How do impulsive marine seismic surveys impact marine fauna and how can we reduce such impacts?

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ABSTRACT

A summary of how petroleum seismic survey sources may impact marine fauna from invertebrates to fish, is presented, along with a discussion of the need for developing and testing alternative seismic sources to reduce biological impacts.

1 DISCUSSION

Marine petroleum exploration is conducted using low frequency acoustic impulse signals generated in the water column to image subsea geology (Anon, 2011). The signals are produced by spatially distributed arrays of air guns which simultaneously release high pressure air (2000 psi or 13.8 MPa) into the water column. The arrays of air guns are towed at a constant depth typically in the range 5-6 m, with the arrays designed to focus energy downwards into the earth. The spatial configuration of arrays are either narrow in the array tow direction (10-15 m) and wide in the across track direction (to 50 m) to produce a swath in the tow direction for 2D surveys, or are close to square for 3D surveys (~12-20 m sides) where the intention is to radiate downward energy in many directions. Geophysicists analyse the signals received by long strings of hydrophones to locate reflections off subsea density discontinuities. The travel times of reflections are used as a proxy for range to geological layering while information on the returned signal character improves knowledge of what the reflecting layers are comprised of. The reflected air gun array signals need to be recognisable, for which geophysicists rely largely on the impulse or sudden onset nature of the produced air gun array signal. Several examples of air gun signals are shown on Figure 1 where the sharp signal onset is clear. The resulting oscillations evident in the signals displayed on Figure 1 after the initial peak are produced by the released air having formed a bubble or cloud of bubbles, which oscillate as the bubble or bubble cloud rises, producing the low frequency signal. In commercial air gun arrays the array spatial configuration is designed to reduce these bubble oscillations, enhancing the impulse nature of the signal by reducing trailing 'noise'. Thus air gun array signals, at least in the downward direction where the individual air gun sources sum coherently, are characterised as a relatively sharp impulse which rapidly reaches a peak pressure. The rise time, or time taken to reach peak pressure, is a few milliseconds only, which it should be noted differentiate airgun signals from explosive signals where rise times are on the scale of micro seconds or less.

The signals produced by air gun arrays are intense, reaching high impulse measures when air gun energy is summed directly under the source, with modelled equivalent point source levels in the range 250-260 dB re 1µPa 0-peak level at one m range for 3797 – 5400 cui arrays in the downward direction (Anon, 2011). Source levels radiated in the near horizontal plane may be 6-25 dB lower than the downward direction, as all individual air guns in the array do not sum coherently in any but the downward direction (Anon 2011, Duncan 2017). It needs to be noted here that for transmission of energy from air gun arrays in the lateral plane it is the near horizontal energy only which transmits, so the often quoted high source levels do not apply.

These intense impulse signals will impact on the sensory systems of animals from plankton to whales. A surprisingly high cross-section of marine fauna have sensory systems capable of discriminating sound via its particle motion component, plus some have adaptations to sense sound pressure. The high impulse pressures produced by air gun signals may be above the comfortable dynamic range of many animal sensory systems for considerable ranges from an air gun source, which implies the potential to damage sensory systems exists. Additionally, the high impulse measures may directly physically stimulate small fauna or drive the seabed and so stimulate fauna which live in the substrate, giving the potential for seismic signals to impact other animal organs.

