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OPTIMIZATION OF THE ALGORITHM FOR ESTIMATING TIME OF ARRIVAL OF THE ACOUSTIC WAVE FRONT BY CHOOSING THE SIGNAL FILTERING METHOD

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Abstract: *In this paper is described the optimization of the algorithm for determining the time of arrival (ToA) of the acoustic front of shock and detonation waves, which is not based on the application of cross-correlation analysis. In order to increase the signal-to-noise ratio in the initial phase of the algorithm, two approaches were used. The first is the wavelet decomposition of the signal, i.e. the Daubechies coefficient of the seventh order, or "db7", and the second approach in signal filtering is based on the use of the fourth order cumulants. Based on the obtained results, an assessment of the acceptability of the proposed solutions is given. Based on the obtained results, suggestions are given in which cases the use of a certain approach to increase the signal ratio is optimal and desirable to use.*

Keywords: *time of arrival, cumulants, algorithm, wavelets, muzzle wave, shock wave.*

1. INTRODUCTION

The topic of this paper is optimization of the algorithm for determing the time of arrival (ToA) of the acoustic wave front by choosing the signal filtering method. It is well known that for finding efficient and precison methods for estimation of the ToA from acoustic signal significant attention has been paid to the last few decades. Wavefront travel time gives the range and direction of radiating target. In either case the estimation of these time delays is often corrupted by ambient and receiver generated noise, and multipath and finite length observation intervals. Undoubtedly, the application of any method for determing ToA will significantly depend on signal to noise ratio. Increacing the signal to noise ratio is achieved by some filtering method. In this paper, two signal filtering methods are considered. One is wavelet signal decomposition, and the other is based on the application of the fourth-order cumulants.

The algorithm for automatic ToA estimation is developed during past few years and tested and applied to various types of acoustic signals that come from firing from a rifle, mortar and cannon. The description of the algorithm is presentede in several papers [1,3]. The concept of the algorithm consists of amplitude-time analysis in which statistical methods are included. The available literature describes several algorithms used for automatic estimation of ToA values from acoustic signal. Most of them is designed to overcome the limitation of traditional threshold method, the practicality of Hinkley criterion, cumulative energy, power curve, and Bai's CWT binary map method and others. Verification of these algorithms was done on the base of acoustic signals which originate from diferent explosion events such as firing from artillery weapons, and etc [4].

ToA is propagation time of the signal travelling between a source and a receiver in one way direction. Since in order to determine the location of the sound source, it is necessary to have information about ToA from several spatially distributed sensors, it is necessary to ensure the synchronization of the measured signals. A relatively common synchronization technique used in those cases is based on the use of GPS signals, whose accuracy is within limits of 20 ns. ToA multiplied with speed of sound gives mutual distance of the source and receiver. Position of the source in a two dimensional (2D) space is on the circle with the center at the receiver. The position of the sound source is located in the intersection of the circles defined by ToA values and positions of the receiving sensors [5,6].

The simplest procedure for determination the position of the sound source is based on the use of signals from minimum three receiving sensors and their positions. In other words, triangulation is the determination of an object's position based on simultaneous time of arrival (ToA) or range measurements from three stations at known locations. Four ToA measurements yield better position estimation without significant deviation. Namely algorithms based on three ToA measurements are faced with considerable difficulty in determination of the vertical component of the position of the sound source. This problem is possible to resolve if some information about the general location of the source is available, for instance is it bellow or above the measuring stations planes.

In the available literature are explained two common methods that normally being used to estimate ToA. The first is threshold method and the second cross-correlation method. The threshold method can be considered as the simplest among these two techniques; however, it has poor accuracy of estimation. On the other hand, cross-correlation method gives a more accurate estimation than threshold, but it requires both transmitting signal and receiving signal to measure the time lag. Thus, the complexity increases.

Generally, the distance between source and receiver, using acoustic sensor, is measured based on time-of-arrival (ToA) and time difference of arrival (TDoA) which means time differences of estimated ToAs. A ToA measurement requires synchronization between source (transmitter) and receiver. TDoA only requires time synchronization among the receivers since it does not utilize the transmission time from the source [7].

