Estimation of Doppler Spectrum Modes in a Weather Radar for Detection of Hazardous Weather Conditions

Jong Gil Lee* ***Regular Members***

ABSTRACT

In a Doppler weather radar, high resolution windspeed profile measurements are needed to provide the reliable detection of hazardous weather conditions. For this purpose, the pulse pair method is generally considered to be the most efficient estimator. However, this estimator has some bias errors due to asymmetric spectra and may yield meaningless results in the case of a multimodal return spectrum. Although the poly-pulse pair method can reduce the bias errors of skewed weather spectra, the modes of spectrum may provide more reliable information than the statistical mean for the case of a multimodal or seriously skewed spectrum. Therefore, the idea of relatively simple mode estimator for a weather radar is developed in this paper. Performance simulations show promising results in the detection of hazardous weather conditions.

I. Introduction

One of the important potential applications of Doppler weather radar is in a windshear detection system. When the wind abruptly shifts its speed or direction, it can mean deadly difficulty for an airliner particularly at low altitude such as on approach or take-off[1]. This dangerous weather conditions are frequently caused by microbursts. Microbursts are sudden downdrafts of highly turbulent air[2] which appear as if they are designed to cause airline crashes. Since microbursts can occur within a very small geographical scale and the reflectivity of dry microbursts may be very weak, the weather surveillance radar for microburst detection, should have high sensitivity and high resolution of both range and Doppler frequency. For this purpose, the pulse pair algorithm is considered to be the most economical since it is simple to implement and fast enough to process huge amounts of data for real time mapping of the weather situation in an interested area. It is also shown in [3] that the performance of the pulse pair estimator is even better than that of the DFT (Discrete Fourier Transform) estimator at low SNR (signal-to-noise ratio) and narrower widths.

However, the pulse pair method[3] was derived and has been evaluated most often under the assumption that the weather spectrum is symmetric or relatively narrow. With the turbulent situations associated with windshear, these assumptions may not be valid. Some observed weather spectra show that nearly 25% are seriously skewed and can not be considered to be symmetric[4]. The poly-pulse pair method was originally suggested as a way of enhancing the accuracy of spectrum moment estimation, but this method may be also useful in reducing the bias errors of a skewed spectrum. A new modified pulse pair mean estimator is developed in [5] where it shows an improvement over a conventional method by reducing the bias errors of mean estimates.

In the symmetric spectrum, the mean and the mode are same. However, in the case of a skewed spectrum, it may be questionable that the mean is a more representative value than the

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* 인천대학교 정보통신공학과(jnglee@incheon.ac.kr)

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mode. Since the estimation of a few strong modes may be more meaningful for the case of a seriously skewed or multimodal spectrum, a modified Prony method[6] was applied to estimate peak points of weather return spectra. This method may not need any preliminary processing such as clutter filtering by locating strong peak points in the spectrum which may well represent the velocity spectrum modes of wind and clutter signals in each range cell. These peak values may be adequate to identify the hazardous weather conditions by showing the spatial gradient of wind velocity in an interested area. Using a simulation model, some validating results are shown

Ⅱ. Mode versus mean estimation in weather signals

The pulse pair estimator calculates the first two moments of the Doppler spectrum from estimates of the complex autocorrelation function at lag T_s , $\hat{R}(T_s)$[3]. Goodness of this estimator is typically determined by examination of the bias and the variance of the moment estimates. To analyze the bias in the pulse pair estimates, consider the process autocorrelation function $R(T_s)$ expressed in terms of the true mean Doppler frequency f_d , i.e.,

$$R(T_s) = e^{j2\pi f_d T_s} \int_{\frac{-1}{2T_s}}^{\frac{1}{2T_s}} S'(f)\, e^{j2\pi f T_s} df \tag{1}$$

where $S'(f)$ is the zero-mean representation of the weather Doppler spectrum. Unbiasedness of pulse pair estimates is based on the assumption that a spectrum is symmetric or so narrow that the imaginary part of the integral in (1) can be considered as zero. However, the weather return Doppler spectrum is often broad and not symmetric thus causing a bias. This bias effect is analyzed in [5] using a skewed Gaussian spectrum model with various spectrum widths. Since the pulse pair mean estimator bias is sensitive to skew, an alternative may be desirable. Therefore the poly-pulse pair method is suggested as a possible way of minimizing such errors.

