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INFLUENCE ASSESSMENT OF DISTANCE TO THE SOURCE OF PULSE SIGNALS WITH HARMONIC COMPONENTS ON THE TEMPORAL DISTORTION OF THEIR FORMS

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***Abstract*: Within the scope of this article, periodic pulse signal typical samples with harmonic components have been analyzed, including their spectral fluctuations, changes in their frequency range, and the form of signal typical samples depending on the distance. Collected statistical information regarding changes in the duration of typical samples affected by distance change from the signal source to the sensor based on data collected during field experiments. Signal features by which typical samples can be recognized have been outlined and their duration effectively measured. The dynamics of frequency spectrum change and duration of repetitive typical samples have been presented depending on the distance to the signal source. Additionally, the frequency range and average duration range of the researched typical samples, and their variations have been provided based on the gathered statistics data.**

***Index Terms*: Discrete signal, Periodic pulse signal, Signal analysis, Signal distortion.**

I. INTRODUCTION

Distortion of signals, which are spreading through the physical environment may be caused by different factors such as fluctuation of temperature and humidity, the presence of external interfering sources and random processes like noise, and the non-uniform material structure of the environment itself [1].

Also, distortions of these signals can be found during the analog-to-digital conversion due to the nonlinear characteristics of analog-to-digital devices [2]. A typical solution in digital signal processing tasks is the estimation of their shape based on the usage of correlation functions [3]. Furthermore, for signals with harmonic components in their spectrum, non-recursive and recursive digital filters can be applied, which can essentially be considered a form of correlation signal processing. Previously mentioned distortions can be related not only to the shape of signals but also to their phase and frequency characteristics [1].

A notable aspect of spectral and phase distortions is that they can be relatively easily compensated using correlation-based digital processing methods. However, in the presence of time-domain signal distortions, such as compression or stretching, correlation analysis somewhat loses its effectiveness and requires adaptation to possible signal shape variations for successful application [4].

The studied geo-signal, based on field-gathered data, contains different types of distortions which require further research to find sources of such distortions, log their features, and how outside variables affect the signal. The importance of this information is in the understanding of the nature of signal fluctuations, knowledge of which may lead to improvement in the researched signal processing and capturing of searched typical samples.

The conducted study aims to identify characteristic distortions in the waveform of pulse geo-signal typical samples caused by an increase in the distance from the source of their formation. The contribution of this study is an assessment of the time domain fluctuations limits of the investigated pulse geo-signals with harmonic components, caused by the change in the distance to the signal source, and usage estimation of the correlation methods for signal processing.

II. LITERATURE REVIEW AND PROBLEM STATEMENT

Fluctuation of information and measurement signals by amplitude is relatively not difficult to compensate with correlation processing methods. The larger problem is signal distortion of signals when their duration is expanded while the frequency composition remains relatively unchanged [5]. This alteration in the time domain can affect the correlation between signals, impacting the accuracy of analyses that rely on signal alignment.

In the context of structural health monitoring, methods such as baseline signal stretch (BSS) [6] and online recursive empirical mode decomposition (EMD) [7] have been proposed to improve the sensitivity and coverage of guided wave signals. These techniques aim to address the challenges posed by signal stretching, ensuring that the signals are appropriately processed and interpreted despite temporal distortions.

Moreover, in the field of optics, the use of analog optical auto-correlation techniques has been explored to achieve a high-resolution frequency spectrum of ultra-short signal pulses which was covered in the article [8]. These methods involve stretching time by significant factors to enhance the observation/measurement time, which can impact the correlation analysis of signals due to the extended temporal domain.

In the field of geodesy and materials science also was observed issues with correlation caused by signal deformation. In geodetic studies in [5], the influence of aperiodic non-tidal atmospheric and oceanic loading deformations has been shown to significantly impact the seasonal spatial correlation in the global navigation satellite system (GNSS) vertical land motion time series. This highlights how external factors can introduce time-dependent variations that affect the correlation structure of signals.

Source [6] reviews problems, in the context of GNSS, caused by the ionosphere signal distortions, which lead to severe deformations and fluctuations in time domain signals, affecting correlation function. These distortions can impact the accuracy of signal processing and analysis in GNSS applications.

