ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

A modelling comparison between received sound levels produced by a marine Vibroseis array and those from an airgun array for some typical seismic survey scenarios

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ARTICLE INFO

Keywords:
Marine Vibroseis
Marine vibrator
Seismic survey
Airgun alternative
Quieting technology
Noise

ABSTRACT

Marine Vibroseis (MV) may provide a marine seismic sound source that has less environmental impact than conventional airguns. Modelled sound levels from a realistic MV array and airgun array with similar downward energy at frequencies < 100 Hz were compared under three scenarios: shallow, deep, and slope. Changing the layout of the MV array's higher frequency sources reduced sound exposure levels (SELs) by 4 dB. At 100 m range this MV was 20 dB lower in peak-to-peak sound pressure level vs. the airgun array, decreasing to 12 dB lower at 5 km, the maximum modelled range for peak levels. SELs were less clear-cut, but for both shallow and deep water, MV produced 8 dB lower SELs than the airguns at 100 km range because of MV's reduced bandwidth. Overall, MV produced lower broadband SELs, especially at long range, and lower peak pressure, especially at short range, than airguns.

1. Introduction

Marine seismic surveys are conventionally carried out using sound sources consisting of arrays of airguns, devices that produce sound by suddenly releasing high-pressure air into the water (Parkes and Hatton, 1986; Gisiner, 2016). The resulting acoustic signal consists of a short, high amplitude pulse followed by a decaying series of lower amplitude pulses created by the oscillating air bubble (Safar, 1976). Seismic source arrays are typically made up of airguns of a variety of sizes, and designed to focus sound in the vertically downward direction. An airgun array may consist of anywhere from six, to more than forty airguns. In most cases the airguns are arranged in a rectangular array in a horizontal plane at a specified depth below the water surface, usually in the range of 4 m to 10 m. Large source depths are used for large-scale reconnaissance surveys where maximum penetration into the seabed is the priority, whereas shallow depths are used for high-resolution surveys with moderate penetration.

Not all of the acoustic energy produced by an airgun array is directed downward, with a substantial amount of energy that is unused by seismic operators being emitted at angles close to the horizontal. This horizontally directed sound can become trapped in the water column, reducing propagation loss such that the sound can, on occasion, be heard over thousands of kilometres (Nieukirk et al., 2004, 2012). Both the intense sound near airgun arrays and the less intense sound at greater distances can produce negative impacts on marine animals. These impacts can include permanent damage to an animal's hearing (McCauley et al., 2003) at shorter ranges over little time or potentially even over longer ranges with long-term exposure. Documented impacts on marine mammals and fish include changes in vocalizations which could affect feeding, mating, or navigation (Blackwell et al., 2015; Castellote et al., 2012; Cerchio et al., 2014; Pirotta et al., 2014), and displacement from habitat, changes in abundance, or lower catch rates (Castellote et al., 2012; Engås et al., 1996; Hassel et al., 2004; Slotte et al., 2004). Behavioural or physiological (stress) effects (Santulli et al., 1999) and "masking," or obscuring of signals important to an animal, are possible even at long ranges (Nieukirk et al., 2004, 2012).

There is currently considerable effort being expended by a number of companies to develop alternative marine seismic sources that are expected to have a reduced environmental impact while being at least

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http://dx.doi.org/10.1016/j.marpolbul.2017.04.001
Received 6 October 2016; Received in revised form 31 March 2017; Accepted 2 April 2017

as effective as airgun arrays as sources for marine seismic exploration. The basic principle is to replace the short, high amplitude, wide frequency-bandwidth signal produced by an airgun array with a much longer, lower-amplitude signal, with the same acoustic energy in the frequency band required for the seismic survey (usually below 200 Hz and in many cases below 120 Hz, Evans and Dragoset, 1997), and with as little energy as possible outside that band. When advanced signal processing techniques such as matched filtering are used (Urick, 1983), the effectiveness of a signal for seismic surveying is determined solely by the signal's energy and bandwidth, the latter being inversely proportional to the obtainable depth resolution. Consequently a long duration, low amplitude signal should be just as effective as a short duration, high amplitude signal with the same energy, providing they both cover the required frequency band. However, it is expected that the reduction in amplitude would reduce the likelihood of physiological damage to an animal's hearing at short range and that the reduction in bandwidth would reduce the likelihood of negative impacts to species with poor low-frequency hearing response, such as high-frequency cetaceans, at all ranges (Southall et al., 2007). Additionally, in this paper we show that, as a result of propagation effects, the reduction in bandwidth can be beneficial at long ranges even for animals with good low-frequency hearing. Against these expected beneficial effects is the possibility that the longer duration signals may increase the potential for masking of signals important to marine animals (Richardson et al., 1995), but this drawback can be limited in ways discussed below.

