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Thesis of the doctoral dissertation (Ph.D.)

INVERSION-BASED FOURIER TRANSFORMATION ALGORITHM USED IN PROCESSING GEOPHYSICAL DATA

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I. SCIENTIFIC BACKGROUND AND AIMS

Geophysics, when combined with data processing, plays an essential role in the exploration of raw materials, especially in the constantly changing oil and gas industry. It faces new challenges from the increased availability of unconventional resources, shifting supply and demand factors, and environmental pressures, as well as legislative and tax changes and new trends in supply and demand. Geophysics methods are considered the most cost-effective way to gather subsurface data, as they provide low-cost results that offer a large amount of information about the ground structure and other properties. Initially, these methods focused on assessing the potential resources of a basin. However, seismic imaging data obtained through two or three-dimensional processing proved very helpful in understanding the long-term effects of large structures on the earth, leading to positive results and a successful demonstration of the cost-effectiveness of acquiring data about subsurface layers without direct measurement. Advances in geoscience continue to support this premise. Our understanding of the ground layers grows as discoveries are made through cost-effective methods. Currently, geophysicists find seismic to be a particularly compelling method because its workflows are more cost-effective than previous ones for exploring and developing new reservoirs. Modern acquisition and processing techniques provide high-quality subsurface illumination for both conventional and unconventional reservoirs at a lower cost than before. Prestack methods like AVO are used in conjunction with anisotropic velocity analysis to predict the fluid properties of a reservoir. Seismic attributes can be used to indicate stress orientation, the integrity of the overlying cap rock, fault distribution, and reservoir quality. Additionally, these attributes can be used to identify statistical relationships between payout rate and quality through cross-correlation. Easy access to 3D seismic data makes it an essential aspect of many projects, and it is used in a variety of ways, including predicting fluid distribution and migration through rock formations and assessing the performance of enhanced recovery efforts.

When understanding the earth's properties through seismic data, it is frequently suggested to perform a Fourier transform on the x, y, and z axes. This allows for the conversion of complex differential equations into more easily manageable algebraic equations. Performing this with the time axis also helps convert temporal frequency differential equations into traditional algebraic ones. Seismic data analysis relies heavily on the use of the Fourier transform throughout the entire process. A seismic wavefield recorded at a receiver location is called a seismic trace, and its digital form is a time-based series of sinusoids with distinct peaks, frequencies, and phases. The digital data can be transformed into sinusoidal components by performing the Fourier forward transform on the trace, and then an individual Fourier transform is performed in reverse to create the seismic trace from sinusoidal components. Seismic data processing algorithms are often more easily understood when converted into the frequency domain, instead of the traditional time-based method. Frequency filters work well for this process because they use Fourier analysis for their design. These filters are typically multichannel or single-channel and use an operand (such as a trace of seismic activity) and an operator (such as a filter) to process data. To work with digital samples of signals in seismic traces, we need to use the Discrete Fourier transform (DFT), which provides a way to analyze and understand discrete signals in the frequency domain. It is essentially the digital counterpart to Fourier transforms. On the other hand, the inverse Fourier transform is also known as the Inverse Discrete Fourier transform (IDFT), representing the discrete-time version of the inverse transform.

Several factors can affect the accuracy of seismic data, which can be improved using appropriate noise attenuation strategies and implementing signal processing methodologies. The subsequent stages of data analysis incorporate various approaches, including signal processing, statistical analysis, and algebraic calculations. These methods require expertise from both geophysics and other disciplines. Each method typically pertains to a specific target, such as frequency and wavelength filtering, velocity analysis, static correction, deconvolution, and time/depth migration (Yilmaz, 2001). Noise can generate unwanted features and can be divided into incoherent (random) and coherent noise. Incoherent noise can be shown as temporal and spatially random noise, while coherent noise can be shown as linear noise, repercussion, or multiples. The ground roll may also appear in land data surveying and dominate the reflection energy in recorded data. Coherent noise contains low frequencies and large amplitudes (Yilmaz, 2001). This type of noise can be processed by F-K filtering and inverse velocity stacking, but field results have shown that the noise is still present in the seismic data (Maurya et al., 2019). All of these types of noise can cause significant artefacts that have a significant negative impact on interpretation results, from simple structural attributes to prestack impedance inversion and amplitude variations from seismic azimuth-gathers (AVAz) analysis. These noises are linearly projected into the frequency domain during Fourier transformation, meaning that traditional FT algorithms are most sensitive to non-Gaussian noise.

