A Novel Approach to Modelling Multi-Channel and Multi-Phase Signals on an Angular Coordinate Axis (Semani)

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Abstract: This study introduces a new digital signal processing method that holistically plots digital signal vectors collected from multiple channels on an angular graphic axis and aims to obtain a holistic signal matrix in the specified angular range using a vector interpolation technique. The proposed method, Semani, enables the visualization, improvement, and analysis of signal parameters based on phase angles and independent variables using an angular coordinate axis. In the Semani method, multi-channel signals are visualized on a single graph by plotting them on a coordinate axis encompassing all angular directions. This approach divides the angular coordinate axis into sections based on its resolution level of angles (segments) and the rate of change of independent variables (layers) within the analysis window. A graphic pattern (polar, cartesian, cylinder, sphere, etc.) determined on the angular axis is divided into slices according to segments and layers, and the signal is plotted in these sections. The proposed signal plotting and analysis model enables holistic modeling of multi-channel signals collected from different angular directions on a coordinate axis. Additionally, the vector interpolation method used in this model calculates signal vectors for unknown angular directions, enriching the signal. This innovative method allows signals collected from multiple channels, such as EEG, ECG, radar, sonar, and seismic signals, to be effectively visualized on a single graph against their corresponding independent variables (e.g., time, frequency, distance).

1 INTRODUCTION

A signal is generally defined as a function representing the mathematical relationship between at least one independent variable and a dependent variable that varies over time, carrying information about the state of a physical change. Signals can be categorized into two groups: analog signals and digital signals. Digital signals are composed of data representing time-dependent variations, derived from analog measurements converted into digital values, obtained or generated from various data sources, or produced via mathematical functions or computer simulations. The characteristic features of digital signals, such as amplitude, frequency, wavelength, and phase, are derived through various mathematical operations and are used to define a signal's characteristics. Consequently, digital signals consist of numerical sets representing signal samples stored in vector sequences, matrix arrays, higher-dimensional arrays, or other structured data formats.

Multi-phase signals are composed of multiple sinusoidal components with defined phase angles, typically sharing the same frequency. These signals can originate from a single channel or be aggregated from various channels. Examples include communication networks, radar, sonar, antenna systems, and biomedical signals such as EEG, EMG, and ECG. A major challenge in multi-phase signal processing systems is designing advanced algorithms and frameworks that can efficiently handle the increased complexity, inter-channel interference, and synchronization issues while meeting the demands for higher data rates, ultra-low latency, and enhanced scalability in next-generation networks like 6G. (She vd., 2021) (Long vd., 2021).

The Semani technique can represent a multi-channel/multi-phase signal as a single unified signal on a graph. A literature review highlights a lack of

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systems that model digital signal variations concerning independent variables and phase angles or visualize sinusoidal components—such as fundamental frequencies, harmonics, and phase angles—on a unified graph. Conventional spectral analysis methods divide data into separate graphs, complicating the observation of relationships between frequencies and harmonics. This challenge intensifies with an increasing number of sinusoidal components.

Multiple components or phase differences can exist in multi-channel, multi-phase signals, with each element typically conveying distinct information. These signals are encountered in various applications, including imaging and audio processing, recordings made with multiple microphones, and biomedical signals such as brainwaves (EEG) (Kamble & Sengupta, 2023; Mazlan vd., 2024), cardiac rhythms (ECG) (Ruan vd., 2022) and myoelectric signals (EMG) (Rodriguez-Tapia vd., 2020). They are also relevant in fields like seismic signal analysis (Yin vd., 2022), telecommunications, and radio frequencies, where signals are received from multiple antennas or channels. Despite their importance, the integration of multi-channel signals remains an unresolved challenge, and predictions about the signal source often rely on diverse signal processing techniques. Among the approaches discussed in the literature, beamforming is a prominent method used to combine signals from multiple channels, isolating and amplifying those originating from a specific source or direction (Ramírez-Espinosa vd., 2024). This is achieved by either applying fixed weights to each channel (linear beamforming) or dynamically adjusting weights based on channel conditions (adaptive beamforming). Another widely used technique is principal component analysis (PCA), which extracts key components with the highest variance from multi-channel data, summarizing the information into a single representative signal (R. Martin, 2023). Independent component analysis (ICA) is similarly employed, focusing on separating independent sources from mixed signals to create a unified signal form (Melinda vd., 2023). Time-frequency analysis, including methods such as short-time Fourier transform (STFT) and wavelet transform, is used to analyze signals across various time and frequency domains, facilitating the combination of these components into a single signal (Kumar vd., 2021). Additionally, the Hilbert transform provides valuable insights into the phase information of a signal by deriving its analytical form, while neural networks and machine learning techniques can learn important features from multi-channel data and integrate them into a single representation (Engels vd., 2021) (Neupane & Seok, 2020) (Kazemi Lichaee vd., 2024). In communication systems, signal modulation and demodulation techniques, such as phase modulation (PM) or phase shift keying (PSK), play a critical role in integrating signals transmitted via different channels by analyzing their phase components. Despite these advancements, no existing method in the literature directly models multi-phase signals into a unified form without intermediate signal analysis, highlighting the ongoing complexity and challenges in this field (Pham vd., 2021) (Wei vd., 2023).

