Application of Spectral Extrapolation Technique to Stepped-Frequency RCS Measurement

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Abstract ─ "Time domain gating" used in the stepped-frequency radar cross section (RCS) measurement causes the inaccurate frequency domain data, especially at two ends of the band. This paper proposes a spectral extrapolation method for improving the measured RCS at two ends of the band more exactly. The core idea is: the measured frequency domain data are extrapolated to obtain the unknown value out of band with an auto-regressive model (AR model). The parameter in the AR model is calculated by the maximum entropy spectral estimation algorithm. Therefore, the span of the original band is extended, and both ends of frequency on the original band are inside the range of the new band. If the time domain gating is adding to the new band, the precision at two ends of the original band can be greatly improved. The simulation and experimental results show that more effective frequency domain data near the two ends of the band can be predicted by using the spectral extrapolation method, and the maximum error at the ends of the original band is less than 1dB after extrapolation, so it can ensure the accuracy of RCS measurement over the whole frequency band.

Index Terms ─ Auto-regressive model, maximum entropy spectral estimation, spectral extrapolation, stepped-frequency RCS measurement.

I. INTRODUCTION

So far, the stepped-frequency RCS measurement method is widely used in indoor's scattering measurement [1,2]. It uses a vector network analyzer to transmit and receive with variable frequency signals to measure S21 of the target. To obtain RCS of the target, another target with the known RCS (usually a metal ball) is measured. Compared with the traditional continuous wave RCS measurement method, wideband data composed of many discrete frequencies can be obtained in a very short time by the stepped-frequency RCS measurement. However, some of the transmitted signals will be coupled into the received signal due to the receiving antenna is put near the transmitting antenna, which will affect the accuracy of measurement. Besides, the background clutter also has a greater impact on the accuracy of measurement[3].

To eliminate the influence of background clutter and antenna coupling signals, a "time domain gating" technique is commonly used [4,5], which changes the frequency domain data to the time domain response with inverse fast Fourier transformation (IFFT) and then selects the target's signal (the location of the target in the time domain response is known in advance), thus the interference between the antenna coupling signals and background clutter outside the target area are eliminated. However, the gating also has a great impact when the time domain response of the target was changed back to the frequency domain data with fast Fourier transformation (FFT). The original frequency domain data will be contaminated, which is called the "Gibbs effect", that is, the two ends of the frequency band will have a fluctuation, and the range of gating is smaller, the fluctuation at two ends of the frequency band is larger. Normally, we are not concern about the impact of this "edge effect", but when the test frequency is low (such as the L-band), the span of frequency domain data is narrow for the radiation performance of the antenna, the accurate RCS data after gating become very limited.

To reduce the influence of time domain gating, we try to obtain more information on the spectrum. The spectrum estimation methods mainly appears in the field of super-resolution imaging [6-9] and computational electromagnetics [10,11]. However, the applicability of these methods in the field of RCS measurement has not been verified. Reference [12] gives a method of using low-frequency RCS data to predict high-frequency RCS data. The method supposes that the response is a linear

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time-invariant system, and the RCS data is regarded as the far-field power spectral function, then the extrapolation is performed by using the rational function, but the prediction error of this method is large and only simulation data is used for verification. Recently, reference [13] has proposed a basis pursuit (BP) L1 optimization method to eliminate the impact of data errors caused by limited bandwidth through compressed sensing, but it assumes that the original signal has sparse characteristics.

The linear prediction method has been widely used in high-resolution spectrum estimation of discrete data, especially when the sequence is short, a higher resolution than the Fourier spectrum can be obtained. Therefore, the paper presents a spectral extrapolation method based on linear prediction to extend the span of the original band and the two ends of frequency on the original band are inside the range of the new band. Therefore, despite the time domain gating reduces the effective frequency domain data, the precision at two ends of the original band will also be greatly improved. In this paper, which is an expansion submitted to the 2020 ACES Proceedings paper, more detail of the method is described. The simulation and experimental results are given to show that the spectral extrapolation method can ensure the accuracy of stepped-frequency RCS measurement over the whole frequency band.