Due to technical issues and the current state of the economy, construction projects may be delayed, leading to missing data in seismic records. Many processes, such as reverse time migration, reverse vector tilt, full waveform inversion, amplitude variation with offset, and more, are heavily impacted by missing data. Therefore, before the data can be used to obtain high-quality results, it needs to be reconstructed from initial seismic data. This becomes increasingly important as the preprocessing stages progress. Different methods have been developed to deal with gaps in seismic records. One such method is wave equation-based reconstruction, which uses the physical properties of seismic waves to create a wave field. However, this method can be costly to use in some applications due to computational limitations. The F-X and F-K domains provide a linear, predictable pattern for prediction filters to use, but this requires the seismic signal data to be equally spaced.

Attributes are specific pieces of hidden information contained within a seismic wave. They represent a smaller subset of the overall information in the original wave and are displayed at the same scale, making them easy to see and understand. They can be computed using a variety of methods. However, the relationships between each attribute can often be complicated. These attributes are calculated to remove extraneous information from the data, making trends or patterns visible that were not present in the original data. They are intended to provide insight into reservoirs that contain oil and gas, as well as information on how they moved and were trapped, by mapping out the geological features associated with hydrocarbon deposits. Cosentino et al., (2001) describes these features as structural elements, such as the thickness and shape of reservoirs, faults, and other geological features. Additionally, a well's petrophysical properties, such as permeability and porosity, are critical to its functionality. The problem here appears when noise exists as in other geophysical methods. Turning inverse problem theory that can help reduce the noisy effect, and consists of a collection of methods that can reject noise and handle it as an overdetermined inverse problem (Dobróka et al., 2012).

Auken et al., (2005) presented an inversion blueprint for continuous resistivity as laterally constrained data as a 1D model and inverted to one system with lateral transitions. They regularized the model and generated the estimated model, which was full of sensitivity analysis of model parameters to apply evaluation of the inversion outputs. The inversion of time-lapse data was used to improve the characterization of the reservoir using full wavefield inversion (FWI), which is capable of determining subsurface changes due to production (Routh et al., 2012). The series expansion-based inversion method was then applied to borehole data in the interpretation process (Szabó, 2015, 2011) and also in processing induced polarization data (Turai, 2011). The 1D Fourier transformation was handled by Szegedi and Dobróka (2014) as a robust inverse problem using the Iteratively Reweighted Least Squares (IRLS) algorithm with Cauchy-Steiner weights (Steiner, 1997), and the results appeared as a significant reduction in noise sensitivity of the continuous Fourier transform. The inversion method gives the ability to estimate the underlying model of physical properties of the rock and fluids to achieve good reservoir characterization (Berteussen and Ursin, 1983). Maurya and Singh, (2020) presented many attributes, such as P-impedance, S-impedance, P-wave, and S-wave velocity, using inversion that depends on creating forward modelling that generates a set of model parameters. Marashly and Dobroka, (2021) showed that the IRLS inversion-based Fourier transform method achieved good results in noise resistance when applied to a synthetic wavelet.

II. ACCOMPLISHED INVESTIGATION

In this Ph.D. thesis, a new inversion-based Fourier transformation (C-IRLS-FT) is introduced using Chebyshev polynomials in discretizing the Fourier spectrum. The procedure is applied to synthetic wavelets and synthetic seismic complex models. The outlier sensitivity rejection for 1D data is assessed using both DFT and C-IRLS-FT methods to demonstrate the ability of Chebyshev polynomials in noise rejection for both Cauchy and Gaussian noise. The technique is then compared with the Legendre Polynomial-based Fourier transform method (L-IRLS-FT) for evaluating its performance in eliminating noise in pre-generated seismic data. In more depth, the inversion-based Fourier transform process (C-IRLS-FT) combined with the Most Frequent Value method (MFV) developed by Steiner can effectively make the Fourier transform more robust.

