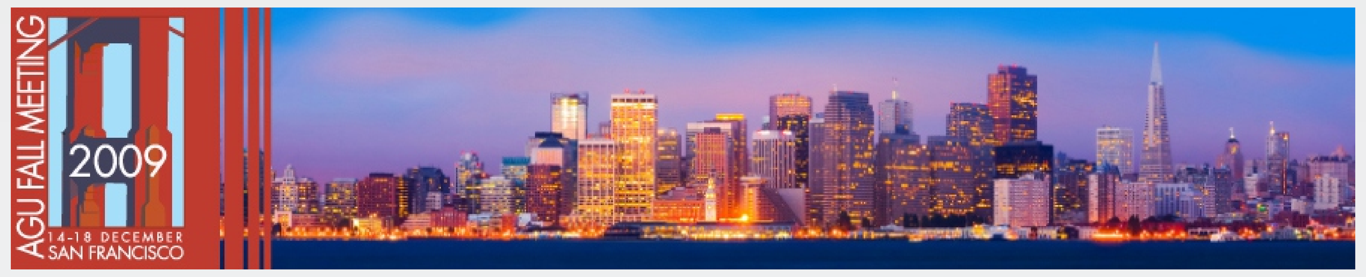

IDENTIFICATION OF TEMPORAL SPECTRAL ATTRIBUTES OF SEISMIC RECORDS BY MEAN OF JOINT TIME-FREQUENCY SPECTRAL DECOMPOSITION

CARLOS I. HUERTA-LÓPEZ, MAURICIO F. UPEGUI-BOTERO, and JOSÉ A. MARTÍNEZ-CRUZADO

IDENTIFICATION OF TEMPORAL SPECTRAL ATTRIBUTES OF SEISMIC RECORDS BY MEANS OF JOINT TIME-FREQUENCY SPECTRAL DECOMPOSITION.

By:
[1,2,3]Carlos I. Huerta-López, [1]Mauricio Upegui-Botero, and [1]José A. Martínez-Cruzado

The spectral characteristics of stationary time series data are generally portrayed with the aid of the classical power spectrum. This latter spectrum is usually calculated from the fast Fourier transform (FFT) of the time series data. Unfortunately, such an approach provides no temporal information and is thus unsuitable for examining seismic records, which exhibit transient nonstationary behavior. A classical approach to obtaining the desired time-frequency information contained in an seismic record is to utilize a short time Fourier transform (STFT) which gives rise to a spectrogram which indicates how the energy in the record is distributed over time and frequency. Of course, the uncertainty principle precludes one from simultaneously obtaining arbitrary fine resolution in both time and frequency. In order to overcome various shortcomings associated with the STFT, a class, known as Cohen's class, of time-frequency energy distributions has been developed in recent years. This class includes the Wigner-Ville (WV), Choi-Williams (CW), and reduced interference distribution (RID). Each possesses certain advantages and disadvantages. The objective of this paper is to compare the performance of these state-of-the-art time-frequency distributions when applied to seismic records associated with seismic data collected on free-field, as well as vibrations recorded on a building at three differen levels. Tradeoffs between time and frequency resolution, suppression of so-called interference terms, and methodologies to portray large dynamic range will be described in detail.

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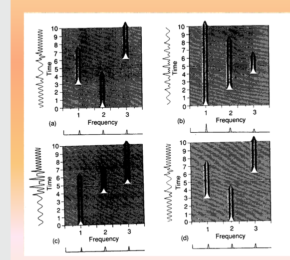
ULTIMATE GOAL

- Implement and test the appropriate time-frequency distribution that best characterize the time-frequency characteristics of multi-component seismic waves for its use in wave parameter estimates.

Why Time-Frequency analysis?



Time-frequency analysis provides information about a signal as a distribution function in time and frequency.

