An Efficient Method to Obtain Wind Speed Gradient with Low PRF Radar

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ABSTRACT

The measurement of wind speed gradient is very important for the detection of hazardous wind shear conditions since they are characterized by the abrupt shift of wind velocity and direction. These weather conditions usually imply high wind speed which requires a high PRF radar for the measurement. However, the measurement of a large absolute wind velocity is not necessary to obtain wind speed gradient. In this paper, a method was proposed to obtain wind speed gradient with a simple low PRF radar which may be very useful for the purpose of practical applications.

요 약

풍속 및 바람 방향의 급격한 변화에 의한 기상위험 현상을 탐지하기 위해서는 공간상에서 풍속의 변화정도를 측정하는 것이 매우 중요하다. 이러한 기상현상들에서 전형적으로 내재된 높은 풍속의 측정을 위해서는 높은 PRF를 갖는 레이다를 필요로 한다. 그러나 공간상의 풍속의 변화정도를 예측하는데 있어서 이러한 큰 풍속의 절대적인 측정값이 꼭 필요한 것은 아니다. 따라서 본 논문에서는 실제적인 측면에서 매우 유용한 낮은 PRF를 갖는 레이다를 이용하여 풍속의 공간 변화율을 얻는 방법을 제안하였다.

키워드

wind shear, wind speed gradient, hazardous weather detection

I. Introduction

A satisfactory airborne radar sensor for the detection of wind shear must possess good ranging capability, both in terms of maximum useable range and range resolution[1]. Otherwise the look ahead range will be too short to provide adequate lead time warning of a wind shear condition or a hazardous wind shear[2] will not be resolved. This suggests a low to medium PRF radar. On the other hand, a capability for unambiguously measuring large Doppler frequencies associated with high wind speed conditions would normally require a higher PRF radar. With adequate range resolution capability, one approach to estimating the change in wind speed throughout a region is to use the difference in mean Doppler from

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range cell to range cell as a first order estimate of the spatial wind velocity gradient. With this approach, it may not be necessary to estimate large absolute wind speeds in any particular range cell, but only the difference in average wind speeds between range cells, i.e., the wind speed gradient. The magnitude of the wind speed gradient determined from adjacent range cells should be substantially less than the absolute mean wind speed in any given range cell, even for high turbulence environments. Thus, it appears that it may be possible to relax the PRF requirement for large unambiguous Doppler measurement, allowing a lower PRF to be used to measure the wind speed gradient. This would inherently allow good ranging capability without compromising the value of the system for detecting wind shear. This paper develops this premise by illustrating the effect of measuring Doppler difference frequency with a reduced PRF. Simulated I and Q data are used to investigate the validity of this method. It is anticipated that many hazardous wind shear conditions can be detected with a reduced PRF if this method is indeed proved to be valid. Relatively simple modification of the signal processing associated with conventional weather radar operating at reduced PRF could enable implementation of the suggested method.

II. Aliasing Effect

With a given PRF, unambiguous Doppler measurement is possible within a ±0.5 PRF range of frequencies. In meteorological measurements where a much wider range of Doppler return frequencies is likely when high wind speed conditions exist, the radar return Doppler which exceeds the PRF/2 magnitude is aliased as a lower frequency. Thus, for highly turbulent conditions where the spread of Doppler frequencies is very high and significant aliasing can take place, the ratio of the peak magnitude of the return at the "mean" Doppler frequency to the level of the return at other frequencies may be significantly degraded by aliasing. Obviously, reducing the PRF would further degrade this "signal-to-noise" ratio and may reduce the ability to locate the peak magnitude of the estimated spectrum of the return. Of course a reduced PRF directly reduces the signal-to-noise ratio in a given range cell simply because for a fixed observation time the number of signal returns is reduced.

Of perhaps even more significance is the effect of aliasing on the measurement of spectral width of the Doppler return. If the reduced PRF Nyquist interval is inadequate to unambiguously represent the breadth of Doppler frequencies present, there can be no way of estimating this width. Coupled with a reduced signal-to-noise ratio, the ability to detect turbulent wind speed conditions within a range cell with reduced PRF radar appears futile. However, the utility of low PRF in measuring large scale wind speed gradients between range cells may not be so limited. To evaluate the effect of aliasing, two different scenarios will be examined. In each situation an assumed return with a postulated spectrum will be represented as an I/Q data sequence. This sequence will be examined with DFT processing at a rate associated with a high PRF weather radar processor. The sequence will then be decimated and reprocessed at a rate which would correspond to a reduced PRF. The decimation process not only reduces the number of data samples, but also produces the same data that would have been obtained had a reduced PRF radar been employed.

