PAPER NAME

345-2262-2-LE.docx

AUTHOR

Muhammad Rendi Jaya

WORD COUNT

3497 Words

CHARACTER COUNT

20062 Characters

PAGE COUNT

11 Pages

FILE SIZE

2.4MB

SUBMISSION DATE

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CONTROLLED-SOURCE ELECTROMAGNETIC (CSEM) DATA PROCESSING WITH HIGH ELECTROMAGNETIC NOISE LEVELS

PENGOLAHAN DATA CONTROLLED-SOURCE ELECTROMAGNETIC (CSEM) DENGAN TINGKAT NOISE ELEKTROMAGNETIK TINGGI

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Received: 2023, October 24th
Accepted: 2024, July 2nd

Keywords:
CSEM;
Noise;
Poststack;
Prestack;
Stacking.

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How to cite this article:

Jaya, M.R., Paembonan, A.Y., Irawati, S.M., & Strack, K.M. (2024). Controlled-Source Electromagnetic (CSEM) Data Processing with High Electromagnetic Noise Levels. *JGE (Jurnal Geofisika Eksplorasi)*, 10(02), 149-159.

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Abstract. The Controlled-Source Electromagnetic (CSEM) method is one of the electromagnetic methods utilized in geophysical exploration. This method provides a subsurface image through the resistivity anomalies of materials encountered by electromagnetic waves. The research area is located near a major city, resulting in high electromagnetic noise. Electromagnetic noise can be categorized into two types of the noise namely periodic noise and sporadic noise. Eliminating noise is a crucial objective to enhance data quality, as it can introduce uncertainty into interpretations. Three noise removal techniques are employed: pre-stack to filter the harmonic noise, stacking to remove the sporadic noise, and post-stack for smoothing. The CSEM data used consists of signals in the time domain with a 10-second period and a 50% duty cycle. The results of applying these noise removal techniques indicate that all three methods are highly effective in noise reduction. The pre-stack technique can remove periodic noise, while sporadic noise is addressed by the stacking technique, and signal smoothing can be achieved using the poststack technique.

Abstrak. *Metode Controlled-Source Electromagnetic (CSEM) merupakan salah satu metode elektromagnetik yang digunakan dalam eksplorasi geofisika. Metode ini memberikan gambaran bawah permukaan melalui anomali resistivitas material yang dilewati oleh gelombang elektromagnetik. Daerah penelitian berada dekat kota besar, yang menyebabkan tingginya noise elektromagnetik pada data CSEM. Noise elektromagnetik terbagi menjadi dua jenis, yaitu periodic noise dan sporadic noise. Menghilangkan noise menjadi tujuan penting dalam meningkatkan kualitas data, karena dapat menciptakan ketidakpastian dalam interpretasi. Untuk menghilangkan noise, digunakan tiga teknik noise removal, yaitu pre-stack (filtering), stacking, dan post-stack (smoothing). Data CSEM yang digunakan berupa sinyal dalam domain waktu dengan periode*

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10 detik dan duty cycle 50%. Hasil penggunaan teknik noise removal menunjukkan bahwa ketiga teknik ini sangat efektif dalam menghilangkan noise. Teknik prestack mampu menghilangkan periodic noise, sedangkan sporadic noise diatasi oleh teknik stacking dan sinyal dapat diperhalus dengan menggunakan teknik poststack.

1. INTRODUCTION

The Controlled-Source Electromagnetic (CSEM) method is one of the geophysical techniques utilized for exploration activities. The CSEM method provides a subsurface depiction of anomalies in the resistivity values of subsurface materials penetrated by diffusing electromagnetic waves (Ziolkowski & David, 2012). CSEM is highly sensitive to subsurface resistivity, which aids in geological interpretation due to resistivity correlates with rock matrix, porosity, and the pore fluids. Furthermore, source signals can be transmitted in multiple directions and received by several receivers (Ashadi et al., 2022).

In the CSEM method, two signals are recorded by the receivers namely the electric field (E-field) and the magnetic field (B-field). CSEM measurements can be conducted in close proximity to inhabited areas, leading to high levels of electromagnetic noise (Paembonan et al., 2017; Henke et al., 2020; Morbe et al., 2020). This significantly impacts the challenging data processing of CSEM due to the high noise in the signals recorded by the receiver (Pankratov & Alexey, 2010). If the data is distorted by the noise or poor quality, the data must be treated using several approached. hence, a serious consideration must be given to the removal of high electromagnetic noise from the recorded signals.