Physical changes, represented as signals, are inherently independent of coordinate systems. However, mapping them to coordinate axes, as in current systems, introduces dependencies that distort their visualization, especially for complex changes. Semani resolves this by decoupling signals from coordinate dependencies, allowing flexible graphical representations. For multi-channel signals, existing methods analyze vector behaviors for different phase angles separately, combining results to reconstruct the original signal. No system predicts intermediate signal behaviors or unifies these analyses into a single graphical model, further limiting comprehensive signal evaluation. Semani addresses these challenges by providing a novel approach to signal modeling and analysis. It enables the visualization of multi-channel/multi-phase signals and their associated parameters in a unified graphical representation, significantly simplifying the observation of relationships between signal components. Moreover, it uses an interpolation-based technique for estimating intermediate signal vectors between two known signal vectors with a specific phase angle, facilitating more comprehensive signal modeling and analysis.

The biggest difference between the graphs drawn on the existing angular coordinate axis definitions and the proposed method is that in existing methods, one of the angular axis parameters generally represents angles and the other represents signal amplitudes. In the Semani method, one of the axis parameters represents the angles and the other represents the independent variables of the signal vectors, and the signal vectors in each angular direction are represented over these independent variables.

In the Semani method, when frequency values are selected as independent variables and signal power values as amplitude, the energy, frequency, and vibrations of multi-directional signals — recommended by the great scientist Nikola Tesla— can be visualized on a single graph. (Martin, 2022).

2 MAIN SCOPE OF THE STUDY

The primary aim of this study is to develop a comprehensive system model capable of analyzing and modeling any input signal in angular coordinates across independent variables, such as time and frequency. To achieve this, input signals are categorized into two groups: *Sinyal1,* representing monophasic signals with uniform behavior across all angular directions (e.g., time domain audio signals), and *Sinyal2,* encompassing multiphasic signals that exhibit varying characteristics across different angular directions (e.g., biomedical, seismic, or antenna radiation signals).
Semani enables the analysis of both Sinyal1 and Sinyal2 signals by segmenting them into short-time analysis windows and mapping their behavior graphically in angular coordinates.

For Sinyal2 signals, the method uses a vector interpolation method to derive signal vectors for unmeasured angular directions, creating a signal matrix that allows comprehensive angular modeling.

The Semani method provides a graphical representation of signal vectors in different angular directions and enables the enrichment of the input signal by deriving signal vectors in unmeasured directions using the interpolation method. This approach allows for detailed time-domain analysis or frequency-domain analysis using standard spectrum analysis methods (e.g., Fourier Transform) enabling visualization of key spectral features, such as fundamental frequencies and harmonics, within an octave-based frequency band structure.

Semani further introduces the ability to map signal parameters (e.g., frequency, amplitude, phase angle) using color palettes, enabling an intuitive visual representation of numerical values. Additionally, it supports 2D and 3D modeling in cylindrical and spherical coordinates, enhancing the analysis of signal behavior in multidimensional spaces.

A key application of this system lies in separating signal and noise components by correlating signal characteristics with angular coordinates, which is particularly beneficial for noise analysis in multi-directional signals like seismic or biomedical data.

This system aims to simplify and enhance the visualization and interpretation of signal properties across angular and independent variable domains, contributing significantly to advancements in signal analysis and modeling techniques.

2.1 Advantages of the Semani Method

Semani offers significant advancements in signal modeling and analysis by addressing the limitations of existing techniques and introducing novel benefits. It enables comprehensive modeling of digital signals on graphical axes with layers and segments, capturing detailed variations in multi-dimensional data.

Decoupling the angular axis from dependent variables, provides unparalleled flexibility in designing custom graphical patterns, simplifying the visualization of complex multi-phase signals in two or three dimensions. Real-time signal behavior, such as EEG, EKG, and seismic data, can be monitored effectively, with dominant resonant frequencies and harmonics emphasized for deeper analysis.

Semani facilitates the prediction of unmeasured signal data using adjacent measured values, ensuring complete signal representation. Outputs can be converted into formats suitable for machine learning applications, supporting advanced analytics. It revolutionizes antenna power radiation diagrams by enabling realistic modeling of power values across all directions and distances while allowing independent analysis of noise and harmonics.

For the first time, multi-phase signals, including cardiac, brain, seismic, and audio spectrums, can be directly modeled together in a single graphical representation. Semani simplifies the modeling of high-dimensional, complex signals on various coordinate bases, fostering the development of innovative visualization tools and analysis techniques, and making it a groundbreaking approach for diverse applications.

Semani offers extensive applications across various industries, enabling advanced modeling of analog and digital signals. Its capabilities extend to fields such as medicine, engineering, healthcare, measurement and evaluation, telecommunications, and electronics. By facilitating real-time visualization and multi-dimensional analysis of complex signals—such as EEG, EKG, EMG, seismic data, radar, sonar, and audio/music spectra—Semani allows for the precise and detailed study of these signals.

Key applications include real-time monitoring and graphical representation of biomedical signals during patient assessments, enhanced earthquake simulations for predictive technologies, detailed radar and sonar analyses for tracking multiple targets, and comprehensive antenna radiation pattern evaluations. Semani also addresses challenges in tensor modeling by offering effective solutions for multi-dimensional signal modeling, thereby improving efficiency and accuracy. Its potential spans not only industrial and biomedical applications but also groundbreaking contributions to fields like quantum physics, where it could provide new insights into particle behavior and quantum uncertainty principles.

3 METHODOLOGY

Semani enables the modeling and analysis of digital signals within angular coordinate axes, defined based on independent variables and phase angles, on a graphical representation. This approach is implemented on devices with signal processing capabilities, allowing both the real-time and post-recording analysis of signals.

