

## Letter Section

# Remarks on ‘Experimental investigation of non-linear seismic effects’

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(Received 12 April 1991; revision accepted 28 June 1991)

### ABSTRACT

Beresnev, I.A., 1991. Remarks on ‘Experimental investigation of non-linear seismic effects’. *Phys. Earth Planet. Inter.*, 69: 1–3.

This letter is in response to the paper by V.S. Solovev entitled ‘Experimental investigation of non-linear seismic effects’. We reaffirm that experimental results discussed by us in earlier work and by Solovev can be explained only by the assumption of nonlinear effects during wave propagation.

### 1. Introduction

Several papers that have appeared in recent years have demonstrated the significance of non-linear phenomena in vibrator-induced monochromatic wave propagation in the upper part of a geological medium. The most impressive phenomenon is the generation of harmonics with frequencies that are multiples of the fundamental one (higher harmonics).

In a paper by Solovev (1990), attribution of the higher harmonics in the far field to nonlinear phenomena was called into question. We analyze Solovev’s arguments, to understand whether they really disprove the nonlinearity assumption.

### 2. Discussion of data

The method we used to demonstrate the validity of nonlinear phenomena in seismic wave propagation was the analysis of the spatial evolution of ratios of higher harmonics’ amplitudes to the

fundamental one. According to the linear concept they should gradually decrease because of the stronger attenuation of higher harmonics with respect to the fundamental.

In fig. 3 of an earlier paper (Beresnev and Nikolaev, 1988), we showed these ratios for the second and third harmonics. The measured ratios were averaged over 24 recording channels in the geophone array. The averaging precluded any accidental nature of the results. We observed a systematic increase of the ratios with distance, showing a maximum value at about 1500 m from the vibrator, where the contribution of nonlinear effects, in our interpretation, was the highest. The fundamental frequency in this case was 19 Hz. Exactly the same result was described by Solovev (1990) after averaging the individual channels at the bottom of table 1 of that paper, for a signal with a frequency of 20 Hz.

Hence, the averaged results reaffirmed our basic conclusion. However, Solovev wrote that “no...systematic behavior can be observed for any...channel” (pp. 272–273). We insist that it is

meaningless to refer to the readings of individual channels in the array because of the influence of such random factors as local inhomogeneities near geophones, bad quality of the geophone installation or its coupling with the ground. Only the behavior of the average characteristics makes sense.

Solovev had no reasonable explanation for the growth of the relative level of higher harmonics with distance. Our claim is that such an explanation cannot be made within a linear framework. If the relative value of harmonics near the source is rather low, and it becomes much higher at distances of 1.5–2 km despite the influence of dissipation, it cannot be explained only by a source effect, as Solovev claimed. An explanation by a constructive interference effect should also be rejected because of the reiteration of the same results with modulated signals (Beresnev and Nikolaev, 1988) and in different experiments (Beresnev and Nikolaev, 1990). It should be noted that similar behavior of higher harmonics has been independently reported (Dimitriu, 1990).

On the other hand, this result is easily explained by the assumption of nonlinear propagation, resulting in gradual distortion of the waveform as shown in fig. 1 of the study by Beresnev and Nikolaev (1988), which means, in spectral terms, the appearance and growth of higher harmonics.

Further, Solovev showed the phase and spectral amplitude distributions along a surface profile (Solovev, 1990, fig. 1) for three different modes of vibrator operation. The idea was to demonstrate that these distributions meet the expectations of linear theory.

The correct discussion of such graphs, to our mind, should be the following. One shows the behavior of the curves when the linear law holds (a constant vertical shift between curves in this case) and the estimation of what they should look like in the presence of nonlinearity. Then the experimental curve should be compared with theoretical predictions. It is probable that for realistic values of nonlinear parameters the difference between linear and nonlinear behavior of graphs will be negligible on this scale. Solovev wrote that “a prediction of the type of deviation is not the

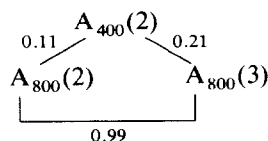
concern here” (p. 273). But it seems that it is absolutely essential, as without such prediction and comparison his statement has no standing. The same remark concerns fig. 3 in his paper.