In the study conducted by Strack et al. (1989), using Long-Offset Electromagnetic data, commonly known as LOTEM, data exhibit high noise levels due to measurements taken near inhabited areas, resulting in cultural noise in raw data. The noise from the industrial area could be handle by using frequency filter. Meanwhile, sporadic noise is best handled using selective stacking with symmetric rejection or area-defined methods, where signal amplitudes are selectively preserved, and noise is statistically rejected.

The data indicates that for LOTEM sounding points, the symmetric-rejection algorithm significantly enhances the signal-to-noise ratio. After selective stacking, the data is smoothed through recursive averaging. The output from transient signals is then converted into apparent resistivity and inverted into a layered Earth model (Paembonan et al., 2022; Strack et al., 2022).

This is the reason why, in this study, CSEM signals in the time domain with high electromagnetic noise require noise removal and an enhancement of the signal-to-noise ratio. Furthermore, exploring how these techniques can be adapted and applied to different geological settings and conditions where electromagnetic noise is prevalent. The study would contribute to more accurate subsurface imaging and resource exploration, particularly in challenging environments where traditional CSEM data processing methods may struggle with high noise levels.

2. LITERATURE REVIEW

2.1. Electromagnetic Method

The electromagnetic method is a geophysical technique that utilizes electromagnetic waves/signals transmitted through a transmitter below the Earth's surface, with the source of these waves originating from natural or artificial sources (Widarto, 2010). The propagation of electromagnetic waves is based on Maxwell's Law, as illustrated in **Figure 1** below. Electromagnetic waves are emitted by a transmitter, and these waves travel or propagate into the Earth, resulting in the generation of a time-varying magnetic field. This electromagnetic field, when passing through or encountering materials with conductive properties, induces the formation of eddy currents or electric currents concentrated within the subsurface conductor. The flow of electric current within a conductor creates a magnetic field around it (secondary magnetic field). The secondary magnetic field produced by these eddy currents is captured or recorded by a sensor or receiver (Widarto, 2010).

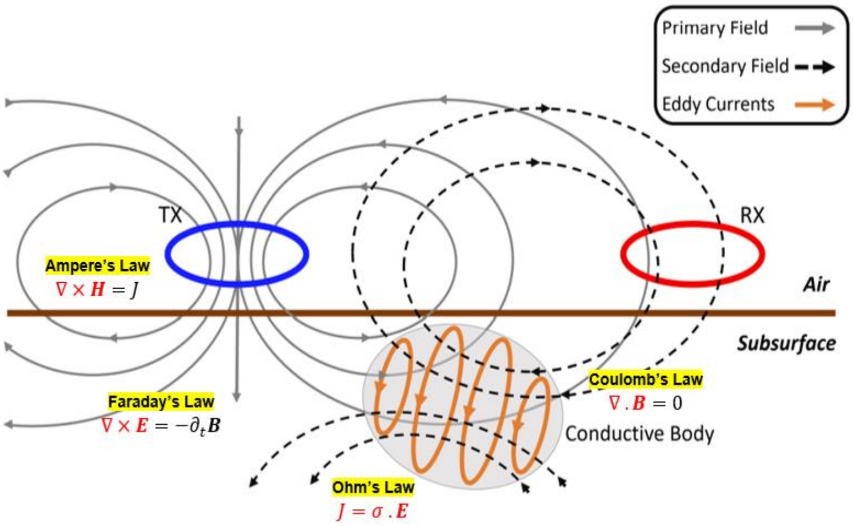

Figure 1. Principles of electromagnetic wave propagation (Wilson et al., 2022).

2.2. Controlled-Source Electromagnetic

The Controlled-Source Electromagnetic (CSEM) method is an active geophysical technique in which the transmitter, acting as an EM wave source, uses artificial signal sources (Akbar, 2010). When compared to the Magnetotelluric (MT) method, which utilizes natural EM wave sources from within the Earth, the CSEM method exhibits physical properties related to the conductivity and resistivity of rock formations. Furthermore, the CSEM method differs from the geoelectric resistivity method, where the conduction source is derived from an electrical current injected directly into the Earth's subsurface.

Acquisition using the land-based CSEM method primarily employs a time-domain system. In **Figure 2**, the electrode dipole sources are buried just below the surface, while a multi-channel receiver array is positioned at the surface or sometimes placed inside boreholes. The sources utilize high-energy direct current that is suddenly turned on and off. In this manner, the field generated by the source induces currents in the receiver coils and in the Earth. Measurements are typically taken during in–active periods, repeated multiple times, and later processed to enhance the Signal-to-Noise (S/N) ratio.