Large mobile fauna, such as whales respond to air gun signals often simply by making course adjustments to avoid the incoming seismic source (e.g.. for humpback whales, McCauley et al. 2003a, Dunlop et al. 2016 & 2017). Less mobile animals may be unable to physically avoid seismic sources. For example Blaxter (1969) presents the cruising speeds of fish which can be maintained for long periods (up to one hour or more) of 2-3 body lengths per second. For a modest size fish of say 40 cm length this equates to 1.6 – 2.3 knots, below the typical seismic vessel speed of 4 - 4.5 kn. For a 20 cm fish the endurance speed is halved and the differential between seismic vessel and fish endurance speed doubles. Thus many fish which may try to flee an approaching seismic source may physically be unable to do so, at least to what can be considered a ‘safe’ range from the seismic vessel beyond which the air gun signal will not lead to physical trauma. Some experiments with fish and seismic have shown physical trauma to hearing sensory organs from seismic exposure (e.g.. McCauley et al. 2003b) while other experiments have shown limited trauma (McCauley and Salgado Kent, 2012) or none (Song et al. 2008) along with no loss of hearing sensitivity (Popper et al. 2005). The ability of air gun signals to impact fish hearing systems thus exists but given conflicting results the mechanisms behind impacts appear to be poorly understood. A series of recent experiments with a single 150 cubic inch (cui or 2.46 l) air gun and effectively sessile benthic fauna have found a host of physical impacts from close range seismic operations, including physiological disruption to immune capability in the spiny lobster (Fitzgibbon et al. 2017), permanent disruption to scallop physiology (Day et al., 2017), or damage to the vibratory sensory organ in the spiny lobster (Day et al. 2016a) as well as resilience of lobster eggs to seismic (Day et al. 2016b). Zooplankton, which cannot avoid a seismic source, have recently been shown to be impacted by a 150 cui seismic air gun, with increased mortality out to a kilometre (McCauley et al. 2017). Thus the high impulse signals produced by current petroleum seismic using air guns can produce a range of environmental impacts, some lethal (zooplankton) but many insidious or not obvious, but all of which reduce an animals' fitness and so its chance of survival.

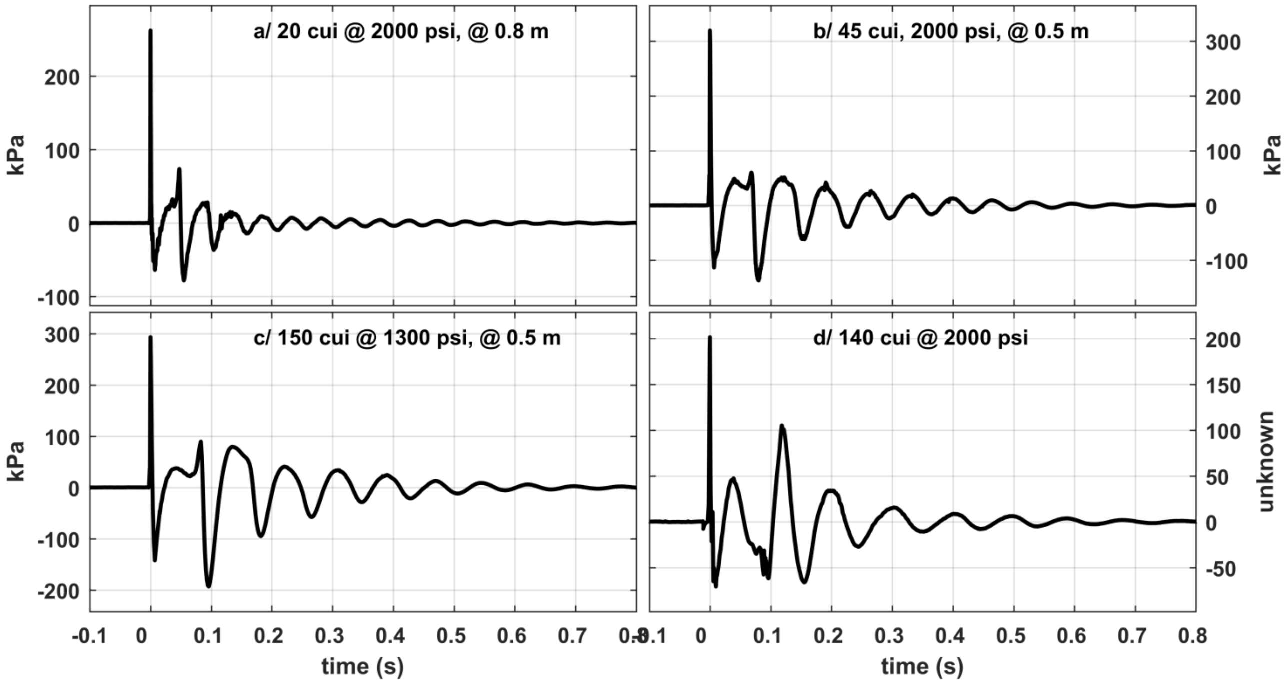

Figure 1: Images of single air gun waveforms (a/ to c/) and a gun cluster (d/, a 20 and 3 x 40 cui guns arranged in a 1.3 x 1.11 m rectangle, with the hydrophone located at the forward end with a 20 and 40 cui inch gun adjacent and recorded with an uncalibrated hydrophone). All sources were at 5-6 m depth.

