An experiment to detect nonlinear seismic responses on exploration/monitoring scales

Kris Innanen*, CREWES, University of Calgary, Calgary, Alberta, Canada
k.innanen@ucalgary.ca,
Gary Margrave, CREWES, University of Calgary, Calgary, Alberta, Canada, and
Malcolm Bertram, CREWES, University of Calgary, Calgary, Alberta, Canada

Summary

One of the objectives of the 2012 CREWES/University of Calgary seismic field experiment, near Priddis AB, was to revisit the idea of measuring nonlinear seismic responses. Our approach involves comparing data from multiple sources activated individually and together. We consider the difference between responses from (1) the CREWES Envirovibe carrying out a linear sweep, (2) a standard (Geokinetics Mertz 22) vibe vibrating at a fixed 25Hz, and (3) the two simultaneously. If the Earth responds nonlinearly to seismic sources, the difference between (3) and (1)+(2) should be non-zero, though relatively small. We show examples of the uncorrelated data for these sweeps, and comparisons of norms of the data differences as above. Differences are visible, which must be examined to distinguish between true seismic nonlinearity and vibe feedback. Pursuing these potential explanations of our measurements is the near term research plan.

Introduction

In 2008, CREWES undertook the “Priddis Pump Probe” experiment (Margrave et al., 2008), in which dynamite sources were shot once into quiescent media and then again into media being excited by a vibe sweep. The idea was that a medium being illuminated by a seismic wave has slightly different properties than when all is quiet, and that this might be detectable through a secondary seismic experiment. If detected, this would constitute evidence of a nonlinear seismic response on exploration/monitoring scales (see also Campman et al., 2012; Zhukov et al., 2007). The 2008 results were reported as being ambiguous. In 2010 an acoustic theory was developed in order to provide an intuitive framework within which such signals (should they be detected) could be interpreted (Innanen, 2010), which treats the linear wave field as an inhomogeneous term in a further PDE for a secondary, nonlinear field. In July 2012, as part of a broader field campaign, CREWES carried out the “Priddis Pulse Probe” experiment, to revisit the question of nonlinearity, using sources with a greater degree of repeatability, namely two vibrators, rather than one vibrator and dynamite. The experiment was configured to minimize what is likely the key obstacle to detection: the fact that the vibrators are adaptive, and therefore, in effect, could impose an apparent degree of nonlinearity on the signal. We do so by confining the vibes to different source lines offset by 100m. Still, a key obstacle in interpreting our results is ensuring that vibe feedback and nonlinearity are not confused. Our purpose in this paper is to summarize the configuration of the experiment and present an initial look at some of the data.

Experimental configuration

In Figure 1 the basics of the experiment are laid out. The secondary source line (to the north, in orange) is occupied by the Geokinetics Mertz 22 (“big”) vibe. The primary source line (to the south, in yellow) is occupied by the CREWES ("mini") Envirovibe. The receiver line is in red; the data we will examine in this paper come from conventional multicomponent geophones which are laid out at 2m intervals along this line. The big vibe illuminates the subsurface with a fixed 25Hz signal, through which the mini vibe sends a standard linear 10-120Hz sweep. As baseline data, we also record the mini vibe at each flag point without the big vibe's signal, and we record the big vibe's signal alone. Figures 2a-d illustrate the configuration we will focus on in this paper, in which the big vibe remains at a fixed point roughly halfway along the secondary receiver line, and the mini vibe steps from west to east, sweeping at each flag point.

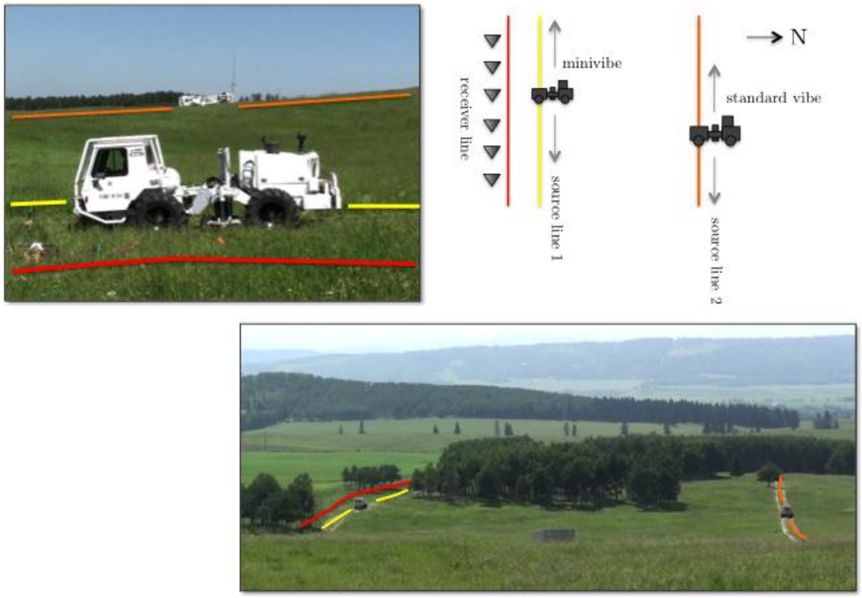

Figure 1: Schematic illustration and photos of the 2012 Priddis pulse-probe experiment. Top left: looking north from the receiver line. Top right: plan-view schematic. Bottom: looking west.