The depth of penetration achievable and captured by the electromagnetic waves beneath the surface can be referred to as the skin depth. The skin depth is defined as the depth in a homogeneous medium where the amplitude of the induced electromagnetic wave becomes 1/e of its amplitude at the Earth's surface (ln e = 1 or e = 2.718...). In this case, the amplitudes of the E-field and B-field are proportional to the penetration depth δ, such that:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{2\rho}{\omega\mu}} \approx 503\sqrt{\rho T} \qquad (1)$$

where δ represents the skin depth (m), T is the period (s), and ρ is the resistivity of the homogeneous medium. From **Equation 1**, it can be observed that the skin depth is inversely proportional to frequency and directly proportional to the period, meaning that the longer the measurement time, the deeper the penetration (Lantu, 2014)

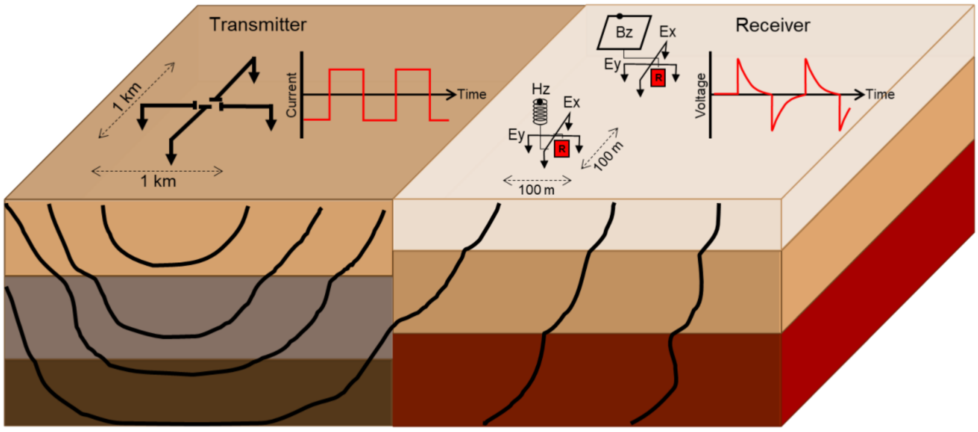

Figure 2. Ground CSEM survey setup (Martinez et al., 2022).

2.3. Distortions in CSEM Data

Strack (1992) classified types of noise into two categories: periodic noise and sporadic noise. Periodic noise, in general, is generated by PLN voltage, telephone cables, pipes, metal fences in the vicinity of the measurement area. In contrast, sporadic noise is caused by geomagnetic signals, lightning that produces natural transient electromagnetic (TEM) events, AC power lines, the equipment used, and the movement of magnetic devices around the receiver sensors.

3. METHODS

The research is located in one of the largest states in the United States, which has salt dome structures for oil and natural gas production. The research area map can be seen in **Figure 3** below. The data used is secondary data acquired through CSEM method acquisition in area X by KMS Technologies. Three measurement points were used, with signal information in terms of voltage (mV) and time (ms), a measurement period of 10 seconds, and a duty cycle of 50%.

The data processing steps for CSEM in the time domain are shown in **Figure 4,** where this research will discuss three techniques used for noise removal. In the first stage, a frequency domain filtering technique will be used, namely a notch filter with a 3dB threshold and a lowpass filter. This means that the CSEM signal, initially in the time domain, will be converted to the frequency domain first using Fast Fourier Transform (FFT), and then FFT will be performed again to transform the signal domain back to the time domain.

The second stage will employ the selective stacking technique, specifically area defined rejection, which will determine the area to be retained. The amplitude frequency distribution will be calculated by shifting an overlapping window over the sorted amplitude for each time sample of all transients. Thus, the percentage of the area beneath each symmetrically positioned distribution curve relative to the maximum will be computed, and all data within that area will be preserved. The final stage will utilize the smoothing technique, namely recursive averaging. In this technique, the focus will be on the value of the smoothing coefficient (α) within the range of 0 to 1. The closer the value of α is to 1, the smoother the resulting signal. These three stages, with the specified techniques, will be described in more detail as follows.