In the pulse Doppler radar signal processor, when estimating the "average" windspeed in a given range cell, there may be a question as to whether "average" should be the statistical mean or the statistical mode (most probable value). The pulse pair algorithm will estimate the statistical mean. The quality of estimates for the statistical mean can be improved using the poly-pulse pair method as shown in [5] by reducing bias errors.

In the symmetric case the mean and the mode are the same. However, with skewness in the spectrum this is not true as seen in [5] which shows that these two values can differ very largely due to the increased skewness and spectrum width. Therefore, the pulse pair mean estimate tends not to be a good mode estimator for broad spectra. The idea of a mode estimator is developed in this paper. A new approach of characterizing a summary statistic of windspeed within a range cell is presented using a classical harmonic decomposition technique. This indicates potential for overcoming the biased mean estimation problem with a skewed spectrum.

The aviational hazard often caused by microbursts can frequently be identified from a Doppler radar return by an S curve characteristic which describes mean windspeed changes along the radar range radial. The mean value of the weather return spectrum is generally considered as representing the windspeed in each range cell. However, in the skewed spectrum case or with the multimodal return spectrum, the modes of spectrum may provide more reliable information than the statistical mean for the purpose of windshear detection. Therefore, the mode estimation technique using the modified Prony method is presented here. Also this mode estimator may be useful in recognizing the weather hazard without the need for clutter rejection filtering. It is particulary attractive since efficient clutter suppression may not be an easy task though several methods have proven to be useful[7]. It has been shown that efficient clutter suppression can be done using an autoregressive least squares (AR-LSQ) method, but mean estimates from clutter-only range cells often fluctuate randomly because there remain only weak background noise signals after filtration. This can also occur when the weather return spectrum falls largely within the clutter filter notch and is mostly removed with clutter rejection processing. Another problem is that radar system phase noise may limit the clutter rejection capability yielding a too low signal-to-clutter ratio in the filtered spectrum thus causing an inaccurate estimation of the mean velocity.

Ⅲ. Spectrum modes estimation by modified Prony method

An alternate approach to identifying the presence of a weather return is to locate strong peak points in the spectrum which may well represent the velocity spectrum modes of wind and clutter signals in each range cell. These peak values may be adequate to identify the microburst S curve signature and detect a hazardous windshear conditions. It does not require processing to estimate the entire spectrum but only involves finding a few peak points of the spectrum. The modified Prony method is investigated here to find strong peak points of simulated weather spectra that include microburst and static clutter signals. The modified Prony method involves approximating a complex data sequence by a model consisting of undamped complex sinusoids. It is similar to Pisarenko Harmonic Decomposition (PHD) method, but the Prony algorithm is generally better than PHD procedure since it needs neither autocorrelation lags nor a more computationally complex eigen equation solution[6][8]. The Prony method requires only the solution of two sets of simultaneous linear equations and a polynomial rooting. It is summarized briefly in the following:

1. Find the coefficients of a complex polynomial minimizing the squared smoothing error.
2. Root a complex polynomial to determine frequencies.
3. Solve for the amplitude of each frequency.

The 2p component Prony model is represented as

$$\hat{x}[n] = \sum_{k=1}^{2p} h_k Z_k^{n-1} \tag{2}$$

where $h_k=A_k\exp(jq_k)$ and $Z_k=\exp(j2\pi f_kT)$. The polynomial constructed with roots that are the Z_k of Equation (2) has the form

$$\Phi(Z) = \prod_{k=1}^{2p}(Z - Z_k) = \sum_{k=0}^{2p} a[k]\, Z^{2p-k} \tag{3}$$

where a[0]=1 by definition. Due to the unit modulus property $Z_{k-1}=Z_k^*$, it can be shown that the conjugate property a[k]=a[2p]a*[2p-k] for k=0 to k=2p must exist between the coefficients. Therefore, the homogeneous linear difference equation that has Equation (2) as its solution is

$$\begin{aligned} a[2p]x[n-p] + \sum_{k=1}^{p}(a[2p-k]x[n-p+k] \\ + a[2p]a[k]x[n-p+k]) = 0 \end{aligned} \tag{4}$$

for 2p+1=n=N, where N is the number of given data points. A more convenient form of (4) can be obtained which yields the conjugate symmetric difference equation

$$\begin{aligned} x[n-p] + \sum_{k=1}^{p}(g_{2p}[k]x[n-p+k] \\ + g_{2p}^{*}[k]x[n-p-k]) = 0 \end{aligned} \tag{5}$$

where $g_{2p}[k]=a[2p-k]/a[2p]$ and $g_{2p}^*=a[k]$. Since N usually exceeds the minimum number needed to fit a model of 2p, i.e., N=2p+1, the squared smoothing error given by

$$\rho_{2p} = \sum_{n=p+1}^{N-p} | e_{2p}(n)|^2 \tag{6}$$

is minimized based on the measured complex data samples where

$$e_{2p}(n)=x[n]+\sum_{k=1}^{p}\left(g_{2p}[k]x[n+k]+g_{2p}^{*}[k]x[n-k]\right) \tag{7}$$