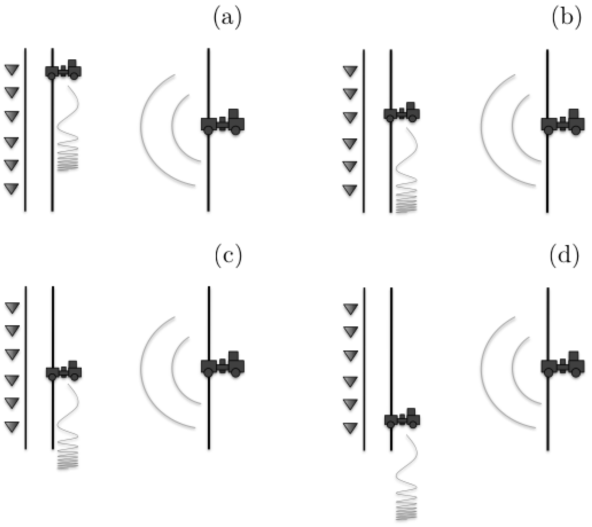

Figure 2: The CREWES Envirovibe occupies each flag location from west (a) to east (d), with the Geokinetics vibe maintaining a fixed location near the centre of the offset secondary source line.

A look at the uncorrelated data

The scheme for comparison is illustrated in Figure 3. In Figures 4a-c an example set of three uncorrelated shot records is illustrated (from randomly selected shot point). They are arranged to match the scheme illustrated in Figure 3: (a) contains the mini vibe sweep alone, (b) the big vibe sweep alone, and (c) the two sweeps simultaneously active. Visually the response of the two active sweeps (in Figure 4c) appears to be the sum of the individual sweeps. The task of identifying nonlinearities lies in detecting subtle differences between (c) and the sum of (a) and (b).

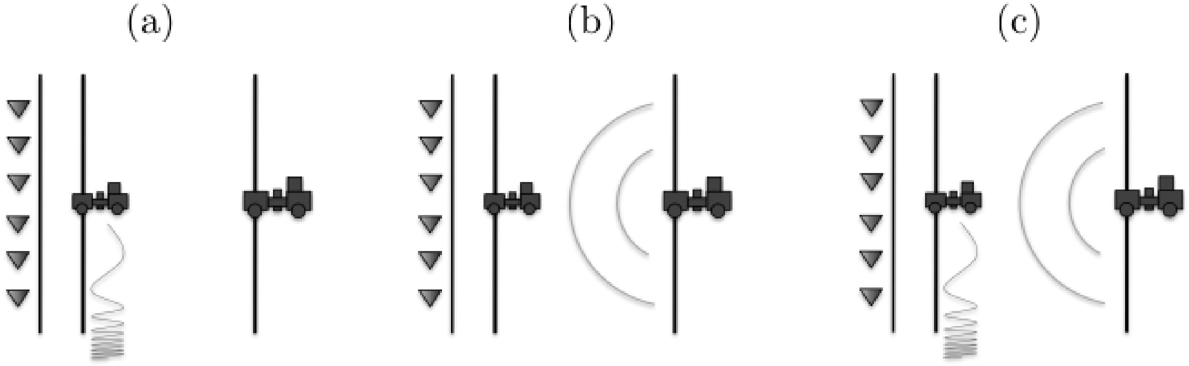

Figure 3: The configuration allows us to compare (a) the “mini” Envirovibe data alone, across the whole receiver line, (b), the “big” (Geokinetics) vibe data alone, and (c) the two vibes together.