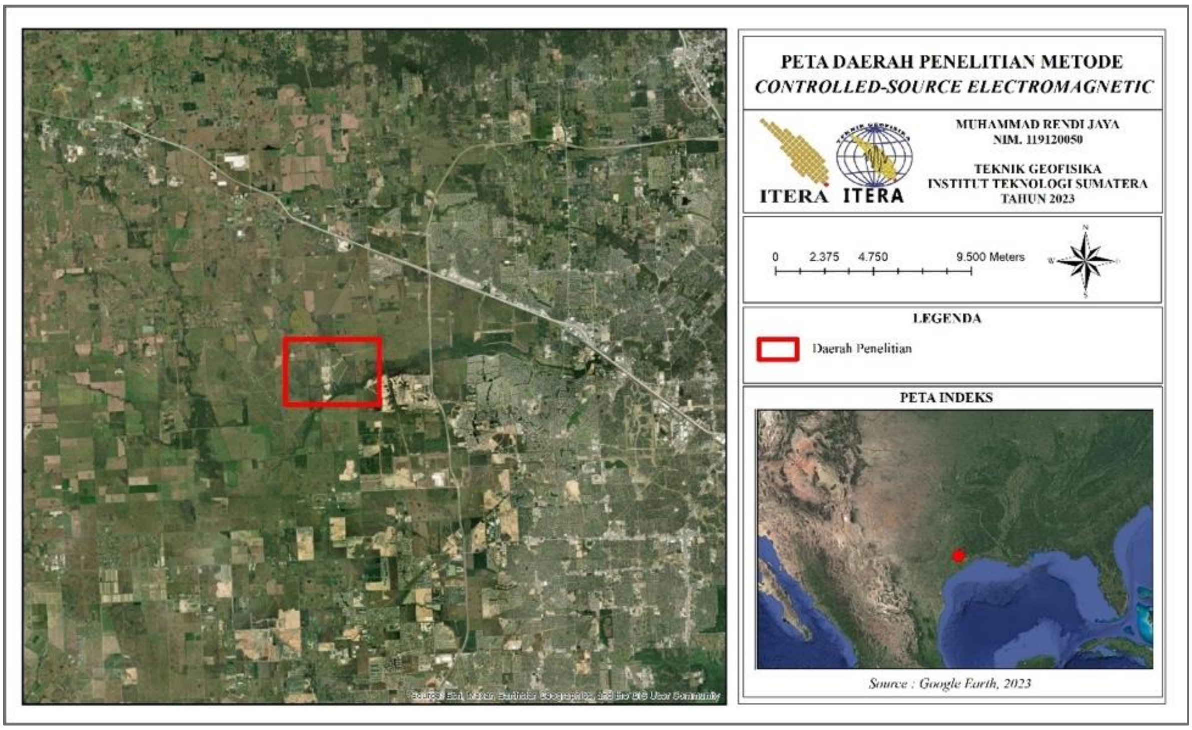

Figure 3. Research map showing the area of the survey area.

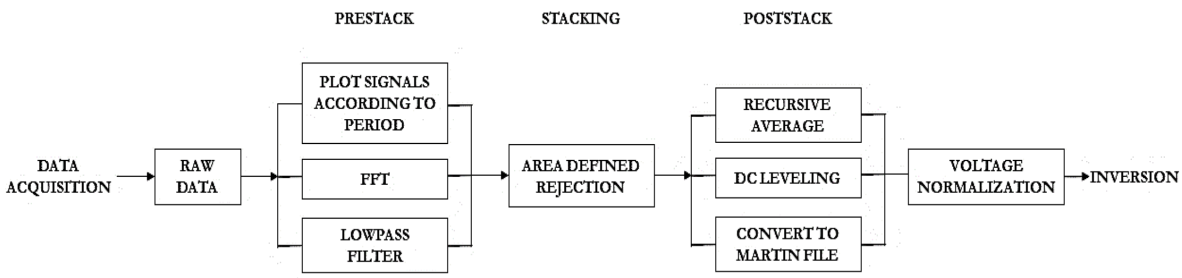

Figure 4. Tags of CSEM data processing in the time domain.

3.1. *Prestack (Filtering)*

This process aims to eliminate periodic noise using a notch filter, which automatically removes the 60Hz periodic noise (illustrated in **Figure 5**) with a 3.00 dB threshold and a lowpass filter that eliminates signals above the specified cut-off frequency. The initial signal processing stage for CSEM signals can be seen in **Figure 6**.

