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PS Seismic Array Response in the Presence of Intra-Array Variations in Element Weights, Elevations, and Positions*

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Abstract

Seismic arrays are systematic arrangements of seismic receivers, sources, or both. The purpose of using seismic receiver arrays is to enhance the signal-to-noise ratio (S/N) by attenuating the undesired horizontally traveling surface waves such as ground roll. The combined effects with variations of element's weights, positions, and elevations on the seismic receiver arrays response were addressed in this study. These variations are common, especially in areas with rugged topography. The objective of this research is to quantify the degradation in the wavelet response of a seismic array caused by the combination of these errors on a 12-element equally-weighted geophone array with various elements' spacing and wavelet incidence angle.

The effects of errors were modeled using zero-mean Gaussian random errors in element's weights, positions, and elevations with 10% and 20% standard deviations. The average from 32 times calculation for each standard deviations was used to obtain statistically significant results.

The ideal array response and perturbed array response were compared through the calculation of their trace energies. As expected, the combination of errors degraded the array response more as compared to individual errors. However, it did not denote that the degradation of combined errors was the total of each single error. Taking the 45° incidence angle as an example, the minimum array response in the ideal case has a trace energy of -43 dB which occurs at a temporal element spacing of 0.054 s. The addition of 10% combined errors degrades the minimum array response by about 17%; while 20% combined errors degrade it by 30%. Therefore, the results of this research indicate that the effects of combined errors are significant and care must be taken in planting arrays as close to the ideal case as possible when acquire seismic data.

Introduction

Seismic arrays are group of seismic receivers, sources, or both planted in systematic arrangement. This research only concentrated on seismic receiver arrays. Seismic receiver array response is the sum of the outputs of the receivers in an array. In terms of reflection seismology, the main purpose of seismic receiver (element) array is to increase the signal-to-noise ratio (S/N) by enhancing the desired signals (reflections) and

attenuating seismic noise during the acquisition of seismic data in the field without any distortion (Al-Shuhail, 2011). There are several aspects influence the response of receiver arrays, including element's position, elevation, similarity between geophones, and ground coupling. The outcome responses attained from the non-ideal field were different as compared to the ideal state (Aldridge, 1989). Aside from those aspects, the variations in weathering layer thickness is capable to degrade the amplitude response of the receiver array (Akram and Al-Shuhail, 2016).

There were publications investigated the response of seismic arrays caused by several variations using impulse signal as incident wave. Gangi and Benson (1989) explained the wavelet response due to errors in weights and position of the elements of the geophone arrays with respect to several variables. These variables include type and nominal error added, number of the elements used, and weighting function. They revealed that the degradation of the wavelet response is a function of a number of elements in the array and weighting function (Gangi, 1989). A similar case was investigated by Al-Shuhail and Gangi (1994), wherein they evaluated the alteration in the array response caused by elevation variations within the receiver arrays. The result of their research demonstrated that the errors due to variable element elevations were higher compared to errors due to disordered horizontal element positions (Al-Shuhail, 1994).

In this study, by combining the previous studies, the response of seismic receiver array caused by the variations of element's position, elevation, and weight were investigated. The combined effects of variable element positions and elevations on the receiver seismic arrays response have not been previously addressed. However, this issue is common in real condition. Hence, this study aims to quantify the degradation in the wavelet response of a seismic array caused by the combination of elements' position and elevation errors. In addition, weight variations were added into this study to make it as close as possible to the real condition. The results of this study may benefit seismic contractor or oil company who are planning to do seismic acquisition.

Methodology

The purpose of this research is to evaluate the effects of the combination of errors in elevation, position, and weight of the elements within the array on the array response. To achieve this objective, the following methodology has been used:

a) Generating the ideal impulse and wavelet responses.
b) Calculating the trace energy for the ideal wavelet response.
c) Generating the errors and applying them to generate the perturbed-array wavelet response.
d) Calculating the trace energy for the perturbed-array wavelet response.
e) Analyzing the percentage of error in the perturbed-array wavelet response.

In this study, Ricker wavelet with 10-Hz of dominant frequency was used as the input to the array, which is the unit impulse. In addition, 12-equally-weighted elements were used in the seismic array. The procedure of wavelet response generation was done for 150 values of Δt or the elements' spacing in time. The elements' spacing in time were calculated by dividing the elements' spacing (Δx) by a constant near-surface velocity ($v=500\ m/s$). The elements' spacing (Δx) varied from 0 to 5,000 *m*. It had a 1-*m* interval between 0 to 100 *m* and 100-*m* interval between 100 *m* to 5,000 *m*. To obtain statistically significant results, the steps (a) and (b) was repeated 32 times and their average response were used in subsequent procedure.

The impulse response of the seismic array can be written as:

$$\boldsymbol{I(t)} = \sum_{n=0}^{N-1} \boldsymbol{W(x_n)\delta(t - x_n n\Delta t)} \tag{1}$$

where $\delta(t)$ indicates the delta (spike) function centered at t=0.