Setting the complex derivatives of ρ_{2p} with respect to $g_{2p}[1]$ through $g_{2p}[p]$ to zero yields

$$\boldsymbol{R}_{2p}\ \boldsymbol{g}_{2p}=\begin{bmatrix}\mathbf{0}_p\\ 2\rho_{2p}\\ \mathbf{0}_p\end{bmatrix} \tag{8}$$

where

$$\boldsymbol{g}_{2p}^{T}=[\,g_{2p}[p],\cdots,g_{2p}[1],1,g_{2p}^{*}[1],\cdots,g_{2p}^{*}[p]\,] \tag{9}$$

and $\mathbf{0}_p$ is a p×1 all zero vector. $\mathbf{R}_{2p}$ can be expressed as

$$\boldsymbol{R}_{2p}=\sum_{n=2p+1}^{M}[\,\boldsymbol{x}_{2p}^{*}[n]\,\boldsymbol{x}_{2p}^{T}[n]+\boldsymbol{J}\,\boldsymbol{x}_{2p}[n]\,\boldsymbol{x}_{2p}^{H}[n]\boldsymbol{J}\,] \tag{10}$$

where **J** is a (2p+1)×(2p+1) reflection matrix and **H** means complex conjugate transposition. Here $x_{2p}[n]$ is defined as

$$\boldsymbol{x}_{2p}^{T}[n]=[x[n],\cdots,x[n-p+1],x[n-p],x[n-p-1],\cdots,x[n-2p]] \tag{11}$$

The fast algorithm to solve the symmetric covariance normal Equation (4) was developed by Marple[6].

After solving for a[1] through a[2p], the roots of the complex polynomial, Z_k, can be obtained using the polynomial factoring algorithm. Then, hk in Equation (2) is computed minimizing the squared error with respect to each of the h_k parameters, i.e.,

$$\boldsymbol{h}=[\,Z^{H}Z]^{-1}\,Z^{H}\boldsymbol{x} \tag{12}$$

where

$$Z=\begin{bmatrix}1 & 1 & \cdots & 1\\ z_1 & z_2 & \cdots & z_{2p}\\ \cdot & \cdot & \cdots & \cdot\\ z_1^{N-1} & z_2^{N-1} & \cdots & z_{2p}^{N-1}\end{bmatrix},\ \boldsymbol{h}=\begin{bmatrix}h_1\\ h_2\\ \cdot\\ h_{2p}\end{bmatrix}$$

Ⅳ. Performance and computational complexity

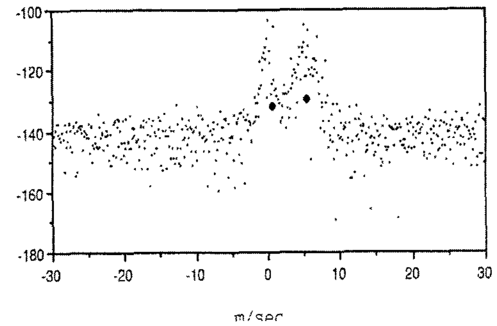
A second order Prony model was used here to find peak points of simulated weather spectra. A 512 point complex data sequence from each range cell was processed. Some typical FFT spectrum plots are shown in Figures 1 through 4 with the Prony method peak estimates also indicated. As seen in Figures 1, 2 and 3, the Prony method is able to locate spectrum peak points. However, Figure 4 shows somewhat inaccurately estimated peak points because of strong clutter power and the closeness of weather and clutter spectral peaks.

In order to check the usefulness of this new approach for detection of windshear, data from all 40 range cells including a dry microburst and clutter were processed and peak velocity points were plotted versus range. The resulting Fig. 5 clearly shows the S curve characteristic around the range cell 27.

