Calibrated airgun source modeling to estimate broadband marine source signatures

Jens Fredrik Wisløff, Daniel Barker, Stian Hegna, Alex Goertz, PGS, Florent Pesnel and Dorian Richelmi, Sercel

Summary

The current implementations of marine source modeling theory have been calibrated and adjusted against measured signatures with a goal of high modeling accuracy within a limited frequency band. As multicomponent streamers and source de-ghosting allows for utilizing a significantly broader range of frequencies in seismic imaging, adjustments to the modeling are necessary in order to achieve a better match between measured and modelled signatures over the expanded frequency band. This includes significant changes to the calibration process such as considering de-ghosted measurements and avoiding the historically rooted standard DFS V filtering. The modeling results after applying the improved calibration show a very good match with measured array signatures over a wide frequency range.

Introduction

While the farfield signature of an airgun array can generally be modelled fairly accurately using approaches based on Rayleigh's (1917) theory of oscillating bubbles, the advent of broadband marine seismic solutions has unveiled limitations in current modeling algorithms outside the traditional marine seismic bandwidth. There are several reasons for this, and they stem from the early implementations of source-modeling procedures.

The efforts to develop an accurate source modeling in the 1980's and 1990's did not take into account the higher frequencies as they were not deemed important, signature lengths were short, and for all practical purposes the DFS-V Out–128(72) Hz (dB/Oct) filter was used for signature comparisons (S. Strandenes, personal communication, 2014). All comparisons between measured and modeled air gun signatures were done after filtering, and consequently, we cannot expect any model calibrated at that time to perform well outside of the frequency range of the described DFS V filter. The measured signatures that were used for calibration included the source ghost, which again masks frequency ranges depending on the shot depth. Within these masking limits, modeling schemes were devised that matched array signatures well enough to even be used for de-signature applications.

As wider frequency ranges have become more desirable, and de-ghosting of signatures more common, we now see that the previously masked information becomes more important, and the modeled signatures become less reliable when used outside the mode they were designed for. Hence, existing source models need to be updated for use in broadband seismic. This includes both calibrating over a broader bandwidth, as well as improving the underlying model such that it will handle deviations from calibrated values in a better way.

In this paper, we first outline the limitations of modelled airgun signatures for marine broadband data if they are based on conventional-band calibration measurements. We then describe a new broadband calibration of the source model based on newly acquired de-ghosted and unfiltered calibration data. This results in higher accuracy modelled signatures that can also be used for planning and processing of marine broadband data such as dual-sensor, multi-level source marine data.

Theory

Marine seismic airgun modeling is often based on the theory of Kirkwood and Bethe (1942) and Gilmore (1952), who describe the dynamics of an oscillating air bubble created by an underwater explosion. It has been shown that a major factor in the energy loss during the bubble oscillation is due to mass transfer inside the bubble (Schrage, 1953). As the bubble oscillates, water may evaporate at the bubble wall and condense inside the bubble to produce a transfer of mass of water into the bubble, causing the dampening we see in the bubble pulses of an air gun signature. The exact rate at which these processes work is difficult to describe theoretically due to the strong variations of temperature and pressure inside the air bubble. Therefore, observed rates have been used as "calibration" in order to make modeled signatures fit recorded data. While this was sufficient for a good fit with traditional bandwidth specifications, it may not be accurate enough for modelling of broadband signatures.

Several other physical effects may be contributing to the differences we currently see between the measured and modeled signatures and should be part of the source modeling theory. This includes a realistic model of the air escaping from the gun to better describe the shape of the primary pulse, and the upward movement of the bubble due to buoyancy. The latter becomes important if longer time signatures are being used for processing.

There may be high-frequency effects, which are not directly reproducible, such as cavitation. While such "noise" will not be especially relevant in the broadband seismic frequency range, it may be important for purposes such as modeling environmental effects.

DOI http://dx.doi.org/10.1190/segam2014-1206.1

In addition to the dynamics of each air bubble, the guns will also interact with each other. While standard interaction between air guns in arrays is well established, the extreme case of clusters (where the bubbles of two or more airguns coalesce), is somewhat less clear. Two-gun clusters are well-researched and routinely used in array design (Strandenes; Vaage, 1992), (Barker; Landrø, 2012). However, the hunt for low frequencies has culminated in the proposal of large "hyperclusters" (e.g., Hopperstad et al. (2012)), which are far beyond the scope of the both, the original model, and the original calibration of existing modeling algorithms.