The robustness of the C-IRLS-FT to outliers and its outstanding noise suppression capability justifies the method being applied in the field of seismic data processing. To make the Hilbert transform more robust, we applied our C-IRLS-FT in its calculation and define a robust analytical signal. As an application example, we calculate the absolute value of the analytical signal that can be produced as an attribute gauge (instantaneous amplitude), also instantaneous phase was tested. The new algorithm is based on dual inversion: the Fourier spectrum of the time signal (channel) is determined by inversion, and the spectrum obtained by the transformation required for the Hilbert transform is transformed back into the time domain using robust inversion. The latter operation is carried out using the Steiner weights calculated inside of the Iterative Reweighting Least Squares (IRLS) method (robust inverse Fourier transform based on inversion). To discretize the spectrum of the time signal, we use the again Chebyshev polynomials in a series expansion. The expansion coefficients are the unknowns in the inversion. The results show that the procedure has remarkable resistance to outlier noise and noise suppression, an order of magnitude better than that calculated by using the conventional DFT in calculating the Hilbert Transform.

Building on the principles of the one-dimensional Hilbert Transform, the two-dimensional (2D) variant has emerged as a potent instrument in image processing. Particularly, it has made considerable strides in earth science-oriented applications, such as edge detection, noise reduction, and image enhancement. The 2D Hilbert Transform is characterized by a convolution operation with a 2D Hilbert kernel, yielding a 2D analytic signal that combines the original image data with its Hilbert Transform. This operation provides valuable insights into spatial frequency content and phase information. In this research, we examine the conventional 2D Hilbert method and the newly developed 2D C-IRLS-HT and 2D H-IRLS-HT (with Hermite basis functions) methods, focusing on their capacity to detect anomalies within noisy datasets. Our findings reveal that the traditional Discrete Fourier Transform (DFT)-based 2D Hilbert Transform encounters numerous challenges, such as substantial noise levels, less distinct edges, and the presence of outliers, which hinders accurate anomaly detection. However, applying the 2D H-IRLS-HT method to a noisy synthetic dataset showed notable improvements in terms of clarity, quality, and noise reduction. The elimination of outliers further enhanced the interpretability of the data, enabling clearer identification of anomaly boundaries. The superior performance of the 2D H-IRLS-HT and 2D C-IRLS-HT methods underscores their potential as reliable alternatives for anomaly detection, especially in challenging environments where conventional techniques might be less effective.

Continuing our exploration, comprehensive geophysical measurements were performed in the eastern region of area Syria, spanning approximately 128 km^2, by an exploration company. Employing a gravity meter and GPS locating, robust measurements were obtained and corrected considering the rock density of the region. These measurements aimed to extract valuable subsurface geological information. During the initial stages of previous research, we utilized Surfer software to identify the structure within the dataset. As the study progressed, we incorporated a more advanced method, the 2D C-IRLS-FT, particularly in the low-pass filter process. This method was systematically applied to evaluate the gravity measurement dataset. Our primary objective was to assess the effectiveness of this method before any comprehensive analysis using a two-dimensional low-pass Butterworth filter. The 2D C-IRLS-FT method, when integrated with Fourier Transform, enabled the decomposition of gravity data into its frequency components, facilitating a more detailed interpretation of subsurface structures. As the investigation continued, the MINIMAG device captured magnetic readings every twenty seconds, highlighting the necessity of applying the 2D C-IRLS-FT method for pole reduction and overall data quality enhancement. The pole reduction process using C-IRLS-FT enhanced the coherence of the geological structures within the dataset, leading to a noticeable improvement in data quality. This process, coupled with the elimination of noise and outliers, resulted in a more distinct representation of the structure, facilitating a more reliable interpretation. Our work also included a novel technique that combined the 2D C-IRLS-FT method and k-means clustering for denoising seismic data, specifically within a seismic section that contained significant noise. This method involved transforming seismic data into the frequency domain, identifying significant spectral components through clustering, and filtering out noise components. The results demonstrated the effectiveness of this method in denoising seismic data, with the filtered data preserving significant spectral components while eliminating the noise. In essence, this study underscores the value of employing advanced methods like the 2D C-IRLS-FT and k-means clustering for data analysis and interpretation in geophysical studies. These techniques fostered robust and accurate interpretations, paving the way for identifying key geological characteristics and assessing the underlying spatial patterns and relationships more accurately.

