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Time Frequency Single Source Point Detection Based Method for Radar Signal Sorting

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Abstract

Common sorting method have low sorting rates and is sensitive to the Signal-to-Noise Ratio(SNR), detection of time frequency single source point is applied to sort unknown complicated radar signal, high sorting accuracy can be got. The single source points of each radar source signal is detected, then the mixing vector in the corresponding single source point set was estimated by Singular Value Decomposition (SVD), the mixed matrix is estimated simultaneously by cluster validation technique, based on k-means clustering algorithm. Finally, Pulse Description Words (PDW) of each radar signal can be worked out. Experiment results demonstrated that the radar emitter signals extracted by this method showed good performance of noise-resistance and clustering at large-scale SNR.

Keywords: *Time-Frequency Transformation; Single Source Point; Radar Signal; Cluster Validation; Blind Separation*

1. Introduction

Radar recommaissance is a key part of electromagnetic countermeasure. The mixed signal is sorted by reconnaissance system and the pulse description words of each signal pulse can be calculated to locate radiation sources or assess the threat of each source. In [1], Blind Signal Separation (BSS) was applied in radar signal sorting, a method based on fourth-order cumulant was proposed to accomplish signal sorting and achieved good results, but the number of source signals had been already known in that simulation experiment, the circumstances of unknown signal numbers was not mentioned in that paper. In [2], another blind separation method based on fixed point independent component analysis algorithm was proposed to solve the problem of overdetermined radar signal sorting, but the method can not accomplish underdetermined radar signal sorting.

In order to solve the problem of unknown signal numbers in radar signal sorting by BSS, too many methods have been presented. In [3], a robust algorithm under the condition of unknown signal source number was proposed. In that algorithm, the data received by the array was pretreated via the projection transformation to inhibit model errors and reduce data dimension, thus improving the robustness and lightening the computation load. Then, the number of signal could be estimated according to the transformed m-Capon spatial spectrum function. In [4], the author took advantage of the straight line clustering of the sparse source signals, standardized the aliasing signals, then the aliasing signals were formed spherical cluster, thus the linear cluster was turned into density cluster. And the clustering center was searched and obtained by using the ant clustering algorithm, the aliasing matrix can be accurately evaluated. In a word, most methods require clustering to avoid the problem of unknown signal numbers, thus a good clustering algorithm is the key to solve this problem. The problem of underdetermined signal sorting can be settled by two methods: 1. Using the sparsity of source signals; 2. 'Two-step approach'. Both of them work under the condition of sparse signal. In the

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actual situation, sometimes, the sparsity of signals can not be found in different domain, thus non-sparse signals sorting must be considered.

The goal of this paper is to solve the problem of underdetermined radar signal sorting under the situation of unknown number of source signals, a sorting method based on time frequency single source point detection is presented. Single source point of each radar source signal is detected, and the mixing vector is estimated by SVD, finally the mixing matrix can be estimated simultaneously by the cluster validation technique based on k-means clustering algorithm, so far, the radar signal sorting is accomplished. In the method, the k-means clustering algorithm has been improved, the radar signals can be estimated accurately.

2. Problem Statement

In the process of radar reconnaissance, all kinds of radar signals radiate to the same airspace, and the reconnaissance system can only intercept the mixed signal. So we can only sort radar signals via the mixed signal, and the number of radars are always more than antenna array. Suppose the number of radar signals is P, the number of antenna array is M. So the intercepted signal or observed signal can be described as

$$x(t) = As(t) + n(t) \tag{1}$$

Where $x(t)$ is observed signals $x(t) = [x_1(t), x_2(t), ..., x_M(t)]^T$; $s(t)$ is radar source signals, $s(t) = [s_1(t), s_2(t), ..., s_P(t)]^T$; $n(t)$ is antenna noise, $n(t) = [n_1(t), n_2(t), ..., n_M(t)]^T$; A is mixing matrix, $A = [\alpha_1, \alpha_2 ..., \alpha_P]^T$. In the matrix A, the (i,k) element is

$$\alpha(i,k) = b_{ik} e^{-j2\pi f_k \tau_{ik}} \tag{2}$$

Where b_{ik} is amplitude attrnuation, τ_{ik} is time delay, f_k is signal frequency. Taking the Short-Time Fourier Transformation (STFT) of (1), we obtain

$$x(t, f) = As(t, f) + n(t, f) \tag{3}$$

The time-frequency plane is formed by t and f , $x(t, f)$, $s(t, f)$ and $n(t, f)$ are fourier transformation of observed signal, radar source signals and antenna noise.

