Remote Sensing of Turbulence:
Radar Activities

FY02 Year-End Report

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Introduction

In FY02, NCAR was given Technical Direction by the FAA’s Aviation Weather Research Program Office to perform research related to the detection of atmospheric turbulence by remote sensing devices. Specifically, the research summarized in this report has been focused on developing an improved turbulence detection algorithm for the WSR-88D radar network.

In previous years’ reports, radar data from two NEXRAD-like radars, the Mile High radar and CSU’s CHILL radar, have been analyzed along with in-situ aircraft turbulence measurements. While these analyses have been useful for algorithm development and for demonstrating the feasibility of accurate radar detection of turbulence, some special attributes and idiosyncrasies of the WSR-88D radar that affect performance could not be accounted for. Beginning in FY01, radar data from the Goodland, Kansas WSR-88D (KGLD) collected during the STEPS-2000 field experiment has been used for development and verification of NCAR’s improved turbulence algorithm. Several flights the South Dakota School of Mines and Technology T-28 aircraft penetrated thunderstorms during STEPS-2000 and provided in-situ data. In particular, the time series of vertical acceleration data from the aircraft have been used along with other flight variables to ascertain eddy dissipation rate (EDR), an aircraft-independent quantity, for comparison with the radar turbulence algorithm output. Last year’s report included a qualitative analysis of the STEPS-2000 radar and aircraft data, showing via overlay plots a convincing correlation between radar-measured second moment and aircraft-measured EDR. The current report continues that analysis by presenting quantitative comparisons of co-located radar and aircraft turbulence values.

Quality control of the WSR-88D spectrum width data continues to be a focus of the algorithm development efforts. Spectrum width is the primary turbulence indicator used by NCAR’s improved turbulence algorithm, and so is directly related to the quality of the output. Unfortunately, several problems affect the quality of spectrum widths provided by NEXRAD radars. For this reason, NSSL has joined NCAR in investigating spectrum width quality control issues, providing useful technical information and analyses of WSR-88D data.
Quality Control of WSR-88D Spectrum Width Data

NCAR’s improved WSR-88D turbulence detection algorithm makes use of all three Level-2 data fields: reflectivity, radial velocity and spectrum width. In the past, NEXRAD data has been used primarily for applications that require only reflectivity and radial velocity fields, so most quality-improvement efforts have been focused on these quantities. In the meantime, very little attention has been given to the quality of the spectrum width measurements. Because higher moments are generally more difficult to measure accurately, the spectrum width data is more susceptible to errors than are the reflectivity and radial velocity data.

During the analysis of the STEPS-2000 data, a variety of data quality problems with the spectrum widths have become apparent. When this became apparent, NCAR contacted the NSSL and OSF for help in investigating these problems and ways to mitigate them. As outlined in last year’s report, several sources of error in the WSR-88D spectrum width measurements had already been investigated by the OSF, and suggestions for software and operational changes had been made. Dick Doviak at NSSL also provided information on other problems affecting spectrum width. These included spectrum width bias at large SNR due to signal clipping and/or receiver saturation (improper AGC settings), bias in regions of overlaid echo due to a lower than optimum “overlaid echo” threshold, width bias at low SNR due to improper noise compensation and finally, the use of a low-end SNR threshold which is too small.

According to a memo provided by Dick Doviak and included in last year’s report, the method by which the WSR-88D computes spectrum widths often creates a larger number of 0 values than expected. The method, called “pulse-pair”, is based on the following formula:

$$\sigma_v = \frac{v_z}{\pi} \ln \left( \frac{S^2}{R \left( T_r \right)} \right)^{1/2}$$
(Doviak and Zrnic, 1993, eq. 6.27), where \( \hat{S} \) is an estimate of signal power and \( \hat{R}(T_s) \) is the autocorrelation at sample lag time \( T_s \). Because of errors in the estimates \( \hat{S} \) and \( \hat{R}(T_s) \), the argument of the natural logarithm is sometimes less than one and its value is negative. When this occurs, the WSR-88D reports a spectrum width value of 0. According to Doviak, this might be expected to occur most often when the spectrum width value is small, the SNR is low, and/or the noise floor estimate is high.