III. NEW SCIENTIFIC RESULTS

1. Thesis One

I have developed an improved inversion-based Fourier transformation method with Chebyshev polynomials, as basis functions (1D C-IRLS-FT) using one-dimensional synthetic datasets. Using a time-domain 1D synthetic wavelet (contaminated with Gaussian- and Cauchy noises) a comparison is made between the proposed inversion-based technique and the conventional Discrete Fourier Transformation (DFT) method. The results indicate that the inversion-based Fourier transformation (1D C-IRLS-FT) method demonstrates the robustness and a significant ability to mitigate the influence of outliers compared to the outcomes achieved using the conventional DFT method.

2. Thesis Two

Owing to the effectiveness of the IRLS inversion technique in processing 1D datasets, the inversion-based Fourier transformation algorithm is further developed for the processing of 2D datasets with the use of the Chebyshev polynomials as a basis function (2D C-IRLS-FT method). To assess the accuracy, stability and outlier sensitivity, a 2D synthetic dataset (contaminated with random Gaussian and Cauchy noise) was used. Upon data examination, it becomes clear that the 2D C-IRLS-FT technique demonstrates superior noise reduction capabilities in comparison to the traditional 2D DFT approach.

3. Thesis Three

We further explored the application of the inversion-based Fourier transformation procedure to computing seismic attributes. We have demonstrated that the newly developed method, referred to as (1D) C-IRLS-HT, outperforms the traditional Hilbert transform method in reducing noise for two seismic attributes. Specifically, when applied to process noisy Reflection Coefficient (first attribute) and the Instantaneous Phase (second attribute) data, the Method C-IRLS-HT demonstrated a significant noise reduction, resulting in more accurate and reliable data compared to the traditional Hilbert transform method. These findings underscore the effectiveness of the C-IRLS-HT procedure as a more robust and reliable method for data analysis in situations where noise reduction is essential.

4. Thesis Four

We introduced the 2D C-IRLS-HT and 2D H-IRLS-HT Hilbert transform methods and sought to evaluate the efficacy of the conventional (DFT-based) 2D Hilbert transformation method and the newly developed procedures in detecting anomalies within a noisy dataset. The traditional DFT-based 2D Hilbert transform encountered numerous challenges, including substantial noise levels, less distinct edges, and the presence of outliers, all of which impeded accurate anomaly detection and characterization in complex datasets. Our investigations show that compared to conventional methods, when the 2D H-IRLS-HT was applied to the noisy synthetic dataset, the results exhibited marked improvements in clarity, quality, and noise reduction, which led to a more accurate representation of the underlying spatial patterns. The superior performance of the 2D H-IRLS-HT and 2D C-IRLS-HT methods underscores their potential as a robust and reliable alternative for anomaly detection, especially in challenging environments where noise and outliers might compromise the effectiveness of conventional techniques.

5. Thesis Five

In the concluding analysis of the research conducted in the eastern part of region Syria, we introduced a more advanced method, the 2D C-IRLS-FT, particularly in the low-pass filtering of gravity data. The inversion-based Fourier transform using the Chebyshev function as basis function (2D C-IRLS-FT method) played a pivotal role in this procedure, enabling the decomposition of the gravity data into its frequency components. Subsequent spectral analysis illuminated the necessity of applying the 2D C-IRLS-FT method to a chosen data segment for noise reduction, pole reduction, and overall enhancement of data quality. The pole-reduction technique further amplified the coherence of the geological structures within the dataset, leading to a noticeable improvement in data quality. The sufficient reduction of noise and outliers from the data yielded a more distinct representation of the structure, thereby facilitating a more reliable interpretation. As an extension of our current research scope, a novel technique that combines the 2D C-IRLS-FT method and k-means clustering was deployed for denoising seismic data. This was specifically undertaken within a seismic section that harbored a significant noise component. This method hinges on the transformation of seismic data into the frequency domain.