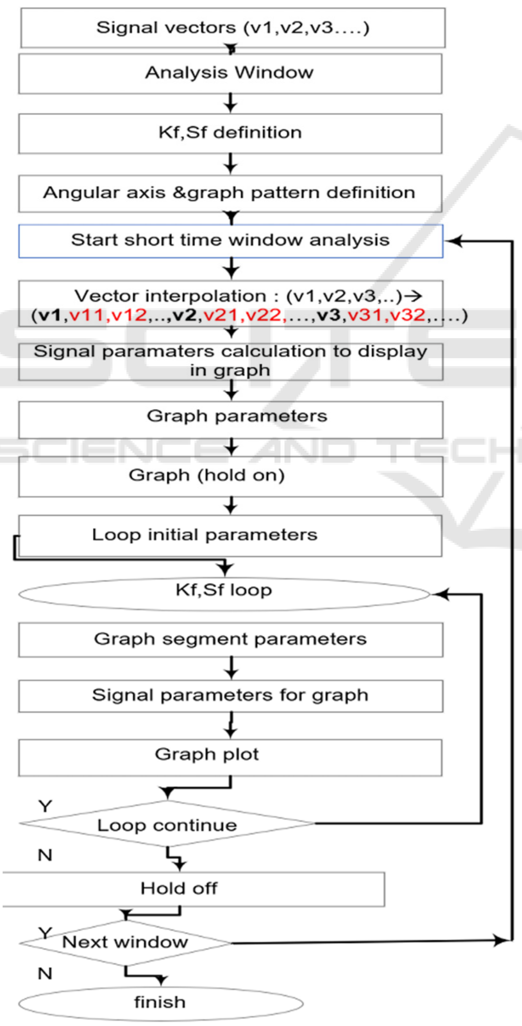

Figure 1: Flowchart of Semani method.

Through windowing techniques, signals are processed within specific analysis windows, providing dynamic visualization and evaluation. The flowchart of the Semani method can be found in Fig.1. Here, signal vectors (v1, v2, v3,…) were taken according to their respective phase angles for modeling. The windowing technique was defined for short-time analysis. For a graphical display on the coordinate axis, the change rate of the independent variable (Kf) and angular resolution (Sf) parameters were determined. Signal analysis was then started for successive windows. Within the defined analysis window, a linear vector interpolation was performed according to Eq. (1) to calculate the missing signal vectors (v1, v11, v12, …v2, v21, v22, …v3, v31, v32,…) for comprehensive visualization purposes (Fig.2). (Here, the user can prefer another vector interpolation method, if desired). Signal feature parameters are derived for graphical visualization. The format for signal representation—such as numerical values, colors, symbols, or other visual elements—is configured based on the graph's design. The 'hold-on' feature was enabled to enable visualization of all signal data within the analysis window during the loop process. Then Iterative processes were initiated for the visualization of signal data across layers (Kf) and segments (Sf) based on the calculated boundaries of each segment. Signal data was displayed on the graph. After visualizing the windowed data, the 'hold-on' feature was disabled and the cycle continued for successive windows.

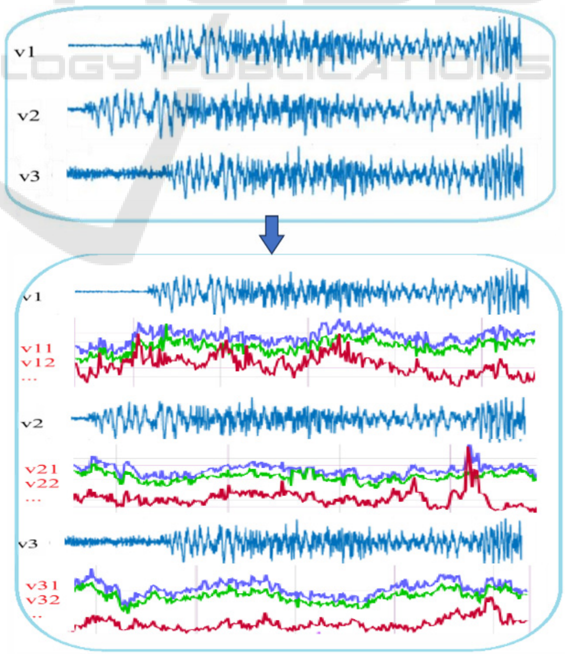

Figure 2: Effect of vector interpolation on signal vectors.

Semani provides a robust framework for the real-time modeling, analysis, and visualization of multi-phase signals such as EEG, EKG, seismic data, and signal spectra. Its layered and angular approach enables the efficient representation of complex data, facilitating deeper insights and advanced applications across industries such as biomedical engineering, structural analysis, and digital signal processing.

3.1 The Linear Vector Interpolation Method

Semani enables the modeling of Sinyal2-type multi-phase signals within angular coordinates by deriving signal vector samples for intermediate angular directions not provided as input. Utilizing the arithmetic averaging method outlined in Equation (1), signal vectors for these angular segments are iteratively calculated based on given input signal vectors. The formula used to calculate the signal vectors between two input vectors x1 and x2 with an angle θ is:

$$B_x(j,i) = \frac{(n-i).x_1(j)\ +\ i.\ x_2(j)}{n}, \qquad j = 1,..,L, i = 1,..,n-1 \quad (1)$$

Here, $Bx(j,i)$ represents the intermediate signal vectors between x1 and x2, where n is the number of segments, and L is the length of the signal vectors. By segmenting the angular coordinate space into equal intervals and generating a comprehensive signal matrix, Semani effectively represents Sinyal2's behavior across the entire angular spectrum. This approach assumes minimal variation in signal characteristics across adjacent angular directions. Additionally, in the Semani method, the signal can be plotted at the desired resolution by dividing the angular axis into layers (Kf) based on the rate of increase of the independent variable. This process facilitates the modeling of time-domain and frequency-domain multi-dimensional signal properties, such as amplitude, power, and phase, with applications in real-time signal analysis and spectrum visualization using Fourier Transform, wavelets, or similar spectral analysis methods. The result is a robust framework for analyzing Sinyal2 signals across time and frequency planes.

