A low frequency air gun source for seismic surveys over subductive plate boundaries

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Summary

For seismic surveys whose structural imaging objectives are deep crustal features associated with tectonic plates, it is necessary that the seismic source comprise as much low frequency energy as possible. Conventional marine seismic surveys whose imaging objectives are relatively shallow typically employ a source with a sharply impulsive signature; however a source rich in low frequencies will necessarily have a signature of much longer duration. In order to generate low frequency energy using air guns, it is necessary to use very large volume elements configured either as single air guns, or as clusters of air guns whose bubbles coalesce into large volume elements. The mechanical shock resulting from firing very large air guns, and maintaining the source at depths required to enhance low frequencies both create significant operational problems. These problems must be addressed in order to produce a stable and repeatable low frequency source signature. The purpose of our study was to demonstrate a novel method for configuring a source array rich in low frequency energy, and to illustrate by means of recorded data the imaging that can be obtained using this source.

Introduction

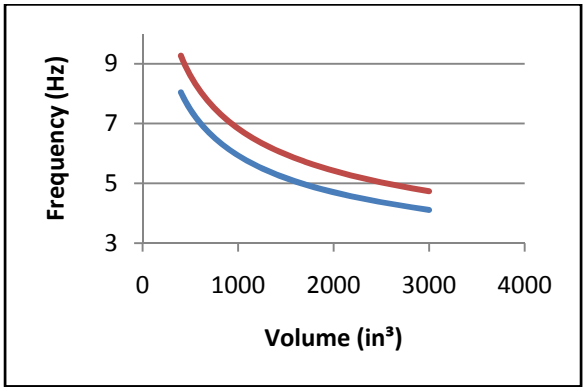
The signature of an air gun source can be modeled reasonably well using algorithms developed over a number of years, calibrated against recorded near- and far-field measurements. In general, the fundamental period of an air gun with volume *V* and pressure *P* is given by:

$$t = C * \frac{(P * V)^{1/3}}{(P(d))^{5/6}}$$

In this equation *P(d)* is the hydrostatic pressure for a depth *d*. The constant *C* is a function of the mechanical design of a particular gun, whose internal dimensions and component weights determine the rate at which air can be exhausted from the firing chamber to the water column.

The following graph shows the relationship between fundamental frequency and volume for depths of 10 metres (blue) and 20 metres (red). The graph illustrates two salient points:

1. A very low fundamental frequency requires very large volumes.
2. As depth increases the fundamental frequency for a given volume is substantially higher.



Frequency vs. Volume – 10 and 20 metres depth

From this graph it is apparent that an array rich in low frequencies will necessarily comprise elements with the largest volumes that can be practically configured.

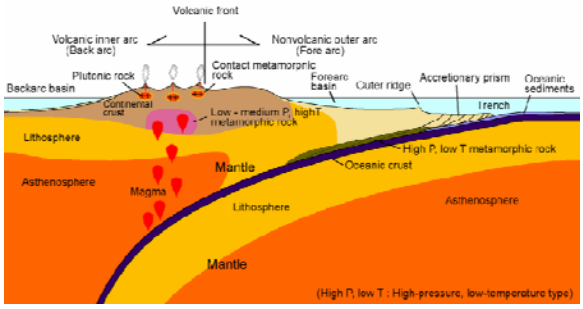
Geologic Objectives and Seismic Survey Design

The islands comprising the nation of Japan reside in a tectonic province characterized by convergent plate boundaries on the northwestern margin of the Pacific Ocean. These boundaries separate the Pacific oceanic plate, the North American continental plate, the Philippine Sea oceanic plate and the Eurasian continental plate.



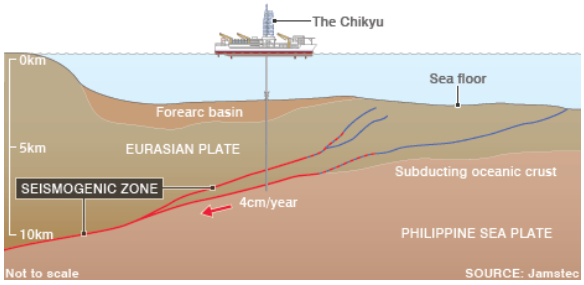
Source: GLGArcs – Hirotoshi Nishiwaki

Much of the seismicity and volcanism occurring in the Japanese island arcs are associated with plate subduction, consequently it is important to understand the structure and dynamics of these subductive plate boundaries. The following illustration from Nishiwaki shows a typical arc-trench system.



Source: GLGArcs – Hirotoshi Nishiwaki

In 2008 Jamstec and its contractor, Nippon Marine Engineering (NME) conducted a seismic survey over the Nankai Trough in Southwest Japan where the Philippine Sea plate subducts beneath the Eurasian continental plate. The Nankai Trough has been associated with several powerful earthquakes in recent memory, most notably the Tonankai and Nankaido quakes in 1944 and 1946 respectively; each earthquake caused some 1,000 fatalities, with a total of about 100,000 houses being swept away in the ensuing tsunami.



