Removing vibrator-induced correlation artifacts by filtering in frequency-uncorrelated time space

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ABSTRACT

Vibrator-to-ground coupling can produce resonance-induced energy that propagates with the primary sweep and produces serious artifacts in the correlated seismogram due to the frequency structure of this offending energy. For sweeps linearly increasing in frequency, the resulting artifact is observed (uncorrelated) to increase in frequency at a linear rate differing from the original sweep. Upon crosscorrelation with the pilot sweep, the artifact-producing energy becomes distributed over an extended range of time while the normal reflected sweep is compressed, by design, into a narrow correlation wavelet. The resulting traces thus exhibit strong amplitudes that increase monotonically in dominant frequency. Display of individual uncorrelated seismograms using a Fourier frequency-uncorrelated time (F-T) transformation reveals the relationship between the primary sweep and the induced artifact. “Surgical” filtering in this new F-T space provides for a first-order removal of both the artifact and the energy in sweep harmonics as induced by the strong first arrivals. Two-dimensional (2-D) spectral filtering of the modulus of the (complex) 2-D transform of the F-T data provides better rejection of the unwanted energy. Application of this trace-by-trace filtering process to a badly contaminated crustal-scale multichannel CDP profile in the southern San Joaquin Valley, California, reveals significant reflections from the middle and lower crust that were obscured in the unfiltered profile.

INTRODUCTION

The quality of unstacked vibroseis seismic reflection data depends not only on source strength and coupling, the presence of reflecting geologic features, and high signal-to-noise recording conditions, but also on there being a minimum of spurious source-generated energy within the field data prior to correlation. Reflected source sweeps within the uncorrelated field data produce well-defined wavelets upon crosscorrelation, but arrivals differing in signal form from the source sweep will appear as artifact signals after correlation. Such unwanted signals can be coherent and of large amplitude or time duration, and can obscure the weaker desired reflections. Subsequent conventional data processing will result in common-depth-point (CDP) stacked profiles of degraded quality.

Source-generated arrivals that are not replicate sweeps in uncorrelated seismograms have anomalous appearances in correlated form, depending on the nature of the offending energy. Spikes in uncorrelated data will replicate the correlation operator (source sweep) in time-reversed order. First- and higher-order harmonics of the sweep will produce correlated “harmonic ghosts” in positive time for downsweep sources and in negative time for upsweep sources (Seriff and Kim, 1970). Strong source-generated energy that is broadband in frequency content and narrow in time duration will smear across time in correlated form, and will mimic the moveout of the original uncorrelated energy.

The California Consortium for Crustal Studies (CAL-CRUST) collected a crustal-scale seismic reflection profile in the southern San Joaquin Valley-Tehachapi Mountains during October, 1986. Within the shot gathers from this survey, coherent large-amplitude artifacts are generated in the crosscorrelation operation. Using frequency-time displays of uncorrelated seismograms (F-T space), the cause of the artifacts can be isolated to specific frequency and time intervals.
Because of these well-defined intervals, the offending energy can be successfully removed by filtering the data in 2-D F-T space. The most effective filtering is accomplished by weighted scaling of the modulus of the 2-D Fourier transform of the F-T signal. This paper presents a discussion of the problem as seen in the CALCRUST data, possible remediation methods, and their application to the CALCRUST profile.

IDENTIFICATION OF THE PROBLEM: CRUSTAL PROFILE, SAN JOAQUIN VALLEY

The CALCRUST 1986 survey explored the crustal relationship between the San Joaquin-Tehachapi structures and the adjacent Garlock transform fault (Figure 1). The survey was conducted with a 400-channel MDS-16 recording system and four large [40 000 lb (18,000 kg) peak force] vibrators, using 8-32 Hz, 32-s sweeps with a 13-s listen time. Both correlated and uncorrelated shot gathers were recorded for subsequent processing.

