8.5A DATA ANALYSIS TECHNIQUES: SPECTRAL PROCESSING

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Most radars used for wind sounding use a data-processing scheme similar to that illustrated in Figure 1. The processing method shown uses spectral analysis and assumes a pulse Doppler radar. Radial profiles of the first three moments of the Doppler spectra are estimated: signal power P, mean radial velocity V_r, and spectrum width W. The input signal is the backscattered signal for each radar resolution cell after translation to a convenient frequency. The receiver limits the bandwidth with a filter that is (usually) matched to the transmitted pulse. Complex video is obtained by baseband mixing with a reference voltage. Samples of video are generated for each pulse repetition period T and for each range resolution cell centered along the antenna axis; these voltage samples represent the composite amplitude and phase of the scattering process in the resolution volume. The averaging that occurs in each step of the data processing is examined in this paper.

The signal-to-noise ratio SNR can be improved for some radars by summing the complex video samples from a number J of consecutive received pulses. Since the noise bandwidth is determined by the radar pulse width, noise samples taken at the pulse repetition period will be uncorrelated; therefore the noise power increases linearly with the number of samples added. The signal. however, remains well correlated for approximately 0.2 λ/W seconds (NATHANSON, 1969) where λ is the radar wavelength. Typically W is about 1 m/s, so the correlation time is milliseconds with microwave radars and seconds with VHF radars. If, in addition to being correlated, the phase of the signal samples changes very little between samples, then signal samples can be added so that signal power increases with the square of the number of samples added. This occurs for radars whose unambiguous velocity $\lambda/(4T)$ is much greater than the radial velocity of the scatterers. The SNR improves by the number J of samples averaged, and the unambiguous velocity will decrease to $\lambda/(4JT)$. Two points should be noted. (1) It is not necessary to use time domain averaging to improve detection. The SNR improvement can be obtained in later processing, but time domain averaging minimizes the calculation burden in succeeding processing stages without sacrificing sensitivity. (2) Time domain averaging filters the input signal so that signal components with velocity greater than $\lambda/(4JT)$ will be aliased and may be greatly attenuated (SCHMIDT et al., 1979). Without time domain averaging when signal components are aliased they are not attenuated. We select J as large as possible such that $\lambda/(4JT)$ is greater than the maximum expected mean radial velocity and such that the signal is correlated for much longer than JT.

The next step in signal processing is to compute the power spectrum of K (averaged) signal samples. K is selected such that the available coherent integration is realized. If K is too small, sensitivity is reduced; if K is too large, the calculation burden is increased without improving sensitivity or retrieving additional information. Figure 2 shows how the SNR in the spectral domain improves as dwell time T_D = JKT increases. The improvement factor is given by

$$K \left[\text{erf} \frac{\Delta V}{2\sqrt{2}W} \right]$$

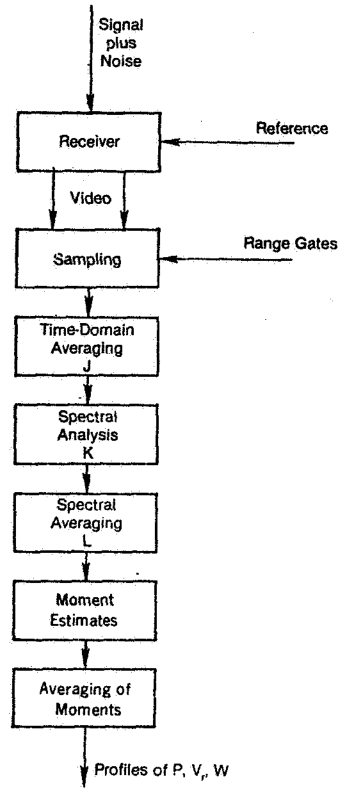

Figure 1. Data processing sequence. Spectral processing for a pulse Doppler radar is illustrated.

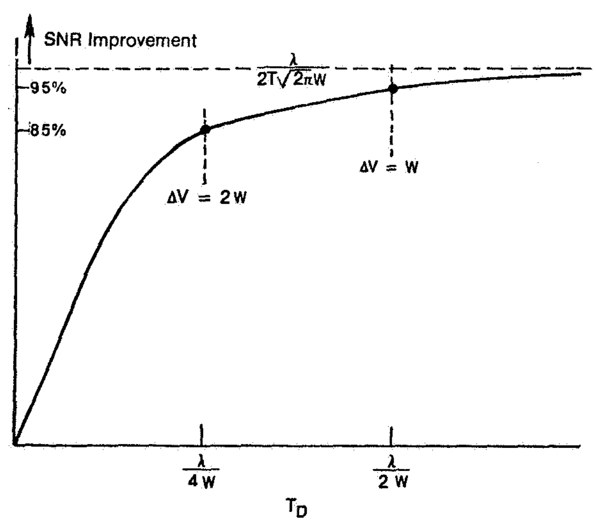

Figure 2. Signal-to-noise ratio improvement by spectral processing. The limiting value is $\lambda/(2T\sqrt{2\pi}\,W)$. Dwell times longer than $\lambda/2W$ improve spectral resolution but yield little SNR improvement.