Moreover, the presence of signal distortions, caused by spoofing attacks, can affect the symmetry of correlation functions in receivers, necessitating the development of new detection methods [7]. Additionally, distortions in GNSS signals, known as "evil waveforms," can cause significant disruptions in cross-correlation functions [8]. These distortions pose challenges in accurately processing and interpreting GNSS signals, impacting various applications reliant on precise positioning data.

In geology, time-series processing plays a vital role in accurately separating various errors from the deformation signal, ensuring that the deformation signal is not mistaken for noise during filtering processes [8]. This highlights the importance of handling time domain deformation correctly to avoid misinterpretations in subsequent processing stages.

Article [14] reviews and compares time domain and frequency domain distortion compensation approaches for orthogonal frequency division multiplexing (OFDM) systems. Those systems have issues with distortions due to nonlinearities, such as power amplifier distortions. Additionally, what was introduced is a new analytical model of OFDM systems with clipping and filtering suitable for analyzing the time-domain distortion compensation approach.

The study of vibrations in various contexts, such as in the analysis of surface characteristics of materials or fault detection, emphasizes the importance of understanding how deformation in the time domain affects signal processing outcomes. Article [15] analyses the influence of manipulated variables on time domain statistical characteristics and frequency of vibration signal captured during continuous drive friction welding. Study [16] provided a method of mechanical time domain vibration waveforms analysis based on quantum probability. That method was created to extract fault information from the time domain waveform effectively. Both studies highlight the importance of time domain signal analysis to capture distortions which may lead to valuable information on the research.

Another publication on the topic of faults captured by vibration signals [17] explores how a regularized sparse filtering model can help with fault diagnosis. The overviewed problem of speed fluctuation influence on the vibration signal and fault diagnosis results highlights the importance of accounting for external factors on the signal analysis and its further processing.

Similarly, in dynamic signal evaluation, the impact of external factors like pressure fluctuations on time-domain signal fluctuation is assessed using correlation analysis methods in the article [18].

Source [19] covers a review on the principles and applications of the photonic time-stretching imaging technique, its recent development, and the future trends. It shows how that method improved the speed of optical signal processing compared to traditional imaging methods. This highlights the importance of signal deformation analysis, particularly understanding how time domain signal stretching can improve existing signal processing techniques.

Article [20] verifies the theory that small signal changes in amplitude-frequency or phase-frequency response may cause time domain distortions or phenomena of paired echoes related to the pulse signal sent through dispersive transmission lines with discontinuities. The results of the study didn't confirm the theory, although it was recorded that pulse signal dispersion caused by the transmission line caused time-domain distortion. That information highlights why the theoretical connection of influences on the signal requires additional study using available methods like theoretical methods, simulations, or field experiments.

III. SCOPE OF WORK AND OBJECTIVES

During the conducted field studies on the propagation of geo-signals over various distances, it was established that typical samples under investigation are similar in shape, however, their duration may vary.

Studies were conducted using a developed autonomous device based on an 8-bit microcontroller ATmega328p with embedded 10-bit resolution ADC [21], a sample rate of 100 Hz, which satisfies the conditions of the Nyquist-Shannon theorem based on the geo-signal frequency spectrum range. The captured digital signal was transferred through a UART interface.

Fig. 1 shows an example of mentioned previously typical samples of the signal.

Signal distortion in the time domain, in this case, time stretching of the signal, leads to distortion in the frequency spectrum, which can be a result of absorption properties and the non-uniformity of the physical environment through which they were transferring.

As it is demonstrated in Fig. 2, the frequency spectrum of the signal in the range from 0 to 20 m. Here we can see that the signal exists in the range from 8 to 28 Hz.

The frequency spectrum of the signal, shown in Fig. 3, is in the range from 80 to 100 m. In this case, we can see that the signal frequency ranges now from 5 to 14 Hz. Those spectrums demonstrate how the distance of transfer through the physical environment can affect the frequency spectrum. Additionally, increasing the distance from the signal source results in the absorption of energy of its high-frequency components by the environment through which it transfers.