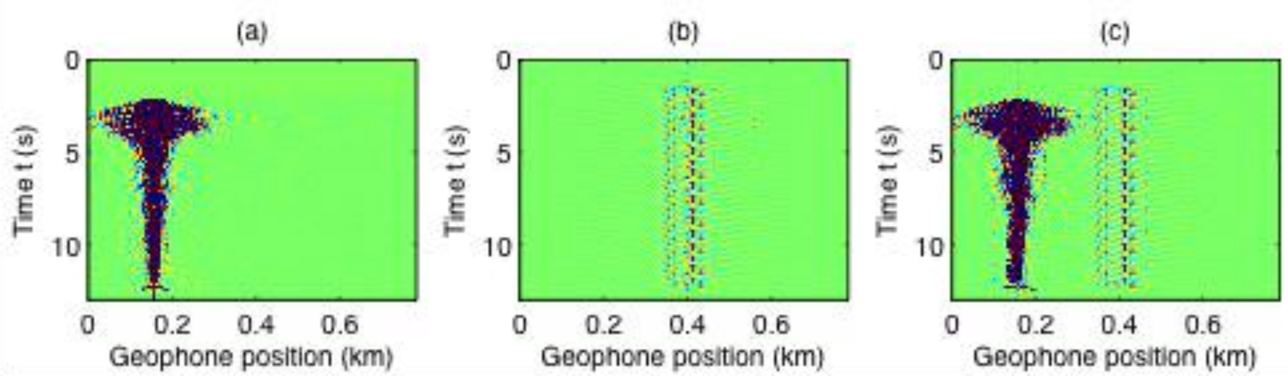

Figure 4: An example of the uncorrelated data. (a) Mini vibe signal alone; (b) big vibe signal alone; (c) mini and big vibes active simultaneously.

Early indications are that “something is going on”, namely behaviour that is unexpected from the point of view of linearity; we have not as yet been able to confirm or falsify it as nonlinear. In Figure 5a, traces extracted from Figure 4 are examined. In (a), the difference between *both* and the *big vibe* is plotted in black, and overlain on top of this is the *mini vibe* trace in red. Any clear differences between the red and black traces would constitute potential nonlinear behaviour. Clearly, at least at certain times, there are some significant differences between these traces. In Figure 5b, two mini vibe sweeps taken one after another (without a background sweep) are also plotted to establish a baseline of repeatability. The “both minus big” trace and the “mini vibe alone” traces take on a very noticeable relative phase shift. This appears to us at present to be the most promising trail to follow in an attempt to positively identify a nonlinear signal.

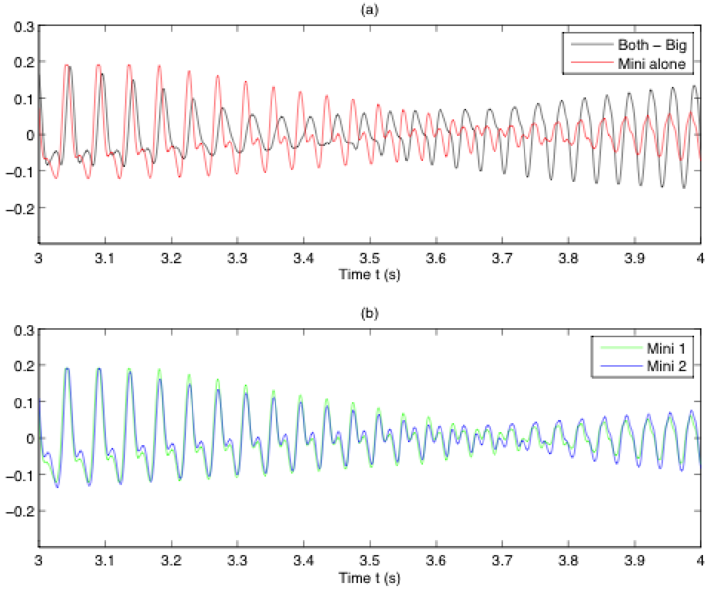

Figure 5: Trace comparisons. (a) The big vibe signal is subtracted from the simultaneous vibes, and plotted in black opposite the corresponding mini vibe trace in red. (b) Two collocated mini vibe traces are similarly compared (blue and green) as a baseline. Some phase differences occur between 3 and 4s in (a).

Comparison of data norms

We have also examined *data norms* for evidence of violation of superposition. Two components of the data are considered: the vertical component and one horizontal component. For each shot along each line, we formed the difference between "both big and mini" and "big alone + mini alone" shot records, and calculated the associated 2-norm. In Figure 6 we plot these values in red, in comparison to a control, or baseline difference between two repeated mini-vibe sweeps (in blue). The significant increase in the mean red vs. the mean blue could be an indication of nonlinearity, but, additional scale factors (of 2, or 3) may need to be applied to the blue curve, and this is an issue of ongoing research. Whether the average discrepancy constitutes a true anomaly is therefore uncertain. However, we point to peaks in the red curve, which are present in both components, and which are unlikely to be matched by the blue curve regardless of scale factor, as representing avenues for further investigation.

