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Jammer Identification: Spectral Correlation Function and Wavelet Coherence

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ABSTRACT

Jamming countermeasures are used to decrease or prevent the impact of intentional jamming applied to degrade the quality of information provided by a global navigation satellite system (GNSS) receiver. The maximum performance of jamming countermeasure can be obtained only when a proper technique is applied according to the type of jammer. This paper suggests a jamming identification technique for providing information regarding the type of jamming. The center frequency and bandwidth of jammer signal are inconsistent and may change according to time, and thus a spectral correlation function and wavelet coherence were considered in order to analyze the signal in the time and frequency space. Because the two characteristics derive different analysis results, two different identification techniques were suggested and the performances thereof were analyzed. Numerical results show that the two identification techniques have relative advantages and disadvantages as to time consumed and performance. The suggested methods can sufficiently identify the jammer before the GNSS receiver becomes inoperable because of jamming.

Keywords: jamming, signal identification, spectral correlation function, wavelet coherence

1. INTRODUCTION

As the importance of position, navigation, and timing (PNT) information has increased, the importance of the global navigation satellite system (GNSS) has been gradually increasing. GNSS has been used in several infrastructures as the application field has expanded, and has been a target of aggressive jamming because of its low signal power. When jamming occurs, the quality of PNT information is degraded (Idris et al. 2013); in the worst case, human and material loss could occur because of the inaccurate information. Therefore, in response to jamming, countermeasure techniques are desperately required for safety of life or by military forces.

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Jamming countermeasure techniques can be classified as several types depending on the purpose. Anti-jamming techniques include the controlled radiation pattern antenna technique (Casabona & Rosen 1999), a technology that uses an adaptive-array antenna, implementing space time adaptive processing (STAP) (Sarkar et al. 2001) and space frequency adaptive processing (Gupta & Moore 2004). These techniques, which are digital signal processing technologies applied to array antennas, are methods for reducing the impact of jamming on the receiver. Such techniques reduce the impact of jamming but are incapable of completely removing the jamming, and they also increase the burden on the receiver. In order to combat the setbacks of such techniques, a more aggressive method such as jammer localization technique (Smith & Abel 1987, Lim et al. 2013) to incapacitate or eliminate the jammer was suggested. All of the techniques, however, face a similar problem: maximum performance can be obtained only by applying the algorithm

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appropriate to the characteristics of the jammer signal, whatever the type may be.

To classify jamming signals, several studies have been proposed (Cochran 1993, Musumeci & Dovis 2014, Helal & Ezzat 2018). However, since the wavelet transform is an analysis using a received signal only, correlation result with a known signal cannot be obtained. Therefore, it is necessary to use a signal analysis that can compensate for this. Also, since the jamming signal may be a composite signal, a method such as template matching may be effective to determine which of the implemented jamming countermeasure techniques is most appropriate.

In this paper, a jammer identification method was suggested in order to classify jamming signals. Jamming signals have various bandwidths, and in special circumstances, the frequency thereof changes to a certain direction. Thus, a spectral correlation function (SCF) (Gardner 1986) and wavelet coherence (Torrence & Compo 1998, Grinsted et al. 2004), which are the characteristics that enable observation of the bandwidth and the change in frequency at the same time, were deemed to be appropriate. The common feature of the two characteristics is that they have numerically different results for signals with different changing trends in frequency or bandwidth that are sufficiently distinguishable. By using these techniques, correlation between desired signals can be obtained and applied to a composite signal, and it is possible to compare with a jamming signal that has been previously received. Motivated by these characteristics, we suggested two identification methods in which the signal could be identified by the GNSS receiver without human intervention. The two identification techniques used SCF and wavelet coherence respectively to analyze the signal and have different structures depending on the features of the signal analysis method. In order to verify the performance of the suggested techniques, modeled jamming signals were generated and applied with noise, and the detection probability of each identification technique was derived to analyze and compare.