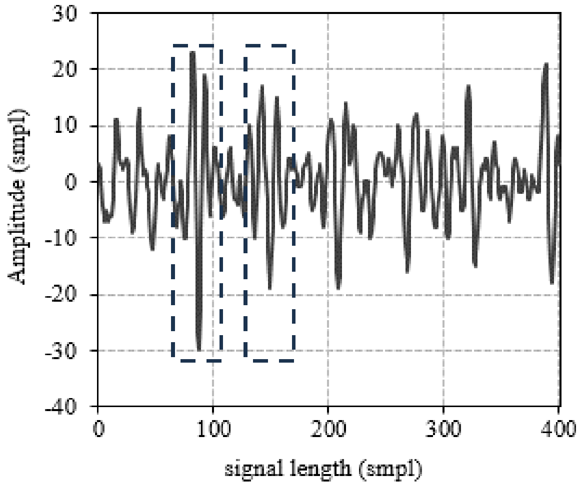

Fig. 1. The studied typical samples with form distortion

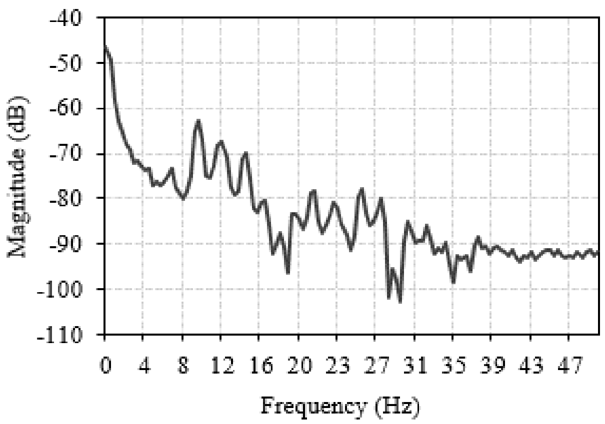

Fig. 2. Frequency spectrum of geo-signal captured in range 0-20 m

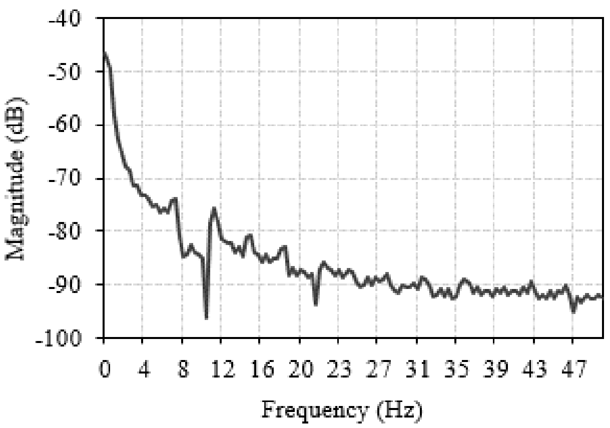

Fig. 3. Frequency spectrum of geo-signal captured in range 80-100 m

The studied signals contain harmonic distortions and that causes difficulties for the detection process of typical samples since correlation is most effective when signals have unique amplitude forms and are constant in duration.

Based on previous research in [22], of investigated signal spectral frequency analysis, a shift in the frequency range and a reduction in its width were observed with changes in the distance from the signal source, which requires further research.

During spectral analysis of the signals obtained during field studies, it was found that the signal frequencies fall within the range from 2 to 28 Hz, with the maximum energy observed in the range from 6 to 14 Hz.

While investigating the impact of distance to the signal source on the frequency spectrum of observed signals within distances of 140 meters with a step of 20 meters, a narrowing of the spectrum from 3 to 28 Hz at distances from 0 to 40 meters to 2 to 17 Hz at distances over 100 meters was observed.

With increasing distance from the signal source, especially beyond 60 meters, its frequency range approaches the frequency range of noises, which also falls within 2 to 17 Hz. The obtained results essentially indicate the possible limited effectiveness of applying frequency filters, as it was confirmed in [23,24] by applying a digital FFT filter for processing experimentally obtained signals within the mentioned frequency range. Additionally, analysis of the investigated sets of geo-signals is based on the results of frequency, presented in Fig. 4.

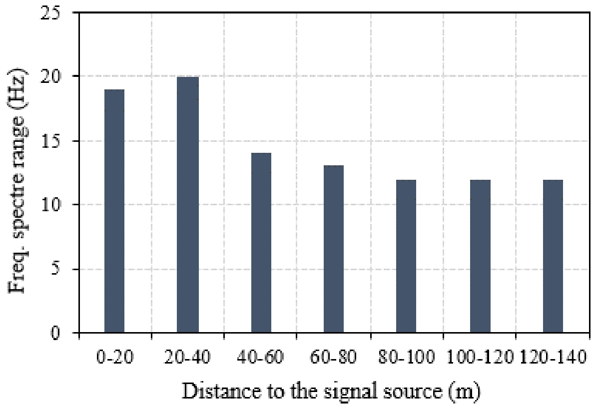

Fig. 4. Average frequency range on the various distances to the source of signal

A significant reduction in the width of their frequency range can be observed with the change of distance from the signal source, decreasing from about 20 Hz within 0 to 40 meters distance range to 12 to 14 Hz after 40 meters. Since the signal spectrum is closely related to its shape, which can be represented as a sum of harmonic components with different phases, it is advisable to investigate changes in the duration of typical samples.