Correlated shot gathers illustrate the severity of a post-correlation artifact within this profile (Figure 2). Expected events such as the first arrivals, surface waves, air wave, and shallow reflections are visible, along with the strong energy between 5 and 11 s which exhibits the moveout of the first arrivals. This correlation artifact energy is narrow band and increases monotonically in frequency from 18 Hz at 5 s to 26 Hz at 11 s. Figure 3 compares the amplitudes of seismogram "X" from Figure 2 and the autocorrelation of the sweep for this shot gather; the correlation sidelobe amplitudes, which would be associated with the first arrival, are much lower than the artifact energy. Attempts to remove the energy using spatial dip filtering, while only marginally successful, did reveal suggestions of reflections within the contaminated interval, warranting further efforts toward data enhancement.

F-T representation of artifact

A more complete understanding of the artifact problem is reached by a close scrutiny of the offending signal character in the uncorrelated seismograms. The 45-s uncorrelated shot gathers are difficult to examine due to the long sweep wavetrains, and the artifact-inducing energy is hard to identify. However, by mapping each uncorrelated seismogram into the frequency-uncorrelated time (F-T) domain, the returning (reflected) sweep(s) and the distorted contaminant sweep energy can be separated. The F-T transformation presents the frequency content along the seismogram. Differing from the single-valued instantaneous frequency along the seismogram (Taner and Sheriff, 1977), the F-T transformation shows the full spectral behavior computed along the seismogram using a moving window. This moving-window decomposition, a version of short-time Fourier (STFT) analysis (e.g., Allen and Rabiner, 1977; Portnoff, 1980; Nawab and Quatieri, 1988), is in essence a series of one-dimensional (1-D) Fourier transforms of the moving window. STFT is well-developed for applications within sonar, music decomposition (Dudgeon and Mersereau, 1984), and speech analysis (Rabiner and Schafer, 1978; Tribollet and Crochiere, 1979).

The signal extracted from an individual uncorrelated seismogram $y(t)$ for a particular window centered at $T$ is

$$y(t, T) = y(t) \text{win}(T - t),$$

and its discrete 1-D Fourier transform can be expressed as

![Fig. 1. Map of southern San Joaquin Valley-Tehachapi Mountains region showing CALCRUST 1986 profile as heavy dashed line. Location of gather shown in Figure 2 and used throughout is noted by the star. 1-5 denotes U.S. Interstate 5. White Wolf fault has up (U) and down (D) components of motion. Inset: SAF denotes San Andreas fault; G denotes Garlock fault. Study area is at junction of San Andreas and Garlock faults.](image_url)
\[ \hat{Y}(f,T) = R(f,T)e^{i\theta(f,T)}, \]

where \( R(f,T) \) and \( \theta(f,T) \) are the standard modulus and phase functions in F-T space. Proper selection of window parameters (e.g., length, taper, time step) is important. The window length must be long enough to produce a robust Fourier transform with the desired frequency resolution but must not be overly long so that many time events are averaged into a single spectrum. While each original uncorrelated seismogram for this study is 45 s in length (11 261 samples at 4-ms sampling), the selection of a window length of 1.00 s (250 samples) is permissible due to the low sweep gradient of 0.75 Hz/s. The window is designed with a cosine taper stretched across each half window so that only the center sample has 100 percent amplitude preservation, but the central samples contribute at nearly this rate. The windowed data are symmetrically padded with zeros to be two powers of 2 greater for the subsequent Fourier transform (i.e., 1024 samples); this provides a more robust transform and a better frequency sampling interval. The window time step is 0.10 s (25 samples) to produce 451 windows. The shape of the window and width of the time step are selected to produce a well-defined image of a (reflected) sweep in the F-T spectrum of an uncorrelated seismogram.

The modulus of the F-T representation for a 32-s vibroseis pilot sweep (8-32 Hz) from the San Joaquin Valley profile is shown in Figure 4a. The slope of the energy in F-T space represents the sweep gradient 0.75 Hz/s. The F-T spectrum for a single uncorrelated seismogram that uses this sweep is shown in Figure 4b. The first arrival, which is similar to the source sweep in Figure 4a, is clearly the strongest event in the uncorrelated seismogram. The first- and higher-order harmonics of the first arrival are clearly identified. Also visible is an event that appears between [21 s, 18 Hz] and [30 s, 26 Hz]. This event has a slope less steep than that of the source sweep, and it appears to originate at a particular point within the source sweep. As discussed in the following section, this is the source-generated energy that, when correlated, produces the strong artifact shown in Figure 2. We refer to this energy in subsequent discussions as artifact-producing energy (APE).