Note that the four samples share a spectrum in frequency

Time-Frequency analysis

- Fourier transform provides no localization in time domain
- Non-stationary signal processing
- Time-varying spectra of signals
- Uncertainty principle

$$\Delta\omega\,\Delta T \geq \tfrac{1}{2}$$

where ΔT is time bandwidth and $\Delta\omega$ frequency bandwidth

Characteristics of distributions

	Advantage	*Disadvantage*
Spectrogram (STFT: Short Time Fourier Transform)	Easy concept	Poor resolution In time and frequency
WVD (Wigner-Ville Distribution)	Detecting Chirp components	Negative cross terms (Interference)
CWD (Choi-Williams Distribution)	Suppressing cross terms	Singularities on synchronous components

Characteristics of distributions

	Advantage	*Disadvantage*
RID (Reduced interference distribution)	No singularities on synchronous components	Small negative distribution, strong cross-terms, limited T-F resolution
RGK (Radial Gaussian kernel)	Suppress cross terms, and works well with multiple parallel chirp signals	Singularities on synchronous components, single kernel for all signal
AOK (Adaptive optimal kernel)	Adapts to temporal characteristics of the signal, reduce singularities, and suppress cross terms	Small negative distribution, small singularities in synchronous components

Cohen's class and kernel

- Generalization of various time-frequency distributions with 'kernel' $\Phi(\theta,\tau)$
- Cohen's class expression is

$$P(t,\omega) = \frac{1}{4\pi^2}\iint A(\theta,\tau)\Phi(\theta,\tau)e^{-j\theta t - j\tau\omega}\,d\theta\,d\tau$$

where $P(t,\omega)$ is the distribution and

$$A(\theta,\tau) \equiv \int x(t+\tfrac{\tau}{2})x^*(t-\tfrac{\tau}{2})e^{j\theta t}dt$$

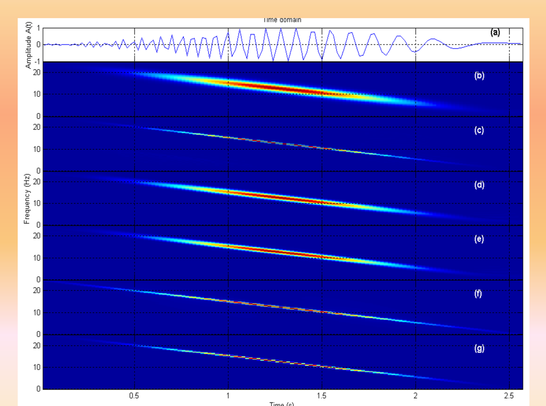
is the moving auto-correlation function of the signal and *x(t)* the signal to be analyzed

Time-frequency distributions kernels

NAME	KERNEL $\Phi(\theta,\tau)$
SP	$\int h^*(u-\frac{1}{2}\tau)e^{-j\theta u}h(u+\frac{1}{2}\tau)du$
WVD	1
CWD	$e^{-\theta^2\tau^2/\sigma}$
RID	2D Low pass filter in θ, τ space
RGKD	$e^{-(\theta^2+\tau^2)/2\sigma^2(\psi)}$ or in polar coordinates $e^{-r^2/2\sigma^2(\psi)}$
AOKD	$A(t:\theta,\tau)$ applied to the optimization of: $e^{-(\theta^2+\tau^2)/2\sigma^2(\psi)}$

SP: spectogram, WVD: Wigner-Ville distribution, VWD: Choi-Williams distribution, RID: Reduced interference distribution, RGKD: Radial Gaussian Kernel distribution, AOKD: Adaptive optimal kernel distribution.

Examples of T-F Distributions with synthetic signals



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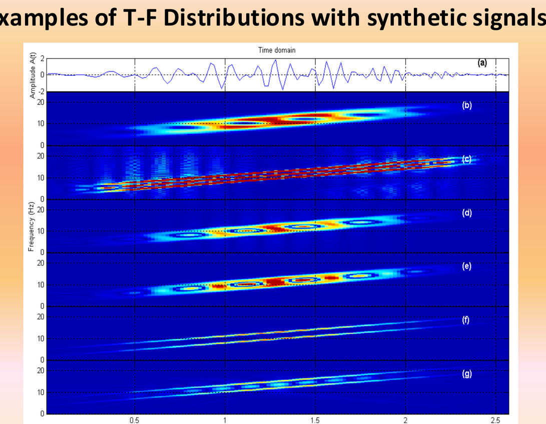