Based on the recorded observations of signal source distance influence on the signal amplitude and frequency spectrum, researched signal requires time domain research of the distance influence on the signal form of searched typical samples to evaluate signal form distortion, for further processing methods selection or improvement based on gathered signal characteristics, how it reacts to outside factors, according to the signal analysis results

IV. SIGNAL TYPICAL SAMPLES: COMMON FEATURES AND COMPLICATIONS RELATED TO THEIR FORM

Based on the results of field experiments, it has been established that the investigated typical samples from the sensor have differences in amplitude shape and duration, complicating the application of mathematical functions such as correlation or convolution using a prepared template. Furthermore, as the distance from the signal sources increases, their energy decreases, resulting in the attenuation of the typical sample's amplitude aperture. Fig. 5, Fig. 6, and Fig. 7 shows how typical samples may change depending on the distance to the source of the signal.

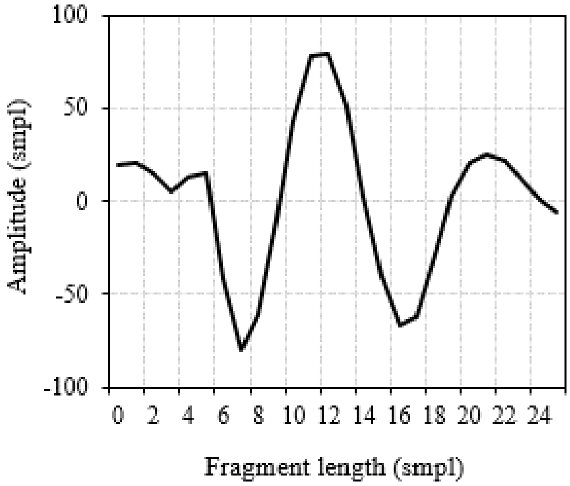

Fig. 5. Example of the studied fragment captured on range from 0 to 20 m

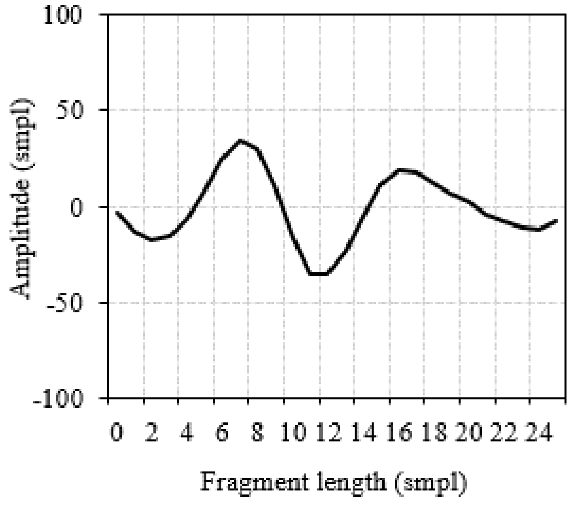

Fig. 6. Example of the studied fragment captured on range from 40 to 60 m

As it has been reviously noted, the amplitude shape of the typical samples also undergoes changes, however, similar characteristic features are observed. These features include the presence of three extrema within 25 samples, observed in 72% of the cases among the set of recorded typical samples of the investigated signal. Additionally, instances of resonance have been detected, where the observed typical samples contain four or five extrema, accounting for up to 14% of cases for each typical sample type regardless of the distance to the signal source.