Crosscorrelation in F-T space

Visualization of the crosscorrelation operation in F-T space explains the development of the correlation artifact and suggests the technique for its suppression. Okaya and Jarchow (1989) discuss the F-T transformation in some detail. The correlation process in F-T space is illustrated schematically in Figure 5. Two arrivals (R1, R2) in F-T space are shown exhibiting the F-T signature of the source sweep in frequency content, time duration, and slope. The sweep correlation operator (SCO) is shown at its initial and final location in the correlation process. Wavelets appear within the correlated seismogram at the time of the onset of energy in the uncorrelated reflected sweep corresponding to their particular arrival times. All desired energy appears with the same slope in F-T space. Energy with other F-T slopes creates correlated signatures differing from the reflected events. In Figure 5 we have introduced such energy into the correlation operation. Because of the contrasting slopes of the correlation operator and the artifact-producing energy, lower frequencies are emphasized at earlier times and higher frequencies are emphasized at later times in the correlated seismogram. The different slope of the artifact energy produces, via the correlation procedure, a narrow-band, monotonically increasing package of energy in the correlated seismogram. The total time during which the sweep correlation operator intersects any portion of the artifact-producing energy is the time duration of the resulting correlated artifact. As is obvious in Figure 2, the effect of this noise can be a serious loss of data in the interval.

For the F-T seismogram of real data in Figure 4b, first-arrival energy ("F") begins at [0.5 s, 8 Hz], and continues to [32.5 s, 32 Hz]. The contaminating APE is present between [24 s, 18 Hz] and [32 s, 26 Hz]. In the correlated seismogram, the artifact energy is drawn out from 5 to 11 s. The shot gather (Figure 2) illustrates the pervasive effect of this contamination.

![Figure 2](image-url)

**Fig. 2.** Portion of correlated shot gather from CALCRUST profile at location of star in Figure 1. An AGC using a 1000 ms window is applied. Note the strong amplitude energy at 5-11 s with the first arrival moveout. "X" indicates the representative seismogram used in the following figures.
FILTERING IN F-T SPACE

Mute filters

Figure 4b presents only the modulus of the F-T transformation for a single uncorrelated seismogram. However, the full complex (STFT) transform for this seismogram can be available for manipulation. Alteration of the amplitude spectra prior to inverse F-T transformation constitutes frequency filtering in F-T space. A first-order solution would apply a band-reject filter to the artifact frequencies. For the San Joaquin Valley data, such a step will reject 18-26 Hz out of an original 8-32 Hz—an unacceptably severe loss, given the limited frequency range of the data. Muting or pie-slice editing of the modulus \( R(f,T) \) uses a real-valued weighted coefficient function \( c(f,T) \):

\[
P'(f,T) = c(f,T)P(f,T) = R'(f,T)e^{i\theta(f,T)},
\]

where \( R'(f,T) = c(f,T)R(f,T) \).

The phase \( \theta(f,T) \) is not modified. The weighted coefficient function \( c(f,T) \) can be visualized as a series of 1-D filter functions applied to the set of Fourier-transformed windows.

The steps involved in the inverse transformation of \( \hat{y}'(f,T) \) back to the filtered seismogram \( y'(t) \) are (a) inverse 1-D Fourier transforming to convert \( \hat{y}'(f,T) \) to \( y'(t,T) \), (b) removing the effects of tapers and zero-padding on \( y'(t,T) \), and (c) reconstructing the seismogram \( y'(t) \) from “inverse” windowing.

To reconstruct the seismogram \( y'(t) \), the effects of the forward windowing must be undone. The forward window cosine taper can be removed by multiplying each window \( y'(t,T) \) by the inverse of the taper. Since the windows overlap significantly, inverse windowing is performed by transferring only the central portion of each window into the output filtered seismogram. The width of each portion (centered about \( T \)) is equal to the window time step, so that for this study, only 25 samples of each of the 250 sample windows were transferred. As a result, blending of the inverted windows was avoided.

