

Time-Frequency Signal Representations Applied to Ultra Wideband Radar

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Abstract: The article shortly discusses possible applications of time-frequency signal representations (TFRs) in ultra wideband (UWB) radar. The article provides a short introduction into the field of TFRs. Then, in order to illustrate the advantages of TFR application in UWB radar, an example of its use in radar processing techniques such as Kirchoff migration is presented. It is shown how the focused radar image resolution and quality can be enhanced using a TFRs extended migration.

Introduction

Ultra wideband short range radar and measurements are of great importance for numerous applications such as surface penetrating radar, surveillance and emergency radar, medical instrumentation, non destructive testing in civil engineering, industrial sensors, microwave imaging etc. In many of these cases, sounding waves must penetrate into liquid or solid materials. In contrast to classical radar such UWB radar applications demand carrier free test signals having a relative bandwidth as wide as possible in order to guarantee high resolution in space.

Often the target scattering observed by the UWB radar is very complex and difficult to interpret. Therefore, it is unfortunately impossible to extract all information about this signal behaviour neither in the time nor in the frequency domain. The large relative bandwidth of UWB systems ideally meets the requirements to examine the scattering and propagation behaviour of the radar waves jointly in time (propagation delay) and frequency, which underlines the importance to implement TFRs. Possible applications may be found in different areas such as:

- Characterisation of the dispersion of the propagation medium due to moisture, random scatterer or the similar one
- Feature extraction of Mie-scatterer (resonant scatterer)
- Analysis of UWB antennas and components
- Analysis of time variant scenario etc.

Furthermore, TFR may be used to suppress or to emphasise certain physical effects in the acquired radar data in order to simplify the interpretation of the target behaviour or to enhance the quality of radar images.

This article is aimed to give a short overview of TFRs theory, to discuss some ideas of TFR application in the field of UWB radar and to provide an example of TFR application in radar processing techniques used for data focusing by Kirchoff migration.

Time Frequency Representation

There is a wide variety of TFRs that possess different features. At the present time, two important TFR groups are discussed - linear and quadratic ones. Short-time Fourier transforma-

tion (STFT) and wavelet transformations can be given as the most important examples of linear TFRs. The quadratic TFRs are however used more frequently than the linear TFRs because of their better time-frequency resolution. On the other hand, quadratic TFRs feature disturbing cross-terms making the interpretation of multi-component signals very difficult. An important class of quadratic TFRs is called the Cohen class [1]. The Wigner distribution (WD) and the spectrogram are the most well known quadratic TFRs belonging to the Cohen class.

The WD is defined by the following formula

$$WD_x(t, f) = \int_{-\infty}^{\infty} x\left(t + \frac{t}{2}\right) x^*\left(t - \frac{t}{2}\right) e^{-j2pft} dt, \quad (1)$$

in which $x(t)$ represents the analysed signal and $*$ stands for the complex conjugation. It features the best time-frequency resolution. However, the WD possesses large amount of the cross-terms. Cross-terms are caused by non-linearity implied in the definition (1).

The spectrogram is defined as a square of the STFT

$$SPEC_x(t, f) = |STFT_x(t, f)|^2 = \left| \int_{-\infty}^{\infty} x(\mathbf{t}) w(\mathbf{t} - t) e^{-j2pft} d\mathbf{t} \right|^2, \quad (2)$$

where $w(t)$ represents a window function. The spectrogram possesses features opposite to the WD. It means that the spectrogram has poor time-frequency resolution and it is almost cross-terms free.

Beside the WD and the spectrogram, there exist a wide variety of quadratic TFRs belonging to the Cohen class that suppress disturbing cross-terms. However, the cross-term suppression is achieved only at the expense of a decreased time-frequency resolution.

Recently, higher order time-varying spectra have been defined. A special case of the higher order time varying spectrum is the L-Wigner distribution (LWD)

$$LWD_L(t, f) = \int_t x^{*L}\left(t - \frac{t}{2L}\right) x^L\left(t + \frac{t}{2L}\right) e^{-j2pft} dt \quad (3)$$

and its dual form (DLWD)

$$DLWD_L(t, f) = \int_t X^{*L}\left(f - \frac{q}{2L}\right) X^L\left(f + \frac{q}{2L}\right) e^{-j2pqt} dt, \quad (4)$$

where $x(t)$ is the analysed signal and $X(f)$ is its complex spectrum. L refers to the order of the LWD, or the DLWD respectively.