Indeed, an extremely high occurrence of 0 values has been observed in the STEPS-2000 data, and is the most obvious data error. An analysis of 572 scans identified as useful for comparing with in-situ aircraft data revealed that the frequency of 0 values appears high by a factor of 10 or more. This anomaly is illustrated in the following histogram, which depicts the distribution of all spectrum width measurements made. This error is compounded by the fact that the spectrum widths are reported only in 0.5 m/s increments, making it impossible to distinguish small from zero values. Therefore, the only solution appears to be marking all 0 values as bad and not using them in the turbulence algorithm. Of course, this solution may cause an upward bias in the turbulence estimates derived from second moments. Ultimately, the use of spectral processing methods for determining moments will mitigate this problem.
Figure: Histogram depicting spectrum width values for all 572 radar scans in the STEPS-2000 dataset that are in the vicinity of an aircraft in-situ measurement.

Another source of error in the spectrum width estimates (and similarly with the reflectivity and radial velocity measurements) is due to noise inherent in the random nature of the received signal. It can be shown that an approximate form for the standard deviation of the spectrum width estimates $\hat{w}$ for the pulse-pair algorithm is given by

$$SD(\hat{w}) = 2v_a \left[ \frac{3}{32\pi^4} \frac{1}{M} \right]^{1/2} \frac{1}{\sqrt{\text{SNR}}} \left( \frac{\hat{w}}{2v_a} \right)$$

for SNR < 10dB, and

$$SD(\hat{w}) = 2v_a \left[ \frac{3}{32\sqrt{\pi}} \frac{1}{M} \right]^{1/2} \left( \frac{\hat{w}}{2v_a} \right)^{1/2}$$

for SNR > 10dB, where $v_a$ is the unambiguous velocity. Note that the error in the width is proportional to the width and inversely proportional to the SNR for small SNR’s. For
larger SNR’s the error is proportional to the square root of the width and independent of the SNR.

These observations suggest two additional quality-control methods for the STEPS-2000 radar data. First, spectral widths from measurements with SNR < 10 dB should be assigned a lower “confidence” value and weighted less in the averaging process. This is achieved by the following map:

![SW confidence as a function of SNR](image)

**Figure:** WSR-88D spectrum width “confidence” used for the NCAR second-moment turbulence methods as a function of SNR.

Notice that the confidence value increases from zero to 1 as SNR increases linearly from zero to 10 dB, remains at 1 up to an SNR value of 50 dB, and then decreases linearly to zero at an SNR of 70 dB. It is zero for all other values. The rationale for the initial increase should be apparent from the discussion above, while the decrease is due to the fact that very large SNRs may be a result of incorrect ACG settings or other processing errors.
A third quality-control measure that may prove useful makes use of the spectrum width field directly. In the ideal case of homogeneous turbulence, the radar-measured spectrum widths will have some variance due to the statistics of the wind field (turbulence length scale and intensity) and additional variation due to measurement error. If convective turbulence is “locally” homogeneous, the local consistency of the spectrum width values should therefore provide some measure of the measurement error. This observation has motivated an attempt to derive an additional spectrum width confidence metric from the local variance or neighboring-point correlations. This effort is ongoing.

Other standard quality control algorithms may be used if necessary to filter out identified regions of clutter or second-trip. For instance, the Radar Echo Classifier developed by NCAR’s Cathy Kessinger, et al., as part of the NEXRAD Data Quality Improvement project might be used. However, neither second trip nor clutter have appeared to be major problems in the STEPS-2000 radar data, perhaps because only scans at 2.4° or greater are being used for comparison with the in-situ aircraft data.

Algorithm Methodology

The improved WSR-88D algorithm is a fuzzy-logic based algorithm in which several different indicators of turbulence are combined using a weighted combination scheme. The weights are based on a variety of quality control indications, or confidence indices, as discussed above. This fuzzy logic methodology has been successfully applied to developing many other algorithms in NCAR’s Research Applications Program.

As mentioned in previous reports, one of the significant problems with the existing WSR-88D algorithm is using un-averaged data to produce the second moments. There are three primary reasons that averaging the radar data (correlations, spectra or moments) is required: (a) turbulence is a random process and hence the only pertinent information about it must be obtained via statistical methods, (b) individual Doppler spectra (and hence second moments) are contaminated by so-called phase noise (due to the interaction of the phases between different scatterers in the pulse volume), and (c) the spectra are inevitably contaminated by receiver noise. Correlation, spectral or moment averaging is required to reduce these effects. The averaging of spectra or correlation
functions prior to computing second moments is far preferable to averaging moments obtained from the contaminated spectra. Unfortunately, the WSR-88D system in its current form provides only moments. However, as mentioned in last year’s report, the averaging of the zero and one-lag correlations over range and possibly azimuth in conjunction with a time-domain pulse-pair spectrum width estimation algorithm may produce improvements and should be investigated. Ultimately, methods based on spectral processing should provide higher quality moments. Still, moment averaging will be required to give meaningful turbulence information.