The mathematical representation of the Ricker wavelet is given as:

$$\boldsymbol{R(t)} = \left[\mathbf{1} - \mathbf{2}\left(\boldsymbol{\pi f_p t}\right)^{\mathbf{2}}\right] \boldsymbol{e}^{-\left(\boldsymbol{\pi f_p t}\right)^{\mathbf{2}}} \tag{2}$$

Moreover, the array wavelet response is the convolution between the impulse response and the Ricker wavelet:

$$\boldsymbol{G(t)} = \boldsymbol{I(t)} * \boldsymbol{R(t)} \tag{3}$$

and it can be written as:

$$\boldsymbol{G(t)} = \sum_{n=0}^{N-1} \boldsymbol{W(x_n)R(t - x_n n\Delta t)} \tag{4}$$

where $R(t)$ is the Ricker wavelet, Δt is the time delay between adjacent geophones and N is the number of geophones in the array.

Following the generation of ideal wavelet response, the wavelet responses with error were generated. To produce the array impulse response with errors, N members belonging to a Gaussian distribution with zero mean and σ standard deviation were generated and were applied to the elements' weights, elevations, and positions, where N is the number of elements in the array. The standard deviations (σ) of the elements' weights, positions, and elevations used in this study were 10% and 20%.

Benson (1989) introduced the normalized arrival time of the n^{th} geophone of the array (τ_{en}) [6], which results of the application of an error in element's position (Ex_n) as indicated below:

$$\boldsymbol{\tau_{en} = (n + Ex_n) \sin\theta \, \Delta\tau,} \quad (5)$$

where n = 0, 1, 2…, N-1.

Furthermore, Al-Shuhail (1993) explained the travel-time to the n^{th} geophone including the effect of elevation as:

$$\boldsymbol{\tau_{en}(\theta) = (n \sin\theta + Ez_n \cos\theta)\Delta\tau,} \quad (6)$$

where Ezn represents the error in elevation of the n^{th} geophone of the array obtained from a zero-mean, σ-standard deviation, Gaussian distribution (Al-Shuhail, 1993).

In equations (5) and (6), $\Delta\tau$ is:

$$\boldsymbol{\Delta\tau = {}^{\Delta x}\!/_{(T_p v)},} \quad (7)$$

where Δx = element's spacing, Tp = dominant period, v =velocity.

In the end, the wavelet responses with errors were generated by convolving the impulse response with errors with the Ricker wavelet using equation (2). This results in the following equation:

$$\boldsymbol{G(t) = \sum_{n=1}^{N} \left[(1 + Ew_n)\, R\left[t - \left(\frac{\Delta x}{V}\right)(n \ \sin(\theta) + Ex_n \ \sin(\theta) + Ez_n \ \cos(\theta)) \right] \right]} \quad (8)$$

where Ew_n represents the error in weight of the n^{th} geophone of the array obtained from a zero-mean, σ-standard deviation, Gaussian distribution.

To investigate the effects of combined errors in array responses, trace energy was used to perform quantitative comparison between the ideal and perturbed array responses. Trace energy, which is defined as the sum of the squared amplitudes of the array response, can be shown as:

$$\boldsymbol{E(t) = \sum_{m=1}^{M} G^2(t)} \qquad (9)$$

where ***G(t)*** is the wavelet response of the array and *M* is the number of samples in ***G(t)***. To simplify the comparison, the trace energies were normalized by using the equation below:

$$\boldsymbol{E_n = \frac{E(t)}{E(t=0)}} \qquad (10)$$

where $E(t = 0) = 2{,}154.3$ represents the case when all wavelets were centered at $t = 0$ and add up in phase.
Furthermore, in decibel (dB) scale, the normalized trace energy is:

$$\boldsymbol{E_n{}' = 20\log_{10} E_n} \ \text{(dB)} \qquad (11)$$

Due to variations in incidence angle and element's spacing, the trace energy of ideal array response was plotted in the three-dimensional surface (Figure 1). However, to simplify the comparison between the results of this study, the angle of incidence (θ) has been fixed. The value of θ throughout this study was 45° and it was illustrated in a two-dimensional curve (Figure 2).

Results

The results were obtained using the methods and procedures described previously. The results illustrated by three figures. Figure 4, Figure 5, and Figure 6 show the trace energy from array response affected by combined errors of elements' position, elevation, and weight. Figure 4 and Figure 5 show three-dimensional surfaces, which represent the average of 32 array wavelet responses of an equally weighted 12-element array, with 10% and 20% standard deviation errors in the elements' position, elevation, and weight respectively. The perturbed array response was expected to be the most affected wavelet responses by these combination of errors. The degradation of perturbed array response appeared in small incidence angle caused by the effect of error in element's elevation. The trace energy tends to be similar with the trace energy of ideal array with increasing the incidence angle.

Moreover, the two-dimensional curves (Figure 6) at 45° incidence angle present significant degradation. The degradation of the perturbed array response can be differentiated by looking at a global minimum in the curve. The ideal curve reached minimum trace energy at -45.6 dB at Δt = 0.054 s. The trace energy reachs the global minimum point when the the wavelet response has destructive interference (Figure 3b).