II. THE SPECTRAL EXTRAPOLATION OF STEPPED-FREQUENCY SIGNAL

As shown in Fig. 1, the target's time domain response multiplied with a gating is equivalent to convolving the original band with a sinc function, resulting in fluctuations on the frequency domain data, especially at two ends of the band. If the original band is extrapolated by the linear prediction, then the span of the original band is increased. Although the new frequency domain data will also fluctuate after gating, but the two ends of frequency on the original band are inside the range of the new band, thus the measurement errors at two ends of the original band will be greatly reduced.

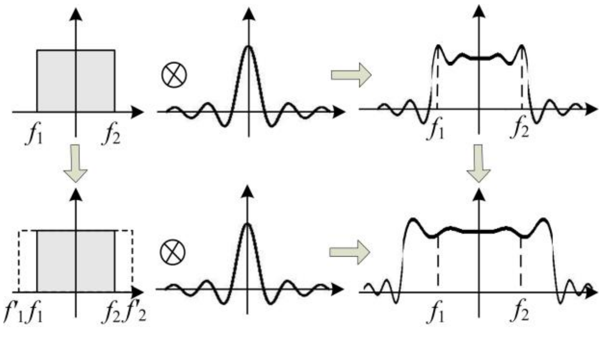

Fig. 1. The principle of spectral extrapolation.

The spectral extrapolation method is based on the auto-regression model (AR model) in the modern spectral estimation theory [14,15]. The AR model is a kind of linear prediction. The model parameters are calculated by Burg algorithm. For example, the N points data are known, the data before or after N points can be predicted by the model, which is similar to the interpolation. The AR model is recursive by N points, and the interpolation is derived from two points (or a few points), both of them are to increase effective data. Since the predicted data has the same autocorrelation function as the known data, so the predicted data contains the information of known data. It has proved that the extrapolated sequence has the largest entropy, and then the maximum information of the unknown spectrum is obtained. The detailed procedures are as follows:

According to the definition of the auto-regressive model, the current data x (n) can be represented by a linear combination of previous data x (n-1), x (n-2) ... x (n-m):

$$x(n) = -\sum_{i=1}^{m} a_m(i)\, x(n-i) + e(n), \tag{1}$$

where, $\hat{x}(n) = -\sum_{i=1}^{m} a_m(i)\, x(n-i)$ is prediction data of x(n), $e(n)$ is prediction error, $a_m(i)$ is the coefficient of linear combination.

For the forward prediction, the prediction data $\hat{x}^f(n)$, the forward prediction error $e^f(n)$, the forward prediction error power ρ^f are as following:

$$\hat{x}^f(n) = -\sum_{i=1}^{m} a_m(i)\, x(n-i), \tag{2}$$

$$e^f(n) = x(n) - \hat{x}^f(n), \tag{3}$$

$$\rho^f = \frac{1}{N-m}\sum_{n=m}^{N-1} \left|e^f(n)\right|^2 . \tag{4}$$

For the backward prediction, the prediction data $\hat{x}^b(n-m)$, the backward prediction error $e^b(n)$, the backward prediction error power ρ^b are as following:

$$\hat{x}^b(n-m) = -\sum_{i=1}^{m} a_m^*(i)\, x(n-m+i), \tag{5}$$

$$e^b(n) = x(n-m) - \hat{x}^b(n-m), \tag{6}$$

$$\rho^b = \frac{1}{N-m}\sum_{n=m}^{N-1} \left|e^b(n)\right|^2 . \tag{7}$$

The coefficients $a_m(i)$ are calculated by the following recursion formulas:

$$a_m(i) = a_{m-1}(i) + k_m a_{m-1}^*(m-i), \tag{8}$$

$$a_m(m) = k_m, \tag{9}$$

where, k_m is the recursion coefficient, and i = 1, 2,..., m-1.

According to the recursion formulas, The relationship of e^f(n) and e^b(n) are given by the following formulas:

$$e^f_m(n) = e^f_{m-1}(n) + k_m e^b_{m-1}(n-1)\,, \tag{10}$$

$$e^b_m(n) = e^b_{m-1}(n-1) + k^*_m e^f_{m-1}(n)\,, \tag{11}$$

$$e^f_0(n) = e^b_0(n) = x(n)\,. \tag{12}$$

Let the sum of forward and backward prediction error power is:

$$\rho^{fb} = \frac{1}{2}\left[\rho^f + \rho^b\right]. \tag{13}$$

ρ^{fb} is only the function of k_m, and let əρ^{fb}/ək_m=0, we have:

$$k_m = \frac{-2\sum_{n=m}^{N-1} e^f_{m-1}(n)e^{b*}_{m-1}(n-1)}{\sum_{n=m}^{N-1}\left|e^f_{m-1}(n)\right|^2 + \sum_{n=s}^{N-1}\left|e^b_{m-1}(n-1)\right|^2}\,, \tag{14}$$

where, m= 1, 2,..., p, and p is the model order.

