14.3. Enhancing sensitivity on the polarimetric WSR-88D

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1. Introduction

A polarimetric configuration with simultaneous transmission and reception of horizontally and vertically polarized electromagnetic waves has been implemented with the Weather Surveillance Radar – 88 Doppler (WSR-88D) KOUN in Norman, Oklahoma. The main features of the configuration can be found in Doviak et al. (2000). The transmitted power in each polarimetric channel is two times or 3 dB lower than in the "legacy" single polarization channel. This makes the polarimetric WSR-88D less sensitive than the legacy system, which means the weakest signals just above the noise level are lost in the polarimetric system relative to the legacy system. Some important weather features in weak signal may become harder to identify with the polarimetric radar. Among those are total echo coverage, the thin lines associated with very weak low-level boundaries, and distant echoes along the edges of storms. The US National Weather Service (NWS) is planning to upgrade of the WSR-88Ds with dual-polarization capabilities, thus enhancing radar sensitivity on the dual-polarization systems is one of the main goals of this study.

Meteorologists at NWS forecast offices have seen and been accustomed to data collected with the single polarization "legacy" WSR-88Ds for roughly 20 years. Transitioning to the polarimetric technology in the field offices will be easier if sensitivity of the new radars does not change relative to the "legacy" system.

A technique to enhance radar sensitivity has been proposed by Ivic et al. (2009) based on thresholding that involves signal coherency in the polarimetric channels. This technique is being tested currently on the prototype of dual-polarization WSR-88D KOUN in Norman, OK. Herein we consider a different approach to enhance sensitivity that uses an algorithm of noise speckles removal and coherent summation of signals in the two polarimetric channels. We compare reflectivity fields obtained with our approach to those collected with a "legacy" WSR-88D nearly collocated with KOUN.

2. Formulation of the problem

The WSR-88D KOUN employs a polarimetric mode with Simultaneous transmission and reception of Horizontally and Vertically polarized waves, i.e., SHV mode (Doviak et al. 2000, Zrnic et al. 2006). Other schemes use alternating transmission and reception switches of polarization from pulse to pulse. The SHV mode employs one radar transmitter so that the full transmit power is divided into two channels and the power in each channel is two times (or 3 dB) lower than the transmit power in the "legacy" single-channel system. The dual-polarization (DP) WSR-88D has a receiver for each channel similar to the one in use in the "legacy" system. Thus, the DP system in receive is the same as the" legacy" one and loss of sensitivity in the DP system equals the loss in transmit, i.e., 3 dB.

To compare sensitivities of the DP and "legacy" systems, we put side by side reflectivity fields collected with the DP WSR-88D KOUN and the "legacy" system KCRI which is nearly collocated to KOUN; the distance between the radars is 234 m, i.e., about one radar range gate. Time difference between radar scans at the same elevation angle was less than 2 min. In Fig. 1 reflectivity fields at the lowest elevation (0.5 deg) are shown on March 20, 2010 at 1003Z (KOUN) and 1002Z (KCRI). Inspection of the fields shows a loss of coverage in the KOUN image especially at the fringes of echoes.