The addition of 10% from each type of error caused 17% degradation of the minimum trace energy. However, if 20% standard deviation errors were added to each type of error, it degraded up to 30% of trace energy from the ideal array. Based on quantitative estimation, the degradation of trace energy will be more acceptable, which is less than 10% degradation, if the error in each type of error is less than 5% from the ideal condition. The chart in Figure 7 summarizes the percentages of trace energy degradation for each model. The observation was focus on global minimum point.

Conclusions

Studying seismic array responses is very useful in understanding the effects of different variations. The responses of seismic array caused by the error in element's position, elevation, and weight have been analyzed. The addition of 20% error in each element's position, elevation, and weight could degrade the response up to 30% from the ideal response. As expected, the combination of errors greatly degraded the array response as compared to individual error. However, it does not necessarily indicate that the degradation of combined errors is the total degradation of each individual error.

Although the study was similar as compared to Benson (1989) and Al-Shuhail (1993), different parameters and method were used to quantify the array responses. These methods simplified the comparison between results. The effects of combined errors are substantial and care must be taken into account in planting arrays as close to the ideal case as possible. Based on quantitative estimation, to reach optimum result in seismic acquisition, error in element position and elevation should not reach 7% from the ideal condition. This case will degrade only up to 10% of the trace energy.

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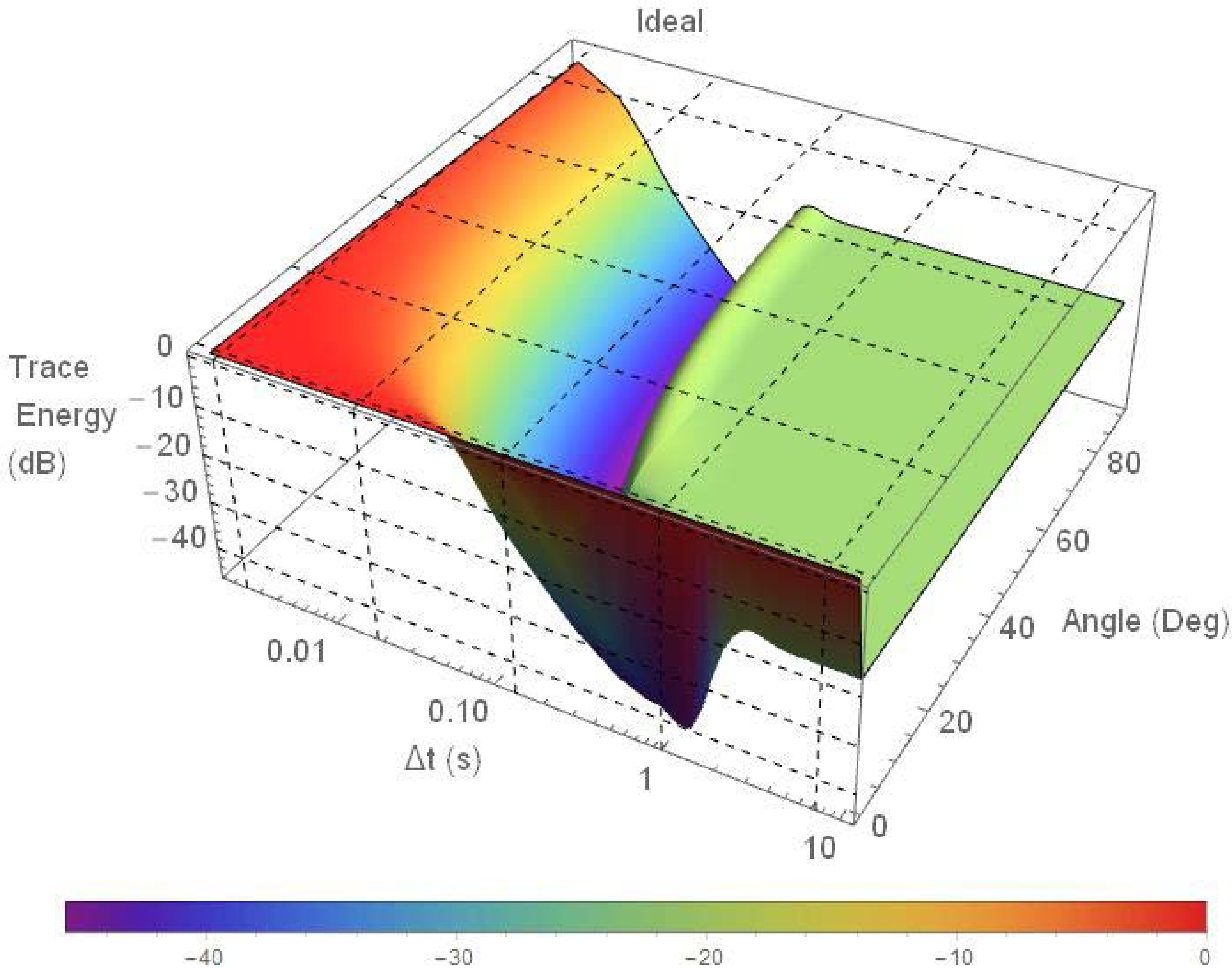

Figure 1. A three-dimensional surface represents the trace energy of an ideal array response with various incidence angles (θ = 0^0 - 90^0).