The amplitude in CSEM signals contains a significant amount of resistivity information. It becomes crucial when the digital filter not only suppresses noise but also preserves amplitudes carrying information (Strack, 1992).

$$\frac{|z_n-1|^2}{|z_n+1|^2} = \frac{|z_p-1|^2}{|z_p-1|^2} \tag{2}$$

In other words, the ratio between the pole and zero vectors will remain the same and will result in a recursive formula in the z-domain.

$$H(z) = \frac{Y(z)}{Z(z)} = \eta\,\frac{(z-z_n)(z-z_n^*)}{(z-z_p)(z-z_p^*)}$$

$$= \eta\,\frac{z^2-2\alpha z+1}{z^2-2\alpha\eta z+1\eta-1} \tag{3}$$

with $\eta = \frac{z_p-1}{z_n-1}$ (normalization $gain$ 1) (5)

defined as $x = \eta\alpha$

we find, $y^2 = \frac{2x}{\alpha} - (1-x^2)$ (6)

where *F(z)* is the filter function given by the output function ratio, *Y(z)*, and the input function, *X(z); zn* and *zp* are the positions of the zero and pole, respectively; η is the proportionality factor that combines the real part of the pole, x, with the real part of the zero, α; and y is the imaginary part of the pole. To eliminate phase shift, a recursive filter is applied twice to the data: first forward and then backward (Strack et al., 1989).

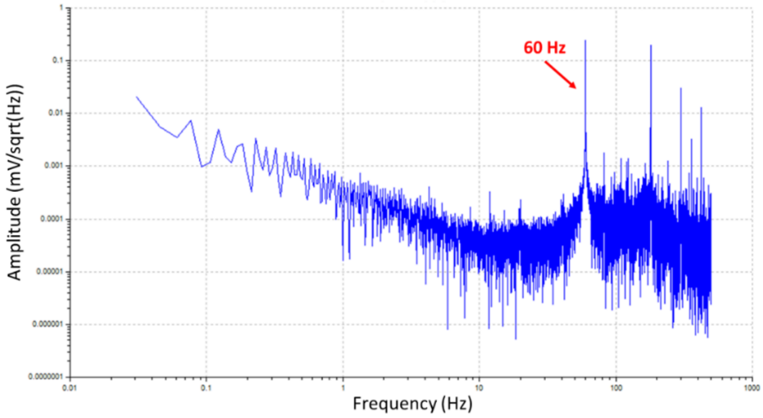

Figure 5. Frequency spectrum of CSEM data. Periodic noise is identified by spikes at the 60Hz frequency (Original figure from this research).

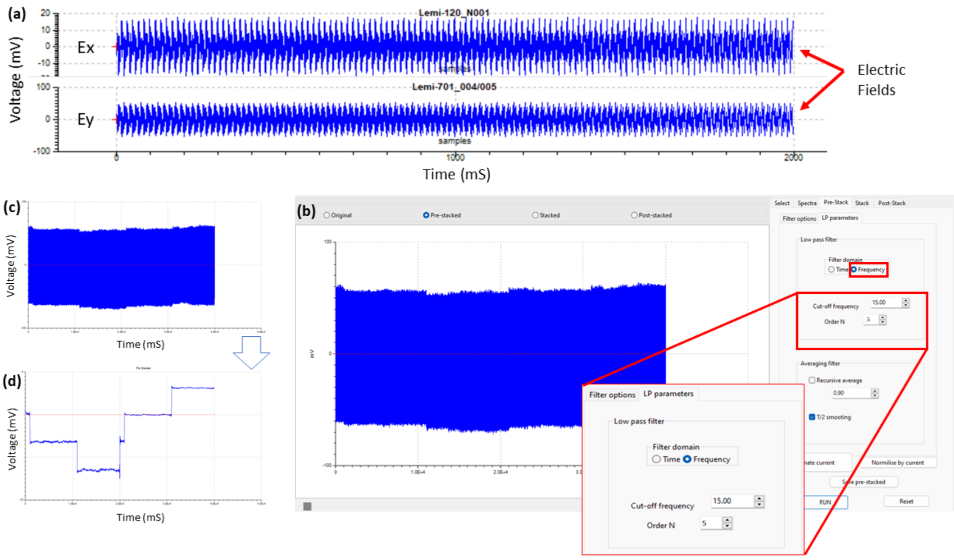

Figure 6. Signal Ex and Ey filtering process in KMSPro Qc; (a) Raw data, (b) Input parameter for frequency cut-off and order, (c) Raw data before filtering, and (d) Signal result after prestack filtering (Original figure from this research).

In the notch filter, we select a value of 60Hz for rejection at that frequency, and for the lowpass filter, we specify a cut-off frequency of 15Hz and an order of 5, where the mathematical formula for the lowpass filter is expressed as Equation 7 (Shouran & Elmazeg, 2020).

$$M_{1p} = \frac{1}{\sqrt{1+\left(\frac{1}{f/_{fc}}\right)^{2n}}} \tag{7}$$

where fc is the cut -off frequency, and n is the filter order.