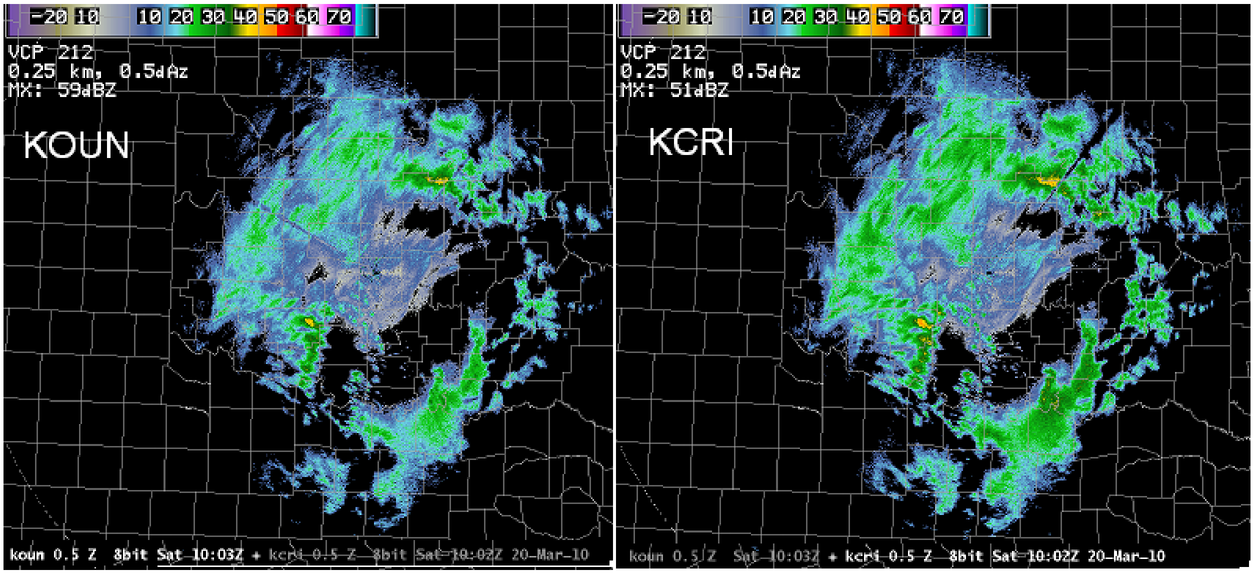

Fig. 1. Reflectivity fields collected with DP KOUN and "legacy" KCRI on March 20, 2010.

The loss of sensitivity on the DP system leads to a shrinking of total echo coverage, especially at long ranges from radar. This leads to slightly smaller areas of precipitation detected by radar, though the precipitation echo lost is so weak that precipitation accumulation would not be adversely impacted. The extent and coverage of precipitation in weak echo, such as shallow light snow events, can be adversely impacted. Additionally, thin lines in reflectivity fields associated with weak, subtle, low-level boundaries created by previous or ongoing convective storms may become less visible. The echo tops become lower because of weak signal loss. Clearly, mitigation of the sensitivity loss in the DP systems is desirable.

3. Noise speckle processing to enhance sensitivity

In the "legacy" WSR-88D, suppressing of noise speckles is done by thresholding data at some level of signal-to-noise ratio (SNR). For reflectivity, the level is set at 2 dB which means all signals with SNR < 2 dB are censored in products based on reflectivity. This SNR level is currently used in KOUN for reflectivity and polarimetric products.

To enhance radar sensitivity, we consider herein an algorithm that is based on Processing of Noise Speckles (PNS). The approach works on two dimensional radar products (Level 2 format), i.e., it can be implemented in the Radar Product Generator, RPG. A sketch clarifying the algorithm is shown in Fig. 2. A field of reflectivity in two dimensions X and Y is placed in a grid of representation cells (quadrates). If there is no signal in a representation cell, it is white. Speckles of weather signal or noise are both shown with gray squares. Numerous approaches can be used to eliminate speckles in the representation cells. The simplest one eliminates single speckles as the one shown in Fig. 2 with coordinates (2,2). In other words, speckles are considered to be noise if they are isolated, and are removed from the field. We also use a version of PNS that eliminates a one dimensional line of speckles; examples are shown in Fig. 2 with row 4 and column 4. Our PNS leaves those speckles in the field that contain at least two adjacent speckles in each dimension. An example is the right 2x2 gray patch in Fig.2. Thus, this version of the PNS algorithm is based on a supposition that the probability to create adjacent speckles by noise is much less than by weather echoes.

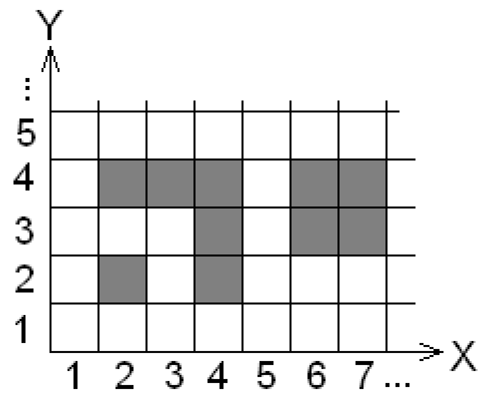

Fig. 2. Representation cells for a two dimensional field with grey speckles inside the cells.