The first situation includes analysis of a pure complex sinusoid with no added noise. The complex sinusoid represents a specular signal with a one-sided bandwidth. Aliasing with a sinusoid signal does not affect the signal-to-noise ratio but only the frequency estimate of the sinusoid itself. The second situation examined involves an analysis of a simulated weather signal which has a Gaussian frequency spectrum typical of weather returns. This particular type signal is degraded by aliasing quite dramatically when considering the reduced PRF system. However, a useful range of mean Doppler difference can be preserved within the available sampling bandwidth.

III. Analysis of a Pure Sinusoid

Consider a situation corresponding to a noiseless specular pulse Doppler radar return present in two adjacent range cells. Fourier analysis of a record of sampled values will yield a spectral estimate which is corrupted by spectral leakage associated with the limited observation record and aliasing associated with the limited sampling rate[3]. In the radar situation the data record is limited by the observation time within a range cell and the sampling rate is just the PRF. Using the complex Discrete Fourier Transform (DFT), two complex sinusoids with a difference frequency less than the unambiguous processing frequency range (Nyquist bandwidth) have been analyzed. Using a sampling frequency (PRF) of 250 Hz, Figure 1 illustrates the difference in the magnitude of a DFT processed sinusoid at 500 Hz which aliased to 0 Hz and a 45 Hz sinusoid which aliased to -75 Hz.

Even though both of these signals are under-sampled and the original frequencies are not preserved, the difference frequency between the two sinusoids is clearly evident.

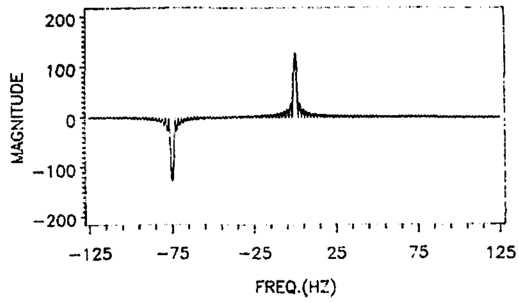

Fig. 1 The frequency difference of aliased complex sinusoids between 500Hz and 425Hz

Theoretically, the aliasing effect on a pure sinusoid does not deteriorate the signal-to-noise ratio. It only relocates the peak and prevents unambiguous identification of the actual frequency. However, with spectral leakage associated with the DFT, there is some deterioration of signal-to-noise ratio in the sense that the leakage power is aliased within the processing bandwidth, resulting in a reduced peak to leakage power ratio. This leakage power is effectively cancelled out in the difference processing associated with Figure 1. As a result, any frequency difference which is less in magnitude than one-half the PRF is preserved and can be detected and estimated as the frequency difference between the positive peak and the negative peak.

Based upon this analysis it appears that if the radar return from adjacent range cells is specular the Doppler difference is preserved and easily recognized even though an absolute Doppler measurement is lost through aliasing. Of course, these signals are not representative of weather radar returns in turbulent wind environments. These signals have been used simply to illustrate the concept. The next section begins a discussion of this approach using more representative Doppler spectra.

Ⅳ. Analysis of a Simulated Weather Signal

1. Power Spectrum Simulation and Generation of I and Q data

A Gaussian power spectrum can be represented by

$$G_k = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[\frac{-(f_k - f_m)^2}{2\sigma^2}\right] \qquad (1)$$

G_k is a spectral coefficient corresponding to f_k ; f_m and σ are the desired mean frequency and standard deviation respectively. The frequency dependent signal power density can now be defined as $S_k = C \cdot G_k$ where C is a signal-to-noise power scaling constant given by

$$C = \frac{10^{SNR/10}}{\sum_k G_k} \qquad (2)$$

where SNR is the signal-to-noise ratio in dB. Defining the receiver's white noise power per discrete frequency, N_k , as the reciprocal of the number of spectral coefficients, i.e.($N_k = 1$) , the power spectrum can be given by

$$P_k = -\ln(X_k) \cdot (S_k + N_k) \qquad (3)$$

where X_k is a uniformly distributed random variable over the interval (0, 1). For this simulation, normalization is performed in the frequency domain with $P_{kn} = P_k / P_t$. In order to transform the power spectrum into the time domain, the real and imaginary components of spectrum were obtained from

$$A_k = P_{kn}\cos(2\pi y_k) \ , \ B_k = P_{kn}\cos(2\pi y_k) \qquad (4)$$

where y_k is uniformly distributed random variable over the interval(0, 1). From these, we can obtain the in-phase and quadrature components through

$$I(i) + jQ(i) = \sum_{k=1}^{m} (A_k + jB_k)\exp(j2\pi ki/m) \qquad (5)$$

where m should be larger than 30 to avoid any aliasing in the time domain[4].

In this particular spectral model the peak of the spectrum represents the strongest Doppler return from within the range cell and is interpreted as the mean wind speed within that cell. The variance of the Doppler spectrum is a measure of the distribution of wind speeds within the cell and will be larger in the presence of turbulence. A less turbulent condition would have a spectrum which is more peaked and which more closely resembles the specular situation discussed in the previous section.