Definition 1: time-frequency support point.

If $\|x(t, f)\|_2^2 > 0$, point (t, f) is the time-frequency support point of $x(t, f)$. When it considers the antenna noise, the criterion of time-frequency support point becomes to $\|x(t, f)\|_2^2 > \xi$, where ξ is noise gate.

Definition 2: time-frequency single source point.

In the time-frequency plane, if $s_i(t, f) \gg s_k(t, f)$ $i \neq k$, we consider that at (t, f) point, there only exist $s_i(t, f)$, point (t, f) is the time-frequency single source point of $s_i(t, f)$.

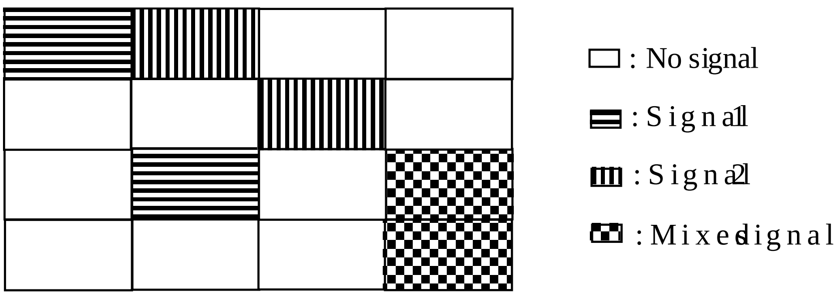

Figure 1. Diagram of Time-frequency Point

As we can see in Fig. 1, each square represents one point, different filling lines represent different signal, no filling lines represent no signal. So the square with horizontal and vertical lines is time-frequency single source point, others are not.

In order to accomplish blind separation of radar signals, a hypothesis, each radar signal exists discrete time-frequency single source points, must be proposed. Vectors can be estimated by detecting all the time-frequency single source points of radar signals, mixing matrix is composed by vectors, so radar source signals can be figured out.

3. Detection of Time-Frequency Single Source Points and Estimation of Vectors

Suppose the time-frequency single source points assemblage of signal $s_k(t)$ is $\Psi(t_{k_i}, f_{k_i})$. So observed signal of any point in the assemblage can be described as

$$x(t,f) = a_k s_k(t,f) + n(t,f) \tag{4}$$

Ignoring the influence of noise, Eq. (4) is simplified to

$$x(t,f) = a_k s_k(t,f) \tag{5}$$

Calculating each channel and the m channel time-frequency ratio

$$\omega = \left[\frac{x_1(t,f)}{x_m(t,f)}, \ldots, 1, \frac{x_{m+1}(t,f)}{x_m(t,f)}, \ldots, \frac{x_M(t,f)}{x_m(t,f)} \right] \tag{6}$$

Bringing Eq. (5) into Eq. (6), we obtain

$$\omega = \left[\frac{\alpha_{k1}}{\alpha_{km}}, \ldots, 1, \frac{\alpha_{k(m+1)}}{\alpha_{km}}, \ldots, \frac{\alpha_{kM}}{\alpha_{km}} \right] = \frac{1}{\alpha_{km}} \alpha_k \tag{7}$$

Eq. (7) indicates that if point (t, f) is one time-frequency single source point of signal $s_k(t)$, the time-frequency ratio is constant. So we can get the estimation of vector via detecting all time-frequency single source points. The estimation of vector is

$$\hat{\alpha}_k = [\frac{1}{L_k} \sum_{i=1}^{L_k} \frac{x_1(t_{k_i}, f_{k_i})}{x_m(t_{k_i}, f_{k_i})}, \ldots, \frac{1}{L_k} \sum_{i=1}^{L_k} \frac{x_M(t_{k_i}, f_{k_i})}{x_m(t_{k_i}, f_{k_i})}] \tag{8}$$

Where L_k is the number of single source points. If we consider the array noise, ω is not a constant, but mixed signal has obvious clustering characteristics, we can statistical detect single source points.