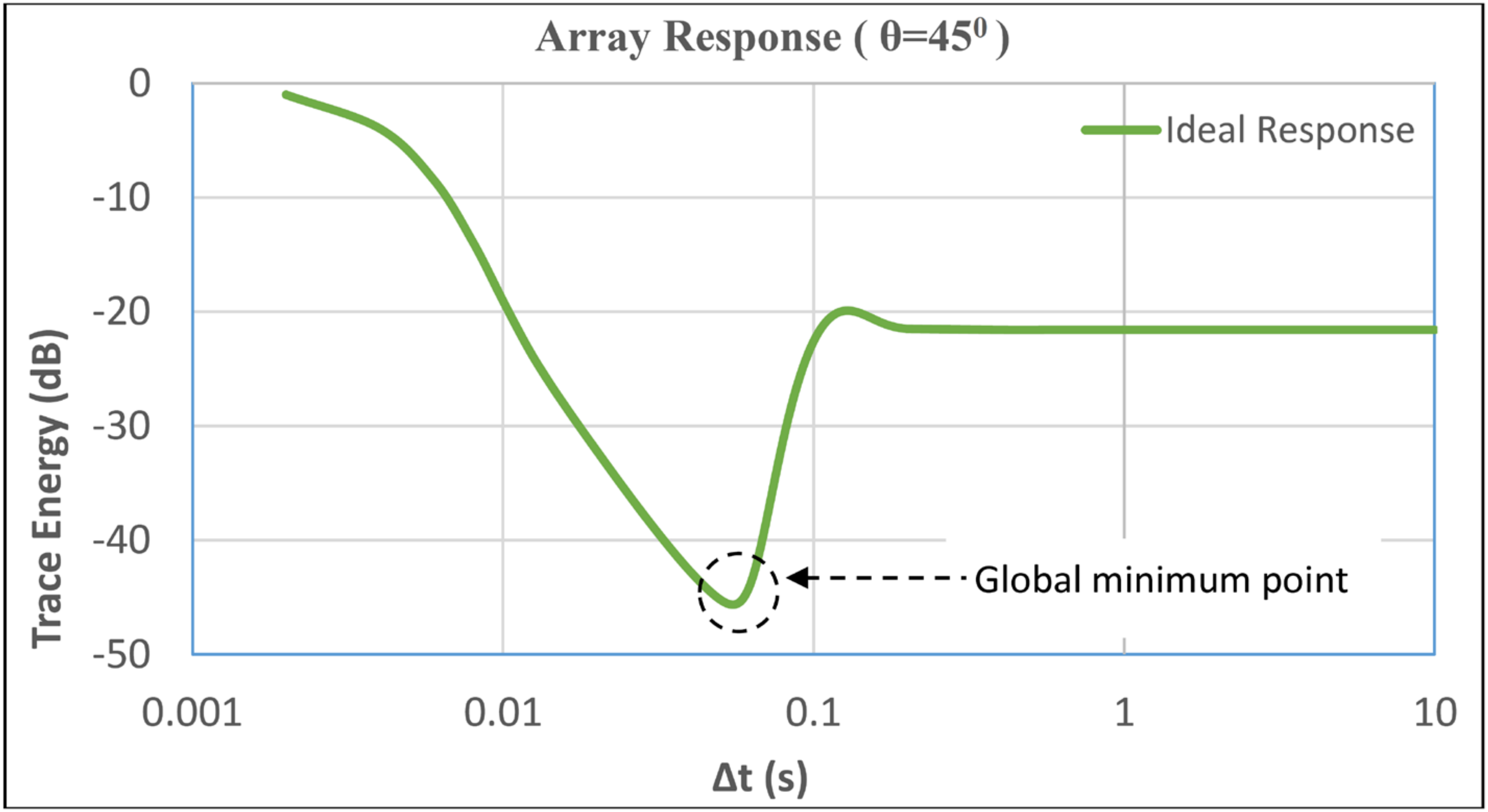

Figure 2. Trace energy of ideal array response with fixed incidence angle (θ=45°).