Comparing definitions of the WD and the LWD, or the DLWD, it is easy to see that there is implied much more non-linearity in the definition of the LWD and the DLWD than in the WD. Therefore, the LWD and the DLWD possess much more disturbing cross-terms. Fortunately, there exist recursive methods for the computation of the LWD [2] and the DLWD [3]. TFRs obtained by the recursive formula from the LWD and the DLWD are referred to as modified LWD and modified DLWD (MDLWD), respectively. The modified LWD and the MDLWD feature low presence of cross-terms and simultaneously good time-frequency resolution.

Since the MDLWD of the first order performed the best results in our experiments, a particular concentration will be paid to the results computed just by this method. In what follows, some examples illustrate the advantages of a TFR-analysis for UWB radar systems characterisation and for radar image enhancement if Mie-scatterer occurs.

TFRs application in UWB radar systems

UWB antennas: One of the possible areas concerns the characterisation of Impulse Radiating Antennas (IRA's) by the TFR-analysis. The development of such antennas is of fundamental importance since their characteristics directly influence the performance of the whole radar system. The shorter is the impulse response of the antennas, the better is possible resolution of the radar system or the easier is the interpretation of the measured data. Resonant effects should be avoided as much as possible. Some general ideas to characterise UWB antennas or IRA's respectively for radiation in solid media are explained in [4]. No attention was however given to investigating resonances that may be caused by the antenna structure itself or by the interaction within an antenna array. With help of the TFR-analysis this drawback may be overcome. Figure 1 shows an example, which enhances the resonance effects caused by the interaction of two adjacent Vivaldi antennas. Note that a short impulse gives a vertical strip in the time-frequency diagram and resonances are horizontal structures.

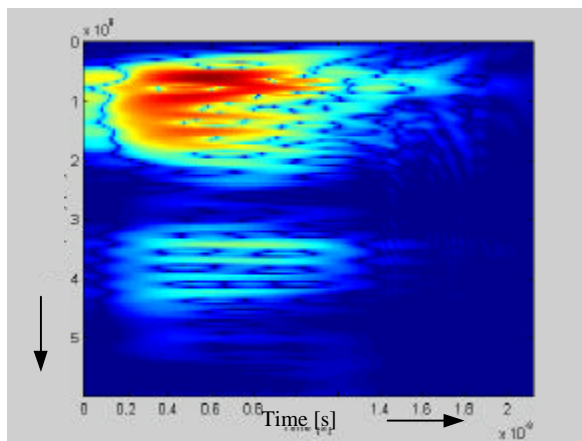


Figure 1 LWD of the cross talk between two Vivaldi antennas used in the radar scanner [6]

Dispersive medium: There are several reasons why a medium is dispersive. One of them is the presence of moisture. The electric permeability of water is frequency dependent. Thus, the behaviour of the material containing moisture is also frequency dependent resulting in a smearing of the shape of a pulsed wave travelling through the medium. This is caused by the fact that different frequencies of transmitted impulse propagate with different velocities. This phenomenon may not be observed in the time nor in the frequency domain, it can however be observed in the joint time-frequency domain using appropriate TFR. Applied TFR should provide reasonably good time-frequency resolution without the

large amount of the disturbing cross-terms. The description of the dispersive medium in the time-frequency domain can be advantageously used for moisture determination. With regards to the fact that TFR provides 2D signal representation it can be supposed that a method using TFRs can replace methods frequently used for material moisture determination such as time domain reflectometry or resonant methods.

TFRs radar image enhancement for Mie-scatterer

Applied to Surface Penetrating Radar (SPR), the IRA's are moved over the surface of the area under test. In that case, a single point scatterer buried in the medium leaves a hyperbolic track (hyperboloid) in the radar data (B-scan, radar volume). For simple cases these characteristic tracks serve as indication of a small buried objects but in more complicated situations, one is often dependent upon an enhancement of the radar image by migration [5] in order to regain the shape of complex objects or the distribution of multiple objects. The effect of migration consists in focussing the hyperbola of individual point scatterer into a single point. However,

migration supposes point or specular scattering and omits interaction between different scatterers. Therefore, the focused radar image is blurred in the presence of resonant (Mie) scatterers. This may cause misinterpretations and mistakenly estimated positions of scatterers.