Time of arrival estimation is significant in the field of Structural Health Monitoring (SHM) technique. This technique is used to perform continuous monitoring of structures to detect the presence of damage. The detection and location of damage by sensing acoustic signals could serve as a form of automated structural inspection. The location damage can be determined using measurements of Time Difference of Arrival (TDOA) of the signals detected at different sensors in an array [8].

In the time domain, Akaike [4] developed a statistical method to determine the transition point in a time series between noise and a coherent signal. This was achieved by using the Akaike Information Criterion (AIC) as expressed in Eq. (1).

$$AIC(t) = t\log_{10}\left(\mathrm{var}\left(x[1;t]\right)\right) + \\ +(N-t-1)\log_{10}\left(\mathrm{var}\left(x[t;N]\right)\right) \quad (1)$$

where *x(t)* is time series signal, *t* – time, *N* length of the time window and *var* is variance function.

The signal *x*(*t*) is partitioning into two sections at a point *t* and calculating the AIC value. This process is repeated for all points within a time window of length *N* and the minimum value of AIC indicates the estimated point of signal onset. Sedlak P. et al. [4] reported that the performance of this method is strongly dependent on the choice of the time window duration *N*. The window size *N* is determined by firstly using fixed threshold detection to obtain a ‘rough estimation’ of onset time, and then a portion of the signal-several hundred samples-is selected before and after this point as the window duration [4,6]. Improvements to the performance of this method have been demonstrated by firstly pre-processing the signal to increase the SNR and then shortening the duration of *N* to a smaller range. The criterion for choosing the new time window is however based on trial and error [4].

2. TIME-VARYING CORRELATION METHOD

Cross-correlation is a measure of the linear correlation (dependence) between two signals, giving a value between +1 and -1 inclusive, where 1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation. The cross-correlation between two signals, *U* and *V*, can be calculated using the expression in Eq. (2).

$$r_{UV}(d) = \frac{\sum_{i=1}^{n}\left(u(i)-\bar{U}\right)\left(v(i-d)-\bar{V}\right)}{\sqrt{\sum_{i=1}^{n}\left(u(i)-\bar{U}\right)^2}\sqrt{\sum_{i=1}^{n}\left(v(i)-\bar{V}\right)^2}} \quad (2)$$

where $\bar{U}$ and $\bar{V}$ are the means of the signals *U* and *V* respectively, *n* is the number of samples, and $d = 0,1,2,...,n$ is the time delay. The magnitude of the cross-correlation function $r_{uv}(d)$ represents the level of similarity between these two signals with the time shift and the maximum value *k*, as expressed in Eq. (3), indicates the time when both signals are aligned with the most similar characteristics.

$$k = \arg\max_{d}\left(r_{uv}(d)\right) \quad (3)$$

Cross-correlation is a computationally intensive process and cross-correlation relies on a large section of acquired signal. This is fine in large open environments with no possibilities of reflections. However, reflections in the form of echoes and reverberations make cross-correlation methods somewhat in accurate.

3. WAVELET AND CUMULANT DECOMPOSITION

Wavelet is a windowing techniques with variable-sized regions. Wavelet analysis allows the use of long time intervals where is possible to get more precise low-frequency information and shorter regions where high frequency inforamtion is available. In our case de-noising of the signal is performed via wavelet decomposition by using of the seventh order Daubishies waveform, see Fig.1.

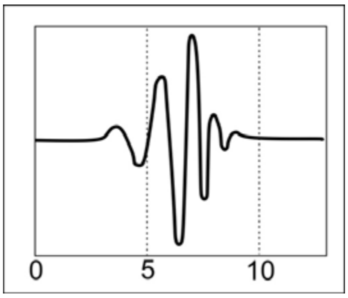

Figure 1. *db7* Daubechies waveform.

As shown in Fig.1, a wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelet analysis means breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet.

An algorithm for determining the time of arrival of an muzlle or shock wave, ToA, which originates from the firing of different types of infantry or artillery projectiles, has been developed in two variants. The first variant of the signal de-noising algorithm uses wavelet decomposition relying on *db7* Daubechies wavelent functions, see Fig.1.