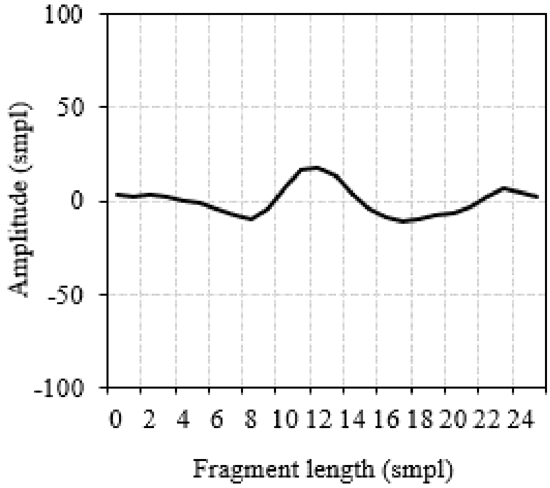

Fig. 7. Example of the studied fragment captured on range from 80 to 100 m

The common thing for all experimental datasets is that all typical samples have at least three extrema and that feature may be used for correlation signal processing adaptation to the signal time distortions.

V. TYPICAL SAMPLES OF TIME-BASED DEFORMATION

As it has been mentioned earlier, the typical samples are characterized by the presence of three extrema. Therefore, the duration of such typical samples can be measured as the sum of the widths of three signal half-periods, visually determining the duration in samples of those signal fragments. Fig. 8, Fig. 9, and Fig. 10 display the typical samples width range based on the width of its three half-periods.

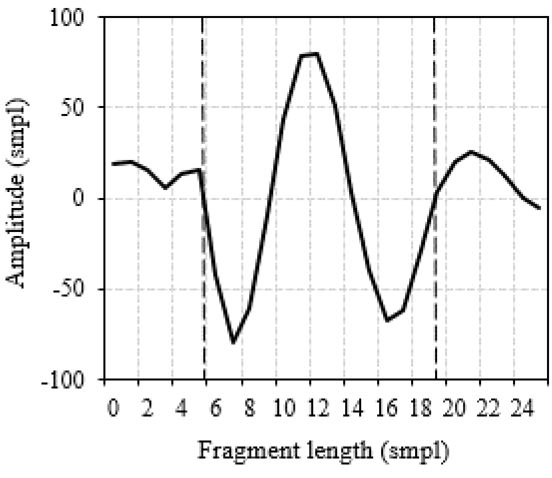

Fig. 8. Signal fragment with measured length of 14 smpl

During the investigation, typical samples were identified separately for each distance to the signal source from the signal datasets obtained in field experiments. Subsequently, they were sorted by duration, which allowed the identification of the most common durations of signal fragments, ranging from 14 to 18 samples.

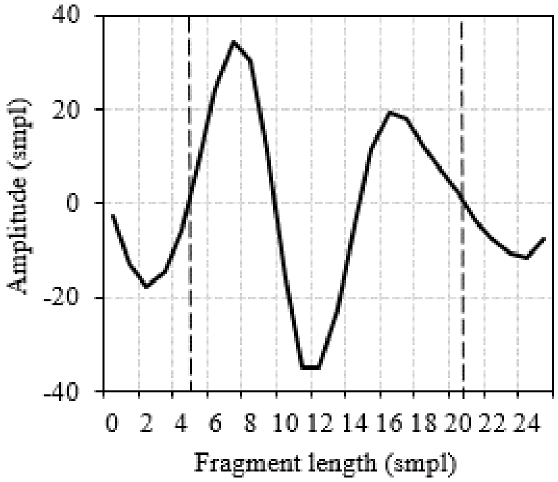

Fig. 9. Signal fragment with measured length of 16 smpl

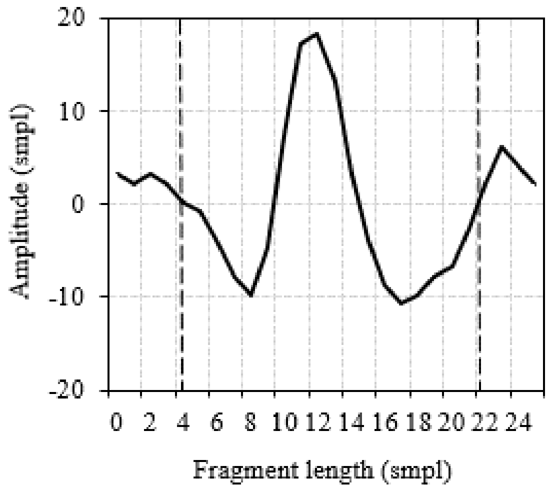

Fig. 10. Signal fragment with measured length of 18 smpl

Furthermore, signal fragments appearing in mirrored amplitude representation (known as signal inversion effect) can be rarely observed. However, these mentioned distortions do not exhibit regular patterns. During the experiment, conditions triggering their periodic manifestation could not be identified.