4 TEST & EVALUATION

The tests were conducted using Sinyal1 and Sinyal2 types of signals, analyzed in both time and frequency domains. The tests showed that Semani allows for modeling various signal types, such as audio, EKG, EEG, and seismic signals, in different angular axes types. The results from these tests demonstrate Semani's versatility in signal processing across various domains, with application examples including audio, music, and seismic signals.

The provided text details the application of a signal modeling system using the Semani method for testing and analyzing both ECG (Electrocardiogram) and EEG (Electroencephalogram) signals in time and frequency domains. Here's a summary and continuation based on the provided information.

4.1 Tests for Sinyal1 (Frequency Domain)

Tests on audio signals at 44kHz sampling rate (Fig.3a) showed the system's capability to model signals in polar coordinates (Fig.3b), offering detailed frequency spectrum analysis. The results highlighted how longer analysis windows improve frequency resolution.

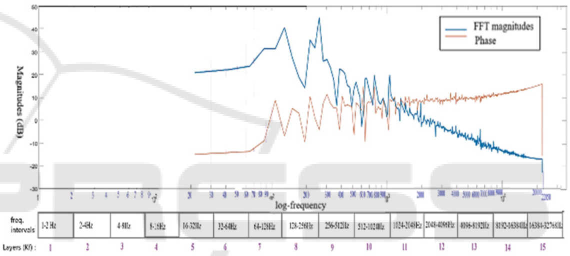

Figure 3a: log-FFT of a speech signal.

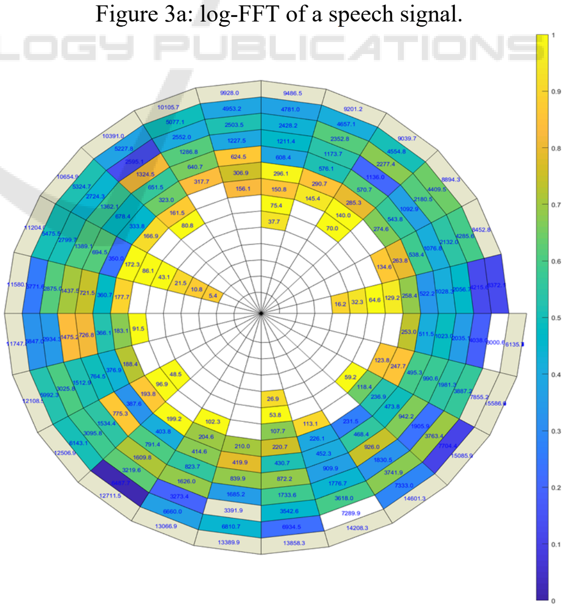

Figure 3b: Normalized log-FFT of the speech signal of Fig3a with Semani method (numbers represent frequencies).

4.2 Tests for Sinyal2 (Time & Frequency)

4.2.1 Signal Modeling for ECG Analysis

Semani was used to analyze ECG signals, specifically from a publicly available 6-channel dataset containing 10-second long samples recorded at 500 Hz sampling frequency. The dataset includes various channels (CH1-CH3, AVL, AVR, AVF, V1-V6). These channels provide both bipolar (CH1-CH3) and unipolar (AVL, AVR, AVF, V1-V6) derivations.

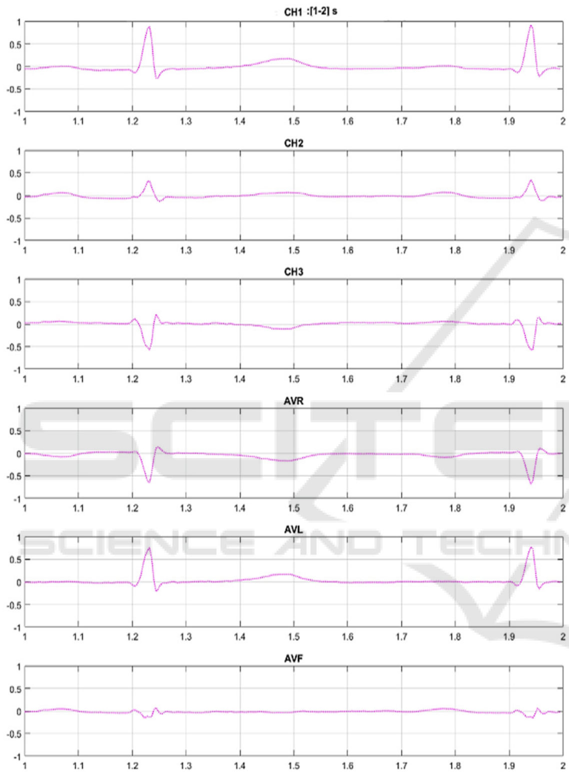

Figure 4a: A time-domain ECG signal from 6 leads.

During the signal modeling, CH1, CH2, and CH3 were used as input data, with additional derivations calculated through linear interpolation from these channels. Fig4a and 4b present a 1s analysis window outputs of an ECG signal in the time domain. Spectral analysis was performed using the FFT technique, and the distribution of the frequency spectrum across angular phases was displayed as can be seen in Fig 5.

