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Prestack data enhancement with phase corrections in time-frequency domain guided by local multidimensional stacking

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ABSTRACT

We present a new approach to enhancing weak prestack reflection signals without sacrificing higher frequencies. As a first step, we employ known multidimensional local stacking to obtain an approximate 'model of the signal'. Guided by phase spectra from this model, we can detect very weak signals and make them visible and coherent by 'repairing' corrupted phase of original data. Both presented approaches – phase substitution and phase sign corrections – show good performance on complex synthetic and field data suffering from severe near-surface scattering where conventional processing methods are rendered ineffective. The methods are mathematically formulated as a special case of time-frequency masking (common in speech processing) combined with the signal model from local stacking. This powerful combination opens the avenue for a completely new family of approaches for multi-channel seismic processing that can address seismic processing of land data with nodes and single sensors in the desert environment.

Key words: Data processing, Noise, Signal processing.

INTRODUCTION

Modern land seismic data acquired with single sensors or small field arrays require significant noise attenuation and prestack enhancement during processing. The classical problem is to separate signal and noise based on certain properties. When the signal becomes completely invisible, this challenge appears insurmountable: suppress the noise, identify weak signal and enhance it. One powerful family of methods based on local multidimensional stacking is quite successful in identifying and enhancing weak signals on prestack seismic data (Zhang *et al.*, 2001; Baykulov and Gajewski, 2009; Hoecht *et al.*, 2009; Berkovitch *et al.*, 2011; Buzlukov and Landa 2013; Garabito *et al.*, 2016; Bakulin *et al.*, 2017). To get reliable signals in case of very noisy data, these methods require stacking with relatively large local apertures reaching hundreds of metres. Several hundreds or thousands of traces may be required to produce an output trace with an increased signal-to-noise ratio (SNR) acceptable for processing. Loss of higher frequencies caused by variable waveforms due to near surface, coupling issues and statics was considered as an unavoidable side effect. If data would contain enough signal in the first place, existing methods like surface-consistent waveform and static corrections etc. may reduce these effects to a certain extent. However, with modern single-sensor seismic in a desert environment, data quality is often so low that we are no longer offered such luxury (Bakulin *et al.*, 2017). Is there a way out?

PHASE SUBSTITUTION AND FREQUENCY-DEPENDENT PHASE CORRECTIONS

While multidimensional stacking approaches do not offer a complete solution, they give us a stepping-stone towards identifying temporal and spatial positions of the signals that are otherwise invisible. To overcome the limitation of losing

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higher frequencies, we need to revisit phase and amplitude information delivered by multidimensional stacking independently. Oppenheim and Lim (1981) showed simple but striking examples that, in the presence of accurate phase information, 2D photo images preserve full structural content even with almost arbitrary amplitude spectra. This was not true in reverse!

As such, we focus on using phase spectra of the enhanced trace as a model or guide allowing us to 'declutter' the data and reveal invisible signals hidden behind. We discover that in the presence of this robust phase estimate – we can solve the insurmountable problem above. Phase spectra from data enhanced with multidimensional stacking can be used in several different ways, for example, as a direct approximation of desired phase (phase substitution) or as a 'guide' to conduct frequency-dependent phase corrections. As for the amplitude spectrum, in a most straightforward approach, it can be left entirely untouched, thus fully preserving local amplitudes. In a more advanced approach – it could be further surgically denoised using the amplitude model of a signal derived from the local stacking results. The importance of phase was previously recognized in seismic processing and inversion (Lichman, 1999; Ulrych *et al.*, 2007), whereas here we discover that phase alone from local stacking could act as a cornerstone for novel enhancement approaches.

