Advanced Time–Frequency Characterization of VLF Transients Using Continuous Wavelet Transform

Ashutosh Kumar[1], Amrendra Kumar[2], D. K. Sondhiya[3]

[1,2,3]Govt. Polytechnic College, Sahibganj, Jharkhand, India.

Abstract:
Continuous Wavelet Transform (CWT) has emerged as a powerful tool for analyzing nonlinear and non-stationary electromagnetic signals. In this study, Very Low Frequency (VLF) transient signals recorded by the DEMETER satellite are analyzed using Morlet wavelet–based multiresolution analysis. The proposed approach provides superior time–frequency localization compared to conventional Fourier methods and enables detailed visualization of transient structures. The scalogram representation reveals resonance characteristics, harmonic components, and temporal energy distribution associated with ionospheric wave–particle interaction processes.

Keyword: VLF Signals, Continuous Wavelet Transform and Spectral analysis.

1. INTRODUCTION

Spectral analysis of VLF signals plays a crucial role in understanding electromagnetic wave propagation in near-Earth plasma environments. Traditional Fourier transform techniques provide only global frequency information and are inadequate for transient signals whose frequency content changes with time. Wavelet transform overcomes these limitations by offering simultaneous time–frequency representation with adaptive resolution [1–3]. This property makes it particularly suitable for the analysis of non-stationary signals such as whistlers and transient emissions observed in the ionosphere.

2. THEORETICAL BACKGROUND

Wavelet transform employs localized oscillatory basis functions called mother wavelets to analyze signals across multiple scales. The Continuous Wavelet Transform (CWT) of a signal x(t) is expressed as:

$$W(a, b) = \int x(t)\, \psi^*((t - b)/a)\, dt \quad \text{.......................................} \quad (1)$$

where a represents the scale parameter and b represents the translation parameter. The inverse relation between scale and frequency enables identification of both low-frequency and high-frequency components. In practical applications, discrete dyadic sampling of scale and translation leads to the Discrete Wavelet Transform (DWT), forming the basis of multiresolution analysis (MRA) [2,4].

In MRA, a signal is decomposed into approximation and detail coefficients corresponding to different frequency bands. This hierarchical decomposition provides efficient representation of transient structures and localized features in signals [5]. The energy distribution of wavelet coefficients plotted over time and scale produces a scalogram, which serves as a time–frequency energy map.

3. DATA AND METHODOLOGY

The VLF data analyzed in this work were recorded by the DEMETER micro-satellite during seismic activity periods. The satellite carries instruments capable of measuring electric and magnetic field components in the VLF range. Wavelet-based scalograms were generated using MATLAB software to visualize time–frequency energy distribution. Morlet wavelet was selected due to its good localization in both time and frequency domains [6].

