs.

Although the resonator source operates in all water depths, it is most useful where other sources fail. As hydrocarbon exploration moves into deeper waters, the signal loss from surface towed sources becomes excessive. In 2000 m (6562 ft) of water signal loss from spherical spreading results in sound levels at the seafloor only 0.05 percent as strong as at the sea surface, (a 66 dB loss in amplitude). For example: a 180 dB source at the surface fades to 114 dB at the seafloor.

DTAGS is currently configured as a towed multi-channel system, capable of recording 48 hydrophones (3 m spacing) for trace lengths of two seconds, at a two kHz sample rate, on a duty cycle of 30 seconds. The system is typically towed at 2 knots at an altitude of 100m above the seafloor. After some conventional, and some unique processing steps, the resulting seismic sections allow detection of both vertical and lateral changes in the sediment as small as 1-2 meters, and can fully resolve features at a scale of 5-10 meters.

To augment its use as a deep-towed multi-channel seismic system, efforts are currently underway to design and build a coupling system to enable the resonator source to be set directly on the seafloor. In this mode we anticipate not only increased excitation of P and S waves, but also increased signal to noise by repeated firings at the same location (similar to techniques used on land with swept frequency systems).

Deep water sources in general, and the DTAGS Helmholz resonator specifically represent an attractive option for achieving commercially useful sound pressure equivalent levels in the earth, while minimizing the instantaneous sound levels in the ocean, particularly the shallow ocean where sound sensitive marine life is concentrated. These advantages are achieved mainly through proximity of the source to the target of interest, and time integration over a highly controlled and repeatable source waveform.

## Potential application of 3D EM methods to reduce effects of seismic exploration on marine life

Dave Ridyard, EMGS Americas

### Introduction

This paper addresses the question “Can 3D EM methods reduce the amount of seismic activity ?”. It does not address the broader question “Is there any need to reduce the amount of seismic activity ?”.

### 3D EM method summary

It has been known for over 80 years that hydrocarbon saturated rocks exhibit higher electrical resistance than brine saturated rocks. In recent years the 3D EM method (Controlled source electromagnetics) has emerged as a powerful exploration tool. A dipole electric source towed close to the seabed generates electric and magnetic fields which are perturbed by any subsurface resistive structures. These fields can be measured by sensors deployed on the seabed. The measurements can be processed to create a 3D image of the subsurface resistive structures. Where a resistor is observed co-located with a prospective hydrocarbon bearing structure, the risk of drilling a dry hole is significantly reduced.

It should be noted that a 3D EM image shows resistors … not hydrocarbon reservoirs. There are many other resistors buried in the subsurface – salt, volcanic rocks, carbonates and methane hydrates all exhibit resistive properties. The deep penetration and high resolution of seismic data is invaluable in creating meaningful, detailed regional geologic models and identifying potential hydrocarbon traps. However, seismic data is clearly more reliable if it is used in conjunction with EM.

### Environmental impact of EM

Receivers deployed on the seabed use biodegradable anchors and have negligible environmental impact. The source uses extremely low spatial and temporal frequencies – typically wavelengths of many kilometers and frequencies of 0.1 to 1 Hz. When these low frequencies are considered in combination with the exponential decay of energy caused by highly conductive seawater, the region of potential influence on marine life resulting from EM transmissions is tiny. Furthermore, since EM methods reduce the number of dry wells drilled, the method can be considered environmentally positive.

### Potential reduction in seismic activity

In theory, broader application of EM methods could reduce “dry 3D seismic surveys” in the same way it currently reduce dry wells. However, the current impact of EM methods on seismic activity is negligible. There are 2 reasons for this.

1) Current EM methods have neither the resolution nor the penetration to replace seismic in a significant range of exploration and production applications.

2) Even where EM technology is effective, it is underutilized by many oil companies due to the wide spread lack of understanding and adoption of the technology.

### Summary and Recommendations

EM offers some, limited potential to reduce the growth in seismic activity, but action is needed in 2 areas to enable this.

1) Further R&D investment is required to grow the application window for EM methods by increasing depth of penetration and resolution of the method.

