A DTDF ENVIRONMENT FOR TIME-FREQUENCY SIGNAL ANALYSIS AND REAL-TIME APPLICATIONS

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ABSTRACT

In our everyday life we are surrounded by phenomena whose spectral content varies as time evolves, such as biological signals, electrical signals, speech signals, etc. The tools used to treat these signals are known as “time-frequency representations”. This on going work presents the development of a computational environment that makes uniform characterization of some well-known time-frequency representations through a MATLAB environment to study the spectral content of sensor-based time-varying spectrum signals on specific applications.

1. INTRODUCTION

Time varying spectra is one of the most primitive sensations we experience since we are surrounded by light of changing color, by sounds of varying pitch and by many other phenomena whose spectral content vary with respect to time. With time-frequency signal analysis tools one can study and analyze these signals and identify the temporal localization of the signal’s spectral components (Figure 1). In particular, the values of the time-frequency representation of the signal provide an indication of the specific times at which the spectral components of the signal are observed.

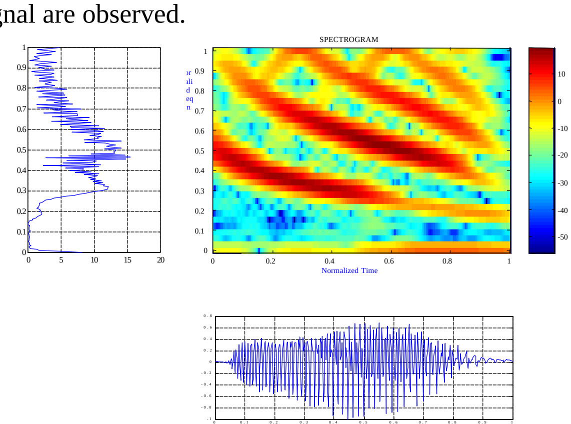


Figure 1. Graphical representation of a time-frequency signal. Its spectrum at the left, its time representation at the bottom, and its time-frequency representation through the spectrogram at the center. This signal is the echolocation pulse emitted by the large Brown Bat, Eptesicus Foscus (The author wishes to thank Curtis Condon, Ken White, and Al Feng of the Beckman Institute of the University of Illinois for the bat data and for permission to use it in this paper).

This is of special importance since the frequency contents of the majority signals encountered in our everyday life change over time; for example, biomedical signals, power signals, speech signals, stock indexes time series, and seismic signals.

This fact is fostering the implementation of time-frequency signal analysis tools in many important scientific and engineering applications, such power line signal analysis, SAR (Synthetic Aperture Radar), spread spectrum signal detection and the analysis of FM signals such as chirp signals (Figure 3).

This paper discusses the design, development and implementation of a discrete-time discrete-frequency (DTDF) environment for signal analysis using time-frequency representations. The DTDF environment makes a unified characterization of some well-known time-frequency signal analysis representations, such as the discrete ambiguity function (DAF), the Wigner Distribution (WD), the short-time Fourier transform (STFT) and the discrete wavelet transform (DWT). The DAF is a time-frequency representation that is broadly used in radar and sonar applications. The WD is widely used for signal detection and parameter estimation. The STFT is widely used in applications such as speech recognition. A relatively new emerging tool is the discrete wavelet transform that is frequently used in applications such as transient signal analysis and image compression.

This paper is organized as follows. In section 2 the mathematical representation of the DAF, the WD, the STFT and the DWT is explained. In section 3 we present the computational environment and explain in detail its internal structure. Section 4 then presents and discusses some results in applications such as SAR. Finally, in section 5, some conclusions are discussed.

2. TIME-FREQUENCY REPRESENTATIONS

The Fourier transform has been the most common tool to study a signal's frequency properties. It establishes in conjunction with the inverse Fourier transform a one-to-one relationship between the time domain and the frequency domain or spectrum space of the signal, which constitute two alternative ways of looking at a signal. Although the Fourier transform (Figure 4) allows a passage from one domain to the other, it does not allow for a simultaneous combination of the two domains.