2. SIGNAL IDENTIFICATION USING THE SPECTRAL CORRELATION FUNCTION

2.1 Spectral Correlation Function

The signal received by the GNSS receiver is a discrete signal that has gone through an RF front-end. The received signal can be assumed to be a time series x_n having n = OK N-1 and time interval δt. Here, in the case where m_x (which is the average of x_n and autocorrelation function R_x) have periodicity, x_n is defined to have cyclostationarity. The autocorrelation function having periodicity can be described with a Fourier series as follows:

$$R_x[n, n+\upsilon] = \sum_{\alpha} R_x^{\alpha}[\upsilon] e^{j2\pi\alpha n\delta t} \tag{1}$$

A Fourier coefficient with spectral components at cyclic frequencies α is called a cyclic autocorrelation function. Such a Fourier coefficient in the discrete domain can be derived as follows (Gardner 1986):

$$R_x^{\alpha}[\upsilon] = \frac{1}{N}\sum_{n=0}^{N-1} x[n]x[n+\upsilon]e^{-j2\pi\alpha n\delta t} \tag{2}$$

where υ is the delay parameter, N is the observation interval, and υ = OK $N-1$. The Fourier transform of the cyclic autocorrelation function R_x^{α} refers to the density of spectral correlation, and can be defined as a SCF (Gardner 1986). The result of the Fourier transform of R_x^{α} is expressed in the following formula:

$$S_x^{\alpha}[k] = \sum_{\upsilon=0}^{N-1} R_x^{\alpha} e^{-j2\pi k\upsilon/N} \tag{3}$$

where S_x^{α} is the SCF result, and the sinusoidal frequency is k cycles per N samples.

Most jamming signals transmit a sine wave of a particular bandwidth or change the directions of the frequencies of the signals completely. Therefore, because most of the jamming signals have periodicity and have different periodicities depending on the type of signal, the features thereof can be derived by analyzing the cyclostationarity of signals by using SCF.

2.2 Feasibility

The frequency characteristics of the signal according to time in the SCF result are indicated in four robes on the two-dimensional plane of the cyclic frequency and spectral frequency. The bandwidth of the signal is indicated in the width of the robe, while the frequency variation direction is indicated in the relative size difference of each robe.

In this paper, the continuous-wave (CW) signal and the sweep CW signals that frequency either rose, fell, or increased in a trigonal form are considered as the cases for jamming signals. The results of analyzing certain forms of jamming signals by using SCF are shown in Fig. 1. As the means for analysis, sampling frequency fs = 47.14 MHz, cyclic frequency resolution $\Delta\alpha$ = 80kHz, and frequency resolution Δf = 2kHz were used. In addition, it was assumed that the signals that had passed through the RF front-end were received, signals have an IF frequency of 1.4 MHz and the sweep CW signal