The steps of the spectral extrapolation method using original frequency domain data are as follows:

Step 1: the initial condition $e^f_0(n) = e^b_0(n) = x(n)$ is given, then k_1 is estimated by (14);

Step 2: the model coefficient $a_1(1) = k_1$ is obtained for m = 1;

Step 3: $e^f_1(n)$ and $e^b_1(n)$ are obtained by k_1 and (10) - (12), then k_2 is estimated by (14);

Step 4: The model coefficients $a_2(1)$ and $a_2(2)$ for m = 2 are calculated by (8) and (9);

Step 5: Repeat step 2 to step 4 until m = p, all of the model coefficients are obtained. Then the forward and backward prediction data can be calculated by the coefficients.

III. RESULTS

A. Simulation results

The effect of time domain gating on the spectrum is simulated. The span of the frequency band is from 8GHz to 12GHz, and the corresponding range of a resolution unit is 0.0375m. Assume that the spectrum without time domain gating is a regular straight line, and then the width of gating with 10 resolution units (0.375 m) and 20 resolution units (0.75 m) are added to the original spectrum respectively. The spectrum after gating is shown in the Fig. 2. From the figure we can see that the time domain gating causes a large fluctuation at two ends of the frequency domain response, and as the width of gating becomes narrower, the range of fluctuation in the frequency band is larger, so if we want to remove more background clutter, a narrow gating should be used, but frequency domain data at two ends of the band will be inaccurate.

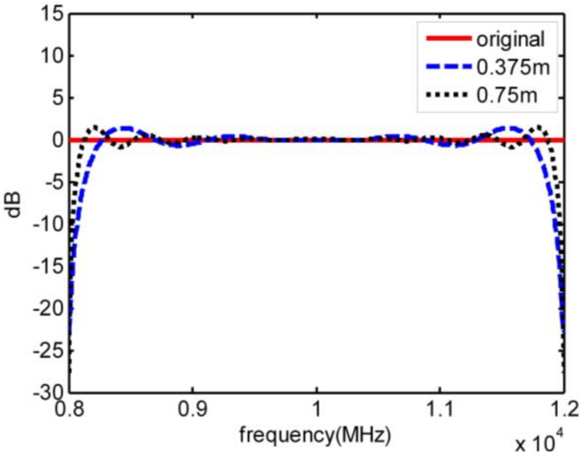

Fig. 2. The frequency domain response with different time domain gatings.

To validate the spectral extrapolation method, the simulation data are shown in Fig. 3. The original data (the red solid line) are combined by the amplitude and phase related to two signals at different distance and a random signal. The purpose is to make the original data have a certain signal-to-noise ratio, which is closer to the actual measured signal. The sectional data in the middle of the original data are selected to extrapolate. The extrapolated data are shown with the blue dashed line. It can be seen from the figure that compared with the original data, parts of extrapolated data near the sectional data are agreed with the original data. So the results validate that more effective data can be obtained by the spectral extrapolation method to increase the band width.

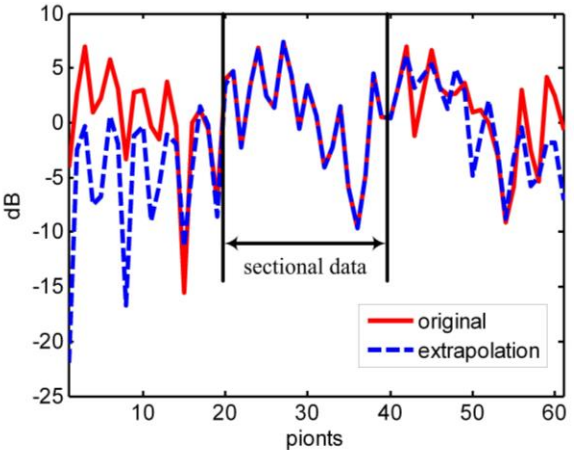

Fig. 3. The compare of original and extrapolated data.