where ΔV is the velocity resolution of the spectral processor $\lambda/(2T_D)$. For small K the improvement factor increases linearly with K; spectral resolution is so poor that all the signal power remains in one velocity resolution element. As observation time increases, the noise power in each velocity resolution element decreases, while signal power remains constant. When the dwell time is increased such that signal power starts to occupy more than one spectral point, SNR improvement no longer increases linearly with dwell time. When the dwell time is $\lambda/(2W)$ or $K = \lambda/(2JTW)$, 95% of the available coherent integration is achieved. Longer dwell times yield little SNR improvement because both noise power and signal power decrease in the velocity resolution element that contains maximum signal. Note, however, that for large K, spectral points can be averaged and the spectrum will still be resolved. If this is done, SNR improves as $T_D^{1/2}$ as expected for incoherent integration. Thus, to minimize calculations we choose $K = \lambda/(2JTW)$ and use any additional observation time to measure new spectra.

The next processing step is the averaging of L spectra, each obtained from JK radar pulses. The L power estimates for each frequency or velocity will be exponentially distributed with a standard deviation equal to the mean (HILDEBRAND and SEKHON, 1974). We expect averaging to improve the spectral domain SNR by $\sqrt{L}$; however, this improvement will occur only if the mean wind is the same for each dwell time. If the mean wind is not the same, then the width of the averaged spectrum increases during the averaging and the SNR improvement will be less than $\sqrt{L}$. It is readily seen that if the mean wind changes abruptly by more than W, then the SNR can actually decrease with averaging time. The dependence of spectral width on averaging time can be deduced by examining the dependence of spectral width on averaging distance as studied by FRISCH and CLIFFORD (1974) and LABITT (1981). They derive the relationship $W \propto d^{1/3}$ where d is the maximum dimension of the observation volume (beamwidth or range resolution, whichever is greater) and d is less than the outer scale of turbulence L_o. If we average for time T_o such that $d < \overline{v}\, T_o < L_o$, then, using Taylor's hypothesis, $W \propto (\overline{v}\, T_o)^{1/3}$ where $\overline{v}$ is the mean wind speed. Therefore, if the averaging time is less than $d/\overline{v}$, then the width of the averaged spectrum is about the same as the width of the individual spectra; for greater averaging time, the width of the averaged spectrum increases as $T_o^{1/3}$. To take full advantage of $\sqrt{L}$ improvement in SNR by averaging spectra, L should be limited to about $d/(JKT\overline{v})$.

The next data-processing step is the estimation of the important spectral moments from the averaged Doppler velocity spectrum. The signal spectrum must be isolated from the measured signal-plus-noise spectrum before the moments can be found. The methods used to do this (and to remove undesired spectral components such as ground clutter near zero velocity) are usually empirical. The average value of the complex time series is usually removed prior to calculating the power spectrum. Noise rejection is accomplished by applying a threshold, either a specified amount above the mean noise level or below the peak level. Another method to locate the signal is to find the maximum power in a velocity window of width equal to the expected signal width. The method used with the 6-m radar at Platteville, Colorado (the Platteville radar is operated cooperatively by NOAA's Aeronomy Laboratory and Wave Propagation Laboratory) is as follows (CARTER, 1982). The mean value of the complex time series is removed prior to calculating the individual power spectra. This filtering is sufficient to remove any clutter. The noise spectra are white (except when interfering transmission is detected), and the mean noise level is found by applying an objective technique (HILDEBRAND and SEKHON, 1974) for each spectrum. A fixed noise level cannot be assumed because the noise is governed by cosmic background. The signal spectrum is isolated by locating the peak value of the averaged spectrum and including all those contiguous spectral points that exceed the noise level. The classic definition of the moments is then applied to the isolated signal spectrum after subtracting the mean noise level from each of the selected spectral points. In very weak signals, or if the input consists of noise only, the algorithm selects the peak and one or two additional spectral points; it therefore becomes a maximum-likelihood estimator of the mean velocity (WHALEN, 1971). It is an unbiased estimator of the mean (in noise it selects a random value between $(\pm\lambda/(4JT))$ for the mean velocity). Since it selects that portion of the noise in the isolated spectral points that exceeds the mean noise as "signal", both power and width estimates are slightly biased by the noise. This method appears to work well for a wide variety of conditions.

Finally, estimates of spectral moments can be averaged. The averaging time depends on the type of information sought and the temporal evolution of the scattering phenomena. For example, the Platteville radar is used primarily to obtain hourly estimates of tropospheric winds; during an hour M radial profiles of mean velocity are measured. At the upper heights the mean velocities are random because of low SNR. Some of the profiles are also contaminated by interference from other transmitters or by scattering from aircraft. The profiles are averaged by applying a simple version of Random Sample Consensus (FISCHLER and BOLLES, 1981). The set of M data points at each measurement height are examined to find the largest subset of points within X m/s of each other. If the subset includes fewer than Y data points, the data are rejected for that height; otherwise the subset is averaged to obtain the mean radial wind. This algorithm rejects data when the SNR is too low and also rejects random points caused by interference. In practice X is 1 m/s (where the maximum radial velocity is $\pm$19 m/s), and the smallest subset allowed is 4 of 12 measurement points.

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