2) Regulatory changes in leasing practices, taxation, accounting (reserves estimation etc.) can accelerate the adoption of EM methods.

## Vibroseis Technology

Rune Tenghamn, PGS Data Processing and Technology

For several decades, airgun sources have dominated the marine seismic acquisition market. Surprisingly, few new source concepts have been presented to the industry during this period. During the eighties, however, developments related to marine vibrator sources took place. These sources were tested mainly for deep target marine seismic applications. These applications have since been limited, due to factors such as high cost, handling and operational difficulties, etc.

During the late nineties, PGS started the development of a completely new electro-mechanical marine vibroseis concept. The objective of the project was to develop a 100% repeatable low-cost vibrator source with an energy output in the frequency band of 6-100 Hz and with a size and weight easy to operate in the field. Target applications of the source are shallow water acquisition, seismic monitoring and environmentally sensitive areas.

A marine vibrator will provide several environmental advantages. Vibrator technology spreads the net source energy over a long period, reducing the acoustic power in comparison to impulsive sources. The peak power of a Marine Vibrator is about 30 dB lower in sweep mode than the corresponding peak power of an impulsive source. This is attractive for applications where high peak power may be problematic. There is no need for heavy equipment and hydraulic systems that can cause hydraulic oil spills. As the electrical vibrator requires only an electrical power supply it can be easily transported to different vessels and locations without any costly installations and potential environmental hazards.

Electrical marine vibrators also have several operational advantages. Due to the high efficiency of the sources, controllable and arbitrary signals can be generated in the frequency band of interest. This fact has been used to develop a control system that makes the acoustic sources repeatable over time. Having a feedback loop for control of the output means that not only can high repeatability be achieved, but the harmonics can also be attenuated. Any mechanical system will generate harmonics. Tests have shown some dramatic change in harmonics generated by a sweep. Some of the harmonics are attenuated by more than 30 dB.

The controllability of the source makes it possible to introduce Pseudo Noise sequences (PN). With the use of PN signals it will be possible to reduce the peak power even more. The PN sequences will not only spread the source energy over time, but will also spread the frequencies over time. This technology will further reduce the peak power for any frequency at any particular time by another 20 dB compared to a sweep.

In a future scenario, we could have an array of controllable marine vibrators with the energy concentrated in the vertical plane through beam steering of the acoustic output. The PN signals would “mimic” natural background noise. By having a continuous “noise” signal the active array would be difficult to distinguish from the natural background noise.

## Low frequency passive seismic for oil and gas exploration and development: a new technology utilizing ambient seismic energy sources

Robert M. Habiger, Spectraseis

### Introduction

A growing number of low frequency surveys at different oil and gas field locations throughout the world have indicated the possible relationship between certain microtremors and the presence of hydrocarbons. These narrow-band, low frequency (from ~1Hz to ~10Hz) micro-tremor signals offer new types of seismic attributes for the optimization of decisions for exploration and development phases of hydrocarbon exploitation.

Although the primary application of this technology to date has been on land, the potential exists for applying in a marine environment and a proof of concept survey was conducted in April, 2007 in the North Sea.

### Data Acquisition

The low frequency data were acquired by using broadband seismometers located on the ocean bottom. The ocean bottom sensors (OBS) can be deployed in deep water and left to record data for days, weeks, or even months. No active sources, such as air guns, are needed in these measurements since only modifications to the earth’s natural background energy are monitored. The OBS units can be easily deployed and recovered using well known operating procedures.

### Data Processing

The main challenges of moving this technology from land to marine applications are adequate coupling of the sensors to the ocean floor for short data acquisition durations and the large amounts of extraneous ambient noise in the oceans. The nature of the ocean noises and how it can interfere with the quality of measurements and analysis will be discussed along with suggestions for mitigation.

The workflow consists of removing unwanted noise, characterizing the measured signal according to time stability and frequency characteristics, and then calculating low frequency attributes related to hydrocarbon micro tremors.

## Conclusions

Low Frequency passive seismic is a new technology that has been applied mostly in land surveys but warrants further investigation and development for application to a marine environment. An initial test has been completed in the North Sea for oil and gas applications and the information gained can be used for planning follow-on surveys to further advance this technology.