Calibrating on ghost-free signatures

The presence of the ghost reflection in the farfield signature from an airgun array conceals important information such as the array's response to its own ghost, or the interaction between the subarrays. As seen in

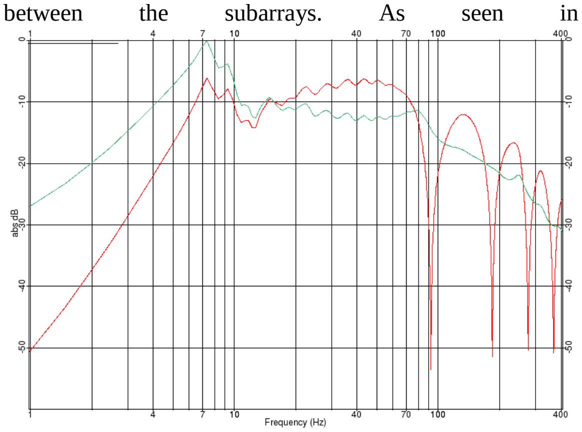

Figure 1, the difference between the signatures with and without the source ghost is a lot more than the notches in the frequency spectrum and is just as prominent in the lower end of the frequency spectrum as for the higher frequencies. Although the interaction effects are of second order, it is essential to take these into account in airgun calibration schemes.

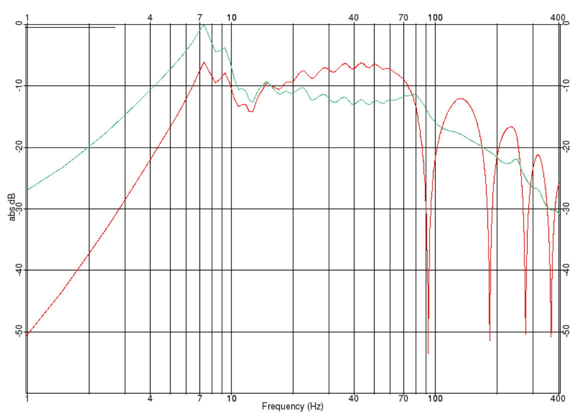

Figure 1: Comparison of the modelled farfield signature from an airgun array with (red) and without (green) the source ghost yet both including the effect of the source ghost interaction.

It is therefore important for any broadband source modeling that the modeling algorithm is calibrated against data without the presence of the source ghost. While we cannot make the sea surface go away, we can design our calibration measurements such that they would allow for an accurate de-ghosting procedure to be applied to the data before calibration.

Awareness of the various interaction effects, especially the interaction of the ghost, is necessary to ensure sufficient accuracy in the de-ghosting process. A de-ghosting process should never contain any statistical processing step which has an aim of flatten the frequency spectrum. The interaction effect of the ghost as well as the interaction between the airguns and the subarrays significantly changes the behavior of the guns in the array and leaves footprints in the recorded seismic data which a statistically based processing step might alter or remove completely.

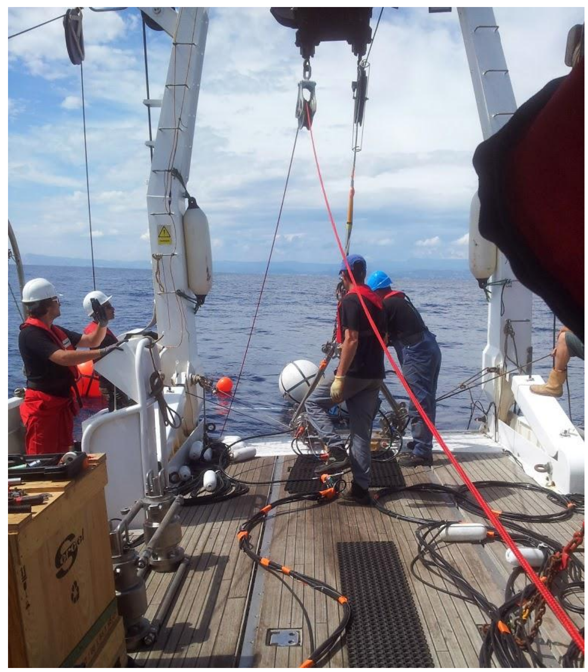

Figure 2: Field setup for the calibration test. Single and cluster guns are deployed from the back deck. An array of farfield hydrophones is deployed using a rope (red).

This has some implications for field measurements done for calibration purposes: on one hand, we would like to measure airgun signatures in an as realistic environment as possible, i.e., in sea water at typical source depths, on the other hand, calibration measurements should be carried out in deep water and at a considerable distance from shore in order to avoid reflections from the sea floor or other objects in the relevant part of the signature. Receivers need to be located in the farfield (the dynamic range in the near field is too difficult to handle for calibration purposes), and their locations need to be precisely known to allow accurate de-ghosting of the data. In order to ensure accurate de-ghosting of the calibration data in the presence of

DOI http://dx.doi.org/10.1190/segam2014-1206.1

unavoidable location inaccuracies, it is desirable to record into an array of farfield hydrophones distributed over different depths and different angles from the source. This way, a proper directional de-ghosting operator can be estimated from the data by inversion. Figure 2 shows a picture of the measurement setup for a calibration measurement campaign in the Mediterranean carried out in summer 2013. An array of farfield hydrophones at various depths and lateral positions is necessary for proper de-ghosting of the data, accounting for the uncertainty in exact receiver position when towing.