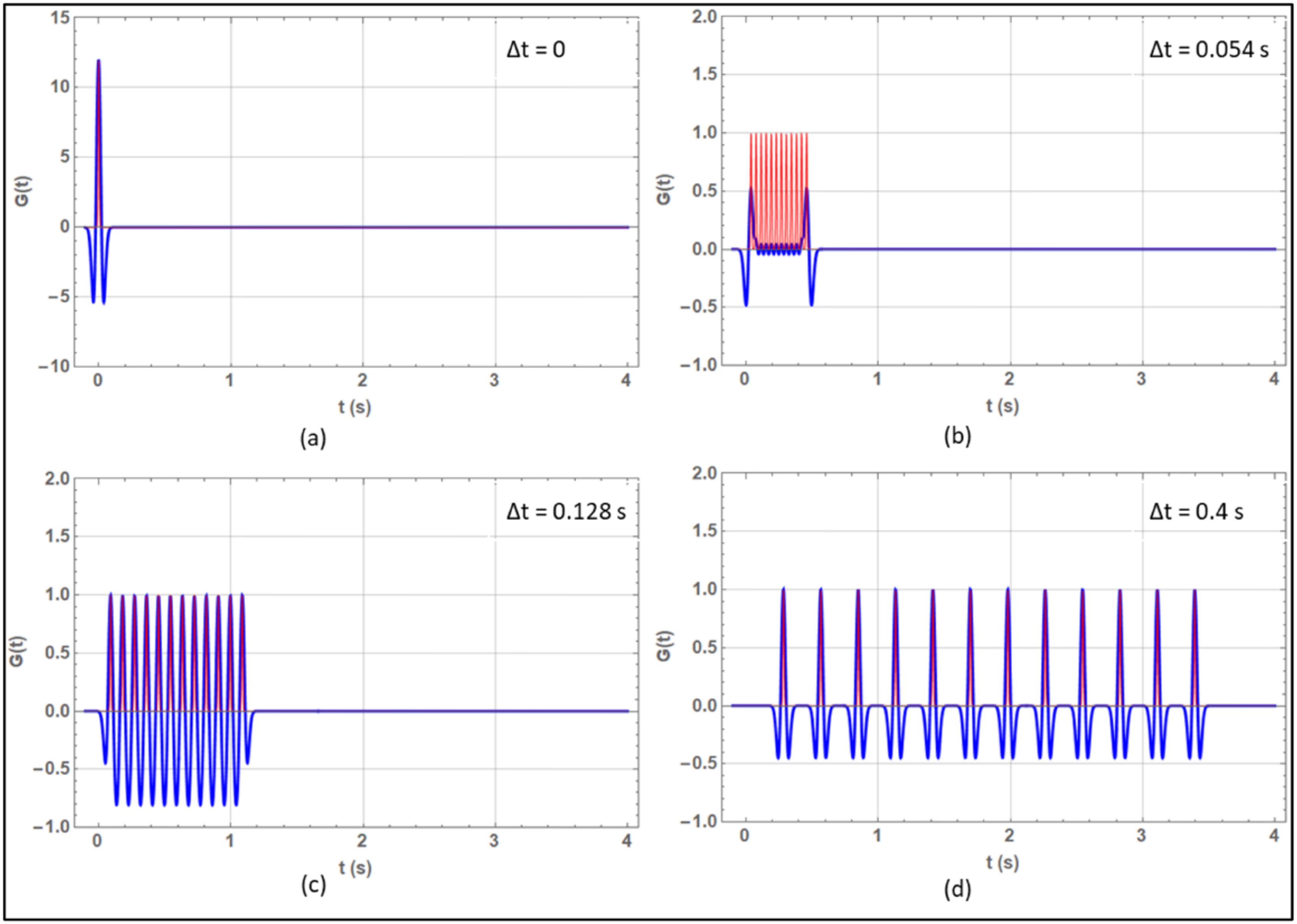

Figure 3. Impulse response I(t) shown by red spikes and Ricker wavelet responses G(t) shown by blue curves, for an equally weighted 12-element array for (a) Global maximum at $\Delta t = 0$, (b) Global minimum at $\Delta t = 0.054$ s, (c) Local maximum at $\Delta t = 0.128$ s, and (d) Constant response at $\Delta t = 0.4$ s.