Another important consideration is computational complexity which must not prohibit real time processing. Of course, the Prony method is computationally much more complicated than other classical spectrum estimation techniques as the model order increases, but as it can be seen from Table 1, the second order Prony model used here requires less computation than the FFT method. Therefore, the modified Prony method shows some promise as a component of a windshear detection algorithm.

Table 1. Comparison of computational complexity where N=512(f(p): the required number of computations for a polynomial rooting)

Method	Computation requirement	Approximate number
FFT	$N\log_2 N$	4700 adds/mults
AR-LSQ	$2NP+P^2$	10500 adds/mults
Prony	$2NP+18P^2+P^3+f(P)$	2300 adds/mults(P=2)



• : FFT spectrum, ◆ : Prony method

Fig. 1. Mode estimates shown in the simulated weather spectrum of range cell 24

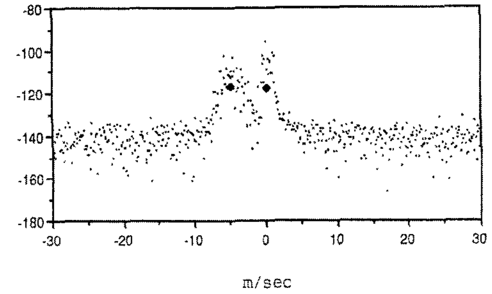


Fig. 2. Mode estimates shown in the simulated weather spectrum of range cell 29

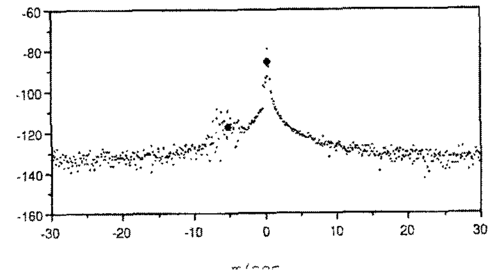


Fig. 3. Mode estimates in range cell 30

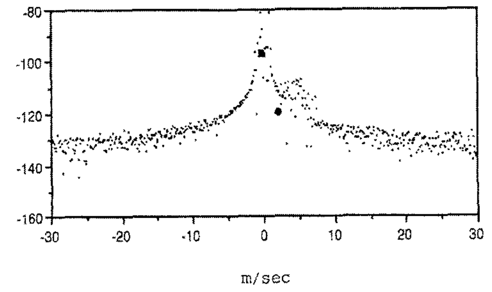
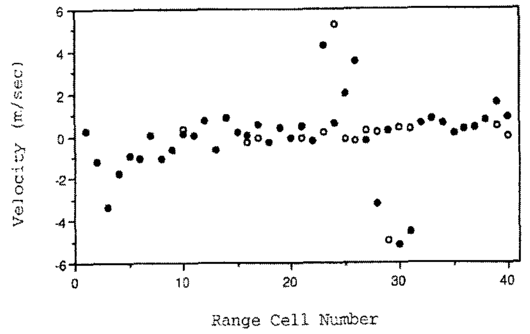


Fig. 4. Mode estimates in range cell 25

Also as shown in Figure 4, where clutter and weather spectrum modes are very close together, identification of a weather return is an inherently difficult problem to solve. In these situations, the Prony method appears of limited use. Other more computationally complicated methods such as the PHD may be necessary.



○: a stronger mode ●: a weaker mode

Fig. 5. Estimated spectrum modes of simulated weather data in all range cells

V. Conclusion

A new approach explained in this paper shows that detection of hazardous weather conditions such as windshear may be possible using a pattern recognition type technique by finding an "S" curve characteristic demonstrated here using the modified Prony method. From the results, it can be said that the very low order Prony model may make it possible to detect the hazardous weather condition without any other preliminary processing. However, this new approach also has the limitation that some valuable weather information such as spectrum width can not be obtained without additional processing. Future works may include a performance evaluation considering detection and false alarm rates by applying this newly suggested method to the experimental data to be obtained from the various field tests..

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이 종 길(Jong Gil Lee) 정회원

1982년 2월: 연세대학교 전자공학과 (공학사)

1985년 1월: 미국 Case Western Reserve University, Electrical Eng. (M.S.)

1990년 5월: 미국 Clemson University, Electrical Eng. (Ph.D.)

1991년 1월~1993년 2월: 삼성전자 특수연구소

1993년 3월~현재: 인천대학교 정보통신공학과 부교수

<주관심 분야>무선통신, 레이다신호처리, 통신시스템, 스펙트럼분석