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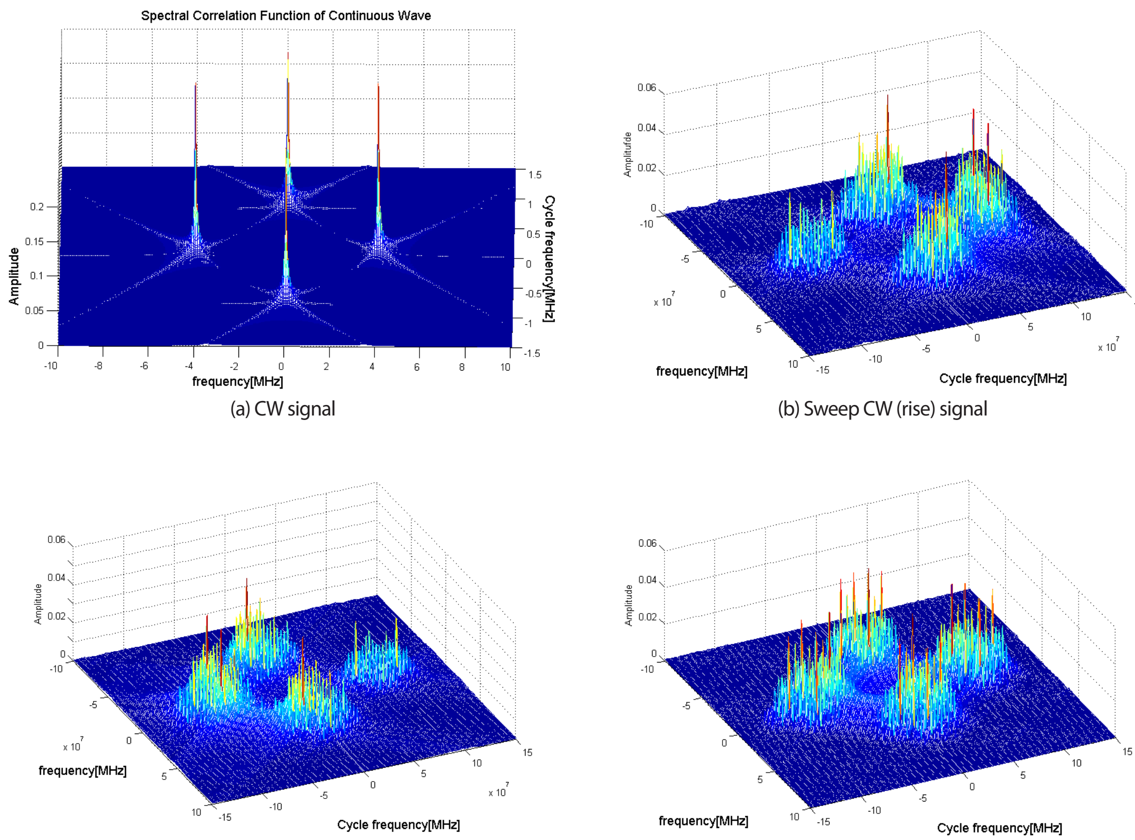


(a) CW signal

(b) Sweep CW (rise) signal

(c) Sweep CW (fall) signal

(d) Sweep CW (tri) signal

Fig. 1. SCF results of jamming signals.

had a ±1 MHz bandwidth, which is identical to the GPS L1/CA signal based on the IF frequency.

In Fig. 1, the differences between the SCF results of each signal have sufficient distinctiveness for identifying signals. The CW signal is clearly distinguished from other signals that have wide robes because of its narrow bandwidth. Figs. 1b,c show how robes of a particular location have low power in sweep CW signals where the frequency rises or falls only in one direction. In Fig 1d, the four robes in the sweep CW signal have a relatively uniform power distribution when the increase and decrease of frequency exist simultaneously.

The technique shown in Fig. 2 was suggested to observe the feasibility of applying the signal identification technique using SCF (Jin et al. 2014). First, the time and frequency characteristics of the received signal were derived by using filtered and normalized SCF results. The center frequency and bandwidth of jamming signal could be obtained using center position and width of robes in frequency axis. The robe width in cycle frequency axis means sweep time of jamming signal. The SCF results of the observed jamming signals had extensive values, and each result showed high similarity. We decided that template matching would be effective, and thus