For the southern San Joaquin Valley data, a two-dimensionally tapered box mute \( c(f,T) \) was designed to remove the APE which is visible in Figure 4b. Figure 6 illustrates the filtering process and its results. The first arrival harmonics were removed in addition to the APE. Following transfor-

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Fig. 3. Comparison of correlation sidelobes and late-arriving artifact energy. This figure helps discriminate between correlation sidelobes associated with the first arrival and the artifact energy. (A) True, ungained, amplitude of seismogram “X” in Figure 2 plotted using a linear amplitude scale. Note the rapid drop in amplitude after the first arrival. Energy between 5-11 s is barely detectable. (B) True, ungained, amplitude of the autocorrelation of the pilot sweep used with the shot gather in Figure 2. The autocorrelation is normalized to the same value as the maximum value in seismogram “X”; the center peak was also delayed to correspond with the time of the maximum amplitude in seismogram “X”. (C) Comparison of amplitudes of the sweep autocorrelation and seismogram “X”. This curve is the ratio of the rms amplitudes of (B) to (A). The rms amplitudes were computed for the sweep autocorrelation and seismogram “X” using a nine-sample (36 ms) moving window. The ratio of the rms amplitudes was expressed using a dB scale: \( \text{db} = 20 \log(\text{rms(sweep)}) - \log(\text{rms(X)}) \). The correlation sidelobes for the sweep autocorrelation are slightly higher than seismogram “X” between 1 and 3 s. A well-defined low (< -60 dB) between 5-11 s indicates the data seismogram is significantly larger than the correlation sidelobes; the energy in “X” (as seen in Figure 2) cannot be correlation sidelobes associated with the first arrival. Sharp peaks in the 5-11 s range are associated with the lower amplitude “beats” as seen in Figure 2 and barely visible in (A).
FIG. 4. F-T representation for (a) sweep alone and (b) uncorrelated seismogram "X" from the gather in Figure 2. Blue represents maximum amplitude; colors trend towards red which essentially represents the noise level (no contribution to the spectra). Only 50 Hz of the 125 Hz (Nyquist) spectra are displayed. The one-second (250 samples) time-domain moving window was stepped in 0.1 s increments. A cosine taper of 0.5 s was applied to the windows and a 1024-point STFT was computed. The STFT modulus of the sweep and data seismogram is shown in (a) and (b). (a) The 8-32 Hz sweep length is 32 s. (b) Labels F, H1-4, APE, and R indicate, respectively, energy in the first arrival, first arrival harmonics, the artifact-producing energy, and the region of reflected energy arrivals. Only 35 of the 45 s uncorrelated data are shown for this seismogram.
mation back to the uncorrelated seismogram, the correlated shot gather in Figure 6 shows a marked reduction in the artifact (as compared to Figure 2), although substantial residual artifact energy remains.

The tapered box mute is only partially effective because it suppresses only the artifact associated with the first arrival energy, and each later reflected sweep will have its own packet of contaminating energy that is not excised by the mute. An uncorrelated seismogram will thus have the APE throughout the domain of the desired reflected energy. A mute to remove all of the APE degenerates simply to an 18-26 Hz band-reject filter, severely compromising the data quality. The exact geometry of a "first-arrival" mute will be offset- and site-dependent, necessitating an elaborate scheme for designing the seismogram-specific mutes. A better scheme clearly is required.

**K_f - K_T Domain and filtering**

A linear source sweep with constant sweep gradient is a line in F-T space. All reflected sweeps will parallel this line, separated only by delays in arrival time. Artifact-producing energy of the type seen in our data will occur throughout the uncorrelated seismogram with a unique slope in F-T space. This property suggests a procedure for separating the two slopes using 2-D Fourier analysis as illustrated in Figure 7. The various events in F-T space are shown schematically in Figure 7a with differing slopes. The 2-D Fourier transform of \( R(f, T) \) will localize coherent energy with similar slope in F-T. Reflected sweeps, first- and higher-order harmonics, and APE will map into separate regions, as shown in Figure 7b.