This behaviour will be demonstrated by a simple example – the scattering at a short (13 cm long) thin wire. The presented data were gathered by a laboratory UWB radar scanner available at Technische Universität Ilmenau which allows scanning of an area of 2 meters by 4 meters with 0.75 mm precision in both directions [6].

As long as the resonances of the wire are within the bandwidth of the radar signal the wire behaves as a Mie-scatterer. Figure 2 represents the measurement data showing the typical hyperbolic track of a small scatterer but several times repeated because of the resonance. In the migrated image (Figure 3) a thin high peak should be expected. But obviously this isn't the case. The dominant peak also doesn't coincide with the real position of the wire.

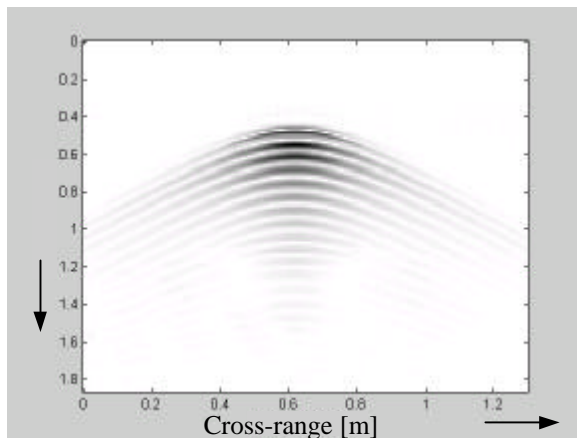


Figure 2 Measurement data in the cross-range propagation time domain

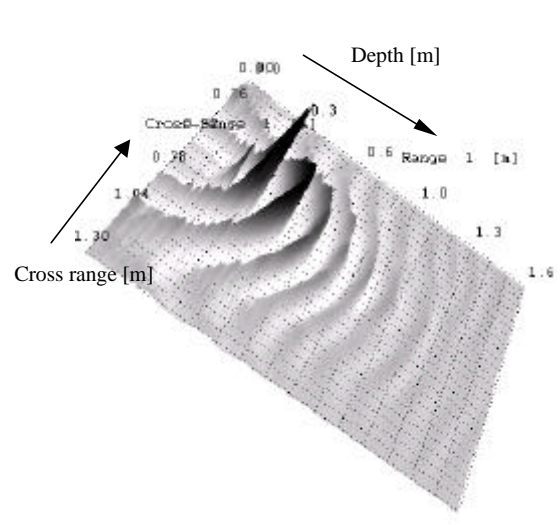


Figure 3 Data in the cross range down range domain after Kirchhoff Migration

With respect to the last inadequacy, it can be shown that by use of TFRs the radar image may be improved. For that purpose, measurement data were processed by a TFR extended migration, in which the migration is performed in time, frequency and cross-range domain (TFCD). In this domain it is possible to reveal simultaneously information about the point and resonant scattering mechanism. Figure 4 indicates their different appearances in an idealised form whereas Figure 5 refers to real data showing an iso-energy surface in the TFCD of the waves scattered by the short wire. Both effects, point and resonant scattering may be well discriminated.

The extended Kirchhoff-Migration is based on this discrimination feature of the TFCD by migrating for example only that data which are situated in a certain "frequency plane". Through this, the radar image can be concentrated on the interpretation of different scattering aspects. In our case the radar image resolution and its quality can be considerably enhanced if only data beyond the "resonance zone" are applied in the migration. This is demonstrated in Figure 6.