The second variant of the acoustic signal de-noising algorithm is based on the use of the fourth order cumulants. The use of fourth order statistics (the kurtosis measure) can provide a way to distinguish speech or other type of signals like explosions from noise. A Gaussian random process exhibit a cumulant with a zero value for any cumulant order higher than two. Estimation of higher order cumulants will in general eliminate Gaussian noise. The most real noise sources have a probability density function close to the Gaussian distribution, but sources of interest like explosions, firing from cannons or guns have different distributions [9]. The fourth order cumulant technique is used in other areas, such as for example the estimation of incoming direction of electromagnetic waves or direction of arrival (DoA) problem [10].

The application of such structured algorithms, based on wavelet or the fourth order cumulant, bypasses the need to use the cross-correlation method for estimating ToA, i.e. the use of two different acoustic signals, or, an acoustic signal and a pseudo signal to determine ToA. The application of wavelet decomposition of the signal gives good results and makes a relatively small error in estimation ToA. The application of the algorithm is illustrated by several examples. These examples originate from firing projectiles from a 122 mm caliber cannon.

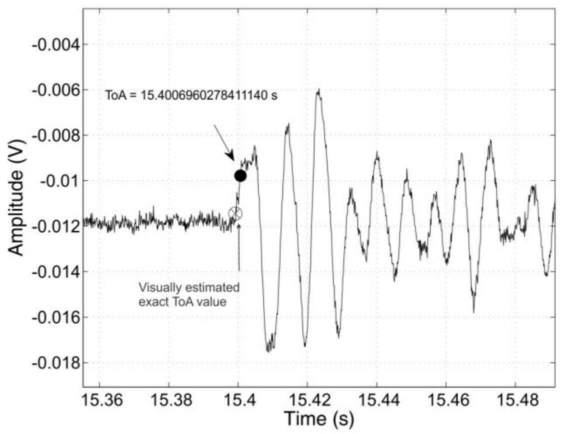

Figure 2. Visually estimated exact ToA value is designated withe ⊗ symbol, and ToA value which is algorithmicaly estimated, with wavelet de-noising of the signal, is designated with • symbol.

The initial acoustic signal, before wavelet de-noising procedure and estimation of the ToA value, is shown in Fig.3.

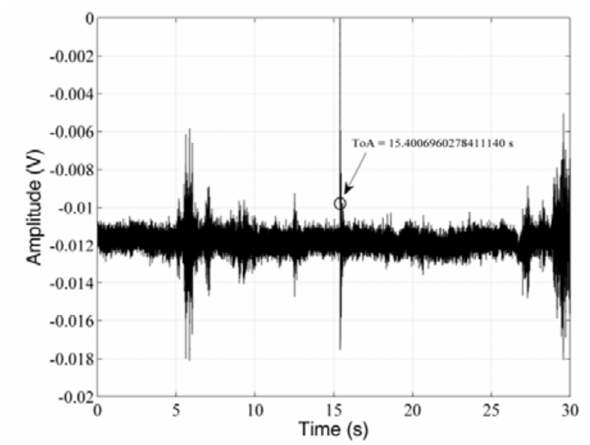

Figure 3. An unfiltered acoustic signal of a total duration of 30 s in which disturbances are expressed in the interval 5-13 s and finally in the interval 37-30 s.

The second example illustrates ability of the algorithm to recognize and estimate two close ToA values which originate from firing two artillery shells in short time interval, see Fig. 4.

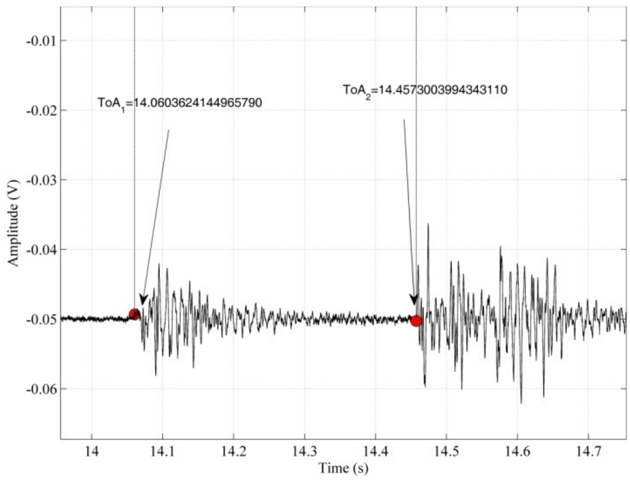

Figure 4. The algorithm with wavelet de-noising of the signal estimate two ToA values which originate from shot from two cannons.