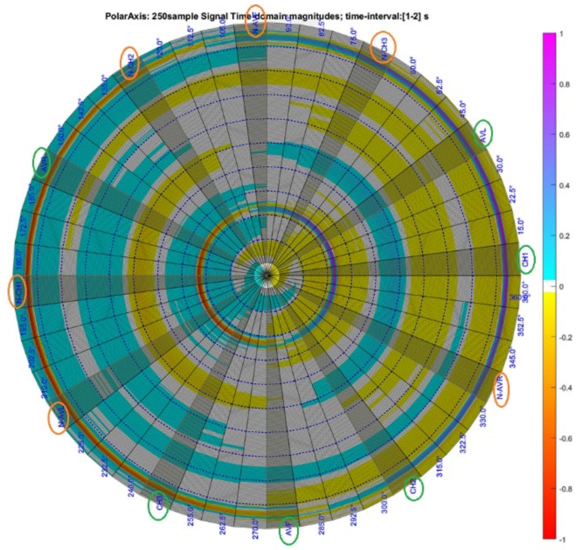

Figure 4b: The time-domain ECG signal of Fig.4a with Semani method.

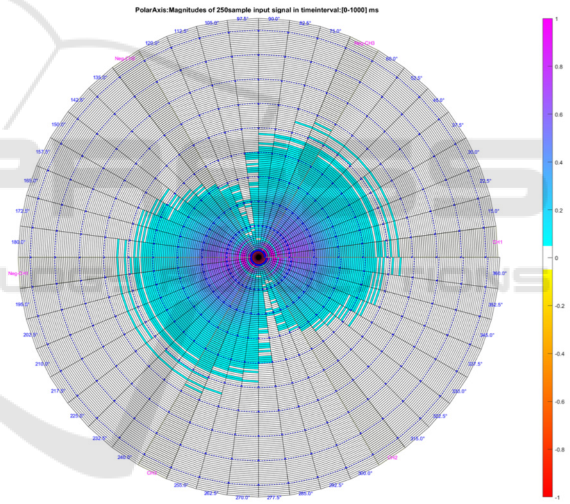

Figure 5: An ECG signal in the frequency domain with the Semani method.

4.2.2 Signal Modeling for EEG Analysis

For EEG signal analysis, Semani used data from Physionet's database, specifically from a project involving non-invasive monitoring for epileptic seizure prediction. The dataset consists of 14 patients, with each recording lasting 3600 seconds, collected using the International 10-20 system at a 512Hz sampling rate.

During the signal modeling, EEG signals from the electrodes were analyzed in both Cartesian and polar coordinate systems. The outer region's 10 electrodes were analyzed (Fp1, Fp2, F8, T4, T6, 02, O1, T5, T3, F7), with the results displayed on polar axes, representing the signal amplitude distributions in angular directions. The analysis was performed using a 1-second window, with a sampling rate of 128 Hz, resulting in 128 layers per second (Fig 6a & 6b). Fig.7 presents a 3D spherical model of an EEG signal by using the same data from 10 electrodes in UD direction. A frame-by-frame analysis of the Semani method can be seen in Fig.9 and in a frame-by-frame analysis of the Semani method in an EEG signal can be seen in Fig.10.

The frequency domain analysis involves visualizing the spectrum distribution of the EEG signals across angular phases, with the FFT technique applied to extract frequency components.

In summary, Semani facilitates advanced signal modeling, both in time and frequency domains, for complex biological signals like ECG, EMG, and EEG. Semani enables detailed analysis of the signals' amplitude distribution and frequency content, using polar and 3D coordinate systems for visualization, as well as spectral analysis through techniques like FFT. This approach allows for a more comprehensive understanding of the signals and their characteristics.

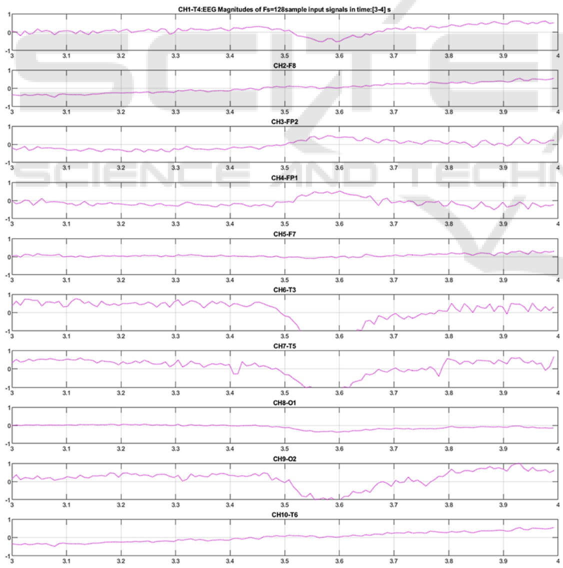

Figure 6a: A time-domain EEG signal from 10 electrodes in a standard 10-20 system.

4.2.3 Signal Modeling for Earthquake Signals

The Semani method was applied to test and analyze Sinyal2-type earthquake signals, first discussing their structure. Earthquake signals are first divided into

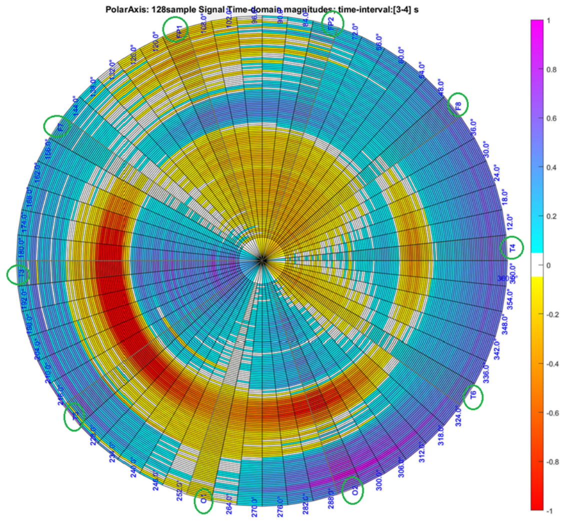

Figure 6b: The EEG signal of Fig 6a with Semani method.