Considering array noise, the matrix of time-frequency ratio becomes a complex matrix. So we take the real part and the imaginary part into the histogram statistics respectively to get the matrix. Firstly, extract the real and imaginary parts of each element in the matrix. Then, divide the real and imaginary parts into M_1 and M_2 groups respectively. The column vector corresponding to each group becomes submatrix. At last, remove the submatrix which number of column less than K_1 and K_2, and the rest of submatrix represent to R_{jk} and I_{jk}. So the time-frequency single source points assemblage corresponding to R_{jk} and I_{jk} is come from one radar source signal.

For example, when $m=1$, the corresponding matrix of time-frequency ratio is

$$\tilde{\omega}=\begin{bmatrix} 1 & 1 & \cdots & 1 \\ \frac{x_2(\tilde{t}_1,\tilde{f}_1)}{x_1(\tilde{t}_1,\tilde{f}_1)} & \frac{x_2(\tilde{t}_2,\tilde{f}_2)}{x_1(\tilde{t}_2,\tilde{f}_2)} & \cdots & \frac{x_2(\tilde{t}_{N_i},\tilde{f}_{N_i})}{x_1(\tilde{t}_{N_i},\tilde{f}_{N_i})} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{x_M(\tilde{t}_1,\tilde{f}_1)}{x_1(\tilde{t}_1,\tilde{f}_1)} & \frac{x_M(\tilde{t}_2,\tilde{f}_2)}{x_1(\tilde{t}_2,\tilde{f}_2)} & \cdots & \frac{x_M(\tilde{t}_{N_i},\tilde{f}_{N_i})}{x_1(\tilde{t}_{N_i},\tilde{f}_{N_i})} \end{bmatrix} \tag{9}$$

The Eq. 8 becomes

$$\hat{e}_k=[\frac{1}{L_k^{'}}\sum_{i=1}^{L_k^{'}}\tilde{\omega}_i(1,t),...,\frac{1}{L_k^{'}}\sum_{i=1}^{L_k^{'}}\tilde{\omega}_i(M,t)] \tag{10}$$

Then work out the autocorrelation matrix of the mixed signal, the autocorrelation matrix is

$$\tilde{R}_i=E\{\tilde{x}\tilde{x}^H\} \tag{11}$$

Where the superscript ‘H’ denotes the Hermitian transpose operation. And the Singular Value Decomposition of $\tilde{R}_i$ is computed through

$$\tilde{R}_i=USU^H \tag{12}$$

Where U is a unitary matrix correspondings to the singular value matrix S, and $U=[u_1,u_2,...u_M]$.

From the above, only one signal exists at the time-frequency single source point, and combining with the characteristics of singular value decomposition, if there is one signal, the feature vector correspondings to the maximal eigenvalue in the singular value matrix S is the estimation of mixed vector. So the estimation of mixed vector is

$$\hat{e}_k=u_{\text{Smax}} \tag{13}$$

Where u_{Smax} is a vector corresponding to the maximal eigenvalue in unitary matrix U.

All above is just the situation of $m=1$, so we should change the value of m from 1 to M, repeat the above process, then all the mixed vector can be worked out.

4. Estimation of Mixed Matrix

The estimation method of vector need go through all the value of m, the result is that the vectors of mixed matrix A are estimated too many times. In order to estimate A, we must clustering all the estimated vectors. But in the context of radar reconnaissance, the number of clustering is unknown, traditional clustering methods are not applicable. A new clustering method based on k-means clustering algorithm is proposed to solve this problem. Specific steps are as follows:

Step 1. Suppose the maximal number of clustering is $c_{\max}$, clustering the estimated vectors to c category, $c\in\{1,2,...,c_{\max}\}$. So mixed matrix A can be worked out as $\hat{A}_c=\{\hat{a}_1,\hat{a}_2,...,\hat{a}_c\}$, the problem becomes how to determine the number of clustering centers c.

Step 2. According to [5], a verification technology is presented for calcuating the number of clustering centers.

Definition 3: compaction between category.