In the case when the useful signal is very noisy or distored due to the conditions under which it propagates, such as the configuration of the ground, long range, significant ambient noise, the state of the atmoshere and others, a different approachmust be used in solvingthe problem of autonomus estimating ToA value. Using the fourth order cumlant analysis in de-noisig of the signal is promissing method. In Fig.5. is presented one such example.

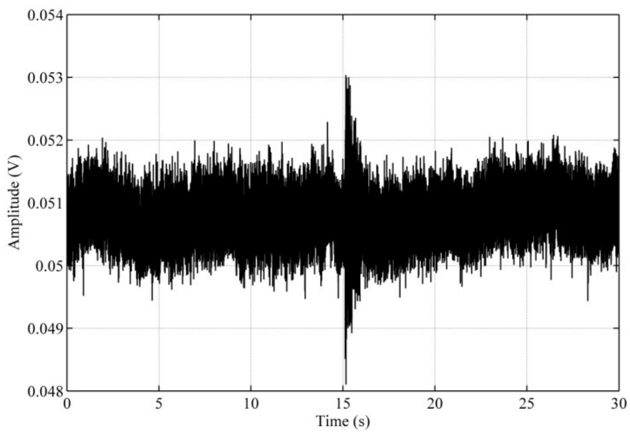

Figure 5. Example of the very noisy acoustic signal of the gun fire. Case when wavelet de-noising did not allow application of the algorithm for estimating ToA value.

In this case, see Fig.5, a more efficient method of de-noising the acoustic signal must be applied. Therefore the second variant of the acoustic signal de-noising algorithm based on the use of the fourth order cumulants is used. The result of applying this variant of the algorithm is shown in Fig 6. Application of the fourth order cumulant made it possible to significantly remove noise from the acoustic signal and significantly increase signal-to-noise ratio. After filtering, a clearly separated acoustic part was obtained, which is the result of shell fired from a cannon. If we apply an algorithm with adaptively adjustable amplitude parameters on such a well-filtered acoustic signal for autonomous estimating ToA, and as result we get an almoust accurate value of the moment when the signal occurs, see Fig. 7.

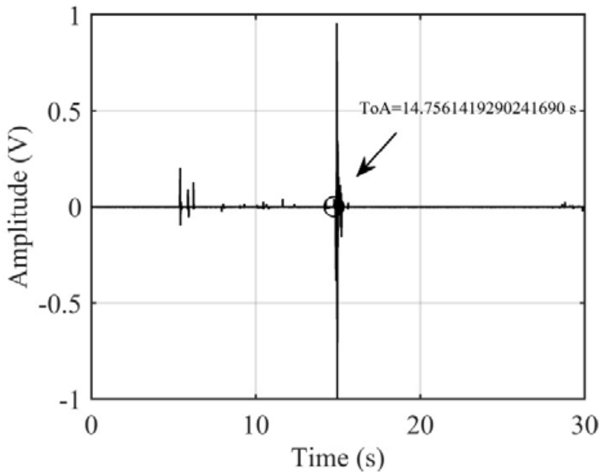

Figure 6. Filtered signal from Fig.5 using the fourth order cumulant and estimated ToA value.

When the Gaussian noise was previously removed from acoustic signal using the fourth order cumulant analysis, it was easy to apply the algorithm for autonomous estimation of the ToA value, as shown in Figures 5 and 6.

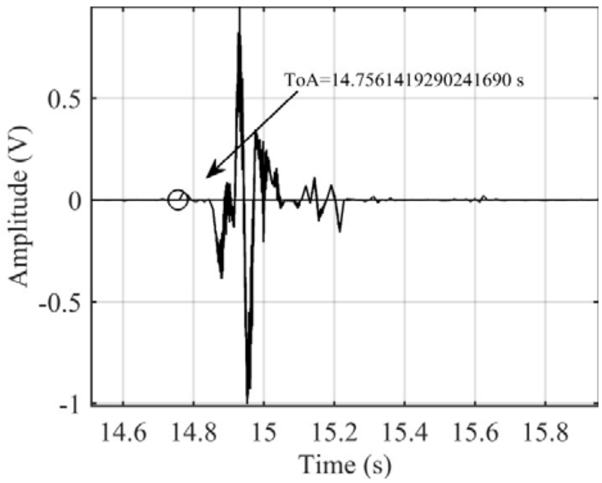

Figure 7. A zoomed-in part of the acoustic signal from Figure 6 that refers to the useful signal - the acoustic signal that is the result of a shell being fired from a cannon.