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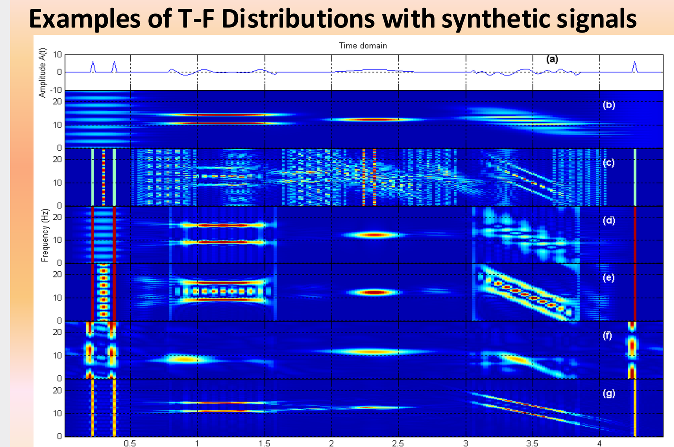

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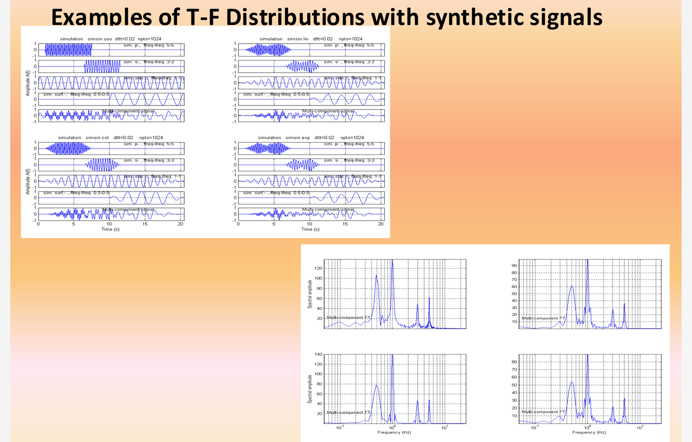

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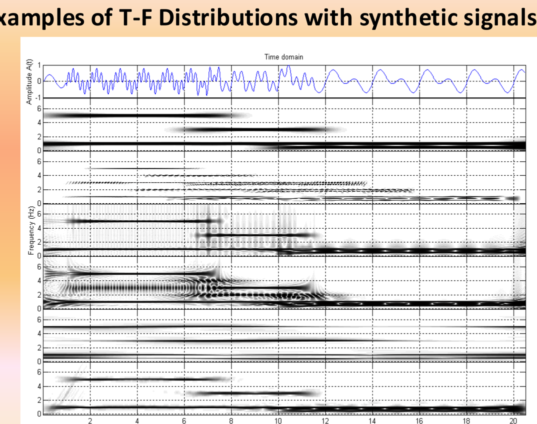

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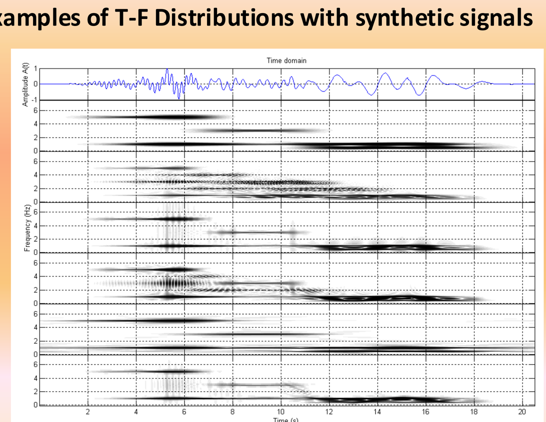

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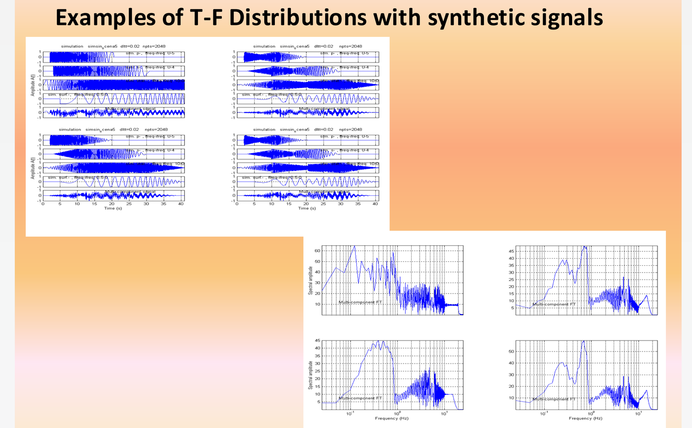

