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Spectral Decomposition uncertainty: A new tool to deal with time-frequency non-uniqueness and better reservoir characterization

Abstract

Spectral decomposition is a well-known technique with applications in, but not-limited to, analysing frequency dependant variation of amplitude with respect to time. Over the past few years, numerous algorithms have been developed (and published) to aid precision in spectral decomposition, however, all these methods, suffer from the Gabor's uncertainty (similar to Heisenberg uncertainty principle, from quantum mechanics) i.e. the frequency and time for a specific amplitude cannot be isolated unambiguously. This has far reaching consequences with respect to seismic interpretation. e.g. after identifying a high amplitude channel in a window of 100ms zone at a specific frequency, locating the extents (vertical & lateral) of the channel within the seismic is still left to the subjective judgement of the interpreter. This introduces significant uncertainty in interpretation of spectral decomposition results. The method discussed in this paper, based on published mathematical foundations (after, Brevdo et. al., 2014, Herrera et.al. 2014, Said Gaci, 2018) aims at dealing with this spectral uncertainty in order to aid improved spectral interpretation.

Introduction

Spectral decomposition of seismic, at its core, involves transformation of the time-amplitude signal into time-frequency-amplitude signal. This is schematically shown in **Figure-1**. For a signal 's' of duration 't', the spectral decomposition process, maps the amplitude at a specific time sample into various frequencies 'f' of varying coefficients 'c'. These coefficients are complex in nature whose absolute value gives the corresponding amplitude at a specific time-frequency pair. During the course of this transformation, the precise location (temporal) of a specific amplitude gets lost or smeared over a range of frequencies. This happens because the seismic signal is inherently non-stationary, which in layman terms, means that at the same time, multiple frequencies manifest themselves to produce a single amplitude value, which is actually the complex sum (geophysically, referred as interference) of all the amplitudes of various frequencies. This non-stationarity, though not obvious in time domain, becomes severe and observable in the frequency domain and is usually referred as Gabor's uncertainty principle. For example, if, a wavelet of 100ms duration and 30Hz peak frequency is convolved with a modelled reflectivity of varying thickness (**Figure 2**), then upon spectrally decomposing the synthetic seismic using a standard short-term fourier transform (STFT) algorithm and plotting the resultant in a colormap, as in **Figure 2**, the Gabor's uncertainty effect may be observed. The exact frequency and time over which the amplitude is brightest (bright red/dark blue) is spread over a large zone centred on the actual modelled time (indicated by the red oval shape). The severity of the amplitude smearing increases as the thickness of the reflectivity interfaces decrease, as observed in the shallower interval indicated by the magenta rectangle, wherein, there is significant spread of amplitude over time-frequency interval, inspite of the presence of multiple high reflection coefficients. This is conventionally and conveniently interpreted as a low amplitude poorly resolved zone in the seismic. This implies that thin bed delineation and accurate interpretation of amplitude becomes very subjective (uncertain) due to uncertainty in time-frequency isolation which suggests that there is ample scope of improvement in the time-frequency representation scheme.

This need of finding better algorithms for spectral decomposition, brings the recently proposed method of 'Synchrosqueezing wavelet transform' (SynCWT) to the forefront. It is an extension of the wavelet transform incorporating elements of empirical mode decomposition and frequency reassignment techniques. This new tool produces a well-defined time-frequency representation allowing the identification of instantaneous frequencies in seismic signals to highlight individual components. The mathematical foundations of the forward and inverse transforms are very well laid out in seminal papers by Brevdo et. al., 2014, Herrera et.al. 2014 and Said Gaci, 2018. The objective of this paper is to layout the applications of SynCWT as a new and robust spectral decomposition tool aimed at reducing the uncertainty that usually envelopes interpretation of spectral decomposition r... arios v... thus e... ation