The 2-D Fourier transformation of the real-valued modulus \( R(f, T) \) creates a complex-valued mapping \( \tilde{R}(k_f, k_T) \). Similar to \( f - k \) filtering of \( t - x \) shot or CDP gathers, filtering within \( \tilde{R}(k_f, k_T) \) can preserve events of specified slope while suppressing events with different slopes in F-T space. Removal of undesired slopes within \( k_f - k_T \) space, will then enhance the desired reflected sweeps in F-T space, presumably at the expense of energy within the harmonics and the APE budgets. We illustrate the \( k_f - k_T \) filter concept with the shot gather used previously.

The \( k_f - k_T \) transformation for the uncorrelated F-T seismogram in Figure 4b is shown in Figure 8. The region of \( k_f - k_T \) space labeled F,R contains the first arrival and the reflected energy. Harmonics of the source sweep map into discrete zones and the APE in Figure 4b maps into its own localized zone. This representation is now amenable to 2-D band-pass filtering that will enhance the primary energy relation to the interfering harmonics and APE.

**Application**

The \( k_f - k_T \) transformation of \( R(f, T) \) in Figure 8 can be filtered by application of an appropriate \( c(k_f, k_T) \) weighting function outlined in the figure around the F.R energy lobe. The subsequent inverse 2-D Fourier transform returns the data to the filtered modulus \( \tilde{R}'(f, T) \) as illustrated in Figure 9, where it is clear that the first arrival harmonics \( H_1, H_2, H_3, H_4 \) and the artifact energy (APE) seen in Figure 4b have been suppressed. Some first-harmonic energy has leaked through the filter, probably from the vicinity of the origin in \( k_f - k_T \) space. Subsequent inverse F-T transformation and seismogram window restoration produces in the time domain an uncorrelated seismogram with diminished harmonic and artifact energy. This process can then be applied to any number of seismograms contained in the shot gathers for this profile; for the CALCRUST profile only the seismograms within 2000 m source-receiver offset needed this filtering. An important feature of this method is that the filter weighting function is not specific to source or receiver location, and the same \( c(k_f, k_T) \) is used through the profile.

Conventional crosscorrelation of the filtered and restored data of Figure 2 produces a much improved shot gather (Figure 10) revealing numerous mid-crustal reflections that had been obscured by the correlation artifact in Figure 2. All contaminated shot gathers across the CALCRUST profile were processed in this manner, with marked improvement. A portion of the CDP profile produced from unfiltered seismograms is shown in Figure 11a, and the same portion of the stacked profile produced from F-T filtered seismograms is shown in Figure 11b. Numerous reflections are seen which were not visible in the unfiltered profile, and the high-amplitude ringing nature of the data has been suppressed.
DISCUSSION

F-T filtering

The sequence of steps in this F-T filtering of an uncorrelated seismogram is the following:

1) Frequency-time transform:  
\[ y(t) \rightarrow \hat{Y}(f,T) \]

2) Separate modulus \( R(f,T) \) and phase \( \theta(f,T) \):  
\[ \hat{Y}(f,T) = R(f,T)e^{i\theta(f,T)} \]

3) 2-D Fourier transform of modulus \( R(f,T) \) only:  
\[ R(f,T) \rightarrow \hat{R}(k_f,k_T) \]

4) Filter \( \hat{R}'(k_f,k_T) \):  
\[ \hat{R}'(k_f,k_T) = c(k_f,k_T)\hat{R}(k_f,k_T) \]

5) Inverse 2-D Fourier transform of \( \hat{R}'(k_f,k_T) \):  
\[ \hat{R}'(k_f,k_T) \rightarrow \hat{R}'(f,T) \]

6) Extract modulus \( R'(f,T) \):  
\[ R'(f,T) = |\hat{R}'(f,T)| \]