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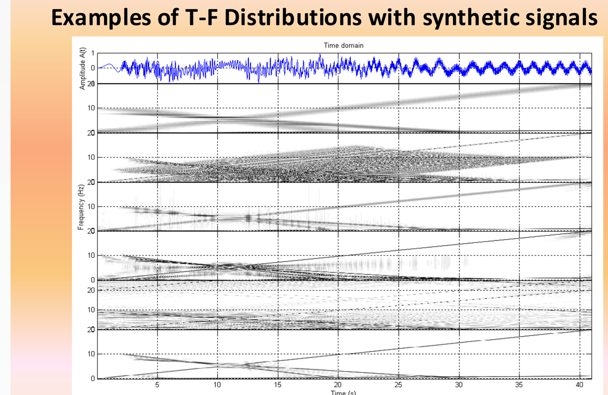
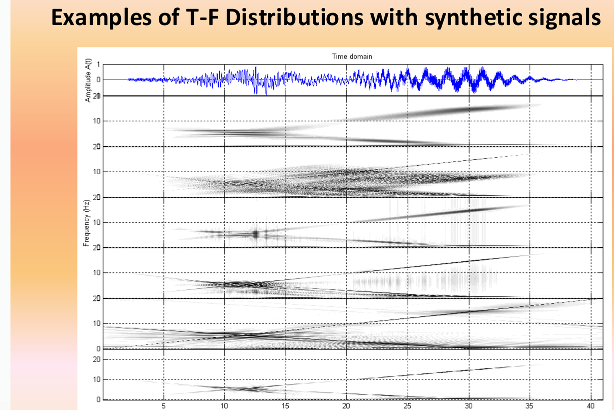
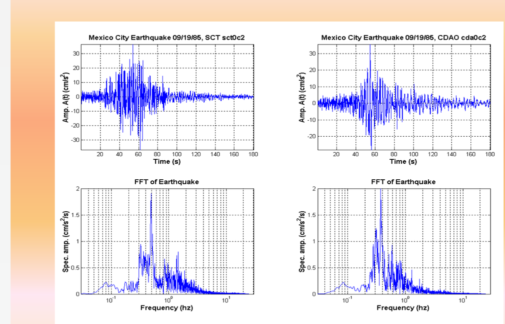
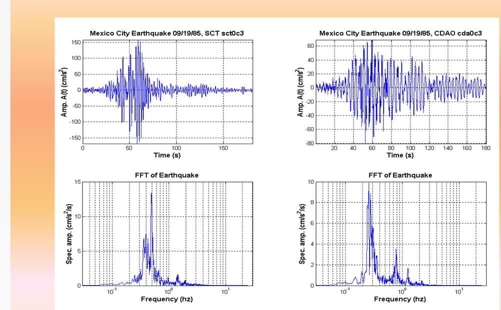
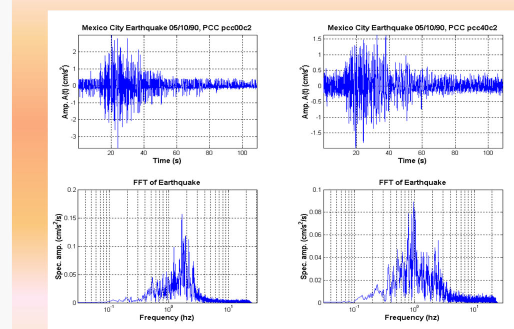


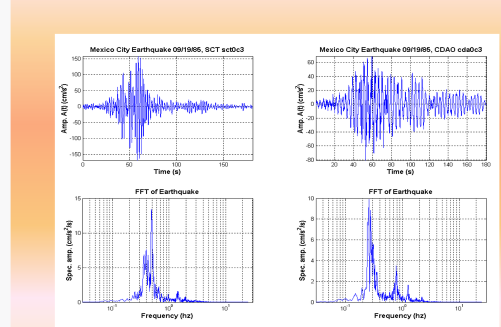
Examples of T-F Distributions with synthetic signals