From the results of the simulation, the extrapolation error is determined by the model order p. In general, the model order p is not known in advance, and a large value needs to be selected at first and determined during recursion. The appropriate model order is selected when the error power is essentially constant. As can be seen from the Fig. 4, when the order is greater than 6, the variation of error power is small, so the model order is 6.

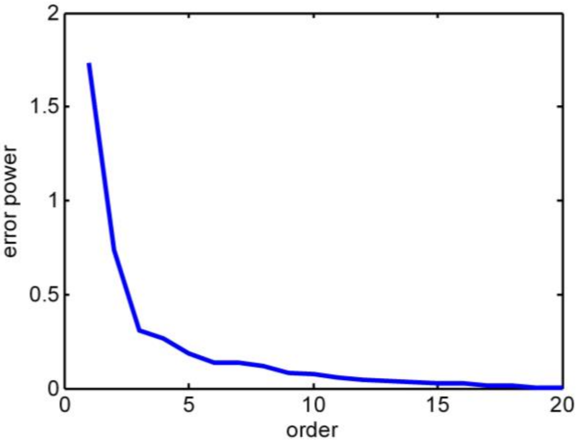

Fig. 4. The error power changed with the model order.

B. Experimental results

Two PEC spheres were measured in the anechoic chamber of Northwestern Polytechnical University. The theoretic frequency domain data of the sphere whose value is known that can be used to compare with measured value to verify the effectiveness of the spectral extrapolation method. One of the spheres with 150mm diameter is used as the calibration target and another sphere with 75mm diameter is regarded as the target to be measured, seen in Fig. 5 and Fig. 6 respectively. A vector network analyzer connected with two horn antennas is used to transmit and receive the stepped frequency signals. The test frequency range is from 8GHz to 12GHz, and the frequency interval is 5MHz. The spheres are put on the center of the turntable, and the test distance from the antenna to the sphere is about 18 meters. The turntable has turned a circle with 1 degree interval.

Fig. 5. 150mm sphere.

Fig. 6. 75mm sphere.

Figure 7 shows the curve of the target changed with angles at three different frequencies without the time domain gating. It can be seen that the curves have large fluctuations at all frequencies, and the measurement error is about 5dB at 10GHz. The main reason is that the echo of the target is rather weak, which is greatly influenced by the clutter.

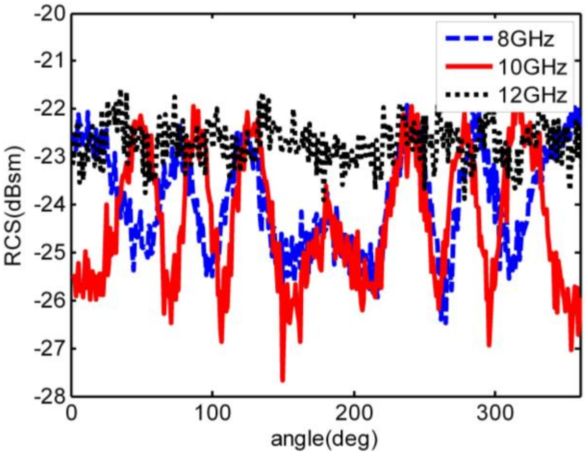

Fig. 7. The RCS results at different frequencies without time domain gating.

In order to eliminate the clutter outside the target area, the frequency domain data of the target is transformed into the time domain response, as shown in Fig. 8. The curve is also represented as the range profile of the target. For the reason that the diameter of the sphere is small, which is in the resonance region at the frequency range. Therefore, in addition to the direct reflection, the backscatter of the target also has diffraction, thus the width of the time domain gating is 0.4 meter.

After adding a time domain gating, the RCS at three frequencies are shown in Fig. 9. From the figure, we can see that the measurement error at 10 GHz is less than 1dB, which means that the impact of clutter is very little. But the measurement error at 8GHz and 12GHz are larger, which can reach to 8dB. The fluctuations at two ends of the band are both increased for the influence of the time domain gating.