MATHEMATICAL FORMULATION USING TIME-FREQUENCY MASKING

To describe mathematical details of the new approach, the framework of time-frequency masking (TFM) from speech processing is particularly fruitful (Yilmaz and Rickard, 2004). Since both speech and seismic signals $u(t)$ are non-stationary, TFM is formulated in time-frequency domain using short-time Fourier transform (STFT; Blackledget, 2006):

$$U(\tau,\omega) = \mathcal{F}\langle u(t)\rangle = \int_{-\infty}^{\infty} u(t)\, w(t-\tau)\, \mathrm{e}^{-\mathrm{i}\omega t}\mathrm{d}t,$$

where $w(t-\tau)$ is the window function centred at time τ, and ω is an angular frequency. STFT is a sequence of Fourier transforms of a windowed signal. STFT provides the time-localized frequency information for non-stationary situations in which frequency components of a signal vary over time. Utilizing STFT allows more flexibility to correct for time-dependent distortions caused by near-surface scattering in comparison to the global Fourier transform.

While in speech processing, there are usually 'observed data' and 'signal', in our approach, we propose using 'original' and 'enhanced' data sets. Original data have already passed through standard processing workflow (noise removal, static correction, deconvolution etc.) and may be considered as 'best we can get'. Enhanced data set from local stacking represents our best estimate of the signal with much higher SNR but reduced high-frequency content caused by suboptimal stacking. For simplicity, we assume that the enhanced data set retains identical structure and number of traces.

Consider a trace $x(t)$ from the original data set and corresponding trace $s(t)$ from the enhanced data set. We aim to extract desired signals contained in $x(t)$ using corresponding enhanced trace $s(t)$ as a guide.

Applying STFT to $x(t)$ and $s(t)$, we obtain complex-valued time-frequency (TF) spectra:

$$X(\tau,\omega) = \mathcal{F}\langle x(t)\rangle \ \ \big(\text{original trace TF spectrum}\big), \tag{1}$$

$$S(\tau,\omega) = \mathcal{F}\langle s(t)\rangle \ \ \big(\text{enhanced trace TF spectrum}\big).$$

TF spectra of the traces are represented as

$$X(\tau,\omega) = |X(\tau,\omega)| \exp\big(\mathrm{i}\varphi_X(\tau,\omega)\big), \tag{2}$$

$$S(\tau,\omega) = \big|S(\tau,\omega)\big| \exp\left(\mathrm{i}\varphi_S(\tau,\omega)\right),$$

where $|\cdot|$ denotes amplitude TF spectra, whereas φ_X and φ_S are phase TF spectra of original and enhanced traces, respectively. In the first method, we assume that the phase of the enhanced data represents the best estimate of the signal phase, and it is the only ingredient we carry forward to produce an estimate of the desired signal.

Phase substitution

TF amplitude spectrum of the original trace is recombined with the TF phase spectrum of a corresponding enhanced trace (obtained from local stacking).

Using notation of expressions (2), TF spectrum of the desired signal trace is given as

$$\hat{S}(\tau,\omega) = |X(\tau,\omega)| \exp\left(\mathrm{i}\varphi_S(\tau,\omega)\right). \tag{3}$$

Corrected time-domain signal estimation is obtained by inverse STFT,

$$\hat{s}(t) = \mathcal{F}^{-1}\Big\langle \hat{S}(\tau,\omega)\Big\rangle. \tag{4}$$

The amplitude spectrum of the input signal is fully preserved in this approach, so there is no suffering from high-frequency loss.

It is convenient to rephrase these transformations using the notion of TFM widely used for single-channel enhancement of noisy speech signals (Yilmaz and Rickard, 2004; Wang, 2008). The noisy registered signal in TF domain $X(\tau,\omega)$ is supposed to be a superposition of desired signal and noise: $X(\tau,\omega)=\hat{S}(\tau,\omega)+N(\tau,\omega)$. TFM is designed as a real-valued filter that is close to 1 in a 'signal dominance' region of the TF spectrum and close to 0 in a 'noise dominance' area. Desired signal's TF spectrum $\hat{S}(\tau,\omega)$ is obtained from registered signal spectrum as follows:

$$\hat{S}\left(\tau,\omega\right)=M\left(\tau,\omega\right)X\left(\tau,\omega\right), \tag{5}$$