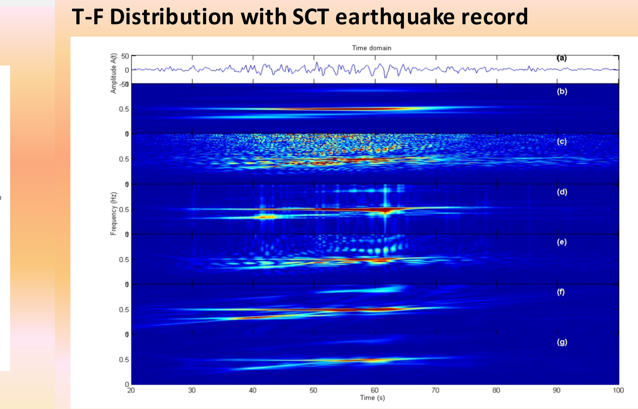




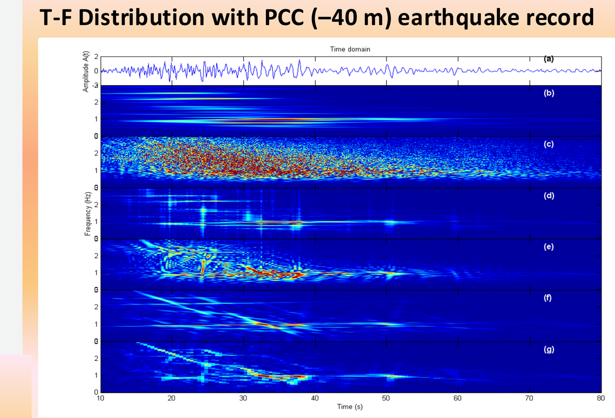




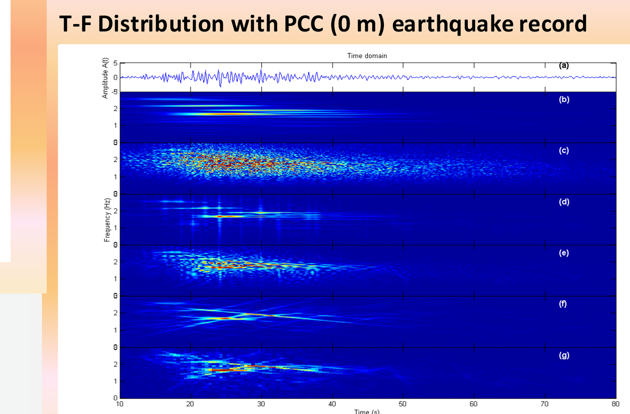
T-F Distribution with SCT earthquake record