IV. PRACTICAL APPLICATION OF RESULTS

The primary focus of the research delineated in this doctoral study is to address the persistent challenge of noise interference and the distortion caused by outliers in a wide array of geophysical datasets. Traditional Fourier transformations exhibit significant limitations when faced with outliers in the context of non-Gaussian noise distribution, thus engendering substantial issues for noisy data sets. The proposed algorithms alleviate this issue by employing a novel robust Fourier transform inversion method, incorporating IRLS with Cauchy-Steiner weights using Chebyshev polynomials, to circumvent these problems. Particular attention has been devoted to seismic, gravitational, and magnetic measurements, all housed within the MATLAB computational environment's algorithmic architecture. This improvement gives the ability to apply the new robust algorithms to other two-dimensional representations that encapsulate geophysical data, which was not possible before in case of severe outliers. By leveraging previous innovations to augment the process of the Hilbert transform in one and two dimensions, we can open a multitude of applications in the field of robust image processing, particularly in edge detection scenarios. Conventional Hilbert transform-based edge detection methods have low resolution and serious noise influence. Therefore, we propose new edge detection advancements engender an array of applications that can be amalgamated with other sophisticated tools to produce noise-reduced techniques. These enhanced techniques will aid in improving the detection capabilities of various geophysical objects, thereby enriching our understanding and interpretation of geophysical phenomena. The strategies demonstrate one-dimensional or two-dimensional datasets, with a very promising vision to be applied in three-dimension in the future.

V. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

JOURNAL ARTICLES

1. Omar Al Marashly – Mihály Dobróka: Hilbert Transform Using the Most Frequent Values Method, GEOSCIENCES AND ENGINEERING, 2022.

2. Omar Al Marashly – Mihály Dobróka: Applying the most frequent values assisted Hilbert transform into seismic attributes. Multiscience, (2023).

CONFERENCE PAPERS AND ABSTRACTS

1- Omar Al Marashly – Mihály Dobróka, Hilbert transform using a robust geostatistical method. IOP Conf. Ser.: Earth Environ. Sci. 942 012029.

INTERNATIONAL CONFERENCE PRESENTATIONS

1- Hilbert Transform using a robust geostatistical method. XXI Conference of Ph.D. Students and Young Scientists, Poland, 2021.

2- Enhancing signal to noise ratio in seismic attributes using the inversion method. XXI Conference of Ph.D. Students and Young Scientists Poland, 2022.

3- New rock physical models describing the pressure dependence of seismic/acoustic dispersion characteristics. EAGE 2023, Vienna, 2023.

4- Lame's Parameter Utilization on Reservoir's Lithological and Pore-Fluid Characterization: Lower Pannonian Case Study. EAGE 2023, Vienna, 2023.

5- The Application of Extended Elastic Impedance to Improve Reservoir Characterization: Pannonian Basin Case Study. EAGE 2023, Vienna, 2023.

DOMESTIC CONFERENCE PRESENTATIONS

1- Hilbert Transform Using the Most Frequent Values Method. INVERZIOS ANKET, Hungary, 2020, Geophysics Department.

2- Hilbert transform using a robust Fourier transformation algorithm. Doctoral conference 2020, Hungary, Miskolc University.

3- Seismic attributes enhancing strategy using inversion on very noisy synthetic seismic data. ISZA -Meeting of Young Geoscientists, Hungary, 2022.

4- Hilbert transform using Hermite function-based Fourier transformation. INVERZIOS ANKET, Hungary, 2022.

5- Noise reduction using Legendre polynomials in seismic traces. Forum for Ph.D. students, Hungary, 2022.

6- Hilbert Transform Using Chebyshev Polynomials with IRLS. ISZA, Meeting of Young Geoscientists, Hungary, 2023.