The data of the conducted studies, divided by distance to the signal source, form statistics on how searched typical samples duration changes. Fig. 11 demonstrates statistics on how many typical samples with specific duration were captured at the distance to the signal source from 0 to 60 meters.

The duration range of the typical samples gradually shifts; for instance, within distances of 0 to 20 meters, their duration is within 17 samples, and with increasing distance from the signal source, this range shifts towards greater widths. Thus, at distances of 40 to 60 meters, we can see that range shifted to range within 13 samples and 20 samples.

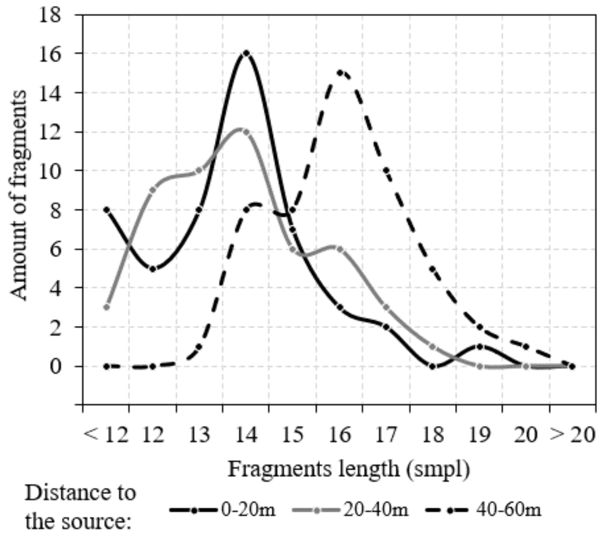

Fig. 11. Quantity of signal fragments with specific form and width on distances up to 60 m

Within the range of 60 to 100 meters, as it is demonstrated in Fig. 12, the typical samples appearance of longer duration is observed with a distance increase from the signal source. When averaging the typical samples number of different durations, the duration range of such typical samples increases; however, it does not shift the starting point of the range to 14 samples of width.

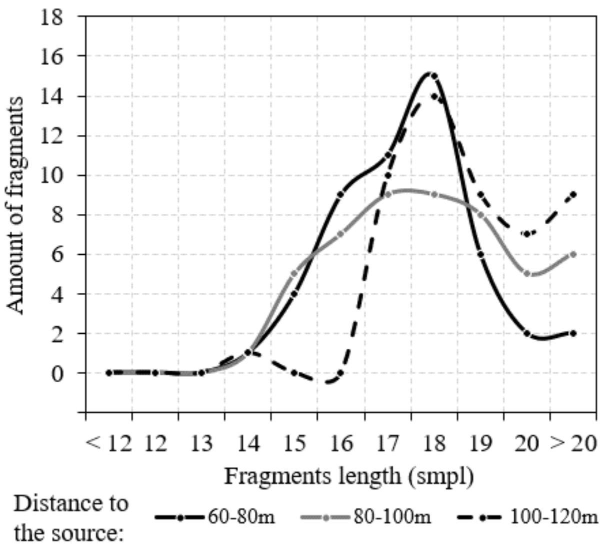

Fig. 12. Quantity of signal fragments with specific form and width on the distances up to 120 m

It should be noted that typical samples at a distance within the range of 100 to 120 meters should not be considered a reliable source of information because the studied signal captured at that distance, has a frequency spectrum close to the noise, which complicates the task of noise separation from typical samples, so we cannot proof that covered typical samples within that range do not resemble noise that was mistakenly perceived as a typical sample.

The majority of gathered typical samples recorded within distances of 0 to 20 meters have a duration of 14 samples, and with distances over 60 meters, corresponding fragments with a duration of 18 samples are observed in most cases.

For distances from 0 to 60 meters, there is a gradual transition to an increase in the duration of typical samples.

VI. CONCLUSIONS

Based on the processed results of field experiments, datasets of digital signals from the geophysical sensor, which were separated based on their spectral characteristics and amplitude shape depending on the distance from the signal source, conducted the analysis of statistical data regarding the width of characteristic signal fragments and their frequency spectrum ranges.