The expression of compaction is

$$scat(c) = \frac{1}{c}\sum_{i=1}^{c}\sigma_{\psi_i} / \sigma_e \tag{14}$$

Where ψ_i is the i category; σ is mean square error of each mixed matrix estimation, and σ is

$$\sigma = \frac{1}{H}\sum_{i=1}^{H}(\hat{e}_i - \overline{e})^2 \tag{15}$$

Where H is the number of elements in each category; $\overline{e}$ is the mean value of $\hat{e}_i$.

$$\overline{e} = \frac{1}{N_0}\sum_{i=1}^{N_0}\hat{e}_i \tag{16}$$

So compaction define the separability of estimated mixed matrix, lower degree of compaction represents better clustering result. Adjusting the Eq. (14), the large value of $scat(c)$ must be classified as one category, naturally the others must be classified as different category.

Step 3. Determine the objective function. Regard the "distance" between different clustering centers as objective function.

Definition 4: the "distance" between different clustering centers.

Define the "distance" to measure the degree of separation, the expression is

$$dis(c) = \frac{d_{\max}^2}{d_{\min}^2}\sum_{i=1}^{c}(\sum_{j=1}^{c}(\hat{a}_i - \hat{a}_j)^2)^{-1} \tag{17}$$

Where $d_{\max}$ and $d_{\min}$ respectively represent the maximum and minimum "distance" between different clustering centers. When the value of $dis(c)$ achieves maximum value, the number c is the best classification number, so that the estimation of mixed matrix A is the best estimation.

5. Computer Simulations

The simulations are performed using MATLAB R2011b running on an Inter (R) Core (TM) i3-4150, 3.50 GHz processor with 4 GB of memory, under Windows 7 OS.

Suppose radar source signals consist of 4 linear frequency modulation (LFM) signals. The number of receiving antenna array is 3. Sampling rate is 2 MHz. The detection threshod and statistical parameters M_1 and M_2 depend on noise, the values are different under different signal to noise ratio (SNR).

The parameters of each radar signals shown in Tab.1 .

Table 1. Parameters of LFM Signals

number	start frequency	time width	band width
1	30MHz	10us	450MHz
2	10MHz	10us	220MHz
3	250MHz	10us	150MHz
4	400MHz	10us	100MHz

Randomly generate mixed matrix A is

$$A = \begin{bmatrix} 0.5774+0.0000i & 0.5774+0.0000i & 0.5774+0.0000i & 1.0000+0.0000i \\ 0.2618+0.5146i & -0.5270+0.2359i & 0.3260-0.4765i & -0.9570-0.2901i \\ -0.3400+0.4666i & 0.3846-0.4306i & -0.2092-0.5381i & 0.8317+0.5553i \end{bmatrix}$$

The estimation of mixed matrix $\hat{A}$ is

$$\hat{A}=\begin{bmatrix} 0.5795+0.0000i & 0.5784+0.0000i & 0.5804+0.0000i & 0.5774+0.0000i \\ 0.2574+0.5148i & 0.3265-0.4755i & -0.5513-0.1700i & -0.5271+0.2358i \\ -0.3396+0.4664i & -0.2078-0.5382i & 0.4782+0.3186i & 0.3847-0.4304i \end{bmatrix}$$

Contrast A and $\hat{A}$, we can see the estimation of mixed matrix very close to the mixed matrix, because of the feature of BSS, the sequence of column vectors in $\hat{A}$ are different from A. In terms of radar signals sorting, the difference of sequence between A and $\hat{A}$ can-not exert any influence, so the method based on detection of time-frequency single source point can solve the problem of underdetermined radar signal sorting under the situation of unknown the number of source signals. So the problem of radar signal sorting becomes a problem of estimate mixed matrix, in other word, the result of estimated mixed matrix is the key to radar signal sorting.

Experiment 1: explore the effect of different SNR.

Firstly, define the matrix estimation error to evaluate the result of estimation. The expression is

$$E_A = 10\lg(\frac{1}{N}\left\|A-\hat{A}\right\|_F) \tag{18}$$

Where $\hat{A}$ is estimated mixed matrix, $\| \ \|_F$ is F norm. The smaller of E_A value, the better of estimated result.

In the experiment 1, SNR changes from -10dB to 40dB, step is 5dB. Under each SNR taking 100 monte carlo analysis, the result shown in Fig.2.