3.2. Selective Stacking

Sporadic noise can be caused by various sources such as water pumps, electrical fences, trains, factories, and/or passing vehicles near the receiver. This noise is recorded and often goes unnoticed; A safe approach to eliminate this type of noise through data processing is to consider the statistics of all signals and analysis the corresponding amplitude distribution, both of which become increasingly important when there are only a few transients, and sporadic noise is not removed during the stacking process. However, it can significantly distort the stacked results as its amplitude is far above or below the signal level (Strack et al., 1989). When acquiring transients with a short rise time, it is also challenging to integrate spike detector in analog or digital form. **Figure 7** shows that selective stacking rejection, based on defined areas, can significantly improve the S/N ratio compared to the regular summation process, which eliminates all data beyond two standard deviations from the mean.

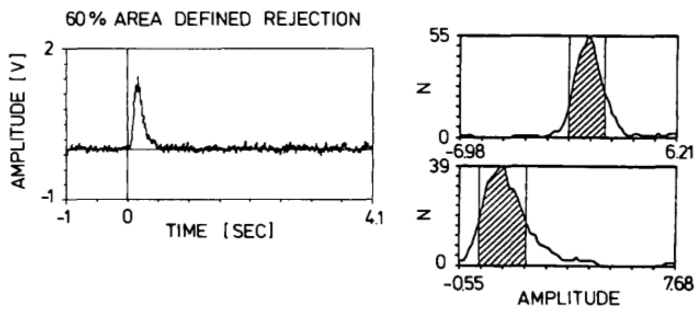

Figure 7. Data stacked using area-defined rejection technique (Strack et al., 1989).

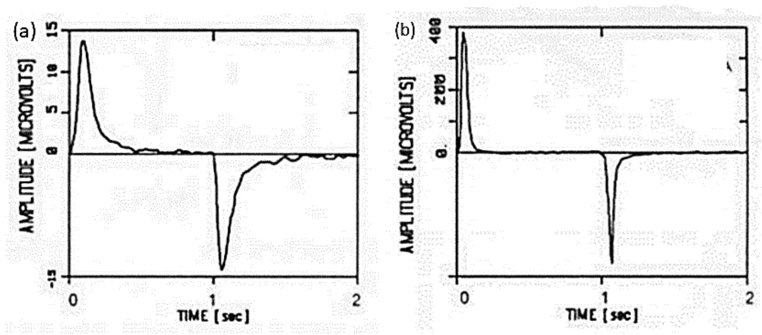

Figure 8. Difference in signals after smoothing. (a) Signal after stacking and (b) Signal after smoothing (Strack, 1992).

3.3. Poststack (Smoothing)

In the final step of transient signal processing, it can be referred to as the smoothing stage. Smoothing using recursive averaging is one of the signal processing techniques to reduce signal fluctuations and produce a smoother signal. In recursive averaging, there is a parameter known as the smoothing coefficient (α), which ranges from 0 to 1. A higher smoothing coefficient range results in a smoother signal (Nugus, 2009). The formula for the recursive averaging technique can be written as Equation 8 below.

$$F_t = X_t + (1 - \alpha)F_{t-1} \quad (8)$$

F_{t-1} represents the previous forecast, X_t represents the current observation, and α is the smoothing coefficient (Nugus, 2009). **Figure 8** illustrates the signal results after the smoothing process. This shows that the ringing effect on the signal, which occurred after stacking, has been eliminated, and the signal has been improved.

4. RESULTS AND DISCUSSION

The CSEM signal processing focuses on improving signal quality through pre-stack, stacking, and post-stack stages. During acquisition, the signals recorded by the receiver are not entirely the desired signals (illustrated in **Figure 9a**). Instead, they include other unwanted signals, often referred to as noise, which directly affects the signal-to-noise ratio.

In **Figure 9**, it shows how raw data from the CSEM signal is highly noisy and demonstrates the quality improvement achieved through three noise removal techniques. A Notch filter is automatically applied to detect periodic noise at a frequency of 60 Hz (the frequency of the American power line) with a threshold level of 3.00 dB. A Lowpass filter is used to suppress frequencies above the cut-off frequency, which is set at 15 Hz with an order of 5. While periodic noise is effectively removed from the CSEM signal (**Figure 9b**), sporadic noise is not as easily eliminated.