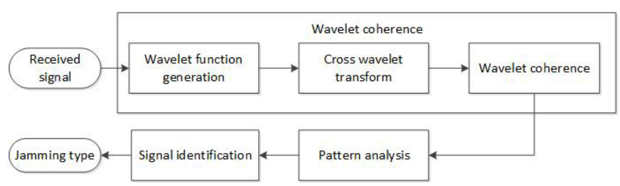
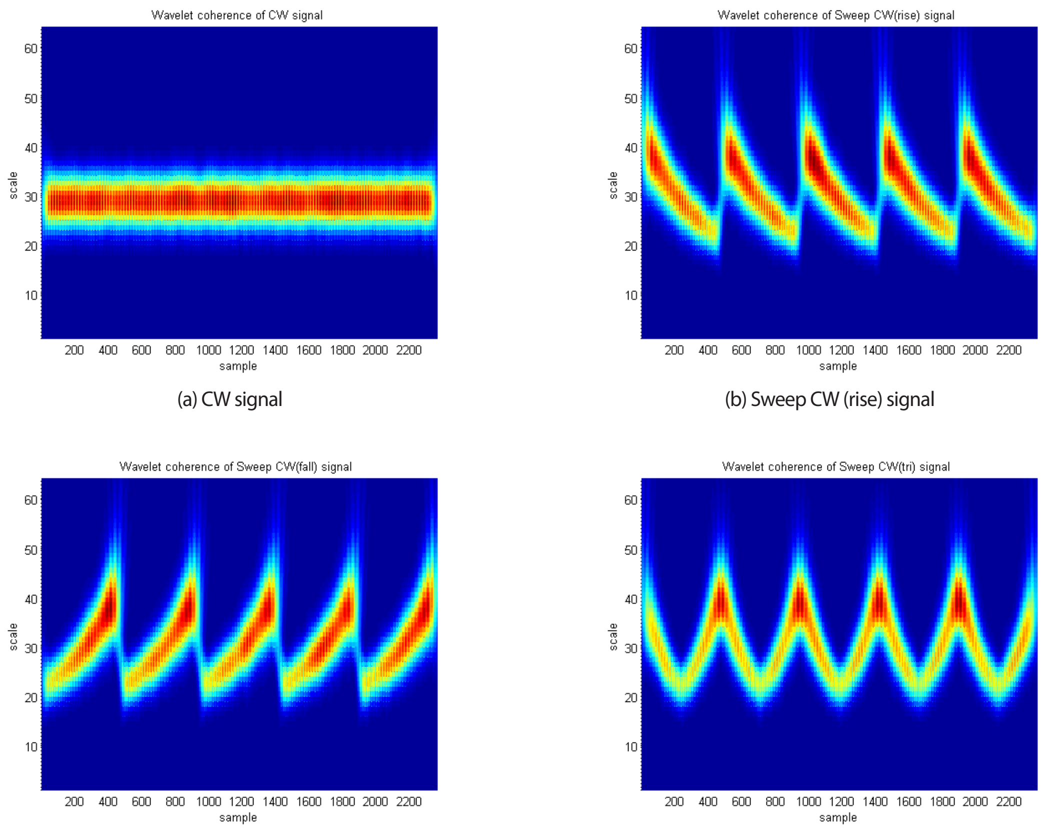


Fig. 2. Block diagram of identification technique using SCF.

the derived characteristics were used in generating templates for each signal type. In this paper, the SCF result of noise-free CW signal based on the estimated center frequency was defined as the CW template. The rising, falling and trigonal sweep CW template are generated using noise-free sweep CW signal based on the estimated center frequency, estimated sweep time and estimated sweep bandwidth also.

The generated four types of templates matched the SCF results of the received signal, and the signal type of the template that showed the highest similarity was defined as a type of jamming signal. Here, the value for identifying the similarity was derived by using the Euclidean distance.

Although this method seems useful, a high number of computations are required in SCF and template matching. In



(a) CW signal

(b) Sweep CW (rise) signal

(c) Sweep CW (fall) signal

(d) Sweep CW (tri) signal

Fig. 3. Wavelet coherence of jamming signals.

the jamming environment, where rapid response is required, a high number of computations and long identification time are significant setbacks that cannot be ignored. Therefore, an intuitive identification method is required depending on the case.