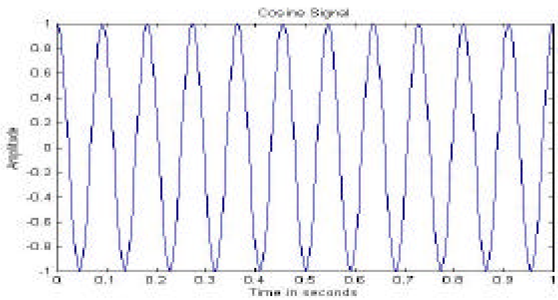


Figure 2. Cosine: a single tone signal, its spectral characteristics does not vary with time.

This presents a problem if we are interested in studying the frequency components of signals which are transient, or their spectral content vary as a function of time, e.g., speech signals.

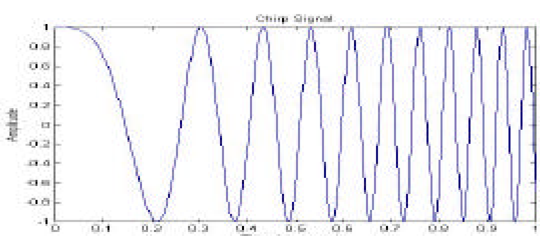
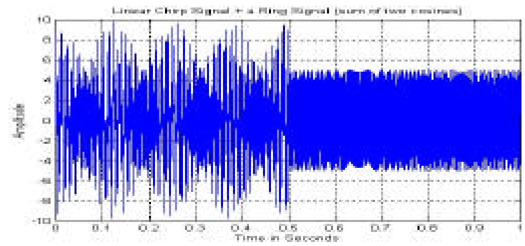


Figure 3. Linear chirp signal (a band of frequencies), its spectral characteristics do vary with time.

Because of the need to explain such signals, the field of time-frequency signal analysis arose. Its main aim is to develop the physical and mathematical ideas needed to understand what a time-varying spectrum is and to use these methods for practical problems (Figure 5).

The tools already exist individually. It then emerges an imperative need of an environment that can create a uniform characterization of these tools for signal analysis in different engineering applications.



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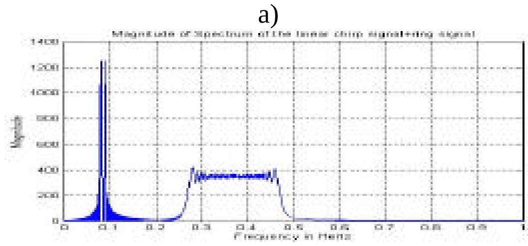

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Figure 4. A time-frequency signal: linear chirp signal + ring signal (sum of two cosines)..a) Its graphical representation in time. b) Its Fourier transform. *We can identify the single tone of the ring signal (left) and the spectrum of the chirp signal changing (right). *Note that with only this information it is difficult to determine which signal proceed the other, and the particular spectral characteristics of each signal.

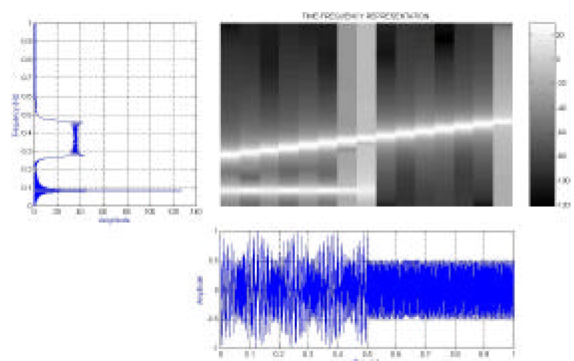


Figure 5. Time-frequency (STFT-explained in section 2.3) representation of time-frequency signal in Figure 5.