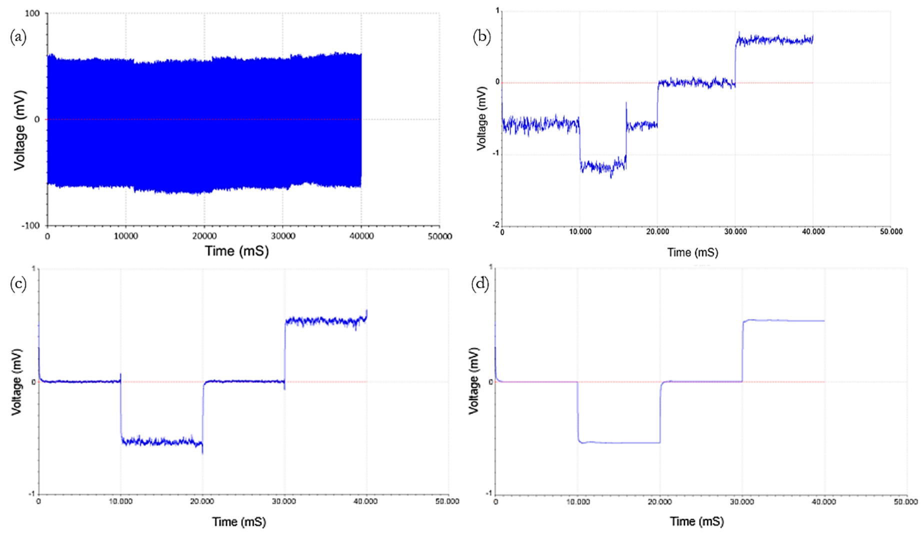

Figure 9. Processing of CSEM electric field component data. (a) Raw data including noise, (b) Signal after filtering, (c) Signal after stacking, and (d) Signal after smoothing.

Sporadic noise can be compensated for by employing selective stacking with the area-defined rejection technique. The Gibbs phenomenon resulting from selective stacking may cause a ringing effect (**Figure 9c**) in the signal, which can be reduced by applying recursive averaging with a smoothing coefficient of 0.9 (**Figure 9d**). The smoothed CSEM signal is stored for one period. In **Figure 10**, the CSEM decay illustrates how electromagnetic wave changes over time, influenced by various properties of the materials it passes through. CSEM decay can also indicate the receiver's position based on the amplitude recorded in the CSEM signal.

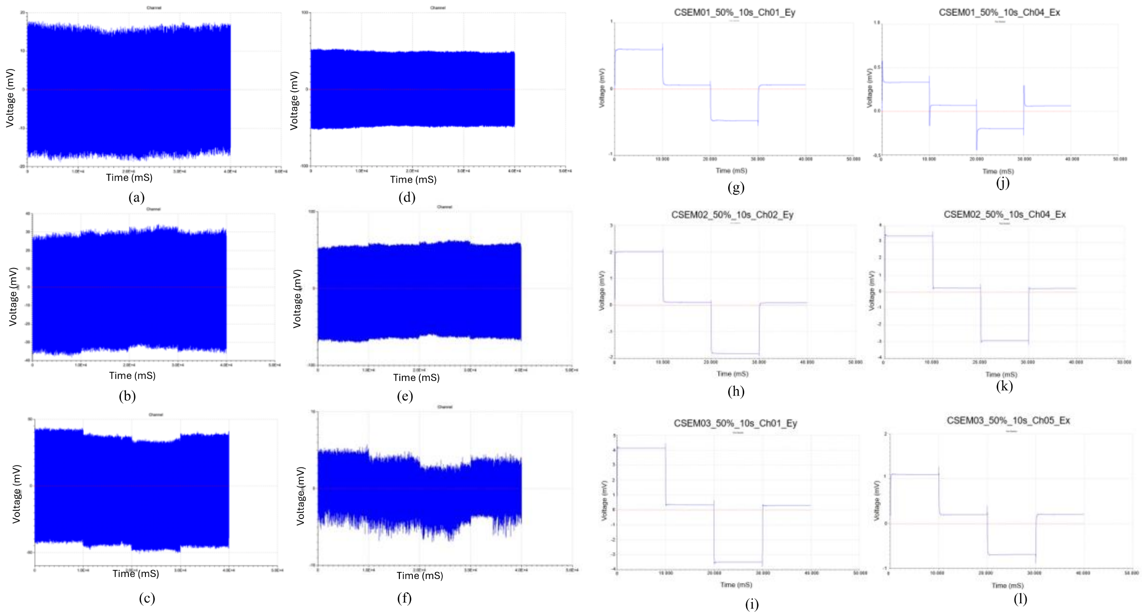

Figure 10. Comparison between raw data (a-f) and processed data (g-l), showing both raw data of Ey (a, b, c) and Ex (e, f, g), and processed data Ey (g, h, i) and Ex (j, k, l).