The NCAR turbulence algorithm performs averaging using either confidence-weighted median or trimmed means of radar-derived values in a disc or patch (range by azimuth rectangle) centered at a point of interest. Not that if a disc is used, then because the azimuthal distance between radar beams varies as a function of range, a differing number of samples will be averaged at different ranges. The number of samples will proportional to the statistical uncertainty in the estimates, so a balance between the number of samples and the spatial domain of the filter is required. If a fixed domain size is used, the errors in the estimates at further ranges will increase; hence, a lowering of an associated confidence index would be required. On the other hand, if a patch is used, then the turbulence may not be homogeneous over the large spatial extents occurring at high ranges, leading again to possibly misleading predictions. In practice, a combination of these two approaches may be used to guarantee a certain number of samples to be included in the average while preventing the spatial extent from becoming unnecessarily large.

Whatever spatial sampling is used, the turbulence estimates provided by the various indicators are then combined using a confidence-weighted sum and a final eddy dissipation rate (EDR) value for the point of interest is derived. Four basic methods may be used to supply the turbulence indicators; these are outlined below.

- The second-moment method makes use of the radar-measured second moment (square of the spectrum width), scaling it by a theoretical quantity dependent on the distance from the radar and an a priori turbulence outer length scale to obtain an eddy dissipation rate (EDR) estimate.
• The combined first and second moment method makes use of a sum of power-weighted second moment values and the variance of the associated first moments over varying spatial extents. In the absence of noise, this quantity can be shown to be equal to the second moment obtained from averaging the spectra obtained from the various pulse volumes. Like the single pulse-volume second moments, these quantities can then be scaled using theoretical quantities into EDR values.

• The third method is actually based on a several quantities derived from the radar moments that are “dimensionally correct”. The formulas for computing these quantities were developed at NCAR and are discussed in a report written for the Juneau Turbulence Project Doppler-on-Wheels (DOW) data analysis effort by Alex Praskovsky and Steve Mueller.

• The fourth method is based on velocity structure functions. Either 1- or 2-d structure functions may be computed from local radial velocity (first moment) measurements, and are then fit to a theoretical curve based on an a priori turbulence outer length scale. The best-fit curve will then determine the EDR value. Structure function methods have shown promising results when applied to lidar data, but their application to the radar case is complicated by the large radar pulse volumes. This is because the radar returns only a weighted average of radial velocities over the pulse volume, not the point wind measurements. In previous years’ work, the theory and numerical computations necessary to adjust for this averaging factor have been performed.

Once these turbulence indicators are computed and have been combined in a confidence-weighted manner to produce a turbulence estimate at each point, the values of this combined field will be analyzed to determine the regions that are deemed to be hazardous. This analysis will include filtering out or connecting above-threshold regions that are too small in extent, and will result in a final hazard diagnosis. The turbulence detection algorithm methodology is diagramed below.
**Figure:** Diagram of the NCAR improved WSR-88D turbulence detection algorithm.
Algorithm tuning and verification

As mentioned above, data collected during the STEPS-2000 field experiment based in Goodland, Kansas, was obtained last year, and comprises the first dataset with both in-situ aircraft turbulence data and WSR-88D radar data. The SDSM&T T-28 aircraft experienced several strong encounters with turbulence during the field experiment, and this dataset is ideal for tuning and verifying the NCAR turbulence algorithm.

In FY02, Matlab software that facilitates comparisons of the STEPS-2000 aircraft turbulence and radar-derived values was developed. There are three main parts to this software:

- A pass through the aircraft data to identify the "nearest" scan (of ~3000 in STEPS) to each aircraft location/time. The formula $dx^2 + dy^2 + dz^2 + (0.01 dt)^2$ is currently being used as the metric ($dx$, etc., in km, $dt$ in seconds).
- Extraction of statistics for any radar field from a "disc" or "patch" near each aircraft location. Timeseries, tracks, histograms, and scatterplots of these values can then be produced using the Analysis tool developed in previous years.
- Calculations of radar-derived quantities via background processing, and ONLY for those regions of scans that are needed for comparison with the aircraft values.

This new software was needed because of a deliberate shift from the MDV to NetCDF radar format, which retains more information about the spatial locations of the radar measurements. However, its development was particularly worthwhile because the new software is more flexible and much faster, allowing computations and comparisons to be done in minutes instead of overnight.