3. SIGNAL IDENTIFICATION USING WAVELET COHERENCE

3.1 Wavelet Coherence

Wavelet transforms are effectively used in analyzing discrete signals having inconsistent power at various frequencies. As described in Section II, a received signal was assumed to have time series x_n with a time interval of δt. In this section, wavelet function $\psi(\eta)$ was also assumed for analysis. A wavelet function should have a zero mean and is placed in the time and frequency domain (Torrence & Compo 1998). Morlet wavelet, which is one of several wavelet functions, is a wavelet suitable for analyzing the characteristics of signals and is defined as the following formula:

$$\psi(\eta) = \pi^{-1/4} e^{-j\omega_0\eta} e^{-\frac{1}{2}\eta^2} \tag{4}$$

where $\omega_0 = 6$ is a dimensionless frequency, $\eta = st$ is dimensionless time, and s is the wavelet scale. The wavelet scale has no physical sense, but it can be described the equation $(F_c / F_a)F_s$. F_c is the center frequency of a wavelet in Hz, F_a is the pseudo-frequency corresponding scale a, and F_s is the sampling frequency.

The continuous wavelet transform of discrete signal x_n can be defined as the convolution of x_n and scaled and normalized wavelet function $\psi(\eta)$:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \psi\left[\frac{(n'-n)\delta t}{s}\right] \tag{5}$$

Wavelet coherence can be defined as how coherent the cross wavelet transform $W_n^{XY}(s) = W_n^X(s)\, W_n^Y(s)$ of two different time series x_n and y_n is in the time and frequency domain. Based on the suggestion of Torrence and Compo, wavelet coherence is defined as the following formula:

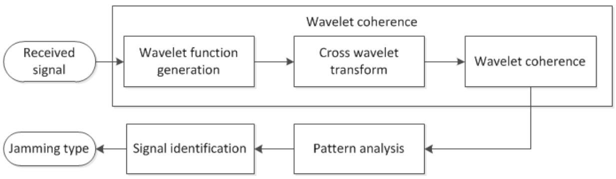


Fig. 4. Block diagram of identification technique using wavelet coherence.

$$R_n(s)=\left.\frac{S\left(s^{-1}W_n^{XY}(s)\right)}{\sqrt{S\left(s^{-1}\left|W_n^{X}(s)\right|^2\right)}\sqrt{S\left(s^{-1}\left|W_n^{Y}(s)\right|^2\right)}}\right|_{W_n^Y(s)=W_n^X(s)}$$
$$=\frac{S\left(s^{-1}W_n^{XX}(s)\right)}{\sqrt{S\left(s^{-1}\left|W_n^{X}(s)\right|^2\right)}\sqrt{S\left(s^{-1}\left|W_n^{X}(s)\right|^2\right)}}=\frac{S\left(s^{-1}W_n^{XX}(s)\right)}{S\left(s^{-1}\left|W_n^{X}(s)\right|^2\right)} \quad (6)$$

where S is a smoothing operator suitably defined in the Morlet wavelet when $\omega_0 = 6$ (Grinsted et al. 2004). The purpose of this study is not to analyze the relevance of two different signals but to analyze the characteristics of x_n. Therefore, wavelet coherence $R_n(s)$ was derived by using the cross wavelet transform $W_n^{XX}(s)$ of x_n and x_n, as can be seen in (6).

3.2 Feasibility

In order to determine the feasibility of signal identification using wavelet coherence, the signal identical to the jamming signal previously generated was analyzed by using wavelet coherence. The analysis result is shown in Fig. 3. It was confirmed that the variation of frequency was clearer than that of SCF and was intuitively displayed. The redder the color, the better the received signal x_n is perfectly autocorrelated at the particular time and frequency determined by scale. Based on this, the frequency of the received signal can be predicted. In addition, the variation of frequency according to time can be confirmed. Note that the lower scale indicates higher frequencies, and thus the variation of frequency seems to be upside down. The identification method designed in consideration thereof is shown in Fig. 4. After deriving the wavelet coherence of the received signal, the pattern displayed in the result of Fig. 3 was analyzed to determine the existence of the signal and the type of signal. The information used in pattern analysis was the maximum coherence value of each sample and the scale in which such value was located. This method has a relatively simple structure compared to the identification technique using SCF, where every value according to the frequency and cyclic frequency was required in order to generate a template.