where TF mask $M(\tau,\omega)$ is typically a real-valued function $0\leq M(\tau,\omega)\leq 1$ (Wang, 2008; Liang *et al.*, 2013). *A priori* estimation of noise power spectra is required for TFM computation. In contrast to seismic data, the evaluation of noise properties in noisy speech signals is attainable with much fewer efforts. However, by adding an enhanced data set from local stacking, we counteract this problem. Phase substitution method can be recast as complex-valued phase-only TFM with

$$M\left(\tau,\omega\right)=\exp\left[\mathrm{i}\left\{\varphi_S\left(\tau,\omega\right)-\varphi_X\left(\tau,\omega\right)\right\}\right], \tag{6}$$

as can be easily observed by substituting (6) into (5) (Williamson and Wang, 2017).

An argument can be made that phase substitution is a rather rudimentary approach. Fortunately, the TFM framework enables a plethora of more sophisticated alternative implementations. One new approach we find useful for multichannel seismic data can be referred under the general name as 'frequency-dependent phase corrections'.

Frequency-dependent phase sign corrections

TF spectrum of the original trace is corrected using phase sign-correction mask (8):

$$\hat{S}\left(\tau,\omega\right)=X\left(\tau,\omega\right)\mathrm{PSM}\left(\tau,\omega\right), \tag{7}$$

where $\mathrm{PSM}(k,l)$ is given as

$$\mathrm{PSM}\left(\tau,\omega\right)=\mathrm{sign}\left[\cos\left\{\varphi_S\left(\tau,\omega\right)-\varphi_X\left(\tau,\omega\right)\right\}\right]. \tag{8}$$

Instead of substitution as in (6), we correct local phase variations in original traces using enhanced phase as a guide. Since near-surface scattering and coupling variations can severely distort phase of neighbouring seismic channels, making them look incomprehensible, just correcting sign of the phase frequency by frequency and frame by frame using 'phase sign-correction mask' (8) can be very advantageous. If original and enhanced data are in phase (phase difference is less than $\pm\pi/2$) at a specific frequency – then no correction is made ($\mathrm{PSM}=1$). If they are out of phase (difference more than $\pm\pi/2$), then phase at this frequency is flipped by $\pm\pi$ ($\mathrm{PSM}=-1$). We assume that the phase difference is wrapped within the interval $[-\pi,\pi]$. Unlike conventional phase-sensitive masks from speech processing of the form $\cos\{\varphi_S-\varphi_X\}$ (Erdogan *et al.*, 2015), the proposed phase sign-correction mask is amplitude-preserving since no values of amplitude spectra are modified. We expect and verify numerically with synthetic data that PSM may achieve better preservation of individual signal features compared with simple phase substitution.

Presented approaches represent only initial examples of what could be done using a powerful combination of TFM and reference guide data sets from local stacking. More sophisticated phase-only masks can be envisioned. Noise presented in the amplitude spectra can be surgically attacked based on amplitude-only masks dominant in speech processing (Wang, 2008; Liang *et al.*, 2013).

Let us illustrate the performance of our new approaches on synthetic and real seismic data.

SYNTHETIC EXAMPLE: SIMULATED LAND SEISMIC WITH THE STRONG NEAR-SURFACE SCATTERING

Using finite-difference acoustic modelling, we simulate a 2D land data set with complex near surface represented by clutter (Borcea *et al.*, 2006) and featuring heterogeneities comparable or smaller than a dominant wavelength (Fig. 1a). Despite the simple subsurface model with four flat reflectors, observe that near-surface scattering has created a continuous blanket of underlying "noise" in common-shot gather (Fig. 2a). Reflectors are either broken-up or invisible or indiscernible similar to what is often seen in real data. Nonlinear beamforming (Bakulin *et al.*, 2017) reveals all four underlying reflectors (Fig. 2b). Stacking apertures of 100 m radius both in common-midpoint gather (CMP) and offset directions suggest that each output trace is a result of the local summation of around 200 neighbouring traces. After enhancement, reflectors exhibit better detectability, coherence and continuity, but finer details at higher frequencies are smeared by local stacking. With phase substitution and phase corrections (Fig. 2c,d), we achieve similar benefits in detectability while minimizing overly smoothed character introduced by the stacking procedure. While all three methods shown in Fig. 2(b–d) generate undisputable