## Passive Seismic Tomography: structural imaging using natural sources

Peter M. Duncan, MicroSeismic

Reflection seismology is a mainstay of the exploration for hydrocarbons, whether onshore or offshore. While the use of controlled sources (dynamite, airguns or vibrators) for such imaging is certainly the standard, it has been appreciated for many decades that one can also use the earth’s natural seismic sources to illuminate the earth’s structure. Much of our knowledge of the interior structure of the earth on a global scale has been derived from imaging involving the transmission and reflection of seismic waves whose source was an earthquake on the other side of the earth. Recent work using surface waves excited by the pounding of waves on the beach has begun to unravel the crustal structure of continents. In the last decade there has been work directed at using these same energy sources to create images useful for hydrocarbon exploration and production. These efforts are driven by both environmental concerns and by the expense of conventional seismic imaging. Collectively we refer to these imaging techniques using naturally occurring or ambient noise sources as passive seismic tomography.

The most straightforward application of this passive technology is commonly referred to as passive seismic transmission tomography (PSTT). PSTT creates 3-D images using the observed travel time of seismic signals originating from micro-earthquakes occurring below the target. A sparse array of independent seismometers is established above the target. The array usually consists of 20 to 100 stations each recording the output of a 3-component geophone. With the array in place, the survey proceeds by simply listening. Assuming an initial velocity model, the observed micro-earthquakes are located in time and space using long-standing location algorithms based upon picks of the p and s phase arrival times at each observation station. Once a number of events has been located one flips the process, assumes the origin time and hypocenters of the events are known, and uses some form of travel time inversion to estimate a new velocity model. As more events are added to the dataset, finer estimates of the velocity structure can be achieved. The process proceeds in this boot-strapping fashion until the desired resolution is reached.

If one cross correlates the time signal recorded by the stations of the array established for PSTT, it is often possible to identify 2 other types of seismic signal that are useful for imaging. The first is the surface waves that course back and forth along the earth’s surface. The speed of travel of these waves is controlled by the velocity of the material that the wave “sees”. Longer wavelengths penetrate more deeply into the earth and therefore sample the earth to a greater depth. This allows one to create a structural image from the rate that these surface waves traverse the array.

The second signal that may be extracted by the cross correlation process contains the multiple reflections of the ambient noise that have been bounced downward from the free surface of the earth and then reflected off velocity contrasts in the subsurface. This technique of recovering 3-D reflection image data from ambient noise signals was first postulated 40 years ago as “daylight seismic”. Recent experimental work has shown promise that such a technique may be able to deliver seismic images with a resolution sufficient to be useful in hydrocarbon exploration.

## The dBht Method for Evaluating Impact, Airgun Silencers and LF Projector Arrays

J Nedwell, Subacoustech

### Introduction

High levels of man-made noise may be created by oil and gas exploration, construction, blasting, and many other offshore activities. Death and injury are extreme effects of underwater sound, occurring mainly where explosives are used. These are relatively well understood and unlikely in a well-managed programme.

However, the more subtle behavioural effects of sound have been an increasing focus of concern internationally. It has been alleged that seismic exploration may have undesirable side-effects upon aquatic animals over ranges of kilometres, or even tens of kilometres.

This paper reports on tests of two possible methods of attenuating the effects of seismic surveying, such that its likely impact on marine mammals will be reduced but its effectiveness as a sound source for seismic surveys would be adequate.

### Estimating effects

The ability to estimate effect is critical in rating or comparing technologies intended to reduce the effects of seismic surveying. A simple measurement of sound, such as its peak pressure, is inadequate to judge the likelihood of, for instance, a behavioural avoidance response. Marine species have a wide range of hearing ability, and the same underwater sound will affect each species in a different manner depending upon the its hearing sensitivity and frequency range. Consequently, many researchers are now advocating the use of audiogram-based weighting scales to determine the level of the sound in comparison with the auditory response of the aquatic or marine animal. Madsen *et al.* (2006), for example, recommend that “*as the impact of sounds impinging on the auditory system is frequency-dependent, noise levels should (as for humans) ideally be weighted with the frequency response of the auditory system of the animal in question*“.