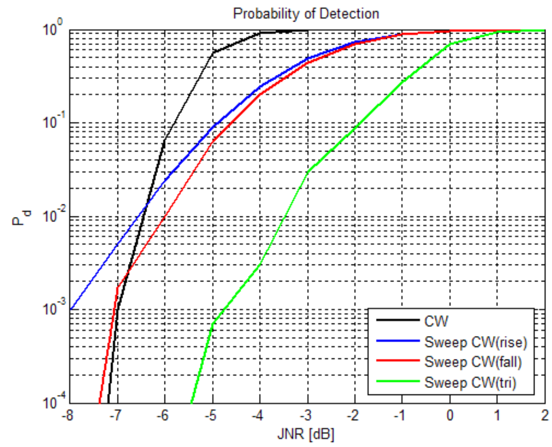


Fig. 5. Detection probability of identification technique using SCF according to JNR.

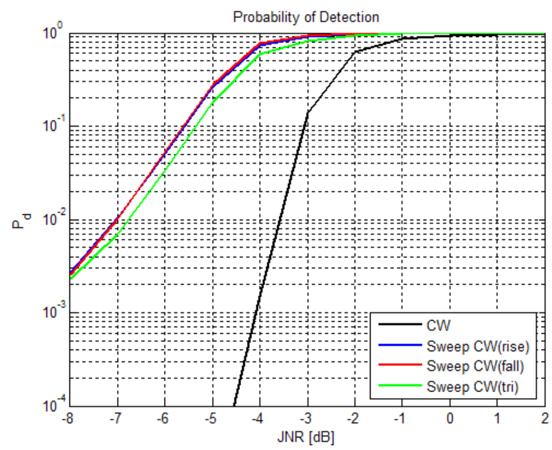


Fig. 6. Detection probability of identification technique using wavelet coherence according to JNR.

4. NUMERICAL RESULTS

Figs. 5 and 6 show the detection probability of the jammer identification technique using SCF for various jammer-to-noise ratios (JNR) and fixed false alarms (P_f = 0.001). These identification techniques, described in Fig. 2 and Fig. 4, are implemented on MATLAB. In order to minimize the difference due to optimization, we had refrained from using built-in function. Nevertheless, some MATLAB functions were inevitably used, and the operating time may have been affected. All algorithms operated in fixed hardware environment and the hardware specifications were 3.3-GHz CPU and 8GB of RAM. This means analysis in a specification example environment and since the operation time of the algorithm may change depending on the simulation environment. Therefore, we cannot judge the performance of algorithm with absolute time, so we compared the relative time between the two technique using performance profiler of MATLAB.

In Fig. 5, It was certain that the jamming signal below a JNR of 0 dB did not have significant influence on the performance of the GNSS receiver, and that it was possible to identify every type of jamming signal over a JNR of 1 dB when the side effects occurred in earnest. However, when one round of the identification process was performed in an environment in this paper, the average time elapsed was approximately 7.7 s. This result is a significantly high value when compared with the time consumption of the other identification technique suggested in this paper.

The result of confirming the performance of the jammer identification technique using wavelet coherence for various JNRs and fixed false alarms is shown in Fig. 6. The success rate of identification of every signal except the CW signal improved when compared with the case when SCF was used. However, in the case of the CW signal, it was confirmed that the identification using SCF showed higher performance. This may occur because the SCF result for the CW signal has more noticeable features than that of other types of jamming signals when compared with the wavelet coherence analysis result. Such features are effective for identification when using template matching.

Meanwhile, the time consumed in one round of performance under the environment identical to that of the SCF identification performance analysis was approximately 0.05 s. The identification speed increased by 170 times compared with that of identification using SCF. Despite several penalties regarding the identification performance of the CW signal, the merit of rapid speed in the identification using wavelet coherence is highly useful in urgent situations such as GPS jamming. Thus, it was deemed that, in consideration of the identification performance and identification speed of every signal, the identification technique using wavelet coherence was more useful in identifying jamming signals.