In our implementation, the PNS algorithm works in a subsystem that emulates the RPG. However, the Radar Data Acquisition (RDA) subsystem is also involved in the algorithm by allowing a nosier signal to go to RPG. In other words, the RDA noise threshold should be reduced. Our experiments with radar data shows that this reduction should be 5 dB, i.e., the RDA SNR threshold can be moved from +2 dB as on the "legacy" system to – 3 dB with RPG PNS on. This 5 dB gain is larger than the loss of 3 dB due to power splitting that means PNS restores the loss of sensitivity in the DP system. Moreover, DP radar sensitivity with PNS appears to be better than sensitivity of the "legacy" system that is demonstrated in Fig. 3.

There is a noticeable dissimilarity in echoes in Fig. 3 at distances within 20 km from the radars. KOUN exhibits strong reflections from ground targets. This is because we tested PNS with time-series data collected with KOUN and applied a simple notch ground clutter filter to the data whereas KCRI uses the more sophisticated GMAP filter. Because ground clutter contamination affects areas close to radar and we consider quite distant echoes to compare sensitivity of the radars, this discrepancy should not be confusing.

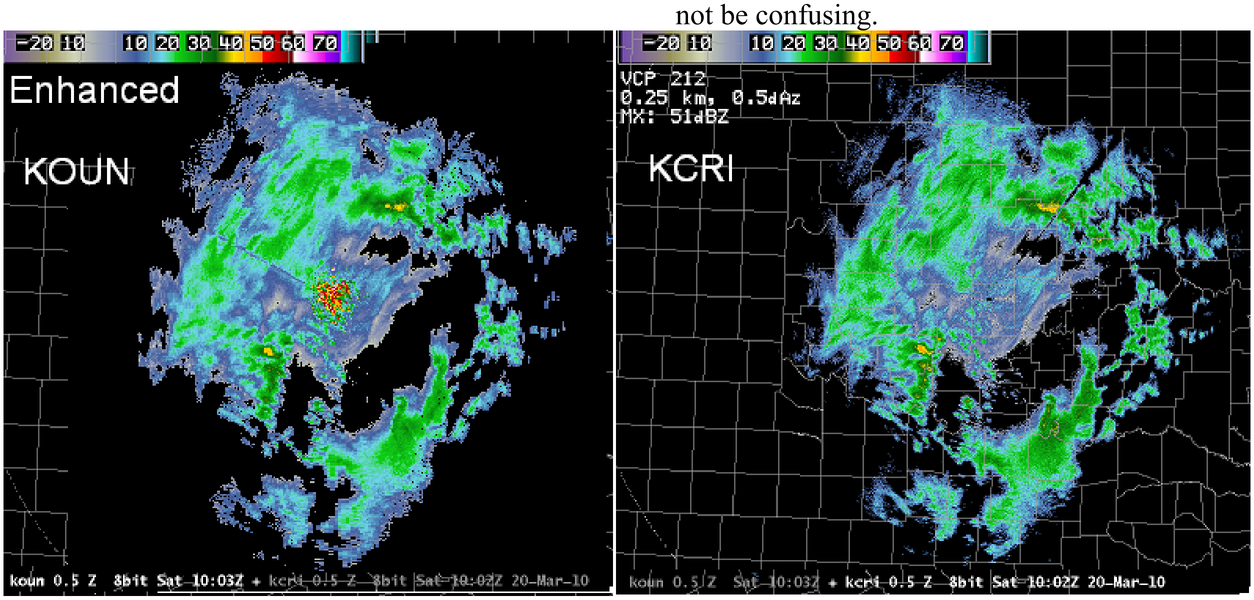

Fig. 3. Reflectivity field obtained with PNS applied to the KOUN's data (left) and the reflectivity field from "legacy" KCRI (right).