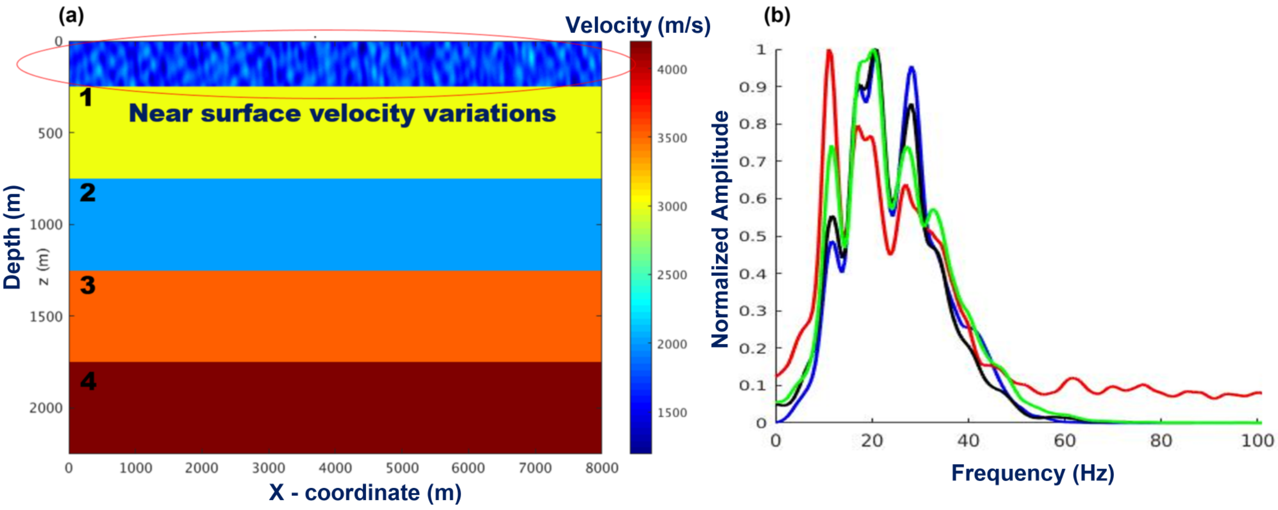

Figure 1 (a) Land synthetic model with near-surface layer modelled as a random clutter with small- and medium-scale heterogeneities. (b) Comparison of normalized amplitude spectra of traces from Fig. 2 (1000 m offset) showing original data (blue), data after enhancement (red), data after phase substitution (green), and phase sign corrections (black). The model is available in the article supplementary material (Fig._1_SuppInfo_vp.segy, Aigure_1_SuppInfo_rho.segy).

improvements, we observe progressively gentler touch going from local stacking to phase substitution to phase corrections with the finest level of details seen on phase-corrected gather. In hindsight, zooming in original gather, we can find evidence of all four reflectors present as a collection of small pieces that are distorted and shifted around. While their detection may have been easy in the absence of any background events, it becomes almost impossible in the presence of a thick blanket of scattered 'noise' from near surface. When one piece of an event is juxtaposed next to another piece with opposite polarity, and this jiggle continues, event tracking is severely hampered by a lack of continuity and further exacerbated by