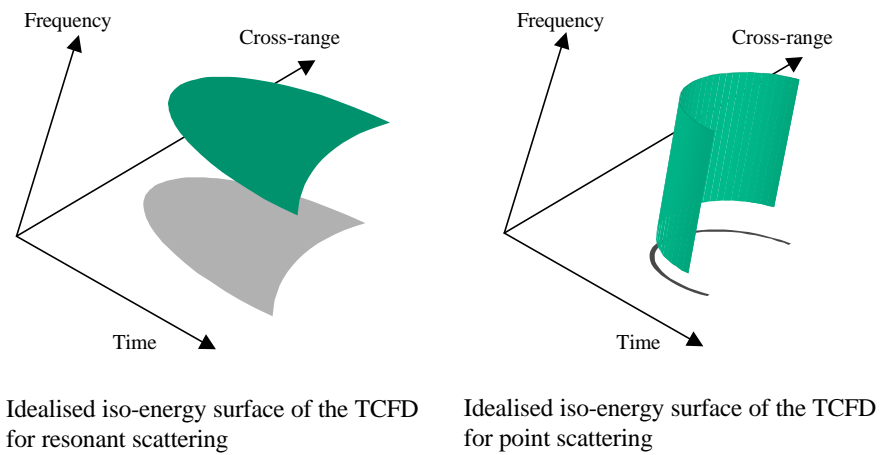


Figure 4 Idealised TCFD's

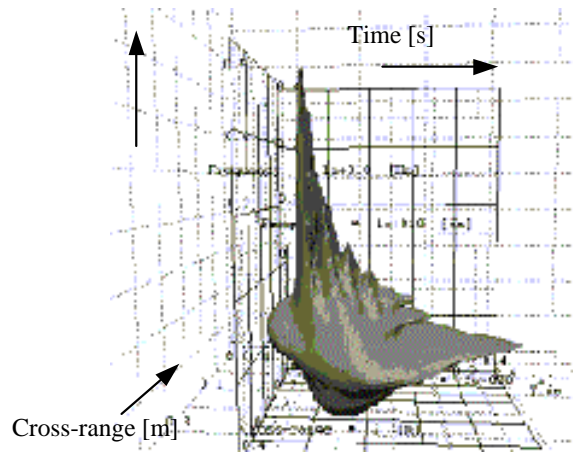


Figure 5 TFCF iso-surface of the scattering signal of a short wire

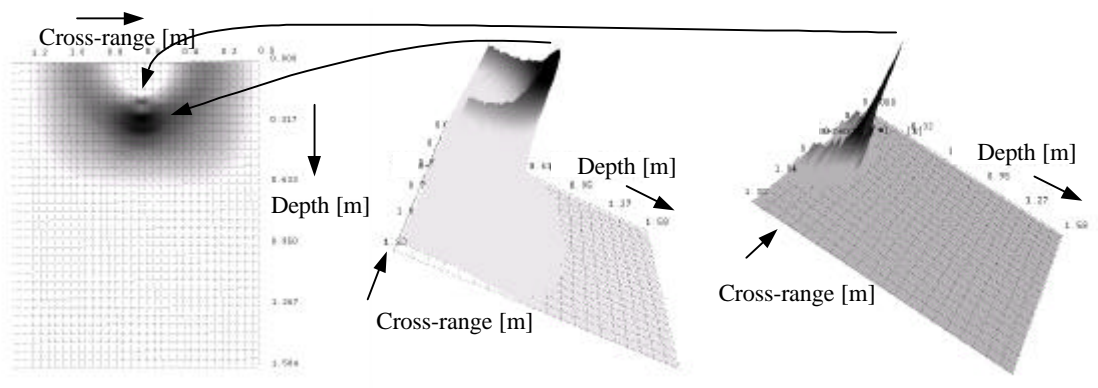


Figure 6 Image enhancement by TFRs extended migration

Left: Classical migration after Hilbert transformation of data. The image is blurred up because of the resonance.

Centre: Migration of "resonant data" in the 1,15 GHz time-cross range plane of the TFCF causing an apparent "over migration".

Right: Migration of "non-resonant data" in the 3,57 GHz time-cross range plane of the TFCF showing the expected sharp data peak of a point scatterer at the correct position.

Conclusion

A short description of the TFRs was given in the article. Some possible TFR application in UWB radar systems were mentioned. An example of the extended Kirchoff migration was presented in which measured data from Mie-scatterer were processed. Obtained results indicate that TFRs can be advantageously used for radar image enhancement. Moreover, data representation in the TFCD which contains more information than the data representation in time or frequency domain can be used for the target recognition purposes.

References:

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