The typical samples consisted of three or more extrema. In the majority, 72% of the collected typical samples had exactly three extrema, and other cases had more than three extrema. That could be utilized for the detection and identification of the studied signal components, considering that the search based on amplitude shape was complicated by signal duration fluctuations.

The frequency spectrum of the investigated typical samples ranged from 3 to 26 Hz, with the frequency spectrum narrowing and shifting towards lower frequencies as the distance from the signal source increases, especially noticeable within the range of 40 to 60 meters.

The studied signal had amplitude, time domain, and frequency domain fluctuations caused by changes in distance to the signal source. The studied typical samples could be increased in time by ~86% or decreased by ~28% related to the average typical sample duration. One of the signal stretching reasons is the non-uniform environment structure of the environment where the signal was spreading. That time domain signal deformation complicated the usage of a single correlation function because the task required usage of the separate templates for various durations. This situation led to an increase in the memory usage for templates and complicated the computational task.

Possible solutions may be additional usage of other signal characteristics, in particular informational entropy, an adaptation of the signal processing correlation methods with the usage of geo-signal extremes, etc.

References

[1] Zhao, Y., Niu, F., Liu, H., Jia, X., Yang, J., & Huo, S. (2020). Source□receiver interferometric redatuming using sparse buried receivers to address complex near□surface environments: A case study of seismic imaging quality and time□lapse repeatability. *Journal of Geophysical Research: Solid Earth, 125(6),* e2020JB019496. DOI: https://doi.org/10.1029/2020JB019496

[2] Saux, B., Borgmans, J., Raman, J., & Rombouts, P. (2024) Origin of Frequency-Dependent Distortion and Calibration for Ring Oscillator VCO ADCs, *IEEE Trans. Circuits Syst. II: Exp. Briefs*. DOI: https://doi.org/10.1109/tcsii.2024.3370121

[3] Wang, B., Chen, X., Li, Y., Zhou, Q., & Li, Y. (2022). Research on Time Sidelobe Analysis on Pulse Compression Signal. *Journal of Physics: Conference Series, 2366(1), 012022.* DOI: https://doi.org/10.1088/1742-6596/2366/1/012022

[4] From Signals to Spectra: Exploring Crosscorrelation with Fourier Transform update – Faster Capital. Faster Capital. Accessed: Apr. 11, 2024. [Online]. Available: https://fastercapital.com/content/From-Signals-to-Spectra--Exploring-Crosscorrelation-with-Fourier-Transform-update.html#Crosscorrelation-in-Time-and-Frequency-Domains.html

[5] Damskägg, E. P., & Välimäki, V. (2017). Audio time stretching using fuzzy classification of spectral bins. *Applied Sciences*, *7*(12), 1293. DOI: 10.3390/app7121293

[6] Mariani, S., Liu, Y., & Cawley, P. (2021). Improving sensitivity and coverage of structural health monitoring using bulk ultrasonic waves. *Structural Health Monitoring*, *20*(5), 2641-2652. DOI: 10.1177/1475921720965121

[7] Dan, D., Wang, C., Pan, R., & Cao, Y. (2022). Online Sifting Technique for Structural Health Monitoring Data Based on Recursive EMD Processing Framework. *Buildings*, *12*(9), 1312. DOI:10.3390/buildings12091312

[8] Zhou, W. (2022). Reaching the Frequency Resolution Limit in a Single-Shot Spectrum of an Ultra-Short Signal Pulse Using an Analog Optical Auto-Correlation Technique. *Journal of Lightwave Technology*, *41*(1), 114-119. DOI:10.1109/jlt.2022.3213188

[9] Gobron, K., Rebischung, P., Van Camp, M., Demoulin, A., & de Viron, O. (2021). Influence of aperiodic non□tidal atmospheric and oceanic loading deformations on the stochastic properties of global GNSS vertical land motion time series. *Journal of Geophysical Research: Solid Earth*, *126*(9), e2021JB022370. DOI: 10.1029/2021jb022370

[10] Ruan, H., Zhang, L., & Long, T. (2016). Sinc interpolation based method for compensation of ionospheric dispersion effects on BOC signals with high subcarrier rate. *Science China. Information Sciences*, *59*(10), 102311. DOI:10.1007/s11432-016-5555-3

[11] Zhou, W., Lv, Z., Deng, X., & Ke, Y. (2022). A new induced GNSS spoofing detection method based on weighted second-order central moment. *IEEE Sensors Journal*, *22*(12), 12064-12078. DOI: 10.1109/jsen.2022.3174019