Within time-frequency tools, the discrete ambiguity function, the short-time Fourier transform, the discrete Wigner distribution and the discrete wavelet transform seem to possess properties that can be very significant for their application to important problems encountered in time-frequency signal analysis. For this reason, we considered it a practical decision to concentrate in these four tools. We proceed to describe these tools in more detail.

2.1 Ambiguity Function (DAF)

The DAF is a time-frequency representation that has as its objective to extract parameters such as frequency shift and time delay from a specific signal (parameter estimation), and is frequently used for signal estimation and Doppler effects. It is defined as follows:

$$A_{x,y}[k,m] = \sum_{n=0}^{N-1} x[n] \cdot y^{*}[n+m] \cdot W_N^{kn} \qquad (1)$$

where, $W_N = e^{-j\frac{2p}{N}}$, $j = \sqrt{-1}$, x is the transmitted signal, k is the frequency shift, y is the received signal, and m is the time delay. Also, * denotes complex conjugation.

2.2 Discrete Wigner Distribution (WD)

The WD was first introduced in the field of physics. It is defined as follows [3]:

$$W_{x,y}[m,k] = \frac{1}{2N} \sum_{n=0}^{N-1} x[n] \cdot y^{*}[m-n] W_{2N}^{k(2n-m)} \qquad (2)$$

where, $W_N = e^{-j\frac{2p}{N}}$, $j = \sqrt{-1}$, x is the transmitted signal, k is the frequency shift, y is the received signal, and m is the time delay. Also, * denotes complex conjugation.

2.3 Short-Time Fourier Transform (STFT)

The STFT is a time-frequency tool that consists of a Fourier transform with a sliding time window. The time localization of frequency components is obtained by suitably pre-windowing the input signal. The STFT is defined as follows:

$$S_x[n,k] = \sum_{m=0}^{M-1} x[m] \cdot w[m-n] \cdot W_M^{km} \qquad (3)$$

where, $W_N = e^{-j\frac{2p}{N}}$, $j = \sqrt{-1}$, x is the input signal, w is the analysis window, k is the frequency offset, and m is the time delay.

2.4 Discrete-Wavelet Transform (DWT)

It is defined as the sum over all the time of the signal multiplied by scaled, shifted versions of the wavelet function *g*.. Given a finite energy signal $x(t)$ and a normalized sampling period $T_s = 1$, we can present a discrete wavelet analysis of the sampled sequence $x[n] = x(t)\big|_{t=nT_S}$, $n \in Z$ as follows:

$$c[s,b] = c[l,k] = \sum_{n=0}^{N-1} x[n] g_{l,k}[n] \qquad (4)$$

where, $s = 2^l$, $b = k2^l$, $l,k \in Z$ and $g_{l,k}[n] = 2^{-\frac{l}{2}} g[2^{-l}n - k]$.

The discrete synthesis operation can be presented as follows:

$$x(t) = \sum_{l \in Z} \sum_{n \in Z} c[l,k] \Psi_{l,k}(t) \qquad (5)$$

where, $\Psi_{l,k}(t) = 2^{-\frac{l}{2}} \Psi(2^{-l} t - k)$, $l,k \in Z$

3. COMPUTATIONAL ENVIRONMENT

The main objective of the environment presented in this paper is the design, development and implementation of a single framework that combines discrete-time and discrete frequency concepts. The framework has been developed with the use of the software package MATLAB. The environment implements discrete-time discrete-frequency versions of well-known time-frequency representations, such as the discrete ambiguity function (DAF), the discrete Wigner distribution (WD), the short-time Fourier transform (STFT), and the discrete wavelet transform (DWT). The environment is divided in three major modules: Analysis and Synthesis module (Figure 6), Demonstration module and a Tutorial module (Figure 7). The Analysis and Synthesis Module provides the user with the essential tools for managing different types of signals as: *.WAV, *.MAT, *.ASCII. It possesses capabilities of retrieval and storage of data. In the environment, special attention was given to the graphical visualization and data rendering capabilities, since signal analysis is one of our man concerns. This part allows the user to choose the type of plot, the color-map, the shading and to rotate the figure. The environment also allows individual use of the tools and comparison of tool application results.