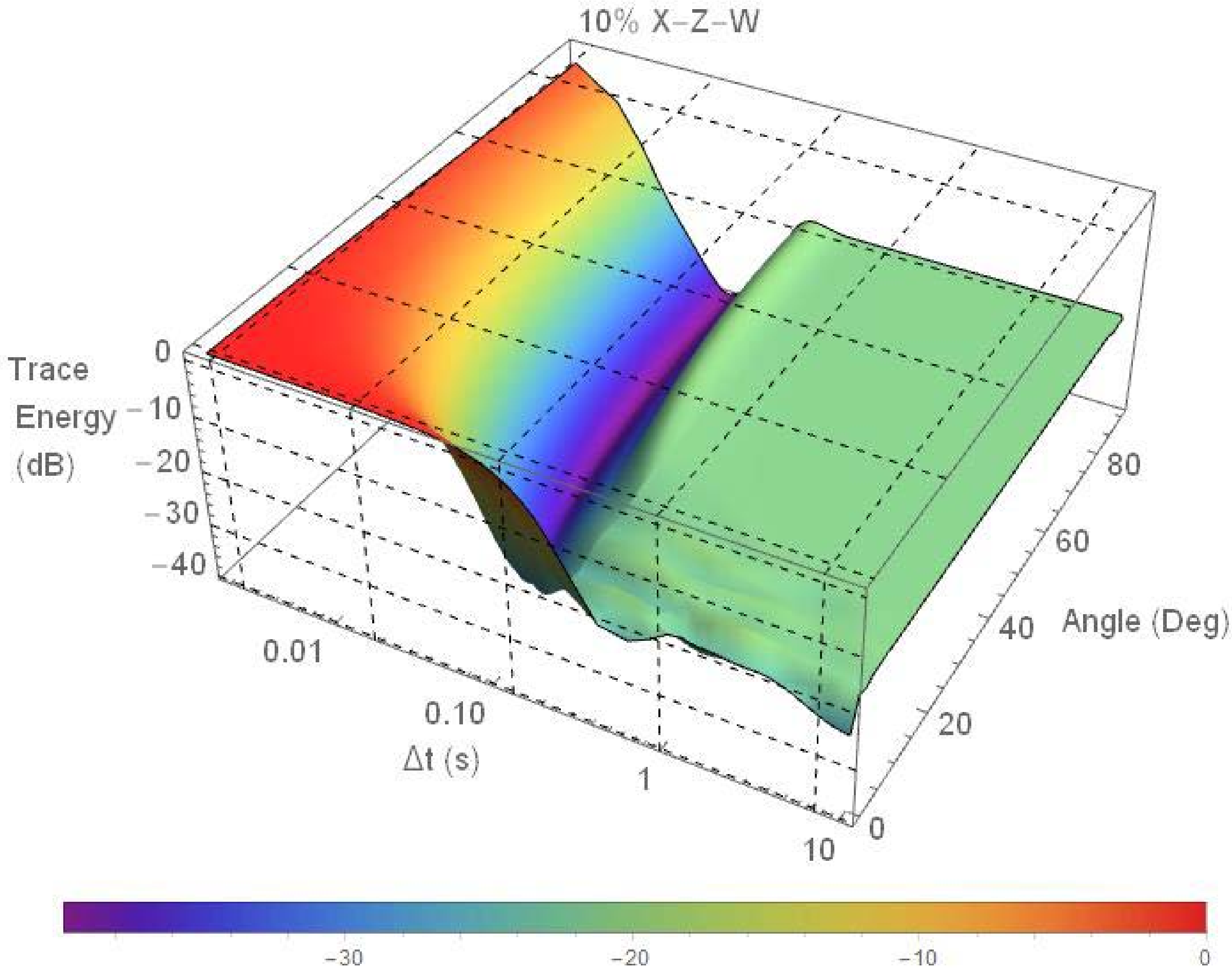

Figure 4. A three-dimensional surface representing the trace energy of perturbed array response affected by 10% standard deviation errors in elements' position, elevation, and weight with various incidence angles ($\theta=0^0$ - 90^0).