There is considerable debate on the scale and severity of these environmental impacts but little discussion of potential mechanisms of how air gun signals may create the impacts observed across a range of fauna and how the seismic signals may be altered to lessen such impacts. Day et al. (2017) suggest damage to gills as the likely impact mechanism of seismic signals on scallops while McCauley et al. (2017) suggest zooplankton were physically 'shaken' to the point sensitive hairs on the distal ends of their antenna which are responsible for motion, orientation and vibratory reception, were damaged, although neither mechanism has been verified. Damage to sensory hair cells on the sensory epithelia of fish (McCauley *et al*., 2003b) and lobster (Day *et al*. 2016) implies the dense mass they were coupled to had been driven into the sensory epithelia, so damaging the hair cells. These mass loaded sensory organs ("mass-coupled systems"), which couple a dense mass against a membrane containing mechanically sensitive hair cells, to convert external physical stimuli into a nervous response by the cell's response to degree and direction of the bending of its hairs, are common across a range of marine fauna from invertebrates to vertebrates. The observed potential damage of seismic signals to scallop gills, zooplankton antennal hairs, or mass coupled systems, can all potentially be related to the impulse nature of an air gun signal and the high accelerations associated with the sharp peak pressures such signals produce.

Direct measurements of the forces imposed by air gun signals on marine fauna in terms of particle motion are currently lacking. An example of ground acceleration as measured by geophones in relation to received sound pressure from a 150 cui seismic source operating at 5 m tow depth in 10 m of water over a sandy seabed is shown on Figure 2. The relationship between sound pressure and the acceleration produced is not obvious in this signal nor are the pressure and acceleration magnitude directly correlated in time. In addition the relationship of air gun signal rise time with forces imposed on an animal has not been investigated. Intuitively one would expect that as the air gun signal rise time increases then the maximum particle acceleration associated with that signal would decrease, so decreasing maximum forces imposed on marine fauna and reducing potential biological impacts. There has been a recent seismic source developed, the eSource (Teledyne Bolt) which by increasing the air gun signal rise time, decreases the signal bandwidth, reducing the energy output at frequencies > 100 Hz which are not used in seismic reflection surveying. There has also been attempts to develop marine seismic sources which produce a longer, controlled and known signature type, such as a frequency sweep, rather than relying on the impulse nature of the signal for locating reflections in the received signals. This is a standard signal type as used in seismic surveys on land, termed vibroseis, but which has yet to be developed as a reliable marine seismic source. These vibroseis signals are much lower in amplitude than air gun signals, but are of longer length and thus put a similar amount of energy into the ground. The vibroseis signals would be expected to have much lower, maximum sound particle motion acceleration values than air gun signals of comparative energy, and thus would not be expected to produce the type or scale of impacts associated with air gun signals. A direct comparison of how an eSource or marine vibroseis compares with a conventional air gun in terms of biological impacts has not been made.