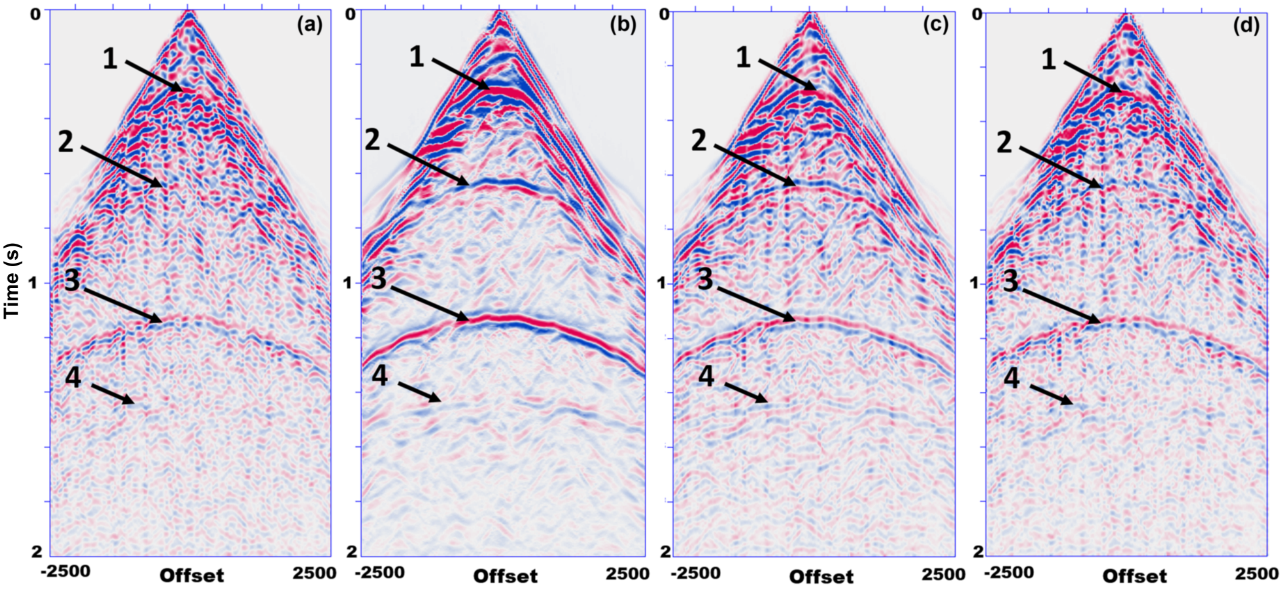

Figure 2 Synthetic common-shot gathers after applying different methods: (a) original data as generated using the model from Fig. 1a, (b) gather after initial enhancement with nonlinear beamforming, (c) final enhanced gather using phase substitution and (d) phase sign corrections. Observe more high-frequency spatial and temporal details on (c) and especially (d) compared with (b). Arrows mark primary reflectors. Modelled data (a) are available in article supplementary material (Fig._2_SuppInfo_data_clutter_var200_corr30.sgy).