7) Reconstruct modulus \( R'(f,T) \) with phase \( \theta(f,T) \):  
\[ \hat{Y}'(f,T) = R'(f,T)e^{i\theta(f,T)} \]

8) Inverse frequency-time transform:  
\[ \hat{Y}'(f,T) \rightarrow y'(t) \]

The frequency-time transformation and filtering are only performed on individual uncorrelated seismograms and not on any type of ensemble average of the uncorrelated shot gather. Steps 3 through 6 operate on the modulus \( R(f,T) \) of the seismogram spectrum. The weighting function \( c(k_f,k_T) \) in step 4 is constructed to take advantage of the known characteristics in F-T space of wanted and unwanted energy.

F-T space is an excellent domain in which to identify and separate the primary, linear vibrator sweep from its harmonics and other anomalous sweep-generated energy that map

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**Fig. 6.** Box muting in F-T space applied to seismogram "X" (Figure 4b). (a) Regions of 0 percent and 100 percent of F-T spectral amplitudes prior to (above) and after (below) mute application. The box mute is designed to suppress the first arrival APE; the first arrival harmonics are also removed. (b) Shot gather of Figure 2 after application of the box mute. An AGC with 1000 ms window is applied. A first-order suppression of the APE artifacts exists; however significant residual artifact energy is present. Some previously obscured reflections have emerged (8 s at -1 km).
into localized zones within F-T space. Mute-type filtering in F-T space is an effective but tedious and computationally expensive approach. The transformation of the F-T representation into $k_f - k_T$ space allows for a more general and convenient separation of reflected sweeps from the other unwanted coherent energy. Preservation of the linear reflection region by a filter operator will reduce the amount of unwanted energy in the reconstructed seismogram. Phase information is not altered in the filtering. We used this procedure on the CALCRUST 1986 data and gained a substantial improvement in the stack quality at mid-crustal depths, compared to the original artifact-contaminated data.

The application of the 2-D Fourier transform to the F-T data panel was a natural approach to filtering the linear features with varying slopes. Other approaches for implementing the filtering in steps 3–6 above may perform as well or better than $k_f - k_T$ filtering. For example, we are experimenting with the use of the Radon transform in decomposing the F-T data. Filtering for the slope (ray parameter equivalent) of the true sweep would simplify to a band-pass operation in the slope parameter. Other more efficient and/or more effective filters can probably be found.

There is no fundamental reason why this method cannot be extended to nonlinear sweeps. In such cases the signature of the true sweep in F-T space will be a curve. Again harmonic and spurious sweep artifacts will have contrasting curve shapes. Filtering is simply complicated by the requirement for a filter weighting function that matches the sweep shape in F-T space, but this does not constitute a serious impediment. Similarly, the method should be applicable equally to up- or downsweeps, and, in the case of the downsweeps, it may be effective in suppressing the harmonic contamination as well.

The F-T transformation is sensitive to the data windowing and associated problem of averaging versus resolution. The data window length must be carefully selected and must be based on the nature of the data and the desired filtering detail. Window tapering and zero-padding also produce computational effects that must be considered. Some numerical experimentation is valuable in selecting the most effective parameters for the F-T decompositions.

![Fig. 6. Continued](image)

**Fig. 6. Continued**

![Fig. 7. 2-D Fourier transformation of the seismogram in F-T space.](image)

**Fig. 7.** 2-D Fourier transformation of the seismogram in F-T space. (a) Schematic in F-T space of principal components of energy associated with a single arrival, R. The arrival has associated artifact producing energy (APE) and two orders of harmonics (H1) and (H2). (b) 2-D Fourier transformation of the amplitude spectrum in 7a into $k_f - k_T$ space, where the principal energy components from all arrivals are localized in discrete linear regions. Only one quadrant of the transform is shown. Many reflections and associated events in F-T space would map into these four linear regions.
Fig. 8. Transformation $k_f - k_T$ of the F-T representation of trace "X" (as shown in Figure 4b). The F-T amplitude spectrum without phase is 2-D transformed. F and R denote first and reflected arrivals; APE denotes the artifact producing energy; H1 and H2 represent harmonics of the F and R arrivals. Blue represents maximum amplitude; colors trend toward red which essentially represents the noise level (no contribution to the spectra). The desired energy (first arrival + reflections) is confined to a well-defined, high-amplitude lobe. The outlined region “c” represents a band-pass filter for enhancing the desired energy, and $k_f - k_T$ filtering preserves only the region within this region.