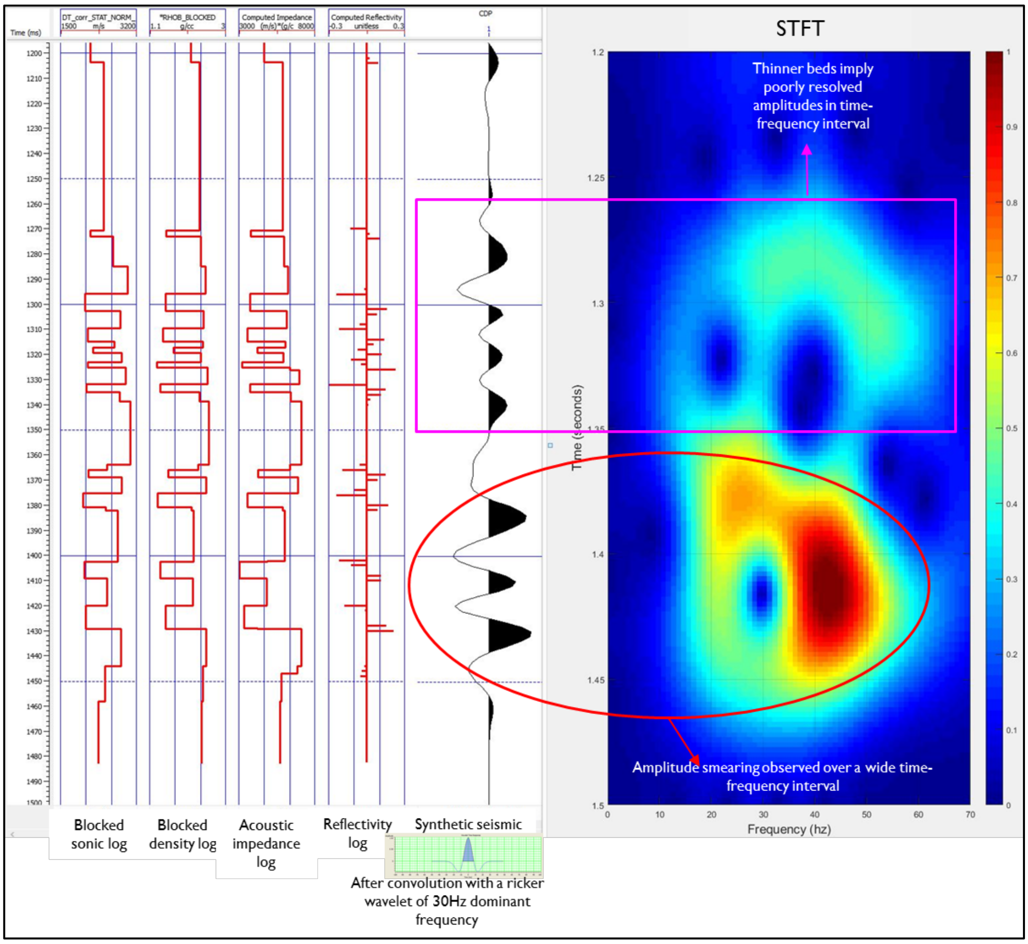
Time → / Frequency ↓	t_1	t_2	$t_3\ldots$	……	$\ldots t_k$
f_1	c_{11}	c_{12}	c_{13}	……	c_{1k}
f_2	c_{21}	c_{22}	c_{23}	……	c_{2k}
$f_3\ldots$	$c_{31}\ldots$	$c_{32}\ldots$	$c_{33}\ldots$	……	$c_{3k}\ldots$
….	….	….	….	….	….
f_i	c_{i1}	c_{i2}	c_{i3}	….	c_{ik}

$$A[f(i), t(k)] = |c_{ik}|$$

i.e. Amplitude at a specific frequency and time is modulus of the spectral coefficient

Figure 1: Schematic explanation of time-frequency decomposition

which help in better characterization of the hidden properties (unresolved) of the seismic signal.



Modelling Results (1D &2D)

Figure 2: Conventional spectral decomposition of a 1D synthetic trace

The algorithm for SynCWT was implemented in MATLAB and applied on the synthetic data described in figure 2. The resultant spectral decomposition is shown in **Figure-3**. As is obvious, in the deeper sequence, there are two frequencies (20-22Hz & 35-40Hz) in the interval 1380-1450ms (shown in red oval) which demonstrate significant amplitudes. This is characteristic of a coal infested interval wherein there are alterations of thick coal events (8-10m) spanning thicker sand/shale units (15-20m). Similarly, in the shallower sequence (1270-1350), there are three distinct frequencies (shown in magenta rectangle), varying with time, at which high amplitudes are distinguishable. This distinct identification of frequencies was not available in Figure-2, thus enabling thin bed delineation. In the shallower sequences, multiple thin coal beds are interspersed in a clastic sequence and in a traditional seismic dataset, such zones appear as poor resolution zones, however, their interpretation may be improved by application of the SynCWT workflow. Traditionally, after spectral decomposition, multiple volumes of different frequencies are interpreted separately. This workflow when applied on the SynCWT results should intuitively reveal additional events in comparison to the same spectral volume of conventional spectral decomposition. This is elucidated by application of SynCWT and conventional spectral decomposition process on a 2D line extracted along a well from a seismic data belonging to the Western onshore area of India. This particular seismic data is influenced detrimentally due to coal presence in the sub-surface.