Calibration

A series of calibration measurement of single and clustered guns have been conducted to improve the current calibration of the G.GUN II in the modeling software. The test setup was chosen to allow sufficient de-ghosting of the farfield signatures and the de-ghosted signatures were used in the calibration process such that a good match between modeled and measured signatures over a broad frequency range could be achieved.

Some of the signature characteristics that are difficult to examine by inspecting signatures with the source ghost are illustrated in Figure 3 where the modeled, calibrated with the old calibration scheme, and the measured ghosted and DFS V-filtered signatures seem to have a reasonably good match (top), but the de-ghosted and unfiltered data (bottom) clearly reveals significant differences between the modeled and the measured signatures. The calibration of a different single gun where the de-ghosted calibration data has been utilized is shown in Figure 4. It shows about the same accuracy as the previous example when it is compared with the measured data that includes the source ghost and the DFS V filter (top), but there is a significantly better match when the signatures include neither the source ghost nor the effect of the DFS V filter (bottom).

The difference between measured and modeled signatures as seen in Figure 3 is mainly arising from the low frequency end which contains most of the bubble pulse energy. This low-frequency energy is signal and can positively contribute to the image if properly deconvolved. Hence difficulties related to deconvolving this energy in seismic data often arise from a lack of understanding the modelling accuracy within this particular range.
In a full array, the interaction effects and hence the change of the resulting pressure output is significantly larger than for a single gun or a cluster and it becomes even more important to interpret the modeling result over a broad frequency spectrum.

Result for the benchmark array

The performance of the re-calibrated G.GUN II modeling has been compared to a signature from a farfield measurement of a full 4135 cu.in array equipped with G.GUN II airguns. The result in Figure 5 shows that the modelled and measured signatures match very well. Note in particular the close agreement in both amplitude and phase below 10 Hz. The measured signature was acquired with a 2 ms sampling rate and is therefore limited to 200 Hz maximum frequency. The measured signature was deghosted by deconvolving a ghost function inverted from the far-field measurements.

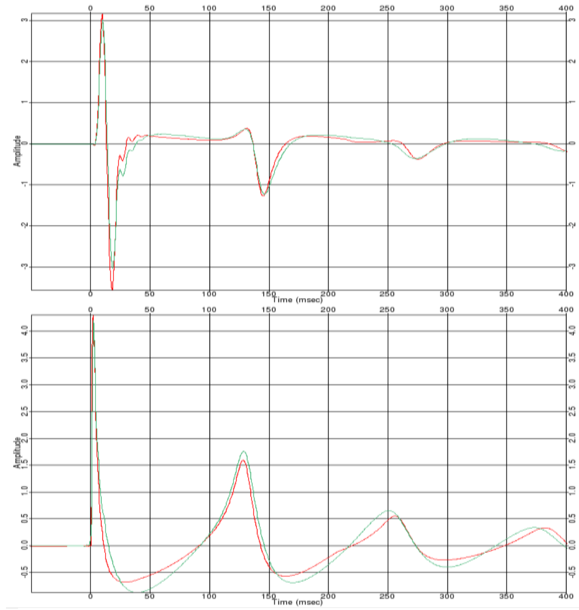

Figure 3: Comparison of a measured (green) and modeled (red) signature of a single airgun (380 cu.in. G.GUN II) with the ghost and filtered with the DFS V filter (top), and the same signatures de-ghosted without the DFS V filter (below). The modelled signature has in this case been calibrated towards a ghosted DFS V filtered measurement using the old calibration scheme.

DOI http://dx.doi.org/10.1190/segam2014-1206.1

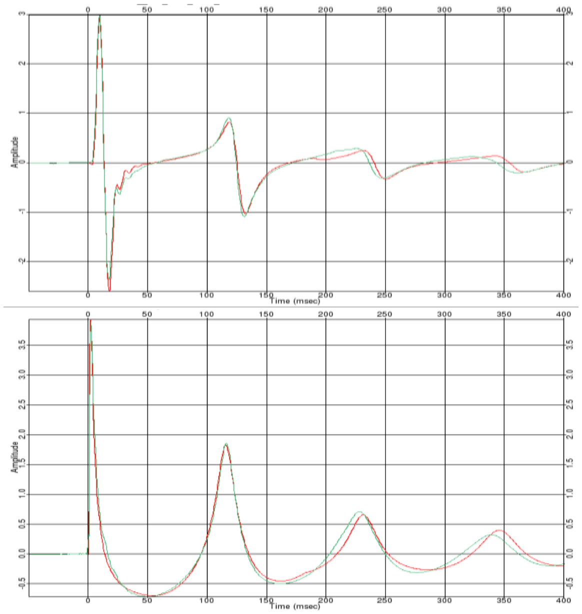

Figure 4: Comparison of a measured (green) and recalibrated, modeled (red) signature of a single airgun (250 cu.in. G.GUN II) with the ghost and filtered with the DFS V filter (top), and the same signatures de-ghosted without the DFS V filter (below). The modelled signature has in this case been calibrated towards a de-ghosted un-filtered measurement.