When looking more closely at the result shown in the diagram, see Figure 7, it can be seen that the moment of the beginning of the acoustic signal originating from the cannon shot is very precisely estimated.

4. ACHIEVED ACCURACY

The accuracy of the applied filtering methods and algorithm for autonomously estimating ToA values was checked as shown in Figure 2. After using a certain method of filtering of the signal and estimating ToA, the actual moment of beginning of the part of the acoustic signal related to the firing of the shell could be visually observed on the diagram, so ToA estimated value is marked with a symbol ⊗, and read its value with an accuracy of the order of microseconds.

$$\Delta ToA = ToA_{exact} - ToA_{estimated} \tag{4}$$

The absolute error (*ΔToA*) of estimated ToA values is calculated according Eq. 4. Statistical analysis of absolute errors was performed on 155 samples when wavelet decomposition of the signal was applied and 41 signal analysis with signal filtering using the fourth order cumulant analysis.

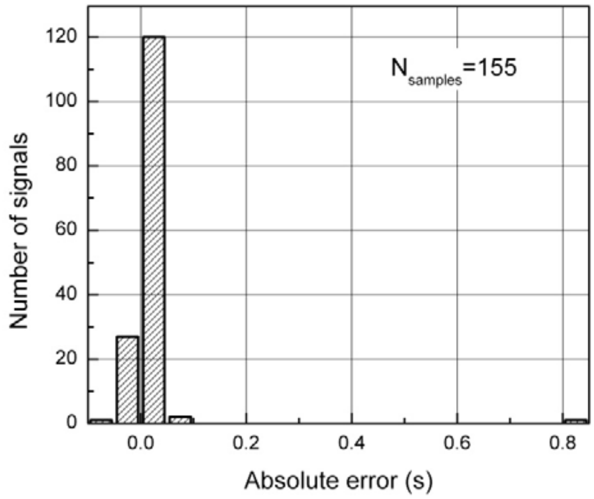

Figure 8. Histogram distribution of the absolute error of ToA estimated values when wavelet decomposition of the acoustic signal is used.

The absolute errors of the ToA vaulues estimation when using wavelet decomposition of the acoustic signal are good grouped around zero, see Fig. 8. Relatively small absolute error was obtained in almost all cases. However, it shoukd be noted that wavelet signal decomposition was applied only in those cases where there was a relatively high signal-to-noise ratio. The signal quality assement was performed before applying the algorithm for estimating ToA value via the crest factor, so the signal is rejected if there was too much noise. The crest factor is a parameter of a waveform showing the ratio of peak values to the effective value.

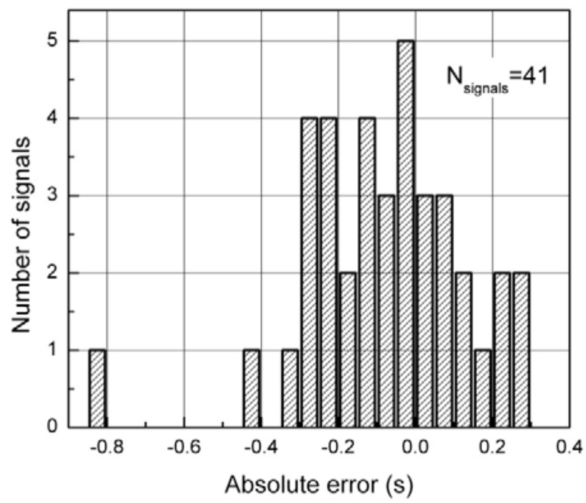

Figure 9. Histogram distribution of the absolute error of ToA estimated values when the fourth order cumulant decomposition of the acoustic signal is used.

The situation regarding accuracy when estimating ToA values is quite different compared to the previous case. The distribution of the absolute error is significantly wider, as are the values of the absolute errors are significantly bigger, see Fig. 9. The explanation of the results thus obtained consists in the following:

- the first, the fourth order cumulant filtering method was applied in all those cases when the signal is very noisy, so that the wavelet decomposition of the signal did not give any result and
- the second, the fourth order cumulant analysis was applied to windows of 200 points, which significantly reduced the time resolution of the filtered signal during ToA estimation process.