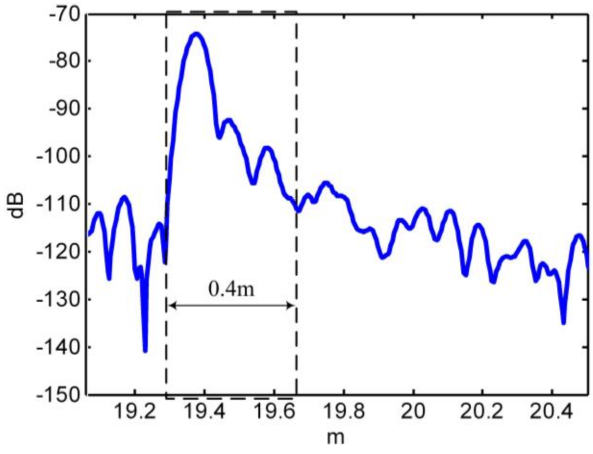

Fig. 8. The time domain response of the target.

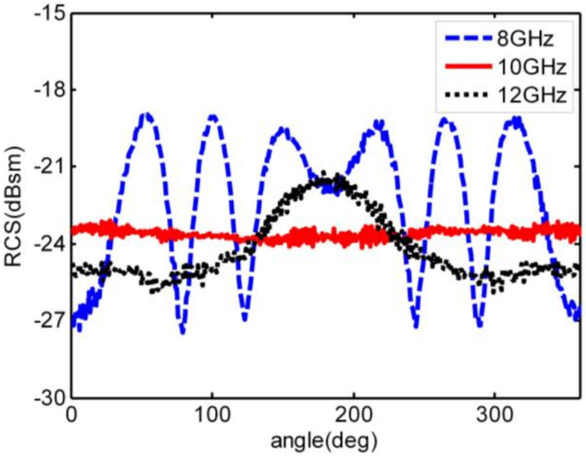

Fig. 9. The RCS results at different frequencies with the time domain gating.

The frequency domain data are extrapolated by the spectral extrapolation method, then the same time domain gating is used to the new frequency band from 7GHz to 13GHz, so the precision at 8GHz and 12GHz on the original band can be greatly improved, as shown in Fig. 10. Compared with the theoretic value, the maximum error is less than 1dB at all frequencies.

The RCS results of three frequencies at different angles after extrapolation are shown in Fig. 11. After extrapolation, the RCS errors at different angles of 8GHz and 12GHz are less than 1dB, which is nearly equal to the errors at 10GHz in the band. It can be seen that the precision on two ends of the frequency band can be greatly improved by using the spectral extrapolation method, and the RCS values near the out of band can be predicted.

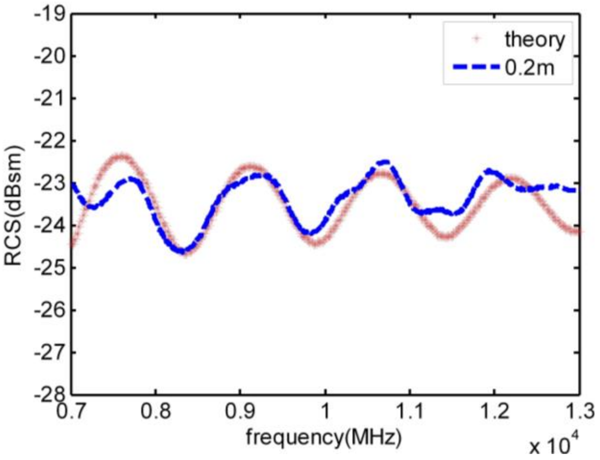

Fig. 10. The RCS results at 7GHz to 13GHz after the extrapolation.

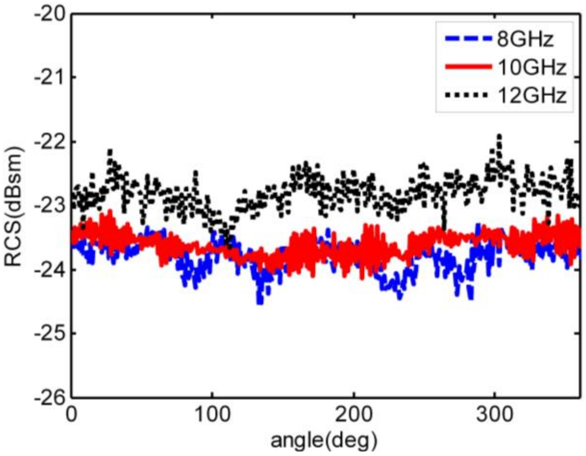

Fig. 11. The RCS results at different angles after extrapolation.