Figure 4 compares the result of conventional and SynCWT based spectral decomposition corresponding to 18Hz & 35Hz. It clearly shows the zones where amplitudes get preferentially illuminated in the SynCWT section, suggesting possible changes in reservoir thickness or reservoir quality. This suggests that SynCWT based spectral decomposition is able to capture reservoir heterogeneity, in this case, being caused due to coal.

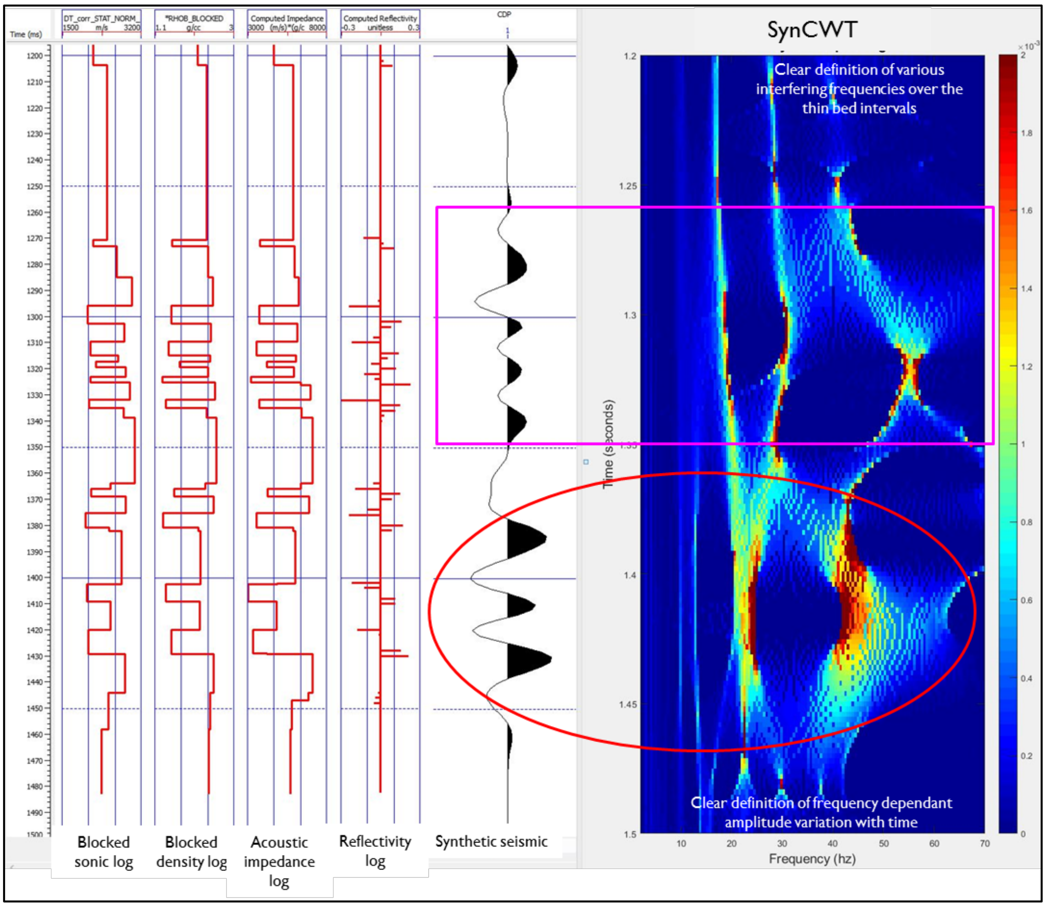


Figure 3: SynCWT spectral decomposition of the 1D synthetic trace

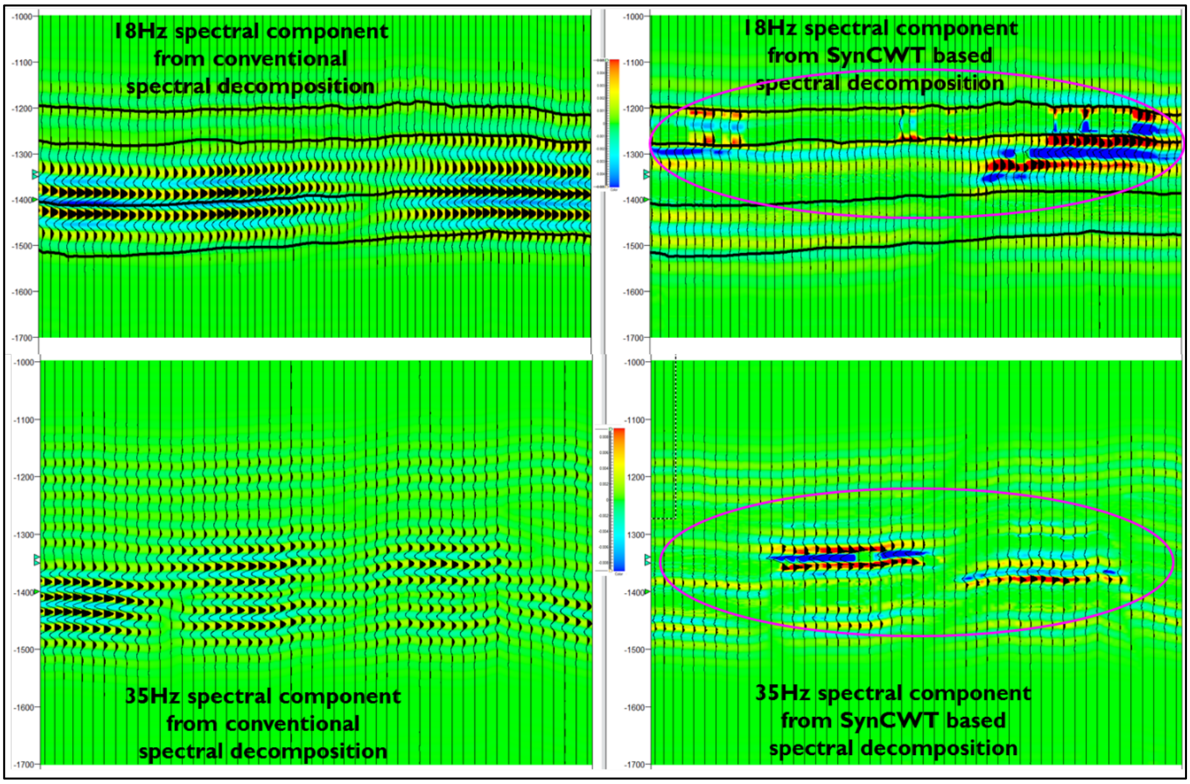


Figure 4: Comparison of 18Hz & 35Hz spectral components vis-à-vis conventional and SynCWT spectral decomposition

Application on 3D seismic data

The SynCWT workflow was applied on a 3D volume along with the conventional spectral decomposition. Three specific frequency volumes were considered for this analysis i.e. 18Hz, 25Hz and 35Hz. RMS amplitude was extracted along a horizon (around 1200ms) from these volumes corresponding to each spectral decomposition method. The results were compared in Figure 5, 6 and 7 for various frequencies. Figure 5 shows that in conventional spectral decomposition the separation between the highest and lowest amplitudes is diffused, whereas this separation is clearly demarcated in the corresponding slice using SynCWT decomposition. This is indicated by the magenta and blue polygons in Figure 5. Similar observations are valid for Figure 6 & 7. These results are in congruence to prior observations wherein SynCWT appears to be a better spectral decomposition tool in comparison to conventional spectral decomposition in terms of better time-frequency isolation of amplitudes.

Conclusions

Any time frequency representation is severely affected by Gabor's uncertainty i.e. exact identification of time & frequency of a specific amplitude is uncertain. This, in turn, limits the scope of interpretation from spectral components in extreme reservoir scenarios (thin bed sequences below seismic resolution). In this context, the applications of the new SynCWT algorithm for spectral decomposition has been demonstrated in this paper wherein, improvement in spectral resolution (time-frequency isolation) has been achieved thereby aiding successful delineation of thin bed interfaces in 1D,2D and 3D scenarios. The SynCWT method has far reaching applications in the seismic driven reservoir characterization and it should be the future of spectral decomposition related tools.