The investigation here is concerned with the ability to measure the difference between spectral peaks when these modeled spectra are subjected to aliasing and differenced. The next subsection analyzes this further.

2. Typical Weather Radar Signals

A data record consisting of 1024 sample points of a representative power spectrum were simulated and I, Q data were obtained from that power spectrum. The simulated signals are assumed to be obtained with a high PRF radar without any serious signal aliasing problems. To analyze the effect of low PRF, one fourth of he simulated signal data were taken (which means one fourth of the original PRF) and processed using the DFT in the same way as the complex sinusoids in Figure 1. Figure 2 is a processed simulated typical weather radar return signal corresponding to a PRF of 2000

Hz and Figures 3 is an aliased versions of this type signal as might be obtained with a low PRF of 500 Hz. Spectrum magnitude differences are plotted in Figure 4 with a Nyquist interval associated with the reduced PRF. In this case the aliased spectral peaks are evident in the difference with the background level between peaks effectively cancelled. The original difference between spectral mean values is preserved and can be observed as the frequency difference between the maximum peak magnitude and the minimum peak magnitude on this plot. This example is intended to represent the computed difference in the spectral estimate of one range cell and that of an adjacent range cell. It appears that the detection of mean wind speed changes between adjoining range cells through low PRF radar is quite possible though signal peaks are not as well defined as in the case of noiseless signals.

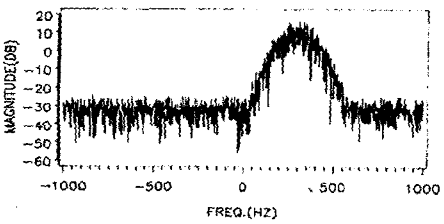

Fig. 2 The DFT result of simulated weather radar signal (mean frq.=+300Hz, S/N=30dB, sigma=0.0652*300, PRF=2000Hz)

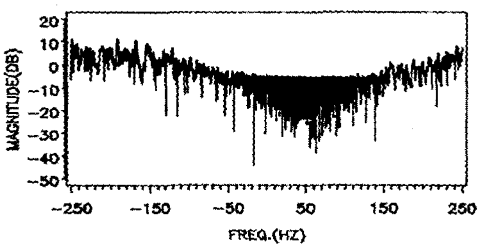

Fig. 3 The aliased DFT result of simulated weather radar signal due to low PRF (mean freq.=+300Hz, PRF=500Hz)

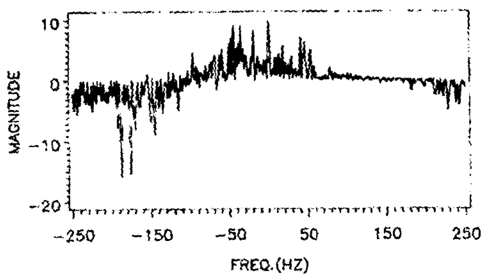

Fig. 4 The frequency difference of aliased weather signals between 475Hz and 300Hz

V. Concluding Remarks

Based upon this analysis it can be readily seen that reduced PRF introduces aliasing and the peak to background ratio (SNR) will decrease accordingly, thus circumventing the accurate estimation of mean frequency and spectrum width. Comparison of Figures 2 and 3 shows that the simulated weather signal of a low PRF radar is more contaminated with the background noise due to aliasing of high frequency components.

In spite of this aliasing problem, it appears that the mean frequency difference between aliased spectra can be preserved and detected because the peak location of the Gaussian spectrum is changed in a predictable way and the broader band incoherent background power level tends to cancel out. It can be noted that a difference in mean frequency larger than PRF/2 causes ambiguities. This demonstration suggests that the DFT magnitude difference of low PRF radar signals between range cells can overcome the difficulties of decreased SNR by aliasing and present the velocity gradient rather clearly.

In evaluating the utility of pulse Doppler weather radar for detection of wind shear from an airborne platform the motivation for low PRF was stated earlier as a desire for large unambiguous range capability. Even though the analysis presented here tends to support the premise that wind speed gradient can be estimated within the Nyquist bandwidth associated with low PRF, other problems may be predominant. Turbulent wind conditions within a range resolution cell can cause a radar return which has a quite broad spectrum with a very small mode.

Another consideration with low PRF radar is that the total magnitude of the return may be small in a turbulent situation and any reduction in return signal level because of a limited number of returns in a processing interval will cause the signal-to-noise ratio to be much too low for any practical use. Finally, a problem with the use of radar on an airborne platform in the neighborhood of urban airports is the clutter environment. High clutter levels may create a signal to clutter level ratio which precludes the use of a low PRF. Therefore, even though the analysis presented in this paper supports the idea that a reduced Nyquist interval may be adequate for estimating wind speed gradients associated with wind shear, it should not be concluded that simply reducing the weather radar PRF is the best means of improving the ranging capability of a weather radar.

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