Abstract— In this paper, we apply a new technique for the representation of terahertz time-domain spectroscopy (THz-TDS) data in time-frequency domain based on Stockwell transform (S-Transform). The S-Transform performs a joint time-frequency analysis which is not the case of the classic Fourier transform where only the frequency content of the signal is provided. Because of S-Transform phase characteristic, it can be employed in cross spectrum analysis and feature extraction. The cross S-Transform matrix is calculated and represented for different substances and showed a significant information that can be used to discriminate between different illicit substances.

Keywords: THz-TDS, time-frequency analysis, S-Transform, cross S-Transform.

I. INTRODUCTION

The security context has changed drastically over the past years. Indeed, fast and reliable detection and identification of dangerous chemical and biological substances is of utmost importance for most safety and security applications. The increased uses of improvised explosives as well as the introduction of new synthetic drugs have spurred the demand for novel detection schemes [1].

Terahertz time-domain spectroscopy has proven to be a very promising technique for detection purposes, as many organic molecules show very characteristic spectral fingerprints in the THz region [2]. Although the strong attenuation of THz radiation in ambient air seems to favor close-contact applications, recent developments have revived the interest in this technique for remote detection purposes.

In most applications, the analysis of the signal is based on the Fourier representation of directly detected THz pulse waveforms [3]. The Fourier analysis, however, does not reveal any time-domain information thus Fourier transform may not be a sufficient tool of analysis and non-stationary signal enhancement. Unfortunately, reflection spectra for many compounds are very similar [4]. Therefore, the simple correlation method is often not sufficient to distinguish substances. Additionally, limited dynamic ranges [5] as well as scattering and diffraction contributions often strongly hinder a simple spectral recognition based purely on the signatures obtained in the Fourier representation. On the other hand, physical perspicacity of the temporal behavior of the transmitted electro-magnetic pulses has often not been investigated in detail up to now. Therefore, joint time and frequency representation provide a better description of signals in time-frequency planes.

The aim of this paper is to investigate benefits of the dynamic analysis by an alternative signal processing method, Stockwell Transform (S-Transform) [6], for an increased performance of the recognition of the temporal and spectral characteristics of different selected samples. By exploiting the full information contained in the data, complementary information may be obtained which can then ultimately help to improve the reliability of the detection scheme.

The classical method includes a cross-spectral analysis to study the phase synchrony and source localization of non-stationary signals [7]. Since the S-Transform localizes spectral components in time, the cross correlation of specific events gives the phase difference and the amplitude of the cross S-Transform indicates coincident signals. The phase of the cross S-Transform at local maxima indicates the phase difference between them.

II. S-TRANSFORM

The S-Transform, introduced by Stockwell et al. [6], combines the stoutness of the Short Time Fourier Transform (STFT) and continuous wavelet transform (CWT) and provides an alternative approach to process the non-stationary signals. It employs a moving and scalable localizing window length. The frequency dependent window function produces sharper time localization at higher frequencies and higher frequency resolution at lower frequencies. Furthermore, the S-Transform has an advantage in that it provides multi-resolution analysis while it is capable of obtaining reasonably accurate amplitude and phase spectrum of the analyzed signals even at the presence of high level of noise [8].

The S-Transform of a time series \( h(t) \) is defined as

\[
S(\tau, f) = \int_{-\infty}^{\infty} h(t) g(\tau - t, f) \exp(-i2\pi ft) dt
\]

(1)

where the Gaussian modulation function \( g(\tau, f) \) is given by

\[
g(\tau, f) = \frac{|f|}{\sqrt{2\pi}} \exp \left( -\frac{\tau^2}{2\sigma^2(f)} \right)
\]

(2)

and the standard deviation

\[
\sigma(f) = \frac{1}{f}
\]

(3)

where \( f \) is the frequency, \( t \) and \( \tau \) are both time.

Since the S-Transform localizes spectral components in time, the cross correlation of specific events gives the phase difference and the amplitude of the cross S-Transform indicates coincident signals. The phase of the cross S-Transform at local maxima indicates the phase difference between them.

The cross S-Transform of two signal \( x(t) \) and \( y(t) \) is defined as
\[ \text{crossST}(t,f) = S_r(t,f) S^*_r(t,f) \]  

where * indicates the complex conjugate.

Indeed, as with classical co-spectrum analysis, the real part of the crossST function gives the in phase components of the local spectra. The imaginary part of the crossST function gives in quadrature components.

III. RESULTS

To report on the performance of the method, we apply the crossST function to analyze the in phase and out of phase components in time-frequency space between two chemicals entities: cocaine and different commercially available generic of ibuprofen.

Figure 1 illustrates the time series (top), spectrum (left) and the S-Transform representation of pure cocaine (a) and ibuprofen (b). The S-Transform shows the complexity of the information and illustrates the richness of the time-frequency representation. The different complexities of the samples could be distinguished. Therefore, the time-frequency domain can be potentially more discriminant than the classic Fourier analysis.

![Fig. 1](image)

The crossST calculated on identical products, as mentioned previously, demonstrate the difference between them. This sensibility could be important to assess the degree of impurity in understudy sample. The real part of the cross S-Transform function gives the in phase components of the local spectra and the imaginary part gives the in quadrature components. This sensibility could be important to assess the degree of impurity in understudy sample.

Future work will focus on time-frequency filtering and feature extraction methods based on S-Transform to validate it on large database of different illicit substances.

IV. SUMMARY

The cross S-Transform calculated on identical products demonstrate the difference between them. The real part of the cross S-Transform function gives the in phase components of the local spectra and the imaginary part gives the in quadrature components. This sensibility could be important to assess the degree of impurity in understudy sample.

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REFERENCES