Fig. 9. Results of filtering seismogram “X” in the $k_f - k_T$ space as viewed in the F-T domain. Blue represents maximum amplitude; colors trend toward red which essentially represents the noise level (no contribution to the spectra). The (F,R) region as extracted using the region C in $k_f - k_T$ space (Figure 8) maps here into the regions F and R in F-T space. The first arrival energy is significantly stronger than the reflections in both unfiltered and filtered results (see Figure 4b). A residual amount of H1 and APE energy has passed through the $k_f - k_T$ filtering.
Source of artifact energy

In the F-T display of an uncorrelated seismogram (e.g., Figure 4b), the artifact-producing energy associated with the first arrival appears at [18 Hz, 24 s] and extends to [26 Hz, 32 s]. The event appears to initiate when the sweep reaches the vibrator-ground resonant coupling condition near 18 Hz, and the generated ground motion is quite large. As the vibrator sweep advances in frequency to 32 Hz, this ground-resonance source seems to be driven to higher frequencies, at a rate lower than the pilot, reaching only 26 Hz when the primary sweep is at 32 Hz. Ground force control was active within the vibrator electronics when the artifact was generated. The maverick 18-26 Hz, 8-s sweep thus becomes another source of energy, which propagates with the down-going primary source sweep.

The artifact in the correlated shot gathers is found in seismograms having source-receiver offsets less than 2000 m, suggesting that the vibrator-ground effects diminished with offset. Seismograms with offsets greater than 2000 m did not require this F-T filtering.

We suspect that this problem may be far more common than generally realized. It occurs fairly late in the correlated...
shot gathers, and thus may not be reached in conventional surveys of 4-6 s listening times. In many surveys, the sweep may not extend to low enough frequencies to excite the phenomenon, or the sweep rate may be high enough to avoid substantial dwell-time and associated energy input at the coupled-resonance frequency. The strongest artifact, related to the first arrival, will also be particularly visible in surveys in areas with very low reflected energy, such as the typical CALCRUST study in an area of complex crustal structure. With little reflected energy, the artifact can dominate the correlated seismogram. We have not yet explored the roles of drive level or possible interactions among multiple vibrators in the generation mechanism of the APE. These studies warrant attention, and we plan to explore them at the first opportunity.

CONCLUSION

Source-generated energy that produces correlation artifacts in a crustal vibroseis profile can be identified and isolated in individual uncorrelated seismograms through the use of a frequency-uncorrelated time (F-T) transformation employing a moving window spectral analysis. The artifact appears to be related to energy generated by a secondary source sweep, apparently due to resonance between the vibrator and the ground, typically in the 15-20 Hz range. This spurious energetic sweep dominates the correlated seismograms in a time range determined by the sweep range and rate, often obliterating any weak mid-crustal reflection in the 5-10 s interval in crustal profiling. Fortunately, the offending secondary sweep displays a rate of frequency change that differs significantly from the primary source sweep, so that the artifact and the sweep harmonics can be suppressed by filtering within the F-T domain. One such filter which is applied to individual uncorrelated seismograms separates the offending energy from primary sweep energy by using a subsequent $k_F - k_T$ transformation of the F-T data. This is effective because the primary sweep and the contaminating energy have different slopes in the F-T domain. Other filtering schemes, such as slant stacking should also work. With proper inverse transformations the filtered uncorrelated seismograms can be reconstructed. The $k_F - k_T$ filter was applied to the CALCRUST San Joaquin Valley-Tehachapi line on an individual seismogram basis, and the subsequent correlated and stacked data show numerous deep reflections which were previously obscured by the artifact. To the extent that such contaminating sweep-generated energy is a problem in vibroseis profiling, this method offers an effective option for improving the quality of the final stacked sections.

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