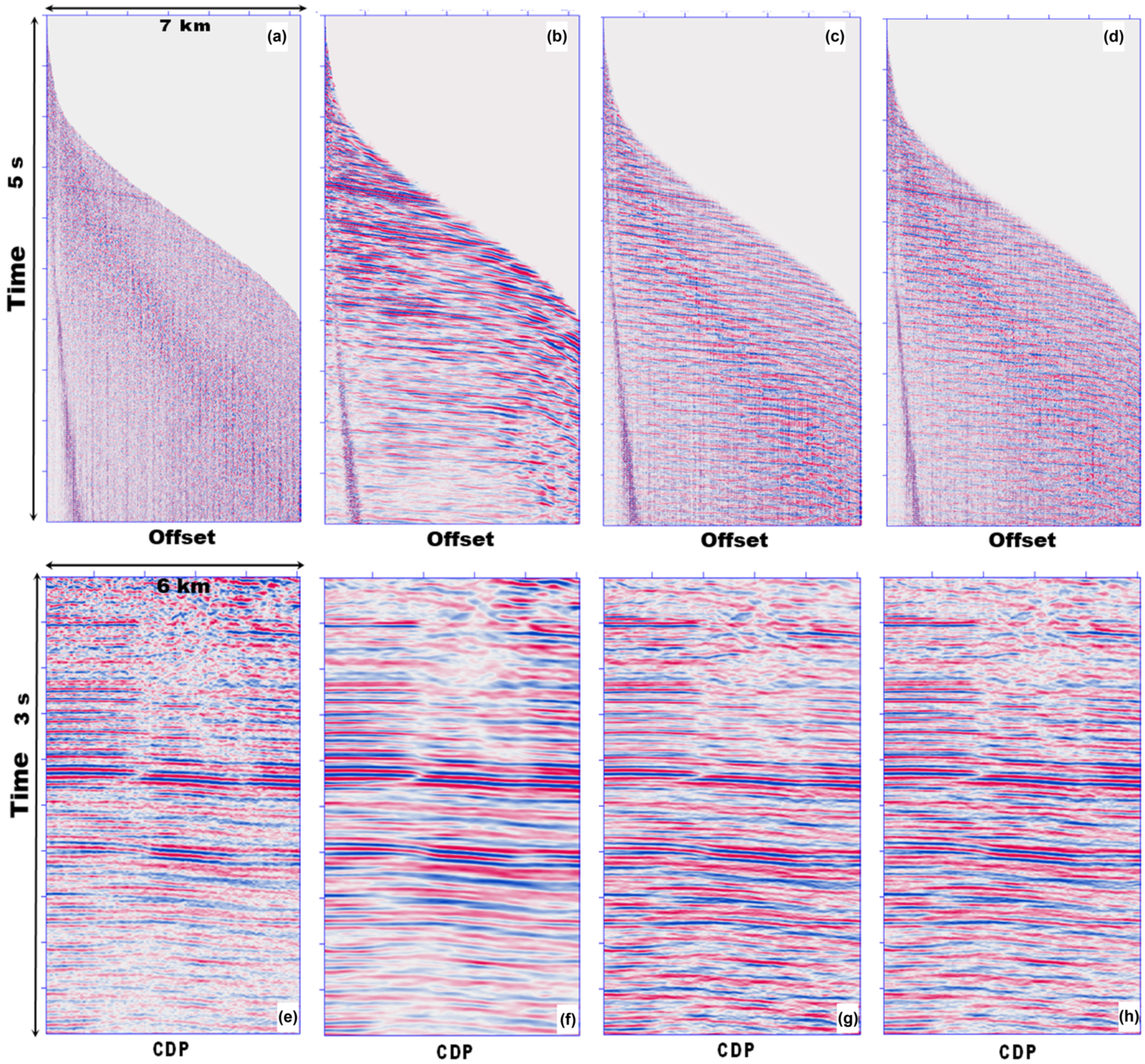

Figure 3 Real data example showing prestack CMP gathers (top row) and stack sections (bottom) obtained with different approaches: (a) original data after conventional processing, (b) data after local stacking with nonlinear beamforming, (c) data after phase substitution and (d) data after phase sign corrections. While nonlinear beamforming (b) dramatically improves coherence and continuity, observe a loss of higher frequencies and oversmoothed character. In contrast, phase methods (c) and (d) deliver significant improvement with much less oversmoothing, preserving higher frequencies and maintaining the original character of the gather and image.

phase distortions changing reflector waveforms from trace to trace. This is precisely where phase sign correction helps us fix reflectors 1, 2 and 3 and restore their coherence and continuity, but only acting where it must, whereas leaving data untouched in good places guided by enhanced phase from local stacking. At the same time, the phase correction method seems unable to fix weaker reflector 4, which is better reconstructed with phase substitution. Amplitude spectra in Fig. 1b further confirm this observation by showing pronounced attenuation of higher frequencies on local stacking (red curve), less so on phase substitution (green), and almost no attenuation on phase-sign-corrected data (black). RMS