Much of the industry effort is focused on developing a marine Vibroseis (MV) system that can produce a constant amplitude signal with a frequency that varies with time. MV is an example of a so-called “controlled source” since, unlike the air bubble produced under high pressure by an airgun shot, the sound it produces can be modified (frequency, duration, amplitude, etc.) in real time. This method has been used successfully in land-based seismic exploration for many years, but the difficulty of building efficient and reliable controlled acoustic sources for the marine environment, together with the effectiveness of airgun sources, have meant that the technology is only now being seriously developed.

Tenghamn (2006) introduced a completely new electro-mechanical MV concept, using frequencies from 6 to 100 Hz. Pramik (2013) reported that, as MV is a scalable source, output level can be adjusted to environmental and operational conditions much more readily than with airgun arrays. MV output can be changed by altering the number of vibrators used in the array (more difficult with airguns due to undesirable acoustic side effects), by changing the output drive level, and by changing the length of the sweep (Pramik, 2013). The controllable nature of the MV source could also bring advantages in signal processing.

LGL and MAI (2011) reported on a comprehensive modelling study that aimed to quantify the relative environmental impacts of MVs and airguns. In that study the MVs were assumed to be deployed in an array with a layout identical to the airgun array it was compared to, and it was concluded that the principal environmental advantages of MVs would be the reduction in peak sound pressure level (SPL_{pk}) and the reduced signal bandwidth. Differences in received sound energy, and hence sound exposure level (SEL), were predicted to be much less than those in SPL_{pk}, but the authors considered that the smaller bandwidth of the MV signals would most likely still result in a reduction in impacts for SEL-related effects, particularly for higher-frequency cetaceans (e.g., dolphins, porpoises, beaked whales). However, they also pointed out that the long duration of the MV signals could result in an increase in masking relative to the short-duration, but higher-amplitude airgun signals. They consider the masking effects of MV to be limited if frequency-modulated (FM) signals are used, due to the instantaneous, narrowband nature of these signals (LGL and MAI, 2011).

The current study differs from that reported in LGL and MAI (2011) in several ways:

- The MV array configuration modelled here was based on a concept array design proposed by Petroleum Geo Services (PGS), and the modelled outputs of the individual sources were based on information published by the company (PGS, 2005) with some additional detail provided directly by the company's engineers. The output of this source is compared to that of an airgun array with similar overall dimensions but with a layout more typical of airgun arrays. The gun sizes were chosen so that the two arrays emitted the same acoustic energy in the vertically downward direction for frequencies up to 100 Hz.
- Modelling was carried out for scenarios different and more extensive than those considered in LGL and MAI (2011).

A U.S. government workshop exploring quieting technologies for seismic surveys, among other noise sources, identified the need to further describe near- and far-field masking issues related to MV (CSA Ocean Sciences Inc., 2014). This study attempts to investigate sound levels from MV and airgun arrays to help in that endeavor.

2. Methods

2.1. Scenarios

Three modelling scenarios were chosen as representative of seismic surveys in a) shallow continental shelf waters (“shallow”); b) deep ocean waters (“deep”); and c) over the continental slope (“slope”). Details of these scenarios are provided in the Supplementary material (Table S1). Two types of modelling were carried out for each source type/scenario combination: a) short range modelling to 5 km; and b) long-range modelling to 100 km.

The short-range and long-range modelling used different computational methods (see “Acoustic propagation modelling and received level calculation,” in the Supplementary material). In both cases the propagation model includes the sea surface and seabed reflections, so the source waveform must be modelled without either of these reflections (except that the effect of the sea surface reflection on the oscillation of the airgun bubble is included in the airgun source model). This contrasts with the way in which airgun signals are often presented in the literature, with the surface reflection included.

Short-range modelling is computationally intensive but is capable of computing a wide range of signal parameters and accurately accounts for both the horizontal and vertical directionality of the source. At ranges of more than a few kilometres it is necessary to adopt a more computationally efficient energy-based method that is practical to apply out to ranges of several hundred kilometres. Although this method only computes the sound exposure level and ignores the vertical directionality of the array, it presents a good approximation for two reasons:

1. For directions close to the horizontal, typical airgun arrays have a comparatively weak vertical directionality relative to their horizontal directionality. This is especially true for arrays with all their sources at the same depth, which describes about 90% of operational airgun arrays.
2. Sound emitted at angles well away from the horizontal undergoes many reflections from the seabed and is rapidly attenuated. The sound field at long ranges is therefore determined by sound leaving the source at angles close to the horizontal which undergoes fewer reflections.

The water column sound speed profile used for all three scenarios was chosen from climatological seasonal sound speed profiles from Locarnini et al. (2006) for 35.5°S, 121.5°E, a nominal location off the south western coast of Australia (Fig. 1). Profiles for all four seasons are given in the Supplementary material (Fig. S1). The southern hemisphere autumn profile was chosen for modelling because it has the most