Nankai Trough Fault Line (Source: Jamstec)

The 2008 survey was part of a 40,000 line-km project conducted by Jamstec using the vessels M/V Kairei and M/V Kaiyo. These vessels were configured with two source arrays during the course of the 40,000 line-km project:

1. A 12,000 in³ array comprising 8 x 1,500 in³ 1500LL air guns.
2. A 7,800 in³ array comprising 4 strings of 8 Annular Port Air Guns.

The Kairei was equipped with a 5,100 m digital streamer deployed at a depth of 6 to 15 metres, and its source was deployed at a depth of 6 to 15 metres during streamer operations; the depths of the source and receiver arrays depended upon the geophysical objectives of the survey. During ocean bottom seismic operations, the M/Vs Kairei and Kaiyo deployed their 12,000 in³ source arrays at a depth of 10 metres, shooting into a spread of OBS receivers approximately 100 kms in length.

Source Array Design and Signature Estimation

The 12,000 in³ array comprising 8 x 1,500 in³ 1500LL air guns was deployed using telescopic booms, in a rectangular configuration measuring 12 metres by 24 metres for M/V Kaiyo, and 24 metres by 80 metres for M/V Kairei. The following illustration shows 4 of the 1,500 in³ air guns as they are being deployed from the stern of M/V Kairei during sea trials. Each 1,500 in³ air gun measures 1.8 metres in length and weighs 250 kgs, including the heavy-duty rigging hardware required to absorb the mechanical shock generated by the large volume air guns.



Source Array being deployed from M/V Kairei

The 7,800 in³ source array used on this survey, which replaced the 12,000 in³ array on M/V Kairei, comprises 4 identical subarrays, and each subarray comprises 8 guns in a linear configuration over a length of 8.7 metres.

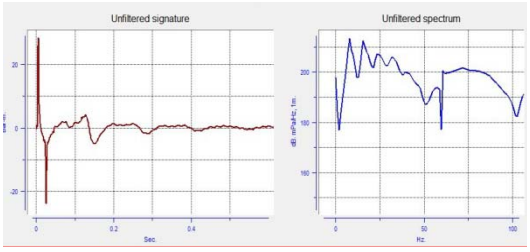


8-Gun Subarray from 7,800 in³ APG Array

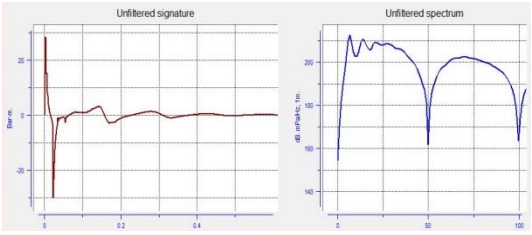
A synthetic far-field signature of the 7,800 in³ source array was modeled using the Gundalf source signature modeling package. The array is characterized by many large-volume air guns in very close proximity, consequently considerable attention is paid to the complex bubble interactions that necessarily define the source signature.

The following illustrations show the modeled signature and estimated spectrum of a single 1,950 in³ subarray of the 7,800 in³ source array at a depth of 15 metres, as well as a

recorded far-field signature and its estimated spectrum at the same depth. The recorded far-field signature includes a notch filter to attenuate 60 Hz noise in the recorded signal.



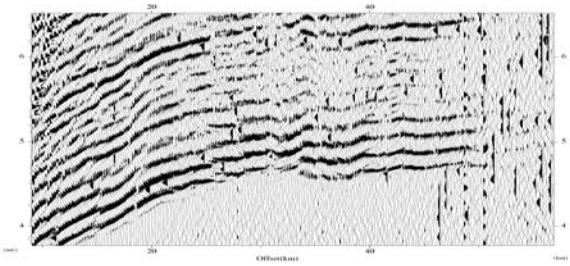
Recorded Source Signature at 15 metres



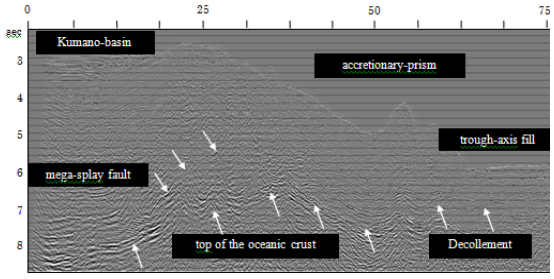
Modeled Source Signature at 15 metres

Seismic Records

The survey was conducted using both a 5,100 m. streamer and an array of ocean bottom sensors spread over a distance of some 10s of kms to over 100 kms. Shot records and processed sections from the streamer survey show useful seismic energy was recorded to a distance of over 100 kms.