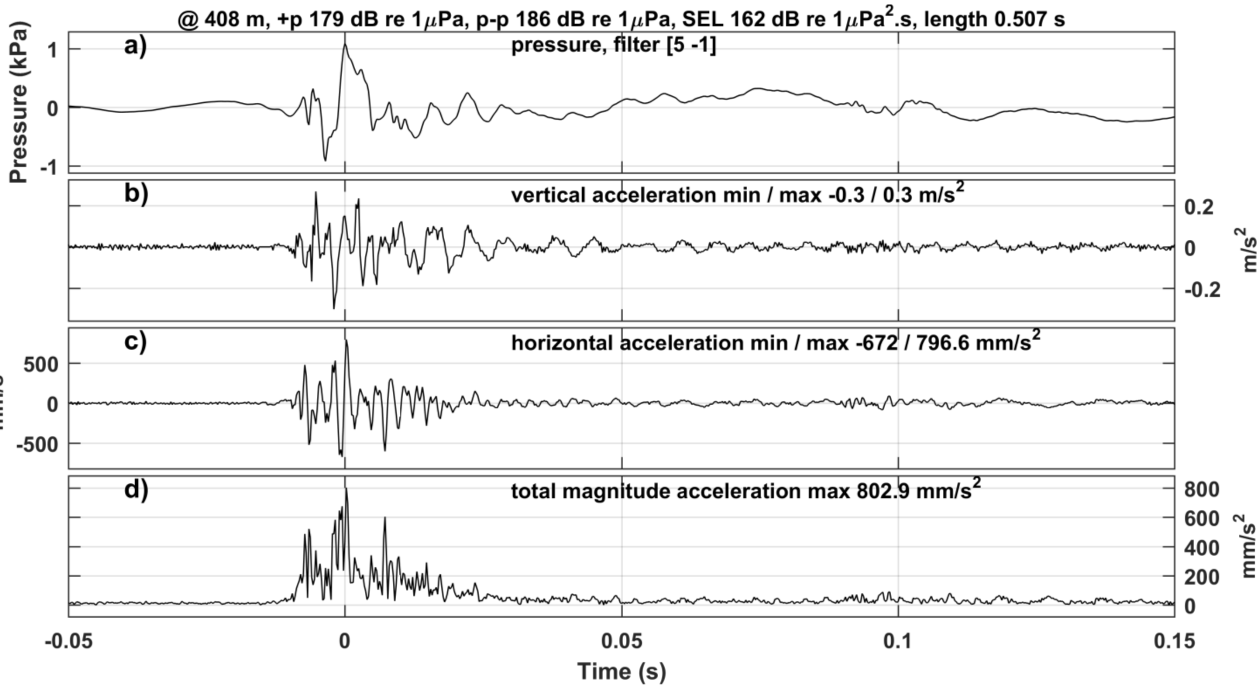

Figure 2: A single seismic signal as recorded at 408 m from a 150 cui air gun in 10 m water depth over a sandy seabed, showing: a) the pressure waveform at the seabed; b) the vertical ground acceleration; c) the horizontal ground acceleration; and d) the magnitude of the total ground acceleration.

There are a number of projects currently being planned to investigate impacts of conventional air gun sources on zooplankton, invertebrates and fish for the types of impacts discussed, plus how commercial fishing operations may be impacted by seismic surveys. Major planned projects for the time frame 2018 to 2022 include: Joint Industry Programme (JIP, http://www.iogp.org/sound-and-marine-life/) experiments on Atlantic cod in the North Sea; Environmental Studies Research Fund (ESRF, Canadian Government, http://www.esrfunds.org/179) proposed experiments on impacts of seismic surveys on zooplankton and Atlantic cod; and the Australian Institute of Marine Science's (AIMS, http://www.aims.gov.au/) North West Shoals to Shore Research Program, proposed experiments on demersal fish and pearl shell (*Pinctada maxima*) in north western Western Australia. In addition the ESRF currently has studies of seismic impacts on shrimp and fish underway. All of these experiments are proposed to use conventional air gun sources. The authors of this paper would like to see parallel studies which:

- Focus on elaborating impact mechanisms of conventional air gun sources on selected species (ie. scallops and fish) then put forward alternative signal types to reduce potential impacts;
- Measure how alternative seismic sources or signal types compare against conventional air gun sources with regards sub-lethal biological impacts on these selected species;
- Model how small fauna such as zooplankton or the mass-coupled sensory systems, interact with conventional seismic sources to predict imposed forces and accelerations;
- Extend modelling to alternative seismic sources or signal types to predict imposed forces and accelerations and so compare these with conventional seismic air gun sources;
- Extend modelling into the geophysical space to determine if alternative signal types are suitable for imaging of petroleum deposits.

Developing and testing alternative seismic sources which are acceptable for geophysical purposes and which reduce or remove potential biological impacts is a win-win situation for everyone, neatly sidesteps the endless arguments on whether observed impacts are real or imagined, and offers a potential commercial opportunity for many.

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