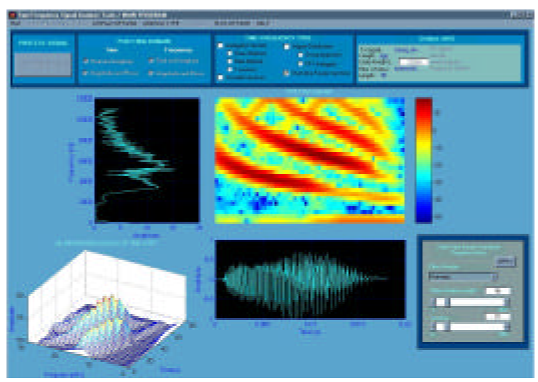


Figure 6. Computational Environment in MATLAB.

The Demonstration Module is a self-paced, step by step demonstration of the entire environment, including a user's guide, which has sufficient information on how to use the environment effectively. The tutorial module (Figure 7) serves as a teaching and reference tool to the user for the technical aspects related with the development of the environment.

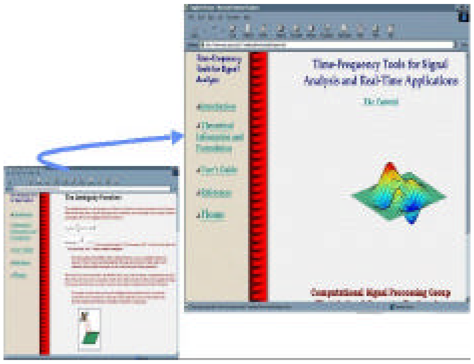


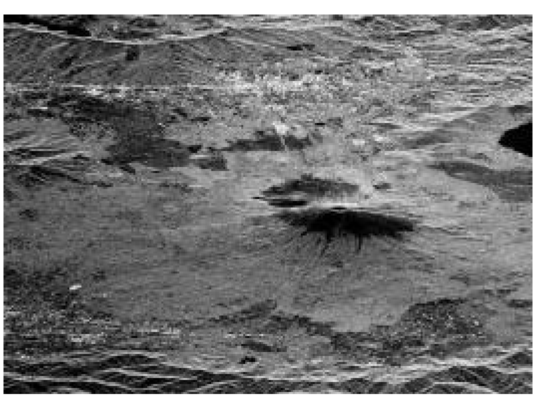
Figure 7. The tutorial in HTML format.

In the following section some results obtained in applications such as SAR signal analysis are discussed.

4. APPLICATION RESULTS

At the present time we have tested the DTDF environment in various applications such as speech and chirp signal analysis. Now, we are using the environment in the analysis of the raw SAR data before the image formation, as a pre-processing operation in order to detect the RF interference. As an example we present two images shown in Figure 8. Figure 8a contains a clean SAR image of Mount Fuji, located in Japan. Figure 8b contains the same SAR image, but the image has been degraded by simulated RF interference, that appears as horizontal bright lines.

We first analyzed the range line of data extracted of the image without interference. Its real part is depicted in Figure 9a. Also the spectral content of this range line was analyzed using the Fourier transform (Figure 9b). The same analysis was performed with the degraded SAR image (Figure 9c,d). Here the interference signal can be visually identified in the amplitude/No. of samples plot as spikes (Figure 9c), but within the amplitude/frequency plot the interference signal can not be easily detected (Figure 9d).