5. CONCLUSION

In this paper, jamming identification techniques using SCF and wavelet coherence were suggested. These two suggested identification techniques analyzed the signals in the time and frequency domain by using SCF and wavelet coherence, and have different identification structures in order to use the analysis results effectively. The information that the identification techniques are required to provide is to identify the type of jammer, and thus the detection probabilities according to the type of jamming signal were derived through simulation. Based on the numerical results, each technique properly performs the identification process but was also found to have relative advantages and disadvantages.

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REFERENCES

Casabona, M. M. & Rosen, M. W. 1999, Discussion of GPS anti-jam technology, GPS Solutions, 2, 18-23. https://doi.org/10.1007/PL00012752

Cochran, D. 1993, Application of Wavelet Transform Techniques to Spread Spectrum Demodulation and Jamming, Arizona State University Technical Report, Report TRC-DC-9302

Gardner, W. A. 1986, The Spectral Correlation Theory of Cyclostationary Time-Series, Signal Processing, 11, 13-36. https://doi.org/10.1016/0165-1684(86)90092-7

Grinsted, A., Moore, J. C., & Jevrejeva, S. 2004, Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlin. Processes Geophys., 11, 561-566. https://doi.org/10.5194/npg-11-561-2004

Gupta, I. J. & Moore, T. D. 2004, Space-frequency Adaptive Processing for Radio Frequency Interference Mitigation in Spread-spectrum Receivers, IEEE Trans. Antennas and Propag., 52, 6, 1611-1615. https://doi.org/10.1109/TAP.2004.829850

Helal, H. G. A. & Ezzat, M. A. A. M. 2018, Jamming and Anti-Jamming Technique in Wireless Communication Systems, in 35th National radio Science Conference, 20-22 Mar. 2018, Cairo, Egypt. https://doi.org/10.13140/RG.2.2.23003.46882

Idris, A. N., Suldi, A. M., Hamid, J. R. A., & Sathyamoorthy, D. 2013, Effect of Radio Frequency Interference (RFI) on the Global Positioning System (GPS) Signals, in 2013 IEEE 9th Int. Colloquium on Signal Processing and its Applications, 8-10 Mar 2013, Kuala Lumpur, Malaysia. https://doi.org/10.1109/CSPA.2013.6530041

Jin, M. H., Yeo, S. R., Choi, H. H., Park, C., & Lee, S. J. 2014, Jammer Identification Technique based on a Template Matching Method, JPNT, 3, 45-51. https://doi.org/10.11003/JPNT.2014.3.2.045

Lim, D. W., Kang, H. W., Heo, M. B., Choi, H. H., & Lee, S. J. 2013, Implementation of a Jammer Localization System Based on TDOA/AOA Algorithm, in ION 2013 Pacific PNT Meeting, 23-25 Apr 2013, Honolulu, Hawaii, USA, pp.406-410.

Musumeci, L. & Dovis, F. 2014, Use of the Wavelet Transform for Interference Detection and Mitigation in Global Navigation Satellite Systems, International Journal of

Navigation and Observation, 2014, Article ID. 262186, 1-14. http://dx.doi.org/10.1155/2014/262186
Sarkar, T. K., Wang, H., Park, S., Adve, R., Koh, J., et al. 2001, A Deterministic Least-squares Approach to Space-time Adaptive Processing (STAP), IEEE Trans. Antennas and Propag., 49, 91-103. http://dx.doi.org/10.1109/8.910535
Smith, J. & Abel, J. S. 1987, Closed-Form Least-Squares Source location Estimation from Range-Difference Measurements, IEEE Trans. Acoust., Speech Signal Process., 35, 1661-1669. http://dx.doi.org/10.1109/TASSP.1987.1165089
Torrence, C. & Compo, G. P. 1998, A Practical Guide to Wavelet Analysis, Bull. Am. Meteorol. Soc., 79, 61-78. https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

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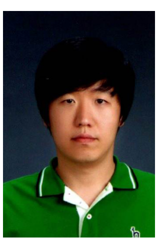

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