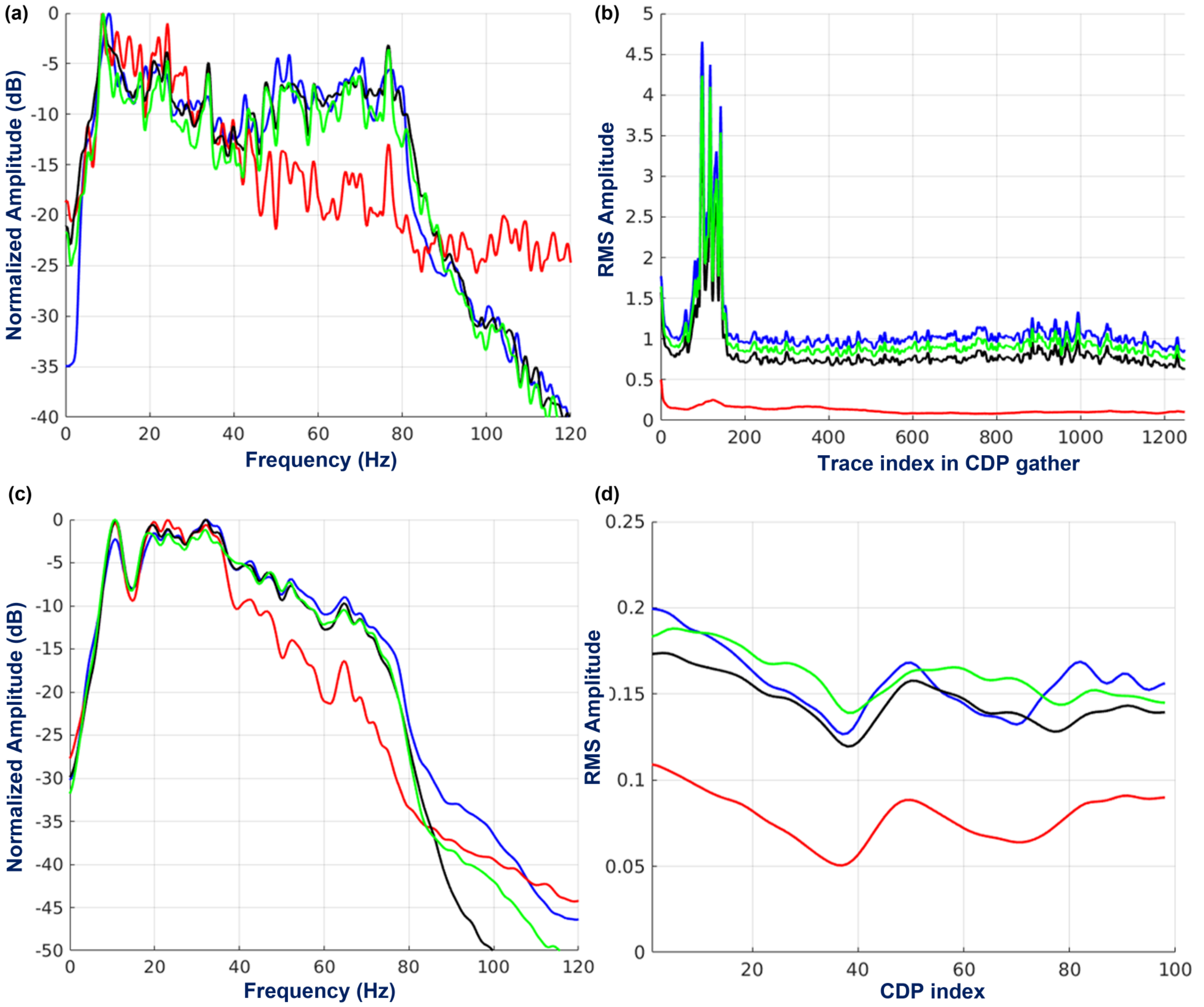

Figure 4 Comparison of corresponding amplitude spectra and trace-by-trace RMS amplitude graphs for data from Fig. 3: (a) normalized amplitude spectra of prestack traces with the offset of 2000 m; (b) RMS amplitudes for all traces inside CMP gather; (c) normalized amplitude spectra of stack sections; (d) RMS amplitudes for all traces in stack sections. Colours denote original data (blue), data after local stacking (red), data after phase substitution (green) and data after phase sign corrections (black).

amplitude values reveal that local stacking attenuates the amplitude and smooths out original details, whereas phase substitution and corrections better preserve them (not shown).