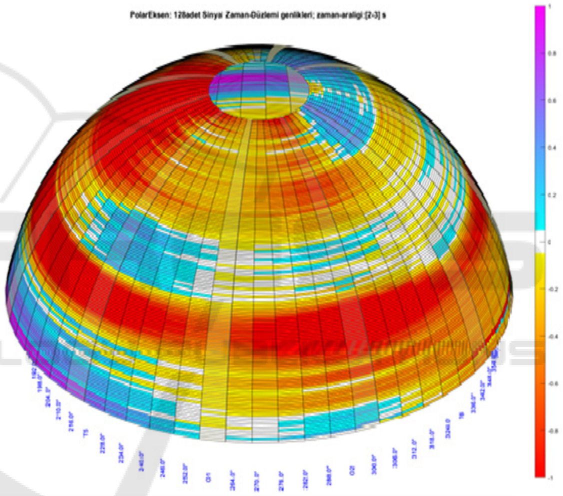

Figure 7: An EEG signal in 3D with Semani method.

body waves (P-waves and S-waves) and surface waves (Rayleigh (R) waves and Love (L) waves).

The data used for analysis, from the AFAD database, corresponds to a 4.1 magnitude earthquake on March 29, 2023, in Kahramanmaraş, recorded at a sampling rate of 100 Hz in three directions: south-north (SN), east-west (EW), and up-down (UD).

For the time-domain analysis, the signals in EW (CH1), SN (CH2), and UD (CH3) directions were used, and linear interpolation generated additional vectors in angular directions.

The body and surface waves were analyzed separately due to differences in amplitude and behavior. The signal data was normalized and processed using the Semani method, producing a matrix according to Eq.1 and representing the signal amplitudes with color-coded angular directions.

For surface wave analysis, Fig.8a and 8b show how the signal amplitudes in angular directions are represented as circular layers, for the 1s analysis window.

Fig. 8b presents a 3D cylindrical model of surface waves in the EW, SN, and UD directions, showing signal amplitudes in circular layers.

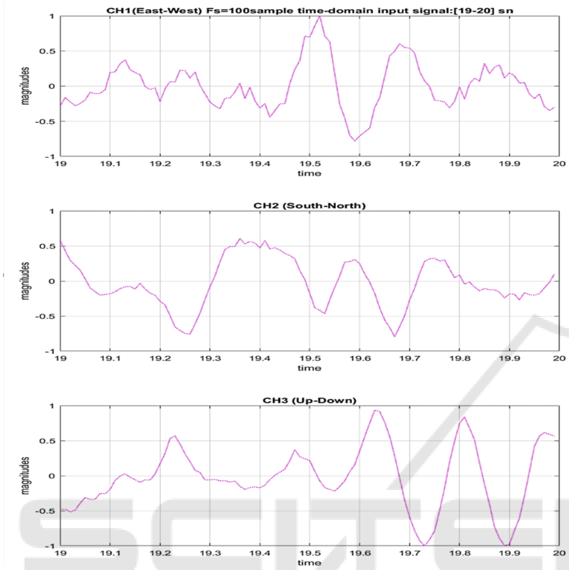

Figure 8a: Surface-waves of an earthquake signal in EW, SN, and UD directions.

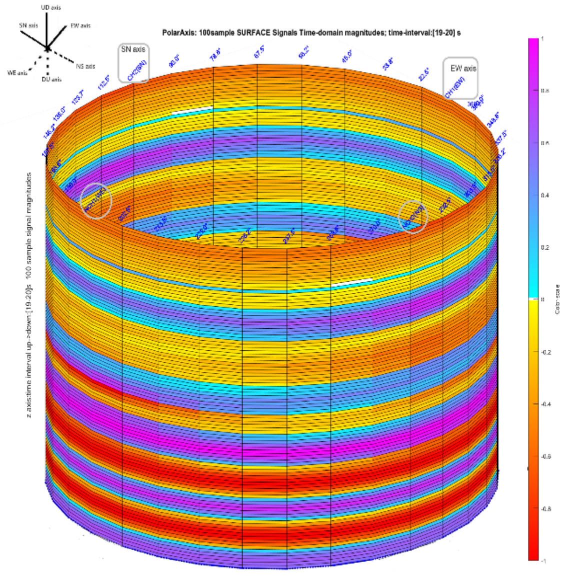

Figure 8b: Surface-waves of the earthquake signal of Fig8a with Semani method (EW, SN & UD directions).