Conclusions

One of the objectives of the 2012 Priddis pulse-probe experiment was to revisit the idea of measuring nonlinear seismic responses on the exploration/monitoring scale. In this initial study, we consider the difference between seismic responses from (1) the CREWES mini vibe as a lone source carrying out a linear sweep, (2) a standard (Geokinetics Mertz 22) vibe as a lone source vibrating at a fixed 25Hz, as well as (3) the two simultaneously. Linearly unexpected phase differences are noted, and may be the best near term "trail" to follow, possibly indicating altered travel times through the 25Hz-illuminated Earth volume. Also, anomalously large differences (measured through the 2-norm) between the "big and mini together" data and the "big alone + mini alone" data represent possible avenues for positive identification of nonlinear signal. The key issue going forward will be to distinguish between vibe feedback and true seismic nonlinearity.

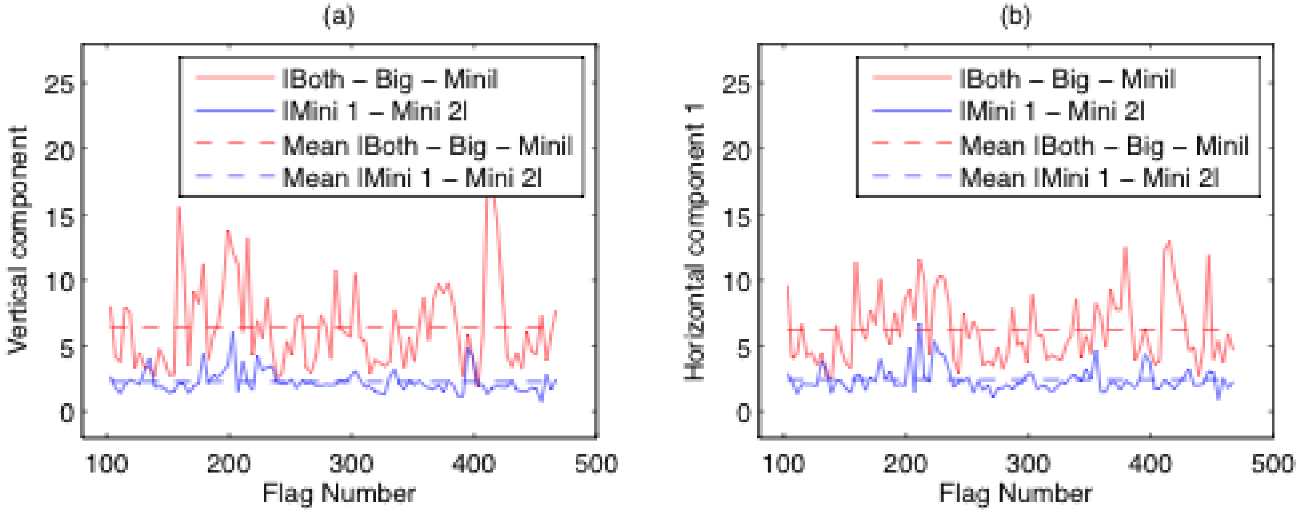

Figure 6: Data difference norms (red) vs. control (blue), which are differences between repeated mini vibe sweeps. A larger average red than blue is a possible indication of nonlinearity but additional scaling may need to be applied between the two. For now we focus on the peaks in the red curve, which no scale-factor would likely account for. (a) Vertical component, (b) one horizontal component.

Acknowledgements

This work was funded by the sponsors of CREWES. Our partners in the 2012 Priddis AB field experiment, Global Geophysical, Geokinetics, and Outsource, are gratefully acknowledged. Kevin Hall, Kevin Bertram, Peter Manning, Laura Baird, and all CREWES students and staff were major contributors to the success of the experiment. We thank Prof. Alison Malcolm for technical discussions.

References

Campman, X. H., Kuvshinov, B. N., and Smit, T. H. J., 2012, Combined-harmonic analysis of seismic data acquired with two vibrators driven at different frequencies, EAGE Copenhagen, Denmark, EAGE.

Innanen, K. A., 2010, An acoustic description of nonlinearity in seismic exploration: CREWES Annual Report Vol 22.

Margrave, G. F., Henley, D. C., Lu, H. X., Hall, K. W., Bonham, K., Bertram, M. B., Gallant, E. V., and Wong, J., 2008, Priddis pump-probe experiment: CREWES Annual Report Vol 20.

Zhukov, A. P., Loginov, K., Shneerson, M. B., Shulakova, V. E., Kharisov, R., and Ekimenko, V. A., 2007, Nonlinear properties of vibrator-generated wavefields and their application to hydrocarbon detection: The Leading Edge, 26, No. 11, 1395–1402.