4. RESULTS AND DISCUSSION

Figure 1: Waveform of Dispersive Whistlers

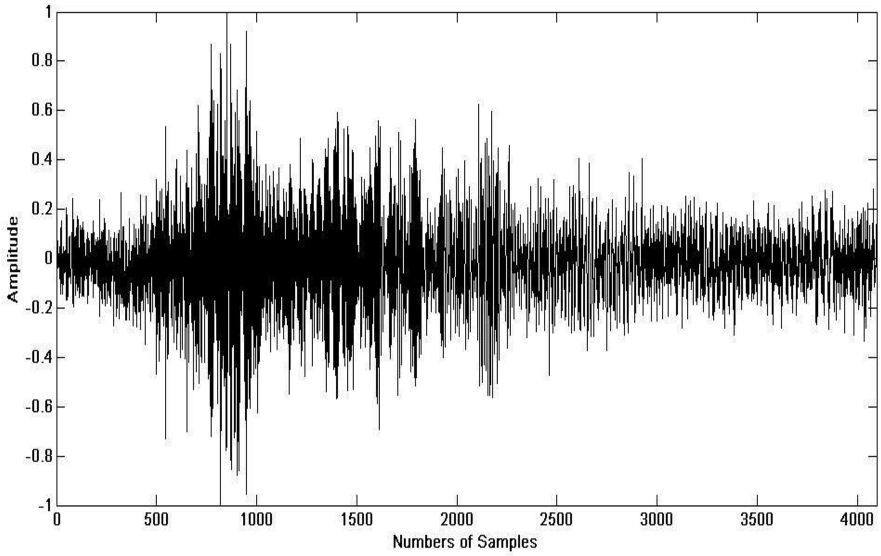


Figure 2: Spectrogram of VLF Dispersive Whistlers

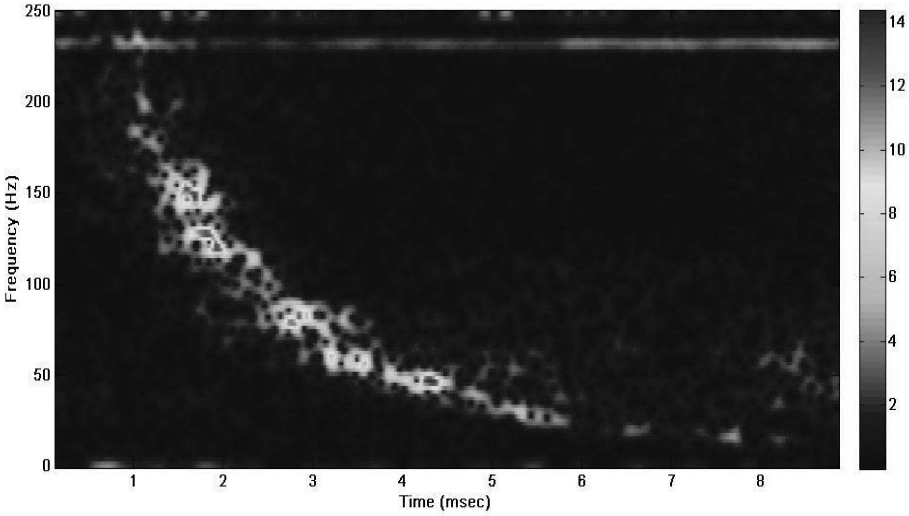


Figure 3. Wavelet scalogram of VLF Dispersive Whistlers.