We see in the lower graph in fig. 1 of Solovev’s paper, showing the amplitude–distance curve, that spectral amplitudes are presented in absolute units ( $\text{m s}^{-1}\text{Hz}^{-1}$ ). Because we took part in the experiment, we can assert that the recording station and geophones were not calibrated. It is surprising that absolute units of spectral amplitudes could be calculated.

Solovev, discussing the data in table 2, asserted that high values of correlation coefficients between curves representing the variation of the spectral amplitude with geophone position, when the vibrator operates at three different modes, stand for negligible influence of nonlinearity. Obtaining the value of 0.99, he stated that the “spectral amplitude is...generated by the source and not during propagation” (p. 274).

The same objection can be made here as above. For conviction, we should know the estimates of the values of correlation coefficients in the nonlinear case. What order of magnitude should we expect: 0.01 or 0.90? Without such estimates it is impossible to say anything about the role of linearity or nonlinearity using some given value of the correlation.

In our opinion, Solovev’s table 2 also contains arithmetic errors which can be revealed by a simple inspection of the numbers listed in it. For instance, let us compare the correlation coefficients between three curves  $A_{400}(2)$ ,  $A_{800}(2)$  and  $A_{800}(3)$ :



Is it possible that two almost identical curves (the correlation coefficient is 0.99) are each so different from the third (coefficients 0.11 and 0.21)?

Let us discuss the conclusions of Solovev concerning fig. 2 of his paper and our evidence of the dependence of nonlinear effects on the source power. Solovev showed, in addition to those of

TABLE 1

Ratios of the spectral amplitudes of the second ( $A_2$ ) and third ( $A_3$ ) harmonics to the fundamental ( $A_1$ ) with maximum and minimum vibrator forces and different source–geophone positions

	Maximum	Minimum
10 m	$A_2/A_1 = -38$ dB $A_3/A_1 = -42$ dB	– $A_3/A_1 = -50$ dB
550 m	$A_2/A_1 = -20$ dB $A_3/A_1 = -10$ dB	– $A_3/A_1 = -32$ dB
700 m	$A_2/A_1 = -30$ dB $A_3/A_1 = -8$ dB	– $A_3/A_1 = -20$ dB

Beresnev and Nikolaev (1988), two spectra recorded near the vibrator plate (1 m away), demonstrating, in his opinion, that strong harmonics are excited at the peak force level by the vibrator itself, and are not the result of propagation non-linearity. Two problems arise which cast doubt on such a claim.

(1) The self-nonlinearity of the geophone, which can be high near the vibrating plate, was not estimated. This can create the same effects as Solovev attributed to vibrator–ground coupling. ‘Forgetting’ his trust in the recordings of the near-plate geophone shown on p. 274, Solovev on p. 275 wrote about their unreliability: “deviations at distances smaller than 100 m might be attributed to recording problems very close to the vibrator”.

(2) If we examine again the ratios of the higher harmonics to the fundamental, we shall see that they increase in this experiment too. Let us refer to Table 1, first published by Beresnev (1986), where the ratios for the second and third harmonics are tabulated for different source–geophone distances and for maximum and minimum vibrator force levels. The second harmonic was not observed at the minimum force level. Let us compare the data on the third harmonic. Its ratio to the fundamental increases with distance at the maximum force level by 34 dB, i.e. approximately 50 times. This increase is slower at the minimum force level. The ratio of the second harmonic to the fundamental does not increase so clearly but does not drop either. Such a behavior is also clearly shown in fig. 2 of Solovev (1990). It is surprising that the author did not observe it.

### 3. Conclusions

We have made an attempt to analyze the objections put forward by Solovev (1990) as regards experimental evidence for nonlinear seismic wave propagation.

The following can be concluded.

(1) The experimental data demonstrated by Solovev showed again that the ratios of higher harmonics to the fundamental substantially increase with distance. No reasonable explanation for this fact was given. The only explanation consists in the assumption of contributions due to nonlinear effects.

(2) The similarity of amplitude–distance curves taken for various vibrator operations cannot be considered as evidence of linearity until the type and value of deviation for reasonable nonlinear properties is estimated.

(3) Independent seismic experiments have confirmed our point of view. Similar nonlinear effects have also been observed in acoustic experiments in rock samples (Johnson and Shankland, 1989).

### Acknowledgment

The author is grateful to A.V. Nikolaev for helpful discussions.

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