The $\text{dB}_{\text{ht}}$ metric developed by the author incorporates the concept of “loudness” for a species. It incorporates hearing ability by referencing the sound to the species’ hearing threshold, and hence evaluates the level of sound a species can perceive, rather than its absolute level. It is critically important to judge the effects of noise reduction of seismic sources in this way, because a modification that reduces the level of high-frequency noise, for instance, may well reduce its “loudness” for a high-frequency hearer such as many marine mammals. The peak level may, however, be unaffected, or even, as in the experiments reported here, increased.

Measurements were made at Vobster Inland Diving Quay, a water-filled former quarry near Mells in Somerset, of the pressure time history generated by an airgun with and without a compliant silencer. The silencer was intended to reduce the high-frequency components that marine mammals can hear, while leaving the low frequency components used for seismic exploration unchanged. It was found that the broadband (chiefly low frequency) output of the airgun was actually consistently higher, by about 3 dB on average, for the results with the silencer. However, there was an associated reduction in level of the airgun at low operating pressures in terms of its $dB_{ht}$(*Phoca vitulina*) value, and hence in its effects on a seal, of about 6 dB. At the higher discharge pressures the silencer material was thought to be collapsed by the airgun discharge, causing it to become relatively rigid, hence having less effect on the acoustics of the airgun. The silencer was thus beneficial for both seismic surveying and for the environment.

While the reduction achieved by the airgun silencer was modest, and, it is thought, well below that potentially achievable, a 6 dB reduction in $dB_{ht}$ level represents a 4-fold reduction in the area of sea in which a seismic survey might have a given effect on a marine mammal, or 12-fold for an airgun array of constant Source Level if the increase in Source Level, and consequent reduction in the number or power of airguns required, is taken into account.

The concept of the low impact seismic array (LISA) was based on the use of inexpensive but powerful and rugged electromagnetic projectors to replace airgun arrays. The prospective benefit was that since the signal could be well controlled, both in frequency content and in the direction in which the sound propagated, the possibility existed of undertaking seismic surveys in environmentally sensitive areas with little or no collateral environmental impact.

The LISA project embodied the idea of using a large array of small but powerful electromagnetic projectors to replace airgun arrays. Initial measurements were made on a small (n=4) array of existing electromagnetic transducers designed by Subacoustech. It was found that a Source Level of about 142 dB re 1 µPa per volt @ 1 metre was achieved, at a peak frequency of 25 Hz. The operating frequency could be reduced to under 10 Hz with reasonable modifications, allowing use of an array for seismic exploration. The results indicate that it would be possible to achieve an array Source Level of about 223 dB re 1 µPa @ 1 metre, which is adequate for seismic surveying.

In summary, both of these technologies have significant prospective benefits in respect of reducing environmental effects during seismic surveying. In the case of the airgun silencer, the technology has additional benefits for seismic surveying, as it increases the level of the airgun while simultaneously reducing its environmental effect on marine mammals.

### Fibre optic receivers and their effect on source requirements

P. Nash, A.V. Strudley, Stingray Geophysical

There is growing interest in the use of Seismic Permanent Reservoir Monitoring to maximise recovery and optimise production by time-lapse reservoir monitoring. In comparison to repeat towed streamer surveys, such systems offer greatly improved repeatability, better seismic signal/noise, and provide additional value from the direct recording of the full 4C vector wave-field. Seabed arrays based on fully fibre optic sensing and telemetry are particularly attractive for this application because of their increased reliability and relative ease of deployment and operation compared to electrical systems.

The characteristics of fibre-optic seismic PRM systems result in different seismic source requirements compared to conventional systems as described below:

*Reduced amplitude*: Permanent seabed systems typically achieve better signal to noise ratio than towed streamer systems because the receivers are directly coupled into the seabed and hence are not subjected to towing or weather induced noise. Also, the signal is only subject to one-way transmission loss in the water column. Further fibre-optic sensors have high sensitivity which, together with the lower noise floor results in reduced requirements for high amplitude sources. For these reasons, seismic Permanent Reservoir Monitoring (Seismic PRM) has so far been conducted with relatively small seismic airgun sources –typically, a towed airgun array with around 70 bar-m p-p output (0-128Hz).