OBS Record – Offset vs. Time



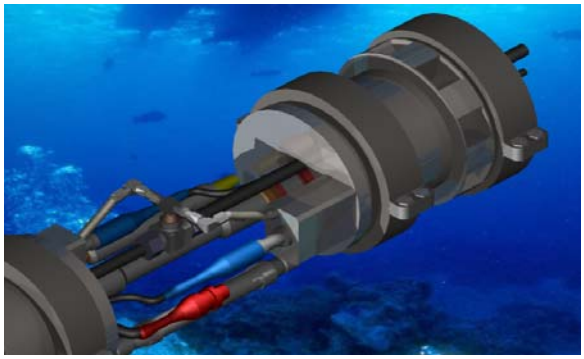
Migrated Seismic Section – Nankai Trough

Mechanical Reliability

Shimizu et al (2008) note that for an array which includes air guns as large as 600 in³, substantial shock loads are generated with the potential to cause significant damage to the electronic and mechanical components of the array. In order to make the array as reliable as possible, a design is proposed that substantially reduces the mass of the electronic components required to control and monitor the source array.

Existing distributed source controllers include electronic packages with substantial mass located near the air guns. The very large accelerations generated by the air guns as they discharge, on the order of 5,000 m/s² or more, create shear and tensile strains that can damage both structural mechanical parts, electronic components and electro-mechanical connections. A configuration is proposed that minimizes the mass of the electronic components situated near the guns, and the number of electro-mechanical connections.

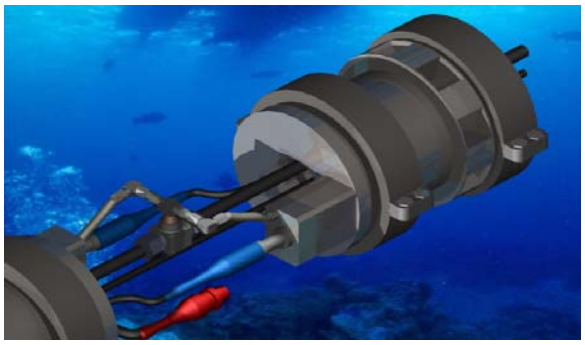
The following illustration shows the configuration for the fully distributed source controller in the 7,800 in³ array configuration described above.



Standard Configuration – Fully Distributed Controller

In an alternate configuration we propose, the electronic components required to control and monitor the air guns are placed inside the solenoid valve body, thereby eliminating 90% of the mass and 75% of the electro-mechanical connections.

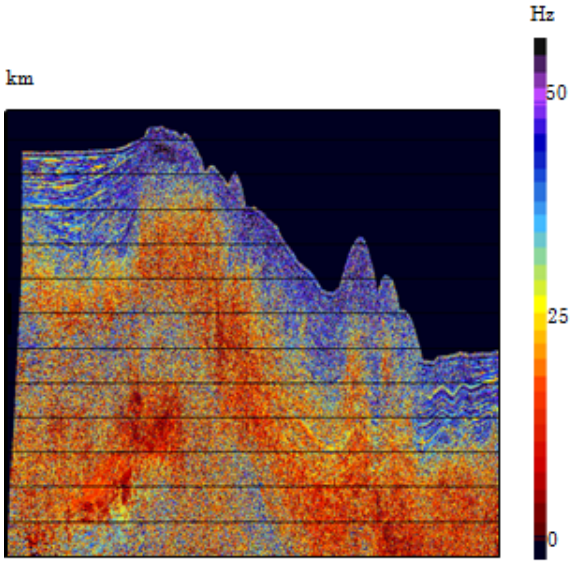
The following illustration shows the reduction in the number of components and connectors that can be achieved by re-designing and re-configuring the control electronics. The mass of the distributed electronics is reduced from 13 kgs to 1.5 kgs, and the number of electro-mechanical connections is reduced from 8 to 3.



Alternate Configuration – Redesigned Controller

Conclusions

Seismic source arrays with significant levels of low frequency energy are better suited for seismic surveys whose imaging objectives are deep crustal features associated with tectonic plates. We have shown that a source array comprising very large volume elements deployed at depths of 6 to 10 metres can image crustal features at depths of 10 to 20 kms.



Instantaneous Frequency vs. Time

The source signature estimation of an air gun array comprising many large volume elements in very close proximity requires considerable mathematical rigor. We show by way of modeling examples the parameterization necessary to effect a satisfactory signature estimation, which can then be used to further improve the seismic image.

Finally, in order to mitigate damage caused by the mechanical shock resulting from firing very large air guns, we propose a novel method for configuring a small distributed source controller with substantially fewer electro-mechanical connectors, resulting in a source array better able to withstand the heavy shock load generated by the large-volume air guns comprising the source array.

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