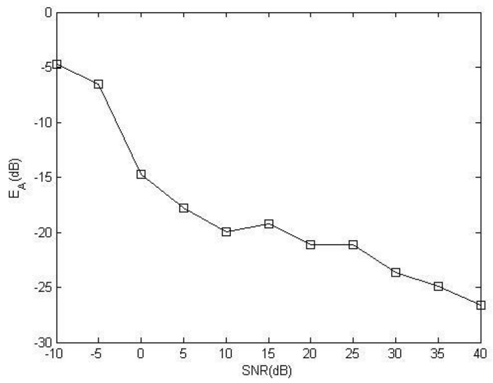

Figure 2. The Matrix Estimation Error under Different SNR

As can be seen in Fig.2, at low SNR, the estimation error in the high value, with the gradual improving SNR, error reduce gradually. Fig.2 shows the estimation error has been in a smaller value as a whole, and higher estimation accuracy of mixed matrix.

When SNR is -10dB, the estimation error is -5dB. In the actual situation of radar recommaissance, SNR always in low level, the method proposed in this paper has practical application value.

Experiment 2: prove the superiority of the method.

Contrast the estimatied results between proposed method, TIFROM algorithm and k-mean clustering method. In the experiment 1, SNR changes from -10dB to 20dB, step is 5dB. Under each SNR taking 100 monte carlo analysis, the result shown in Fig.3.

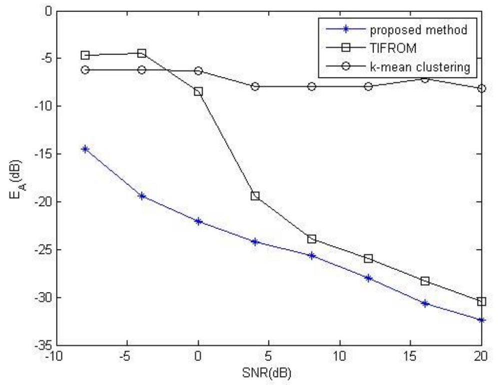

Figure 3. The Matrix Estimation Error of Different Method under Different SNR

In Fig.3, the matrix estimation error is the lowest than TIFROM method and k-mean clustering method. And the error of traditional k-mean clustering method has always been higher, it reflects that traditional k-mean clustering method is difficult to get ideal results without the number of clustering centers.

Experiment 3: explore the effect of different number of snapshots.

In the actual situation, there are two problem overwhelmingly: 1. SNR is low; 2. Lack of number of snapshots. In the condition of lacking number of snapshots, we can-not obtain enough data, so that signal sorting is really difficult. In order to explore the effect of snapshots number, in experiment 3, suppose SNR is 20dB, change number of snapshots from 500 to 10000, step is 1000, taking 100 monte carlo analysis each number, the result shown in Fig.4.

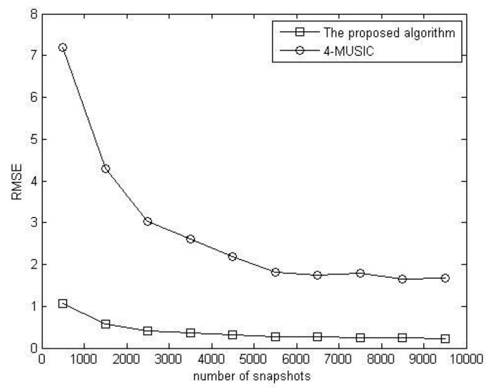

Figure 4. The Effect of Different Number of Snapshots

Contrast the result between proposed method and 4-MUSIC method, result shows that the estimation accuracy of proposed method has always been better than 4-MUSIC method in the condition of different number of snapshots. The proposed method has stronger adaptability.

6. Conclusions

In this paper, we have presented a method based on detection of single source point to solve the problem of radar signal sorting. Our method has obvious advantages, which can be summarized as following.

Firstly, compared with other methods, like TIFROM and k-mean slustering, our method exhibits better performance when SNR is low.

Secondly, compared with traditional signal sorting methods, like 4-MUSIC, the proposed method has a number of advantages, including increased resolution, improved robustness to noise, and stronger adaptability. It should be noted that the proposed method can sorting radar signals in condition of lacking number of snapshots, so that, our method has greater practical application value.