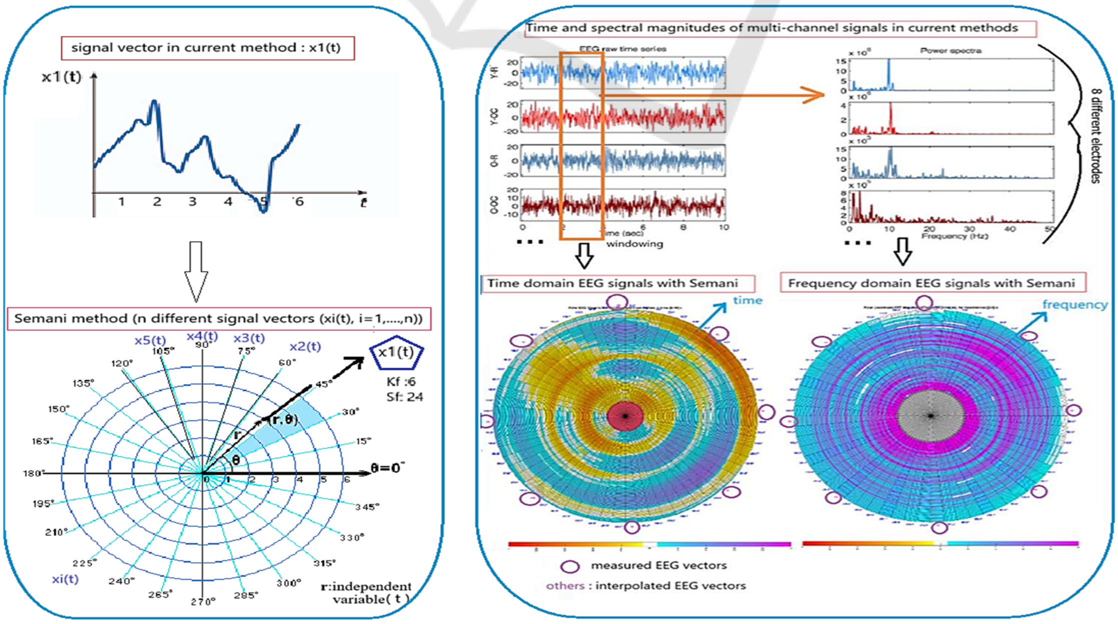

Figure 9: A frame-by-frame analysis of current methods & Semani method.

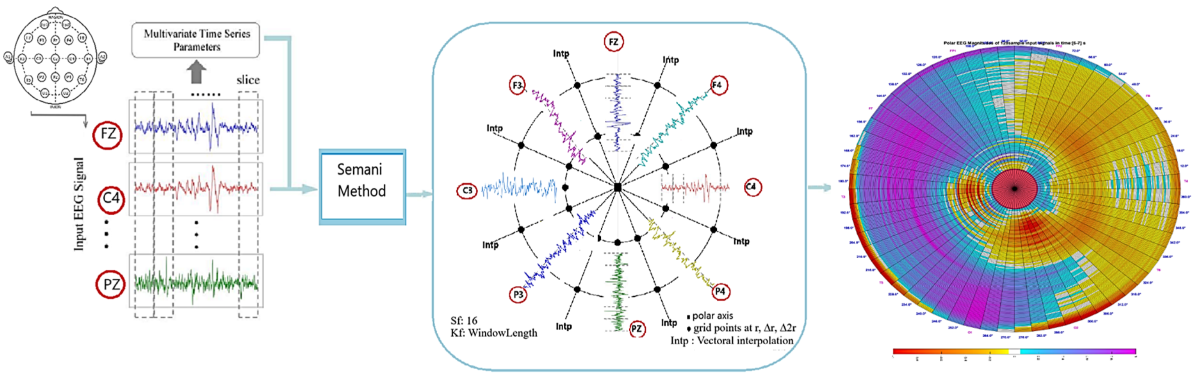

Figure 10: Frame-by-frame analysis example of Semani method in an EEG signal.

5 DISCUSSION

Semani introduces a novel framework for signal modeling and analysis, particularly for complex biomedical signals such as ECG, EMG, and EEG. One of the significant advantages of Semani is its ability to directly represent multi-phase & multi-channel signals in both 2D and 3D spaces, which offers a more comprehensive view of signal dynamics compared to traditional methods. The utilization of polar and Cartesian coordinate systems for signal visualization allows for a clearer interpretation of signal amplitudes across different time intervals and angular orientations, providing richer insights into the characteristics of biological signals.

A key innovation of Semani lies in its handling of multi-dimensional signal data. For ECG signals, the analysis incorporates both bipolar and unipolar derivations, providing a more complete representation of the electrical activity of the heart. The ability to map these signals onto a 3D coordinate system allows for a better understanding of spatial relationships between the various leads and their contribution to the overall ECG pattern. Similarly, for EEG signals, Semani's use of the 10-20 international electrode placement system for signal acquisition and analysis in both the time and frequency domains offers a highly accurate and detailed view of brain activity.

Semani's application in the frequency domain, particularly through FFT analysis, is also notable. By dividing signals into layers corresponding to different frequency bands, it is possible to observe how specific frequency components evolve over time. This level of frequency granularity could prove particularly useful in detecting abnormalities or subtle changes in both ECG and EEG signals, which might otherwise go unnoticed with conventional analysis methods.

Furthermore, Semani's versatility in analyzing signals from different types of electrodes (such as CH1-CH3 for ECG and the 10-20 system for EEG) adds to its potential applicability in diverse clinical and research settings. While Semani is quite effective for standard biomedical signal analysis, there is room for improvements in computational efficiency, especially when using real-time analysis scenarios. As the system is expanded to process more complex signals or higher dimensional data, optimizing processing speed and scalability will be crucial.

In conclusion, the Semani method provides a promising framework for signal modeling and analysis in both time and frequency domains, offering valuable insights into radar, sonar & biomedical signals. Future improvements and refinements, particularly regarding assumptions about electrode placement and computational efficiency, could further enhance its utility and applicability in clinical diagnostics and research.

6 CONCLUSIONS

The Semani method provides a robust and innovative approach for the modeling and analysis of complex biological signals, such as ECG and EEG, in both the time and frequency domains. By utilizing advanced techniques like linear interpolation, 3D signal representation, and polar coordinate analysis, Semani enables detailed visualization of signal amplitude distributions and frequency spectra. The integration of FFT for frequency domain analysis further enhances the system's ability to extract meaningful insights from the signals. The application of Semani to both ECG and EEG datasets demonstrates its versatility and effectiveness in capturing intricate signal characteristics, offering a valuable tool for both clinical and research purposes. The results, as presented through various graphical representations, highlight Semani's potential to improve the precision and understanding of biomedical signal analysis, paving the way for enhanced diagnostic tools and further advancements in the field.