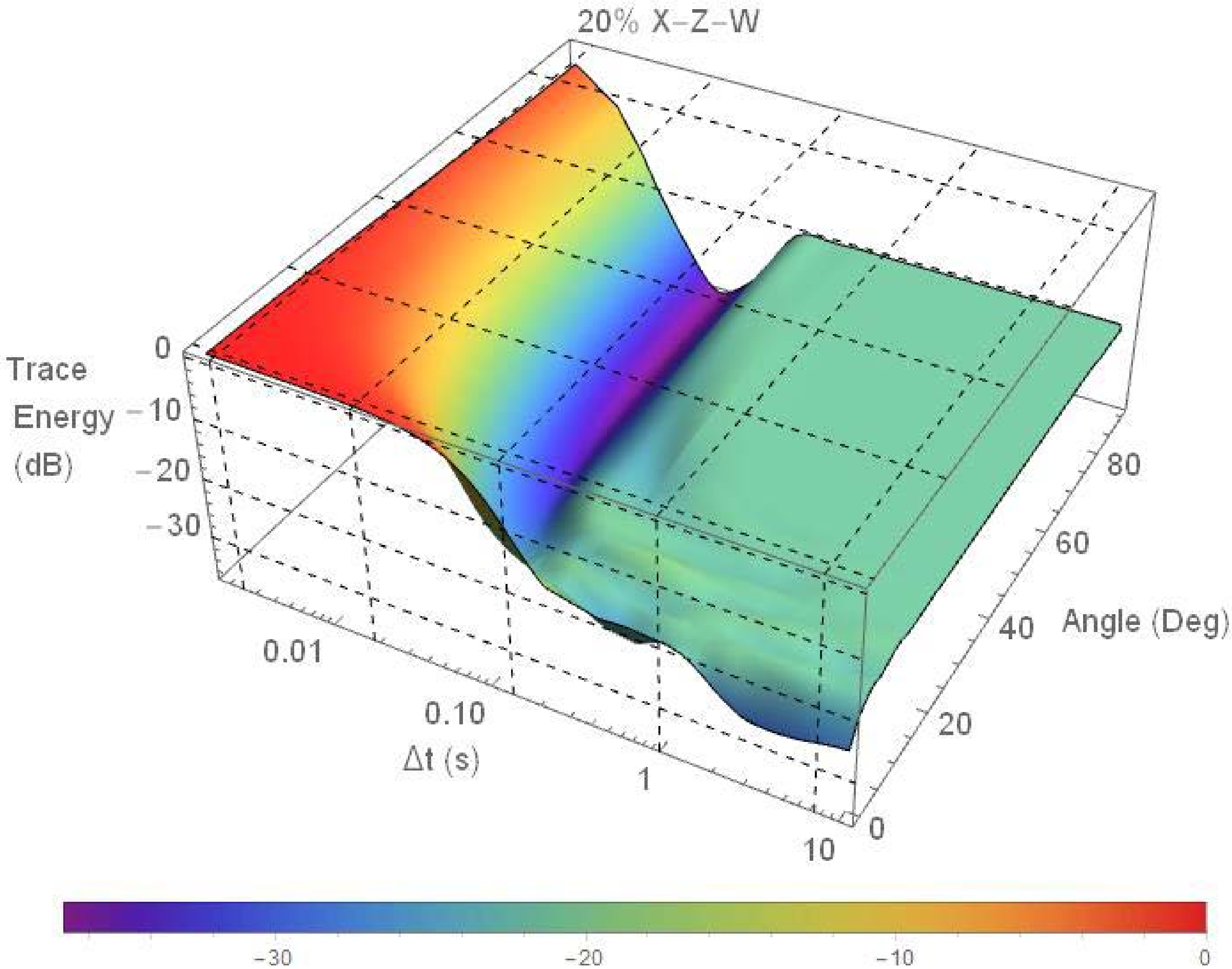

Figure 5. A three-dimensional surface representing the trace energy of perturbed array response affected by 20% standard deviation errors in elements' position, elevation, and weight with various incidence angles ($\theta=0^0$ - 90^0).