[12] Zhuang, C., Zhao, H., Sun, C., & Feng, W. (2020). Detection and classification of GNSS signal distortions based on quadratic discriminant analysis. *IEEE Access*, *8*, 25221-25236. DOI:10.1109/access.2020.2965617

[13] Li, X., Wang, C., Zhu, C., Wang, S., Li, W., Wang, L., & Zhu, W. (2022). Coseismic deformation field extraction and fault slip inversion of the 2021 Yangbi Mw 6.1 earthquake, Yunnan Province, based on time-Series InSAR. *Remote Sensing*, *14*(4), 1017. DOI: 10.3390/rs14041017

[14] Sun, Y., & Ochiai, H. (2021). Performance analysis and comparison of clipped and filtered OFDM systems with iterative distortion recovery techniques. *IEEE Transactions on Wireless Communications*, *20*(11), 7389-7403. DOI:10.1109/twc.2021.3083537

[15] Soares de Alcantara, D., Balestrassi, P. P., Freitas Gomes, J. H., & Carvalho Castro, C. A. (2020). Vibrations in CDFW. *Entropy*, *22*(6), 704. DOI: 10.3390/e22060704

[16] Wu D., Zhuo X., Chen Y., Ren G., & Deng W. (2022) An Approach to Vibration Signal Analysis Using Quantum Probability. *Advances Transdisciplinary Eng., vol. 24.* 336–342. DOI: 10.3233/atde220455

[17] Han, B., Zhang, G., Wang, J., Wang, X., Jia, S., & He, J. (2020). Research and application of regularized sparse filtering model for intelligent fault diagnosis under large speed fluctuation. *IEEE Access*, *8*, 39809-39818. DOI:10.1109/access.2020.2975531

[18] Chen, D., Han, J., Cui, X., & Fan, J. (2018). Identification and evaluation for the dynamic signals caused by pressure fluctuation of aerostatic slider. *Industrial Lubrication and Tribology*, *70*(6), 927-934. DOI: 10.1108/ilt-11-2016-0271

[19] Wang, G.; Zhou, Y.; Min, R.; Du, E.; Wang, C. (2023). Principle and Recent Development in Photonic Time-Stretch Imaging. *Photonics*, *10*(7), 817. DOI: https://doi.org/10.3390/photonics10070817

[20] Gui, Y. F., & Dou, W. B. (2008). Phenomena of paired echoes and transmission characteristics of the pulse signal in dispersive transmission lines with discontinuities. *Progress In Electromagnetics Research B*, *5*, 225-240. DOI: https://doi.org/10.2528/pierb08022202

[21] Six, P. W. M., & serial USART, P. (2015). 8-bit AVR Microcontroller with 32K Bytes In-System Programmable Flash. *Atmel-7810-Automotive-Microcontrollers-ATmega328P Datasheet. pdf.* [Online]. Available: https://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P Datasheet.pdf

[22] Vanchak V. S., Melnychuk S. I., & Manuliak I. Z. (2023). Frequency spectrum distortion of periodic impulse signals with harmonic components affected by distance to the source. *In materials of All-Ukrainian scientific and practical conference "IT in education and industry", Ivano-Frankivsk, Ukraine, Oct. 12, 2023. Ivano-Frankivsk: IFNTUOG.* 217–218.

[23] Vanchak V. S., Melnychuk S. I., & Manuliak I. Z. (2023). Efficiency of low-pass filters based on FFT for SNR improvement of periodic impulse signals with harmonic components. *In materials of XII-th scientific and practical conference "Problems of informatics and computer technologies", Ivano-Frankivsk, Ukraine, Nov. 10-12, 2023. Chernivtsi: Yuriy Fedkovych Chernivtsi National Technical University.* 71–73.

[24] Voronych, A., Nykolaychuk, L., Grynchyshyn, T., Hryha, V., Melnychuk, S., & Nykolaychuk, Y. (2020, September). Development of Theory, Scope and Tools for Entropy Signals and Data Processing. *In 2020 10th International Conference on Advanced Computer Information Technologies (ACIT), Deggendorf, Germany, Sept. 16-18, 2023. IEEE.* 260-264. DOI: https://doi.org/10.1109/ACIT49673.2020.9208912

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