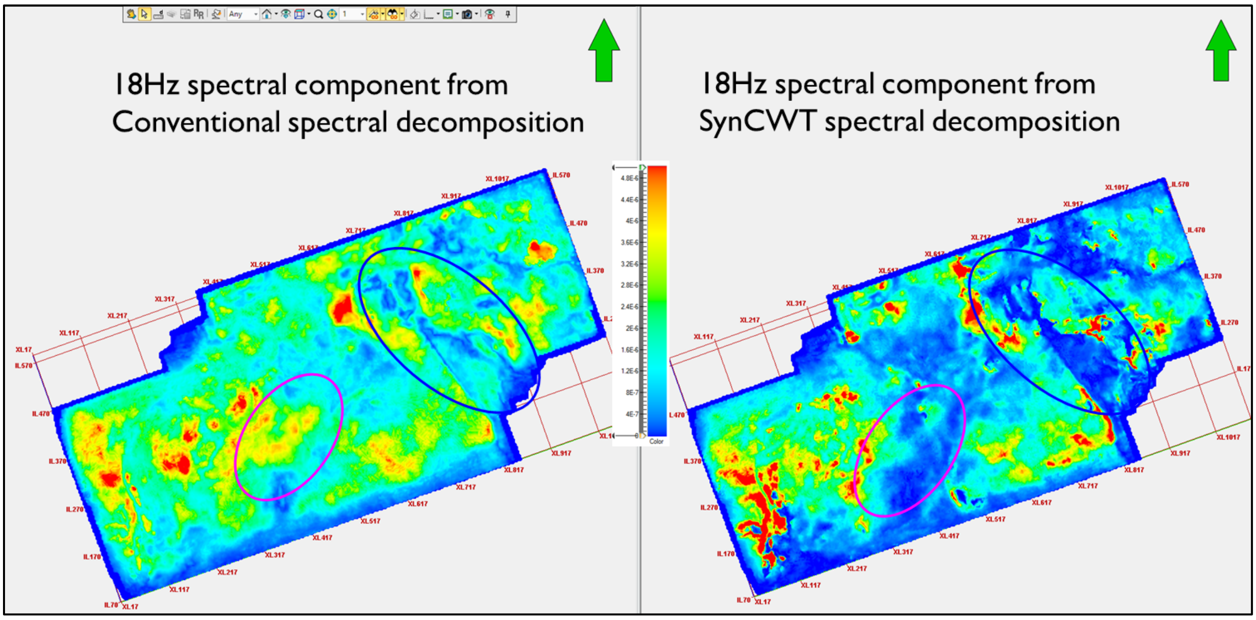


***Figure 5:** Comparison of 18Hz spectral component vis-à-vis conventional and SynCWT spectral decomposition for a specific horizon*

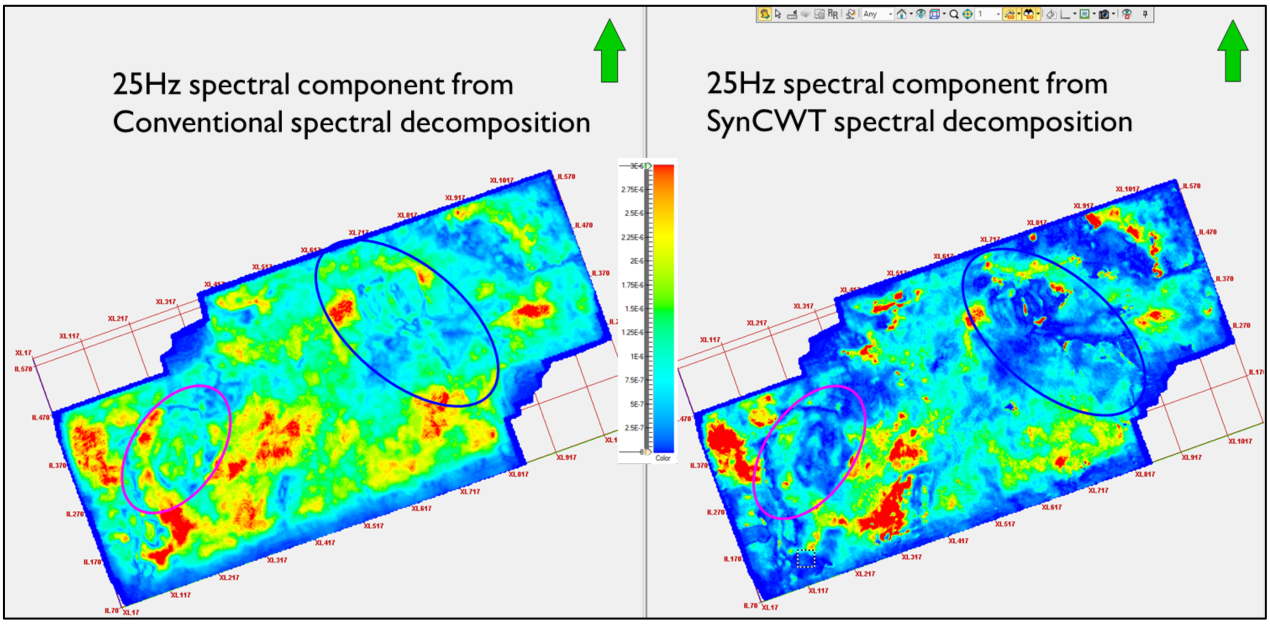


***Figure 6:** Comparison of 35Hz spectral component vis-à-vis conventional and SynCWT spectral decomposition for a specific horizon*

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