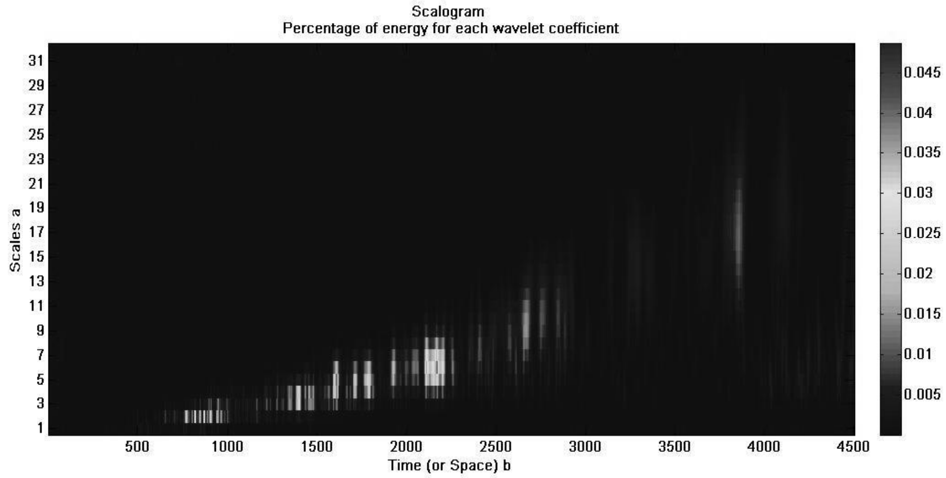


Figure 4. Waveform of Spiky Whistlers

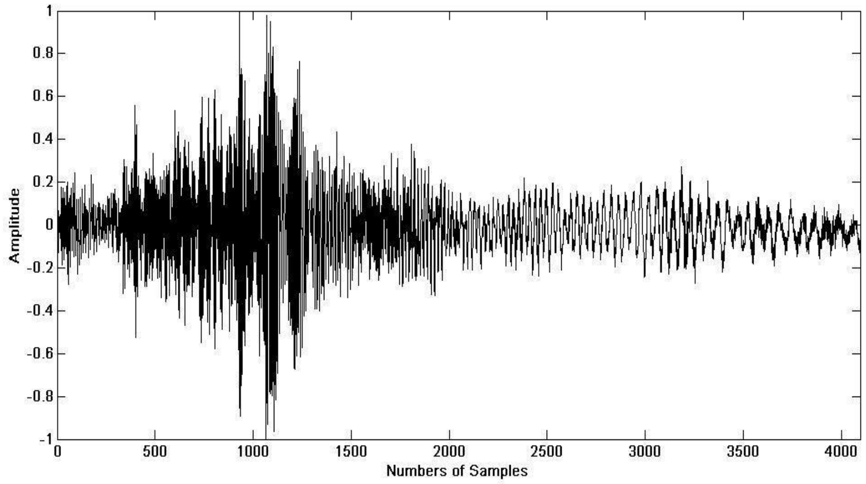


Figure 5: Spectrogram of Spiky Whistlers

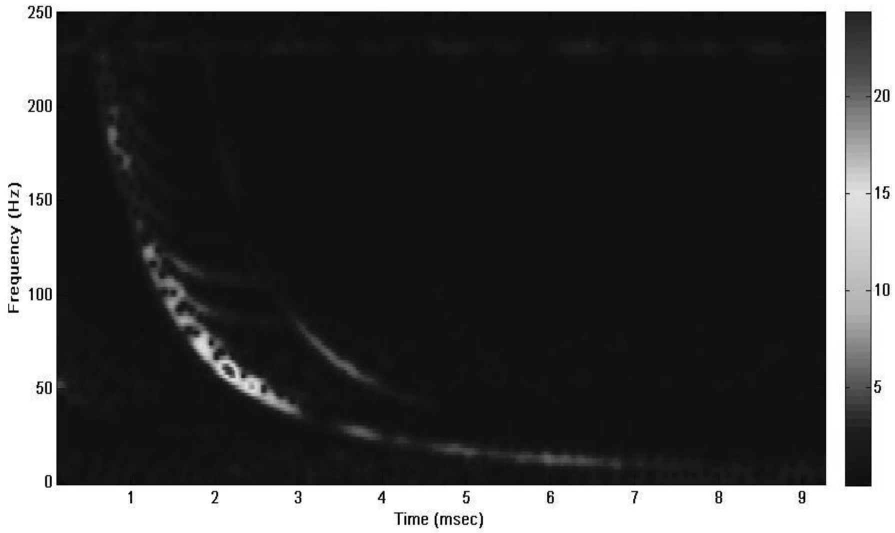
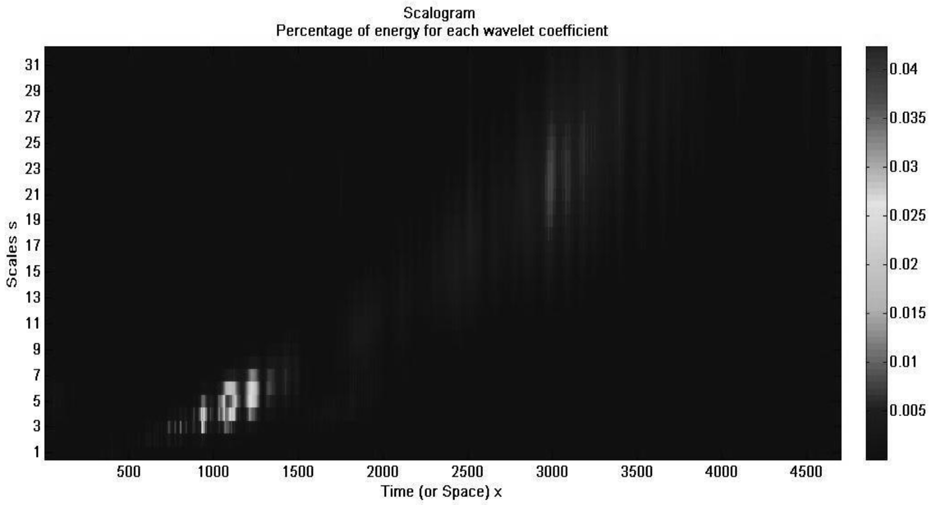


Figure 6: Wavelet scalogram of Spiky Whistlers



The scalograms demonstrate localized high-energy regions corresponding to resonance phenomena and harmonic structures. Variations in scale indicate changes in frequency content over time, confirming the effectiveness of wavelet-based analysis for transient VLF signals. The presence of harmonic bands and energy packets supports the interpretation of wave–particle interaction mechanisms in the ionospheric medium [7–9].

5. CONCLUSION

This study presents a comprehensive time–frequency analysis of VLF transients using continuous wavelet transform. The method provides improved visualization and characterization of transient behavior compared to conventional spectral approaches. The results confirm the capability of wavelet analysis to identify resonance features, harmonic structures, and temporal variations associated with ionospheric electromagnetic phenomena.

REFERENCES:

[1] Chui, C. K. (1992). An introduction to wavelets. Academic Press.
[2] Daubechies, I. (1992). Ten lectures on wavelets. SIAM.
[3] Mallat, S. (1999). A wavelet tour of signal processing. Academic Press.
[4] Mallat, S. (1989). A theory for multiresolution signal decomposition. IEEE Transactions on Pattern Analysis and Machine Intelligence, 11, 674–693.
[5] Jawerth, B., & Sweldens, W. (1994). An overview of wavelet based multiresolution analysis. SIAM Review, 36(3), 377–412.
[6] Morlet, J., Arens, G., Fourgeau, E., & Giard, D. (1982). Wave propagation and sampling theory. Geophysics, 47(2), 203–236.
[7] Kumar, P., & Foufoula-Georgiou, E. (1997). Wavelet analysis for geophysical applications. Reviews of Geophysics, 35(4), 385–412.
[8] Flandrin, P., Rilling, G., & Gonçalves, P. (2004). Empirical mode decomposition as a filter bank. IEEE Signal Processing Letters, 11(2), 112–114.
[9] Wu, Z., & Huang, N. E. (2009). Ensemble empirical mode decomposition. Advances in Adaptive Data Analysis, 1(1), 1–41.