VI. CONCLUSION

The stepped-frequency RCS measurement method has high efficiency and accuracy, but it has a low precision on two ends of the frequency band when a time domain gating is used. This paper presents a spectral extrapolation method which is experimentally demonstrated to be effective. After extrapolation, the two ends of frequency on the original band are inside the range of the new band, so that the measurement precision at the original band can be improved. Moreover, RCS values near the out of band can be predicted by using the spectral extrapolation method. The method can not only be applied to the stepped-frequency RCS measurement but also may be used to other broadband measurements.

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REFERENCES

[1] L. Sevgi, Z. Rafiq, and I. Majid, "Radar cross section (RCS) measurements," *IEEE Trans. Antennas Propagat Mag.*, vol. 55, no. 6, pp. 277-291, Dec. 2013.

[2] C. Larsson and M. Gustafsson, "Wideband measurements of the forward RCS and the extinction cross section," *Applied Computational Electromagnetic Society Journal*, vol. 28, no. 12, pp. 1145-1152, Dec. 2013.

[3] A. Bati, L. To, and D. Hilliard, "Advanced radar cross section clutter removal algorithms," *IEEE Conference on Antennas and Propagation*, Barcelona, Spain, Apr. 2010.

[4] R. A. M. Mauermayer and T. F. Eibert, "Time gating based on sparse time domain signal reconstruction from limited frequency domain information," *Symposium of the Antenna Measurement Techniques Association*, Texas, USA, Oct. 2016.

[5] R. Phumvijit, P. Supanakoon, and S. Promwong, "Measurement scheme of radar cross section with time gating," *International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, Phuket, Thailand, June 2017.

[6] I. J. Gupta, "High-resolution radar imaging using 2-D linear prediction," *IEEE Trans. Antennas Propagat.*, vol. 42, no. 1, pp. 31-37, Jan. 1994.

[7] Y. X. Wang and H. Ling, "A frequency-aspect extrapolation algorithm for ISAR image simulation based on two-dimensional ESPRIT," *IEEE Trans. Geosci. Remote Sensing*, vol. 38, no. 4, pp. 1743-1747, July 2000.

[8] C. M. Tong, P. W. Yan, Z. G. Huang, and F. Z.Geng, "Simultaneous extrapolation of RCS of a radar target in both angular and frequency domains based on bivariate pad é approximant technique," *Asia-Pacific Microwave Conference Proceedings*, Suzhou, China, Dec. 2005.

[9] I. Erer, S. Kent, and M. Kartal, "High resolution radar imaging from incomplete data," *IEEE Radar Conference*, Rome, Italy, May 2008.

[10] J. Ling, S. X. Gong, X. Wang, B. Lu, and W. T. Wang, "A novel two-dimensional extrapolation technique for fast and accurate radar cross section computation," *IEEE Trans. Antennas Propagat Letters.*, vol. 9, pp. 244-247, 2010.

[11] G. G. Zeng, Z. Feng, and S. Y. Li, "The application of genetic algorithm on the frequency extrapolation method using current density from the MOM," *International Conference on Business Management and Electronic Information*, Guangzhou, China, May 2011.

[12] K. Seol, W. Cho, G. Kang, and J. Koh, "RCS at high frequency band using rational functions," *IEEE International Symposium on Antennas and Propagation*, Boston, MA, USA, July 2018.

[13] I. J. LaHaie and G. D. Dester, "Application of L1 minimization to image-based near field-to-far field RCS transformations," *European Conference on Antennas and Propagation*, Krakow, Poland, Mar. 2019.

[14] S. M. Alessio, *Digital Signal Processing and Spectral Analysis for Scientists: Concepts and Applications*, Springer, Berlin, Germany, 2016.

[15] V. K. Nguyen, M. D. E. Turley, and G. A. Fabrizio, "A new data extrapolation approach based on spectral partitioning," *IEEE Signal Processing Letters*, vol. 23, no. 4, pp. 454-458, Apr. 2016.

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