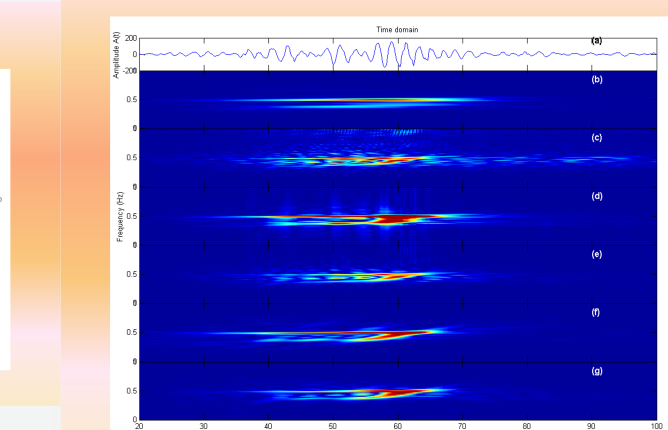


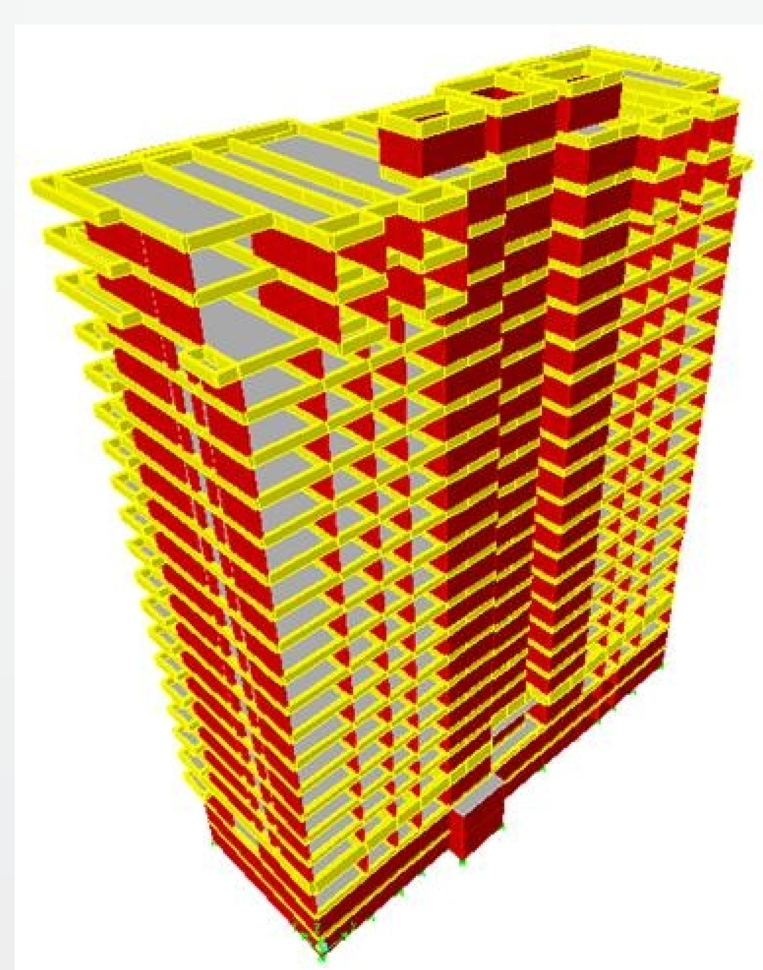
T-F Distribution with PCC (–40 m) earthquake record