The signal quality in the time-domain CSEM data has significant implications for improving the quality of interpretation and accuracy in subsurface structure imaging. This not only facilitates more precise identification of natural resources to be explored but also allows for reduced ambiguity in characterizing lithology and crucial geological formation boundaries in natural resource exploration.

The result show (**Figure 10**) that most of the noise can be handled with about 70% reduced using frequency-filters approximately 20 % using stacking, and the rest bout 10% smoothed using average filtering. The data has significantly increased in signal to noise ratio. The data in **Figure 11** is ready to be used for the next interpretation steps, inversion.

Regarding this research, despite the applied method successfully reducing a major portion of noise in the time-domain CSEM data, there are still several limitations to be considered. For instance, when dealing with highly complex or variant noise, this method may encounter limitations in its effectiveness.

Therefore, further investigation is needed for the development of more adaptive pre-processing techniques and the selection of parameters used in the noise removal stage, especially when variably recorded noise bears a striking resemblance to actual signals. This aims to enhance the quality and reliability of the noise elimination process about 80%. This could describe that the signal processing steps is crucial in time-domain CSEM data leading to the significant contribution for the interpretation

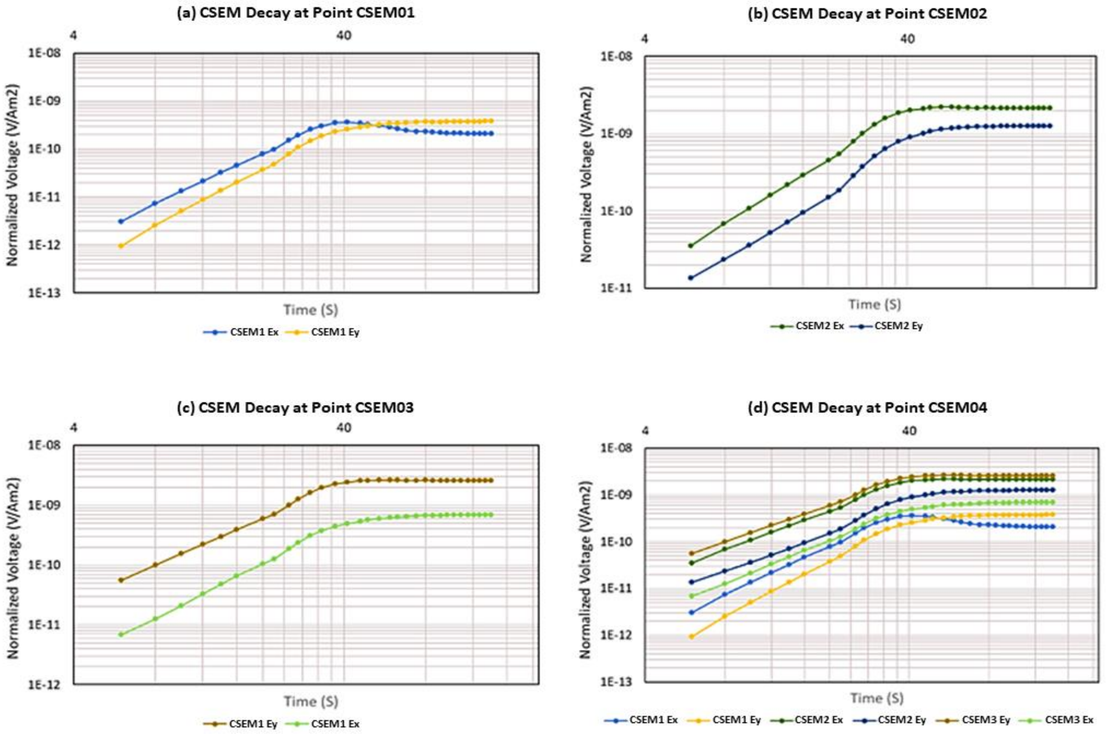

Figure 11. CSEM decay. (a) Point CSEM01, (b) Point CSEM02, (c) Point CSEM03, and (d) All measurement points.

5. CONCLUSION

The CSEM signal is disturbed by high electromagnetic noise, leading to uncertainty in the inversion and interpretation process. However, by implementing noise removal techniques, including pre-stack, stacking, and post-stack procedures, the initially noisy signal can be processed into a smoother form. This results in a signal containing subsurface information without noise interference. Therefore, it can be concluded that the application of these noise removal techniques is highly effective in improving the quality of the CSEM signal about 80% and unlocking the potential for a better understanding of subsurface structures.

ACKNOWLEDGMENT

The researcher extends heartfelt gratitude to KMS Technologies for their generous provision of access to and utilization of the CSEM data, which significantly contributed to the success and findings of this study.

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