References

[1] S. Hong and A. H. Bin, "A Method to Select Radar Signal Based on Blind Source Separation", Modern Radar, vol. 23, no. 3, **(2006)**, pp. 47-50.
[2] X. W. Shu, Z. X. Gan and D. S. dan, "Blind Separation of Radar Signals", Journal of Nanjing University, vol. 42, no. 1, **(2006)**, pp. 38-43.
[3] Q. C. Zhou, H. T. Gao, F. Wang and S. Jie, "A Robust DOA Estimation Algorithm Under the Condition of Unknown Number of Signal Sources", Journal of South China University of Technology (Natural Science Edition), vol. 40, no. 6, **(2012)**, pp. 90-96.
[4] F. Wang and X. S. He, "Underdetermined Blind Separation Based on Ant Colony Clustering", Computer Engineering and Applications, vol. 49, no. 13, **(2013)**, pp. 211-215.
[5] M. K. Pakhira, S. Bandyopadhyay and U. Maulik, "Validity Index for Crisp and Fuzzy Clusters", Pattern Recognition, vol. 37, **(2004)**, pp. 487-501.
[6] S. Cotter, B. Rao and K. Engan, "Sparse Solutions to Linear Inverse Problems With Multiple Measurement Vectors", IEEE Transactions on Signal Processing, vol. 53, no. 7, **(2005)**, pp. 2477-2488.
[7] F. Wang and X. S. He, "Underdetermined Blind Sparation Based on Ant Colony Clustering", Computer Engineering and Applications, vol. 49, no. 13, **(2013)**, pp. 211-215.
[8] A. Cadzow, S. Kim and C. Shiue, "General Direction-of-Arrival Estimation: A Signal Subspace Approach", IEEE Transactions on Aerospace and Electronic Systems, vol. 25, no. 1, **(1989)**, pp. 31-47.
[9] L. De Lathauwer and J. Castaing, "Blind Identification of Underdetermined Mixtures by Simultaneous Matrix Diagonalization", IEEE Transactions on Signal Processing. vol. 56, no. 3, **(2008)**, pp. 1096-1105.
[10] B. H. Tan, M. Zhao and S. L. Xie, "Blind Separation Algorithms of BPSK Signals by Estimating Source Number", Journal of Electronics & Information Technology, vol. 31, no. 7, **(2009)**, pp. 1624-1629.
[11] H. Tang and S. Wang, "Parameters Estimation of DSSS Based on Denoising Source Separation", Systems Engineering and Electronics. vol. 33, no. 8, **(2011)**, pp. 1722-1726.
[12] S. Hosseini, C. Jutten and D. T. Pham, "Markovian Source Separation", IEEE Transactions on Signal Processing, vol. 51, no. 12, **(2003)**, pp. 3009-3019.
[13] K. Nordhausen, E. Ollila and H. Oja, "On the Performance Indices of ICA and Blind Source Separation", IEEE 12th International Workshop on Signal Processing Advances in Wireless Communications. **(2011)**, pp. 461-465.
[14] Y. J. Shen, G. M. Zhang and S. P. Yang, "New Method for Blind Source Separation in Under-Determined Mixtures Based on Gabor Transform", Journal of Vibration, Measurement & Diagnosis, vol. 31, no. 3, **(2011)**, pp. 309-313.
[15] R. J. Wang, Y. J. Han and H. F. Zhou, "Application of Articial Bee Colony Optimization Algorithm in Complex Blind Separation Source", Science China, vol. 44, no. 2, **(2014)**, pp. 199-220.
[16] H. Li and Y. L. Sun, "Under-Determined ICA Algorithm Based on Singular Value Decomposition", Computer Applications and Software, vol. 25, no. 2, **(2008)**, pp. 231-233.
[17] S. Z. Xu, Y. Su and Z. F. Ye, "Blind Source Separation in Underdetermined Mixtures", Journal of Data Acquisition & Processing, vol. 21, no. 2, **(2006)**, pp. 128-132.
[18] J. Y. Wu, W. J. Li, J. P. Huang, J. L. Zhang and D. R. Chen, "Key techniques for Mobile Internet: a survey, Scientia Sinica Informationis, vol. 45, no. 1, **(2015)**, pp. 45-69.

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