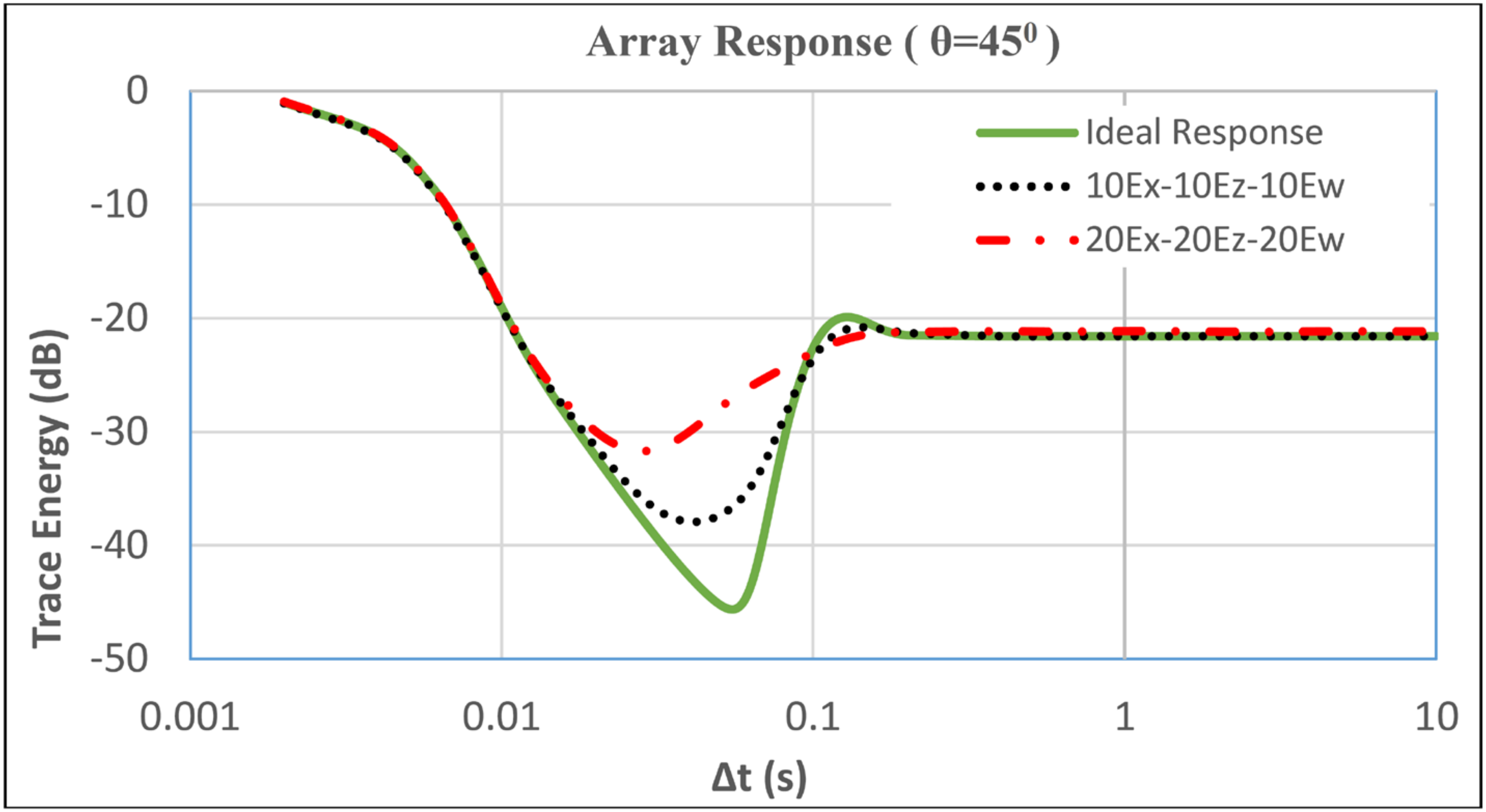

Figure 6. Comparison between ideal array and perturbed array responses with 10% and 20% standard deviation errors in elements' position, elevation, and weight.

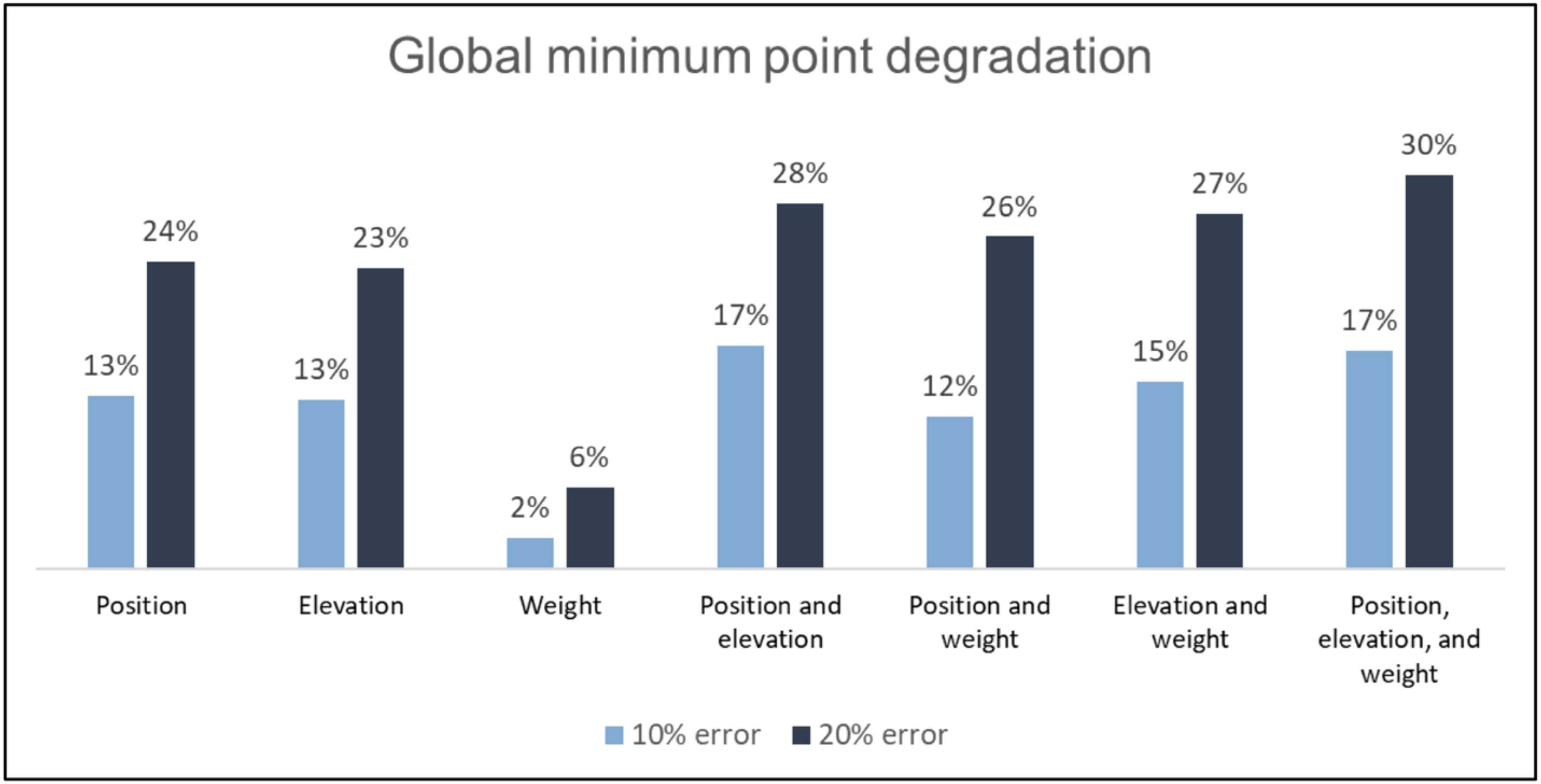

Figure 7. The percentages of trace energy degradation for all the cases throughout the study.