*Reduced airgun volume*: Typically, large volume airguns are used in the array for improved low frequency content. With fibre-optic seismic PRM the availability of pressure and acceleration measurements allows improvement in the low frequency performance by combination of the two wave-fields up to the limit imposed by the low frequency noise floor. The use of accelerometers rather than velocity sensors avoids a low frequency limitation in sensor bandwidth associated with sensor resonance (typically 10 -15Hz for a velocity sensor). Hence the requirement for large airgun volumes may be reduced, with beneficial effects across the whole source bandwidth.

*Reduction in total survey duration*: Because the receiver array is permanently deployed total survey time is reduced compared to towed streamer surveys because no infill is needed and weather downtime is minimised. In areas where Ocean Bottom Seismic is required (e.g. for 4C data), there is no requirement for repeated shots at the edges of the receiver spread unlike the case for retrievable systems. Hence, for the same shot coverage, the total number of shots is likely to be reduced.

*Reduced high frequency bandwidth*: Fibre-optic hydrophones and accelerometers are very broadband sensors with responses into the 10s of kHz range. Typical airgun sources have appreciable energy output at these frequencies and hence the receivers require a large top end system dynamic range (typically ~ 180dB) to avoid sensor saturation. Significant efficiencies in fibre-optic architectures, which would result in reduced receiver array cost, could be gained if this dynamic range requirement were reduced. Hence a seismic source array with reduced high frequency output is desirable.

In summary, Seismic PRM based on fibre-optic technology is likely to be of increasing importance in the near future for improved reserves recovery. Such systems offer a number of potential opportunities for optimisation of seismic survey source requirements and in particular would benefit from reduced high frequency airgun source output, such as a marine vibrator or other non-impulsive, oscillating sources.

## Alternatives to Acoustic (Seismic) Geophysical Data Collection

Ron Brinkman, Minerals Management Service

Minerals Management Service (MMS) is a bureau of the Department of the Interior. Its mission is to manage the mineral resources of the Outer Continental Shelf in an environmentally sound and safe manner.

The collection of geophysical and geological data is critical for the MMS to fulfill its mission in helping meet our Nation’s energy needs. However, the approval of seismic data collection activities must be considered in conjunction with concerns over the impact of these activities on the environment. These concerns are largely focused on sound introduced into the environment from seismic surveys and related activities (i.e., icebreaking, support vessel traffic, and aircraft over flights) and the effects of this sound on marine life and resources.

The issue of effects is further heightened by the lack of scientific certainty on the true impacts, the level of significance of these effects, and the ever increasing public scrutiny over these concerns. Despite these challenges, MMS is still charged with making decisions using the best available information. This leads to more conservative protective measures, additional mitigation and monitoring requirements, public criticism of environmental analyses and decision making, increased litigation, greater uncertainty on costs and risks for companies wanting to conduct seismic activities, impacts to access, and additional costs and delays in agency programs.

Ultimately, MMS must ensure that all seismic survey activities it regulates are in full compliance with all relevant environmental statutes and requirements. It is, therefore, imperative that MMS re-examine its processes for addressing seismic survey activities, both regionally and nationally, to identify where full environmental compliance is not yet reached and develop a plan forward to more effectively integrate seismic surveying and environmental compliance needs in light of these many challenges.

MMS is currently undertaking NEPA mandated geological and geophysical (G&G) Environmental Impact Studies (EIS) in all Regional Offices to determine compliance with call existing Laws. MMS is concurrently studying potential methods of noise reduction to existing seismic surveys. Samples of these studies include the following alternatives:

- Attenuate lateral noise with air bubble curtains, like has been shown in the literature, or with some special bubble curtain material, acting as a more solid (like a curtain) barrier;
- Make arrays more vertically directional, and thus narrow the cone of sound;
- Change the structure of the airguns to reduce high frequency sound (noise) while maintaining the strong source signal and low frequency source needed for exploration.

For more technical assessment and research studies see: http://www.mms.gov/tarprojectcategories/

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