REAL DATA EXAMPLE: LAND SEISMIC FROM THE DESERT ENVIRONMENT

Land data from the desert environment represent the ultimate processing challenge in terms of the signal-to-noise ratio. In addition to near-surface scattering, data may suffer from variable source and receiver coupling, creating additional frequency-dependent phase distortions exacerbating SNR. An example of CMP gather from a challenging 3D land data set is shown in Fig. 3(a). The input data have already been passed through a standard processing flow, including noise removal, statics, surface-consistent-processing etc. and are ready for velocity analysis and imaging. However, prestack data reveal only a hint of a few strongest reflections, despite generally simple subsurface structure with plenty of high-contrast interfaces. Figure 3(b) shows the same CMP gather after data enhancement with nonlinear beamforming (Bakulin *et al.*, 2017) with summation apertures of 150 × 150 m in CMP and offset domain. Approximately 200 neighbouring traces are used in the local summation procedure to produce a single output trace. Reflections are clearly revealed in the entire range of offset and time; however, high-frequency content of the signal is suppressed due to suboptimal stacking; amplitudes are considerably reduced, and events are overly smoothed (Fig. 4a,b, red line). While phase substitution and phase correction methods also make reflections coherent and visible, in contrast to local stacking, they retain higher frequencies, keep more local details and maintain the amplitude level. Recall that phase sign corrections considered here do not change the original amplitudes but just multiply TF spectra of each trace by 1 or −1 according to (7) and (8). Computed amplitude spectra validate our conclusions that new approaches led to the preservation of higher frequencies (Fig. 4a) and amplitudes (Fig. 4b) in the data. Surface-consistent deconvolution or spectral whitening can be applied to recover higher frequencies further, as suggested in Gamboa et al. (2007).

Comparison of stack sections constructed using original and enhanced data fully corroborates that images with enhanced data have better event continuity in the challenging areas (Fig. 3, bottom). Images constructed with phase substitution and phase corrections exhibit finer spatial and temporal details compared with local stacking with nonlinear beamforming. The fact that higher frequencies survive in the spectrum of the stacked sections (Fig. 4c) suggests that we recovered additional signals on prestack records that were coherently added up during the imaging step. We conclude that proposed phase-sensitive TF spectra corrections provide a significant uplift in prestack and poststack data. In these examples, we have applied new approaches at the end of the processing flow. As such, considerable improvement in prestack SNR was not fully exploited. In future work, we intend to introduce them earlier and extract improved deconvolution operators, amplitude scalars, statics, and velocities that are expected to lead to even better recovery of higher frequencies surpassing that of the original image used here as a reference. These prestack improvements are also paramount for any reservoir inversion where reliable recovery of amplitude versus offset is a prerequisite for success.

CONCLUSIONS

We introduced a new family of data enhancement methods by combining local stacking approaches and time-frequency masking from speech processing. We have proved that for multi-channel data, the most valuable ingredient delivered by local stacking is the estimated phase spectra of underlying signals. The proposed phase substitution approach simply recombines original amplitude spectra with the estimated phase and generates an enhanced prestack data that do not suffer from loss of higher frequencies. A more refined approach with frequency-dependent phase corrections "fixes" corrupted phase in a subtler way by altering the signs and using enhanced phase from local stacking only as a guide. This new family of approaches opens up a new avenue in multi-channel seismic processing. Such methods are critical for data from a desert environment acquired with single sensors or nodes that have too challenging prestack quality and SNR for conventional processing. In this short note, we have focused on phase corrections as the most fundamental issue that needs to be solved to find underlying weak reflections and make them visible and coherent. Once this step is achieved, we can further surgically attack underlying noise using time-frequency masking by also utilizing the 'amplitude signal guide' obtained from local stacking.

DATA AVAILABILITY STATEMENT

The synthetic data that support the findings of this study are available in the supplementary material of this article. The real data set associated with this study is confidential and cannot be released.

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