REFERENCES

Engels, F., Heidenreich, P., Wintermantel, M., Stacker, L., Al Kadi, M., & Zoubir, A. M. (2021). Automotive Radar Signal Processing: Research Directions and Practical Challenges. IEEE Journal of Selected Topics in Signal Processing, 15(4), 865-878. https://doi.org/10.1109/JSTSP.2021.3063666

Kamble, K., & Sengupta, J. (2023). A comprehensive survey on emotion recognition based on electroencephalograph (EEG) signals. Multimedia Tools and Applications, 82(18), 27269-27304. https://doi.org/10.1007/s11042-023-14489-9

Kazemi Lichaee, F., Salari, A., Jalili, J., Beikmohammad Dalivand, S., Roshanfekr Rad, M., & Mojarad, M. (2024). Advancements in Artificial Intelligence for ECG Signal Analysis and Arrhythmia Detection: A Review. International Journal of Cardiovascular Practice,8(2). https://doi.org/10.5812/intjcardiovascpract-143437

Kumar, R., Verma, A. R., Gupta, B., & Kumar, S. (2021). Dual-Tree Sparse Decomposition of DWT Filters for ECG Signal Compression and HRV Analysis. Augmented Human Research, 6(1), 3. https://doi.org/10.1007/s41133-020-00041-z

Long, J., Wang, X., Zhou, W., Zhang, J., Dai, D., & Zhu, G. (2021). A Comprehensive Review of Signal Processing and Machine Learning Technologies for UHF PD Detection and Diagnosis (I): Preprocessing and Localization Approaches. IEEE Access, 9, 69876-69904. https://doi.org/10.1109/ACCESS.2021.3077483

Mazlan, M. R., Sukor, A. S. A., Adom, A. H., & Jamaluddin, R. (2024). Review of analysis of EEG signals for stress detection. 040007. https://doi.org/10.1063/5.0181590

Melinda, M., Maulisa, O., Nabila, N. H., Yunidar, Y., & Enriko, I. K. A. (2023). Classification of EEG Signal using Independent Component Analysis and Discrete Wavelet Transform based on Linear Discriminant Analysis. JOIV : International Journal on Informatics Visualization, 7(3), 830-838. https://doi.org/10.30630/joiv.7.3.1219

Neupane, D., & Seok, J. (2020). A Review on Deep Learning-Based Approaches for Automatic Sonar Target Recognition. Electronics, 9(11), 1972. https://doi.org/10.3390/electronics9111972

Pham, Q.-V., Nguyen, N. T., Huynh-The, T., Bao Le, L., Lee, K., & Hwang, W.-J. (2021). Intelligent Radio Signal Processing: A Survey. IEEE Access, 9, 83818-83850. https://doi.org/10.1109/ACCESS.2021.3087136

R. Martin. (2023). Robustified principal component analysis for feature selection in EEG signal classification. International Journal of Systematic Innovation, 7(5). https://doi.org/10.6977/IJoSI.202303_7(5).0004

Ramírez-Espinosa, P., Morales-Jimenez, D., & Wong, K.-K. (2024). A New Spatial Block-Correlation Model for Fluid Antenna Systems. IEEE Transactions on Wireless Communications, 23(11), 15829-15843. https://doi.org/10.1109/TWC.2024.3434509

Rodriguez-Tapia, B., Soto, I., Martinez, D. M., & Arballo, N. C. (2020). Myoelectric Interfaces and Related Applications: Current State of EMG Signal Processing– A Systematic Review. IEEE Access, 8, 7792-7805. https://doi.org/10.1109/ACCESS.2019.2963881

Ruan, H., Dai, X., Chen, S., & Qiu, X. (2022). Arrhythmia Classification and Diagnosis Based on ECG Signal: A Multi-Domain Collaborative Analysis and Decision Approach. Electronics, 11(19), 3251. https://doi.org/10.3390/electronics11193251

She, C., Cheng, P., Li, A., & Li, Y. (2021). Grand Challenges in Signal Processing for Communications. Frontiers in Signal Processing, 1, 664331. https://doi.org/10.3389/frsip.2021.664331

Wei, Z., Qu, H., Jiang, W., Han, K., Wu, H., & Feng, Z. (2023). Iterative Signal Processing for Integrated Sensing and Communication Systems. IEEE Transactions on Green Communications and Networking, 7(1), 401-412. https://doi.org/10.1109/TGCN.2023.3234825

Yin, X., Liu, F., Cai, R., Yang, X., Zhang, X., Ning, M., & Shen, S. (2022). Research on Seismic Signal Analysis Based on Machine Learning. Applied Sciences, 12(16), 8389. https://doi.org/10.3390/app12168389

J. Long, X. Wang, W. Zhou, J. Zhang, D. Dai and G. Zhu, "A Comprehensive Review of Signal Processing and Machine Learning Technologies for UHF PD Detection and Diagnosis (I): Preprocessing and Localization Approaches," in IEEE Access, vol. 9, pp. 69876-69904, 2021, doi: 10.1109/ACCESS.2021.3077483.

Martin, J., "Nikola Tesla: How Energy, Frequencies, and Vibrations Shape Reality", Amazon Digital Services LLC - KDP Print US, ISBN:9798408952731, 2022

Availability of Data and Materials: The datasets used and analyzed in the current study are publicly available as open-source data.

Conflict of Interests: The author declares that the method presented in this study is subject to a patent application under the author's name, which may have potential commercial implications.