The explanation why such a coarse time resolution was used when using the fourth order cumulant method is that the average computer time for processing one acoustic signal is 13.38406027 seconds with standard deviation of 0.7021416 seconds. In contrast, the computer time when using the wavelet method is significantly less and amounts to around 0.4 seconds.

In order to better understand necessary computer time for estimating ToA, it is useful to specify the characteristics of the computer that was used for this analysis. During ToA time analysis a relatively outdated personal computer with a processor Intel(R) Core™ 2 Duo CPU E7500 2,93 GHz with 1,96 RAM was used.

5. CONCLUSION

The paper describes two methods of filtering acoustic signals for the purpose of applying an algorithm for the autonomous estimation of ToA shock or muzzle waves that occur when firing from artillery or personal weapons. It should be emphasized that it is not about competing methods that exclude each other. Rather, it could be said that they complement each other. The method based on the use of the fourth cumulant is applicable in all cases where the Gausinan noise is significantly present in the signal. However, the main disadvantage of using this method is the relatively large computer time required for signal processing, which temporarily excludes this method from being used for source localization using acoustic methods.

The future development of efficient and fast algorithms for calculating the fourth order cumulant, as well the realization of faster computers will bring this filtering method to the same position as wavelet signal decomposition. Also, it will enable the successful processing of signals that were generated at a greater distance and that are therefore significantly distorted.

The application of this new method of filtering acoustic signals will lead to a significant increase the range of locating the sources of shock or muzzle waves.

References

[1] Miodrag S. Vračar, Ivan Pokrajac: Application of the algorithm for time of arrival estimation of N-waves produced by projectiles of different calibers, doi: 10.1121/2.0000648, Proc. Mtgs. Acoust. 30, 055008, 2017.

[2] Ivan Pokrajac, Miodrag Vračar, Nadica Kozić, Radiana Brusin, Milan Stanojević,: Position Determination of Acoustic Source Using a Discrete Probability Density Method Supported by Joint Detection and Time of Arrival Estimation, Scientific Technical Review, Vol.67, No.1, pp.29-37, 2017.

[3] Ivan P. Pokrajac, Miodrag Vračar, Tamara Šević, Vasilija Joksimović.: Position Determination of Acoustic Source Using Higher-Order, Spectral Analysis for Time of Arrival Estimation, Scientific Technical Review, Vol.69, No.3, pp.41-48, 2019.

[4] F.Bai,D.Gagar, P.Foote,Y.Zhao, Comparison of alternatives to amplitude thresholding for onset detection of acoustic emission signals, ELSEVIER, Mechanical Systems and Signal Processing 84, pp 717-730, 2017.

[5] RAVINDRA S. AND JAGADEESHA S. N., Time of arrival based localization in wireless sensor networks: a linear approach, Signal & Image Processing: An International Journal (SIPIJ) Vol.4, No.4, August 2013.

[6] Mohamed Khalaf-Allah, Time of Arrival (TOA)-Based Direct Location Method, Conference Paper, DOI: 10.1109/IRS.2015.7226229, June 2015.

[7] Chee Sheng Tan, Rosmiwati Mohd-Mokhtar, Mohd Rizal Arshad, Time of arrival estimation using fast Fourier transform overlap for underwater distance measurement, Indian Journal of Geo Marine Sciences, Vol. 48 (07), pp. 1070-1080, July 2019.

[8] Lu Cheng, Hoahui Xin, Milan Veljkovic, Acoustic Emission Source Location on i girder based on Experimental Study and Lamb Wave propagation simultation, XII Conference on Steel and Composite Construction Coimbra, Portugal, 2019.

[9] Mikael Swartling, Benny Sällberg, Nedeljko Grbić, Direction of Arrival Estimation for Speech Sources Using Fourth Order Cross Cumulants, IEEE, 978-I-4244-1684-4/08, pp 1696-1699, 2008.

[10] P. Palanisamy and N. Rao, Direction of Arrival Estimation Based on Fourth-Order Cumulant Using Propagator Method, Progress In Electromagnetics Research B, Vol. 18, 83 (99), 2009.