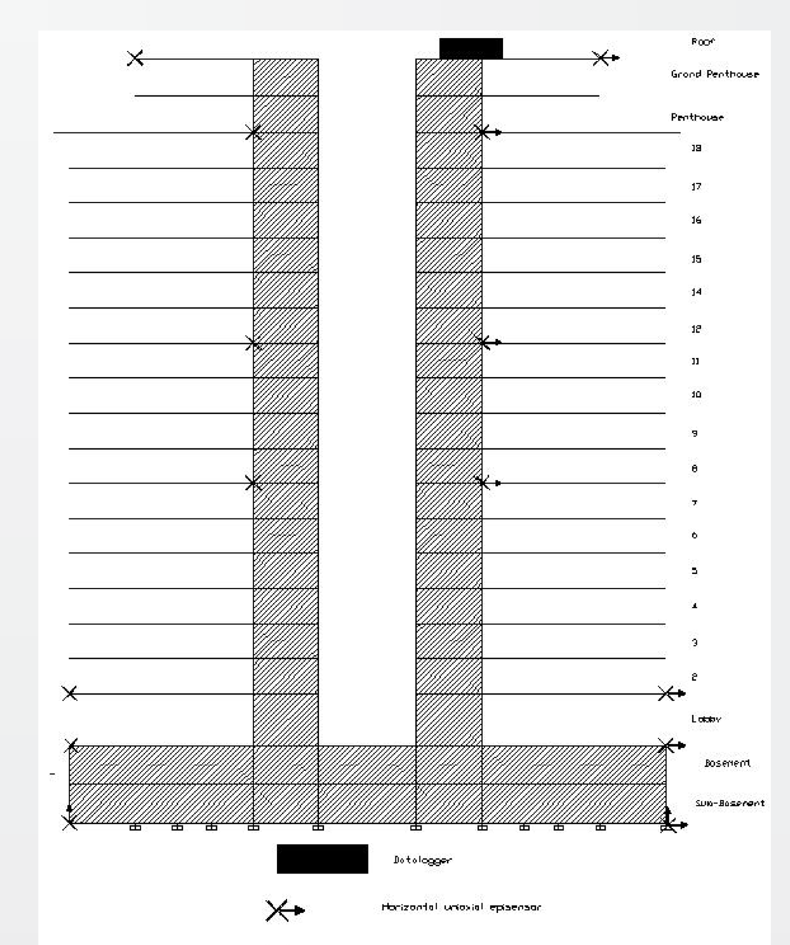


T-F Distribution with PCC (0 m) earthquake record









Analysis and Interpretation

The time-frequency distributions obtained when using seismic-, and generic-waveform synthetic signals showed that within its intrinsic limitation of fine time-frequency resolution, the SP is well suited for time-frequency decomposition of: (i) frequency modulated single component signals, and (ii) multi-component signals with constant frequency (or quasi-constant) in which the frequency of the components are apart each other at least by a factor of two. The algorithm of the WVD, in its effort to provide fine time-frequency resolution of multi-component signals, introduces numerical artifacts (interference and cross-component terms). The CWD distribution, exhibits clear synchronization effects, and still experiences some limitations in resolving frequency modulated parallel signals. It does better in resolving parallel signals with constant frequency, the Gaussian shape pulse, and the impulses. The RID shows an improvement in resolving frequency modulated parallel signals, and removes a great amount of the synchronization effects, but strong cross-components are evident between relatively close parallel signals. The RGKD does well only when working with frequency modulated parallel signals (or quasi-parallel). The resolution significantly decreases in resolving non-parallel signals and/or signals that converge at some point. The AOKD offers the best tradeoff between the reduction of the numerical artifacts and the resolution of the time-frequency decomposition for the more general case of multi-component signals.

The joint time-frequency characteristics of the earthquake seismic waves studied here exhibit interesting features from the engineering or the seismology interpretation point of view. Lets first describe the interpretation that may be obtained when using only the SP time-frequency distribution. Global characteristics about the frequency distribution are quite clearly evident, but details about its time duration are limited, as well as any inference related with energy concentration due to the (probable) interaction between different seismic wave phases. When using the WVD time-frequency plot, energy concentrations are possible to observe. This is mainly due to the significant increase of the time-frequency resolution, but at the same time a large amount of cross-term interference masks the true signal of the earthquake record. As indicated in Figure 4.43(b) (indicated with inclined arrow) there is an apparent concentration of energy at ~ 1.4 Hz that is not observed in the FFT spectrum or in the SP. This artifact is due to interference effects.

Without being conclusive some time-frequency distribution trends are possible to identify. Wen using the CWD, cross-term interference is reduced, making it possible to identify more clearly the spots where the concentration of energy occurs. However, continuous trends of the signal in time and frequency are not possible to follow with reasonable detail. The RID time-frequency distribution offers a better trade-off between the signal time-frequency distribution and suppression of numerical artifacts (such as cross-term interference and synchronisation effects) of the algorithm. Both energy concentration spots and the time-frequency trends seem to be somewhat clearer and also consistent with the partial information seen in the distributions previously described. Because the time-frequency trends here are neater and consistent, some dispersive characteristics may be interpreted, even though currently this interpretation of earthquake wave identification may not be conclusive. The RGKD time-frequency distribution shows the cleanest and the best-resolved time-frequency characteristics of the signal.

The identification/interpretation of the frequency components of the earthquake waves is now possible to interpret without doubts, so now it may be possible to identify a wave with dispersive characteristics. Also, the times when the maximum amplitudes occur in the time domain of the earthquake record correspond also to the times where several time-frequency characteristics of the signal intersect each other. Finally, the AOKD time-frequency distribution shows comparable resolution with the one obtained with the RGKD. The only drawback is the presence of weak cross-components between two of the components. However, the time-frequency decomposition was improved, and the dispersive characteristic component is now better defined. On the basis of this analysis, once again it appears that the signal-dependent kernels (RGKD and AOKD) provide the clerest TFD's.