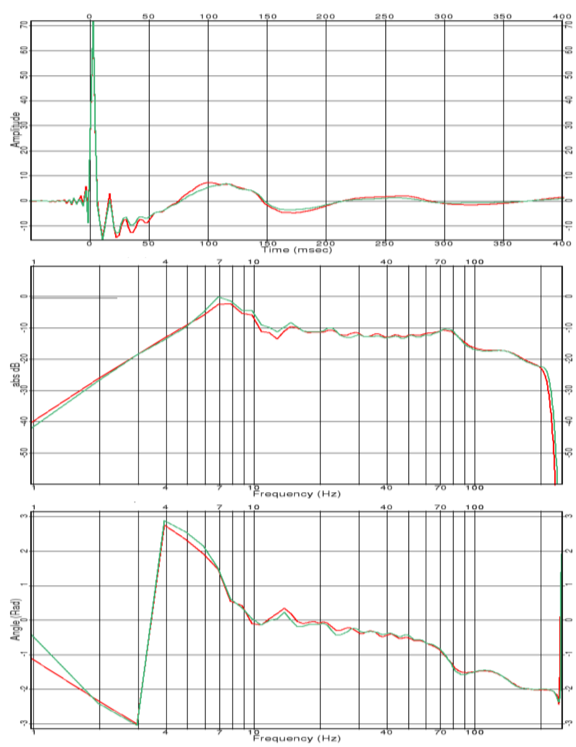

Figure 5: Measured (red) and modeled (green) signatures for a 4135 cu.in G.GUN II array compared in time, frequency and phase, data courtesy of Total.

The modeling has only been calibrated towards single and clustered guns, and not all volumes present in the 4135 cu.in array were included in the range of volumes used in the calibration. The physics of the airgun modeling handles all interim volumes within the calibrated range as well as the interaction effects without any additional tuning of the signatures to achieve the result shown here. This result is in line with previous statements that the airgun modeling can predict relative changes very well and together with accurate calibration measurements shows great promise in accurately modeling airguns over a broad frequency band. Especially the comparison to ghost-free measured signatures shown in Figure 5 underscores that the modeling accuracy is principally suited for broadband processing.

Conclusions

Ghost-free marine broadband seismic requires higher accuracy in forward-modelling of airgun array signatures compared to conventional marine seismic. The accuracy of the modeling can be greatly improved by basing the calibration process on broadband calibration data. This requires the ability to properly de-ghost the calibration data by acquiring time- and space-redundant data in a controlled, yet realistic environment, as well as the omission of any limiting instrument filters.

When de-ghosted, unfiltered broad-band measurements are utilized, the validity range of the modeling is greatly improved and shows a very good match with measured signatures over a broad frequency range. Comparison with a measured, de-ghosted farfield signature shows the increased accuracy of the modeling.

Acknowledgements

We are grateful to the crew of COMEX Minibex, Marseille, for the support during the measurement campaign. We would also like to thank Total for allowing the use of the data which has been utilized to produce the array benchmark signature shown in Figure 5.

http://dx.doi.org/10.1190/segam2014-1206.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Barker, D., and M. Landrø, 2012, Simple expression for the bubble-time period of two clustered air guns: Geophysics, **77**, no. 1, A1–A3, http://dx.doi.org/10.1190/geo2011-0169.1.

Gilmore, F. R., 1952, The growth or collapse of a spherical bubble in a viscous compressible liquid: California Institute of Technology, Report No. 26-4.

Hopperstad, J. F., R. Laws, and E. Kragh, 2012, Hyperclusters of airguns — More low frequencies for the same quantity of air: Presented at 74th Annual International Conference and Exhibition, EAGE.

Kirkwood, J. G., and H. A. Bethe, 1942, Shock and detonation waves: Gordon and Breach.

Rayleigh, L., 1917, On the pressure developed in a liquid during the collapse of a spherical cavity: Philosophical Magazine, **34**, no. 200, 94–98, http://dx.doi.org/10.1080/14786440808635681.

Schrage, R. W., 1953, A theoretical study of interphase mass transfer: Columbia University Press.

Strandenes, S., and S. Vaage, 1992, Signatures from clustered airguns: First Break, **19**, 305–312.