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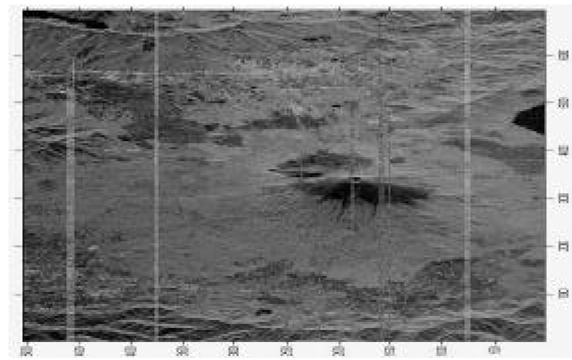

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Figure 8. a) SAR image of Mount Fuji located in Japan. b) SAR image degraded by simulated RF interference.

Since this range spectrum is very noisy it is difficult to decide, whether a peak is caused by RF interference or by a target on the ground. This led us to the next step where a time-frequency signal analysis was performed. We proceeded to use the STFT. Figure 10 depicts the result of the STFT of the examined range line in Figure 9, showing the spectrogram, and a three dimensional surface plot of the STFT. The spectrogram is defined as the square magnitude of the STFT, and it provides a distribution of the energy of the signal in the time-frequency plane.

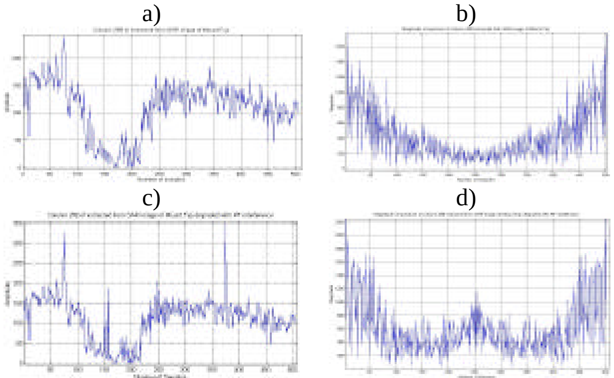

Figure 9. a,b) Graph of column 298 of SAR image in Figure 9a and its corresponding spectrum; c,d) Graph of column 298 of SAR image in Figure 9b that has been degraded by simulated RF interference and its corresponding spectrum.

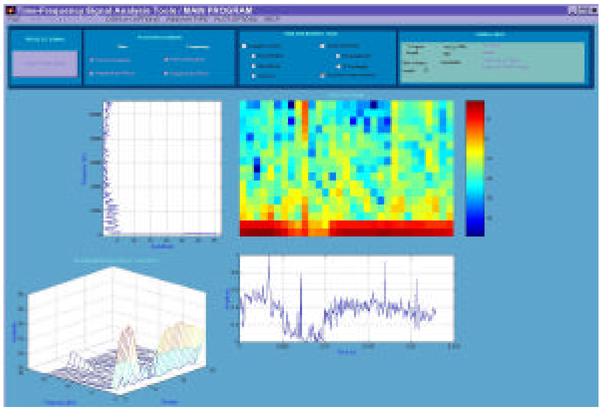

Figure 10. STFT of signal in Figure 9c

The frequency axis is in the vertical direction, and the time axis is in the horizontal direction. The range line is subdivided into several segments where each segment is converted into frequency domain and all together form the STFT. At the right of the spectrogram, the color bar helps determine the content of frequency at a specific time. The blue color (bottom of the color bar) means low quantity of frequency content and the red (top of the color bar) means high quantity of frequency content. From here we can determine that there is high content of frequency at low frequencies. Now the interference signal still appears, as a peak in the frequency domain and the extension of this maximum in time is also visible.

5. CONCLUSIONS

A computational environment for the analysis of discrete time discrete frequency (DTDF) time-frequency signals has been presented. Application results using the DTDF environment were discussed, where the main objective was the detection of RF interference that can degrade the SAR image formation process can be improved by the use of time-frequency signal analysis tools. For this the STFT was used. The RF interference can be detected and visualized easily in the time-frequency plane. This makes it easier to develop filters for the interference removal.

6. REFERENCES

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