Discussion and Conclusion

According to published studies, the general advantages/disadvantages of the SP, WVD, CWD, and the RID TFD from a pure signal processing point of view are summarized in the following. The SP lacks the time-frequency resolution, however, a good educated guess of the signal components can be inferred from it. The WVD offers a significant improvement in time-frequency resolution, but it suffers from cross-term interference when applied to multicomponent signals such as earthquake data. The cross-term interference causes the time-frequency distribution to occasionally be negative. Furthermore, for multi-component seismic signals the presence of cross-terms makes impossible to carry out a detailed signal identification/characterization, and only general characteristics are possible to identify. The CWD overcomes the WVD limitation suppressing in great amount the cross-term interference, but some time-frequency resolution is lost. Also, when different time and/or frequency components are present at the same frequency and/or time synchronization effects occur producing singularities in the time-frequency distribution. The RID overcomes these problems to a significant extent, even though some small synchronization and cross-terms may be present

After analyzing the results of this time-frequency study, the following remarks summarize the findings. It was observed that for global frequency distributions in which no fine time-frequency resolution is necessary, the SP is well suited for identifying the dominant frequencies contained in the seismic signals, and for time-frequency decomposition of: (i) single component frequency modulated signals, and (ii) multi-component signals with constant frequency (or quasi-constant) in which the frequency of the components are apart each other at least by a factor of two. The use of the SP is not recommended for use with frequency modulated multi-component signals. The frequency resolution of the SP is limited, which restricts its use for highly resolved time-frequency characteristics of multi-component signals. Even though the WVD has significant time-frequency resolution, the information that the TFD exhibits is blurred by the interference cross-terms. This poses difficulties for any well-supported and realistic interpretation of the time-frequency characteristics of multi-component signals. These numerical artifacts are the main drawback of the WVD. Therefore, when working with multiple component signals, the use of the WVD is not recommended. The CWD suppresses much of the cross-term interference. However synchronization effects prevail and some of the details gained in the WVD are lost. Firthermore, the CWD still experiences limitations in resolving frequency modulated parallel signals. It does better in resolving parallel signals with constant frequency, Gaussian shape pulses, and impulsive signals.

The RID facilitates the identification/interpretation of time and frequency components of the seismic waves, however, strong cross-components are still present for some components of the signal. The RGKD does exceptionally well when working with frequency modulated parallel (or quasi-parallel) signals. However, the resolution decreases in resolving non-parallel signals and/or signals that converge at some point. The best tradeoff between the reduction of the numerical artifacts and the resolution of the time-frequency decomposition, for a wide class of multi-component signals is offered by the AOKD time-frequency distribution.

It is now possible to interpret some seismic signals that exhibit frequency dispersive characteristics. Also, particular frequency components can be identified with the respective times that match with the maximum amplitudes in the time domain of the earthquake record. Those maximum amplitudes correspond to a point in the time-frequency plane where several time-frequency characteristics of the signal concentrate.

The sensitivity and resolution of the four fixed kernels, and the two signal dependent kernels TFD's were studied in detail. The results showed that the signal-dependent kernels TFD's offers the best trade-off between time-frequency resolution and reduction of numerical artifacts. The use of either the RGKD or the AOKD TFD is recommended because they appear to provide the best results, even though in the worst case some of the fixed kernel TFD's here presented could be used to help in the interpretation by checking for the common features present in all of them. Now that is possible to obtain the cleanest possible time-frequency representation of complex signals like the earthquakes, the bases for seismic wave parameter estimations are being set considering the following: (i) the dispersive wave propagation characteristics can be specified by the group velocity and the phase velocity, (ii) because the instantaneous frequency (the time-varying frequency for given specified time, calculated as the normalized first frequency moment of the time-frequency distribution) and group delay (the mean arrival time of an specific frequency component, calculated as the normalized first time moment of the time-frequency distribution function) information can be extracted from the time-frequency distribution. Also examination of the TFD's allows us to estimate the time duration of a specific wave. The computed group delay of a wave measured at two observation points (the difference) provide the necessary information, in the frequency range of interest, to compute the group velocity of energy propagation, and finally (iii) from the extension of the time-frequency analysis to the cross time-frequency analysis, the phase difference between the two observation points can be computed and because the distance between the observation points is known the phase and group velocities can be estimated.

FURTHER WORK

Based on the time-frequency distribution, establish criteria (e.g. Phase and group velocity) for the identification of seismic waves.
Developing '*kernel*' that is especially suitable for earthquake time series.
Use of *cross* time-frequency distributions.

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