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Spectral Analysis of VLF Transients Using Fourier Transform Methods

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Abstract - Very Low Frequency (VLF) electromagnetic signals in the range of 1–30 kHz are widely used for investigating ionospheric and magnetospheric processes. These signals are typically non-stationary and contain transient components arising from lightning discharges, power-line interference, and seismic disturbances. Traditional Fourier Transform techniques provide global frequency information but lack temporal localization. This paper presents a detailed investigation of Fourier Transform (FT), Fast Fourier Transform (FFT), and Short Time Fourier Transform (STFT) for spectral analysis of VLF transients. The limitations associated with fixed resolution analysis are discussed, and the results demonstrate the importance of time–frequency representation for non-stationary geophysical signals.

***Key Words*:** Fourier Transform, spectral characteristics and non-stationary geophysical signals

1. INTRODUCTION

Spectral analysis of naturally generated VLF radio waves observed on ground and satellite platforms has played an important role in understanding several aspects of ionospheric and magnetospheric physics (Smith & Helliwell, 1960). VLF signals are transient in nature and often contain harmonic and nonlinear noise components originating from global lightning, power-line radiation, and occasionally seismic activity. The generation of VLF transients and the formation of their spectral characteristics remain subjects of active experimental and theoretical research (Rioul & Vetterli, 1991). Fourier Transform methods have traditionally been used for the analysis of frequency content; however, their applicability is limited when signals exhibit strong non-stationary behavior.

2. THEORETICAL BACKGROUND

The Fourier Transform decomposes a signal into orthogonal sinusoidal components and provides global information about the frequency content. For a continuous signal x(t), the Fourier Transform is expressed as:

$$X(f) = \int x(t)\, e^{(-j2\pi ft)}\, dt$$

The inverse Fourier Transform reconstructs the original signal from its spectral representation. In practical applications, signals are sampled and finite in duration; therefore, the Discrete Fourier Transform (DFT) is used.

$$X[k] = \Sigma\, x[n]\, e^{(-j2\pi kn/N)}$$

The Fast Fourier Transform is an efficient computational algorithm for evaluating the DFT with reduced complexity. Although FFT significantly improves computational speed, it still suffers from spectral leakage and aliasing problems when analyzing transient signals. To overcome these limitations and obtain both time and frequency information simultaneously, the Short Time Fourier Transform is applied by introducing a moving window function.

$$STFT(t, f) = \int x(\tau)\, w(\tau - t)\, e^{(-j2\pi f\tau)}\, d\tau$$

The squared magnitude of the STFT is known as the spectrogram. The performance of STFT depends strongly on the selected window size, which introduces a trade-off between time resolution and frequency resolution governed by the uncertainty principle (Rioul & Vetterli, 1991).

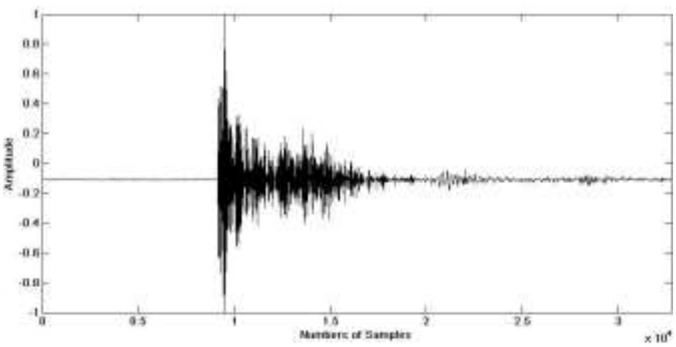

Fig. 1 Waveform of VLF signal observed by satellite.

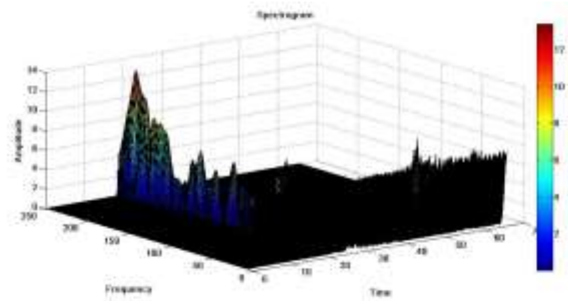

Fig. 2 STFT spectrogram for different window lengths.

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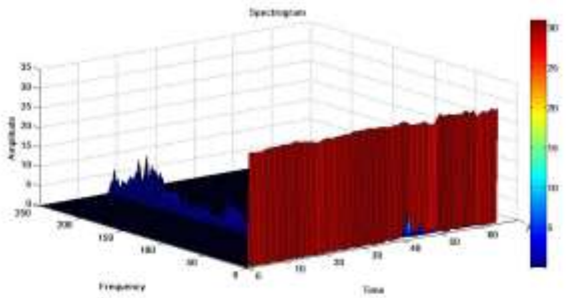

Fig. 3 Constant resolution time–frequency plane.

3. RESULTS AND DISCUSSION

The analyzed VLF waveform clearly demonstrates transient characteristics with bursts appearing at different time intervals. The STFT spectrogram obtained using different window sizes illustrates the trade-off between time and frequency resolution. A shorter window provides better time localization but poorer frequency resolution, whereas a longer window improves frequency resolution at the cost of temporal accuracy. The constant resolution property of STFT further limits its effectiveness for signals containing both slow and rapid variations simultaneously.

4. CONCLUSION

This study presents a comprehensive investigation of Fourier-based spectral analysis techniques for VLF transient signals. The results demonstrate that while FFT provides efficient computation of global spectral content, it lacks temporal localization required for non-stationary signal analysis. STFT improves time–frequency representation but suffers from fixed resolution limitations. These observations highlight the necessity of adaptive multi-resolution techniques for accurate characterization of VLF phenomena.

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