There is another useful feature of PNS which is demonstrated in Fig. 4. Within range of KOUN, there are several transmitters that create interference signals on KOUN products. An example of interference contamination is shown in the left panel of Fig. 4. One can see three major features of echoes in Fig. 4 (left). 1) Clear air echoes that fill in distances up to about 50 km. 2) An echo in the south-east quadrant with very low correlation coefficient (ρ_{hv}) values. This is an echo from wild fire smoke (Melnikov et al., 2008). 3) Radial streaks around azimuth 325^{o}; these are contaminations from interference signals. The right panel in Fig. 4 presents the field after PNS application. It is seen that the PNS removes not only noise speckles but also interference contamination.

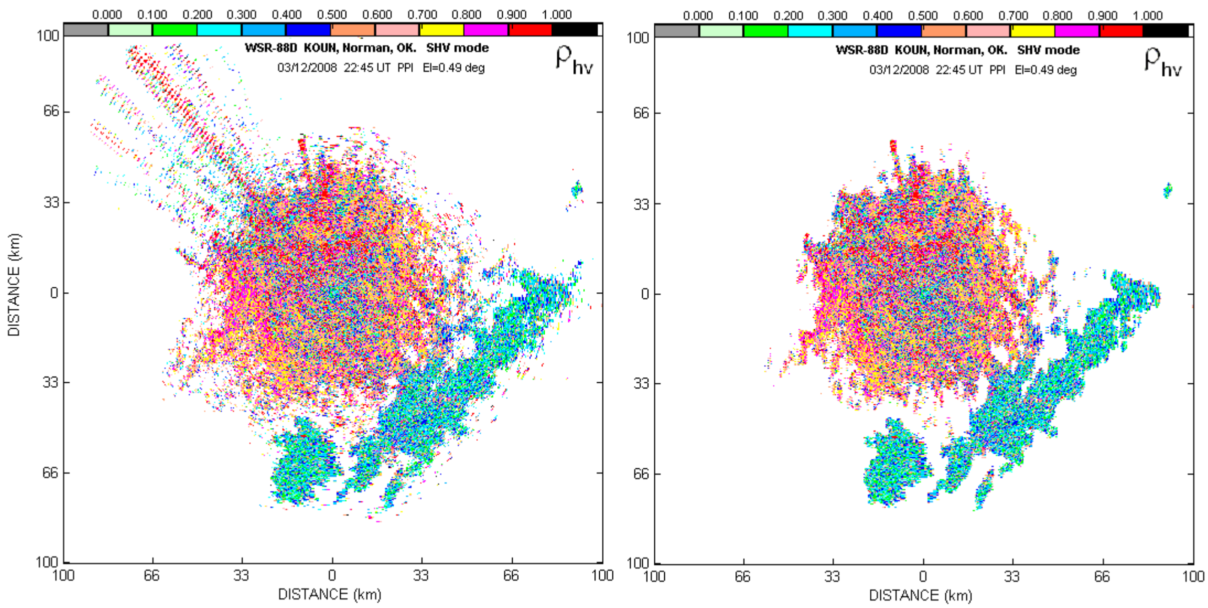

Fig. 4. Fields of the correlation coefficient with interference streaks in the North-West direction (left panel) before applying PNS and (right panel) after. Low correlation coefficients in the South-East quadrant are from wild fire smoke.

4. Coherent summation of signals to enhance sensitivity

Echoes from clouds and precipitation have high correlation coefficients, i.e., ρ_{hv}>0.95. This condition justifies the coherent summation of signals in the horizontal (H) and vertical (V) channels to increase the detection capability of the polarimetric WSR-88D. The coherent sum of voltages, e, in the H and V channels is:

$$e_{sum} = e_h + e_v = s_h + n_h + s_v + n_v \,,$$

where s and n are weather and noise voltages correspondingly in the channels marked with the superscripts. The mean power of the sum signal is

$$P_{sum} =< (e_h + e_v)(e_h^* + e_v^*)$$
$$= S_h + S_v + < s_h^* s_v > + < s_h s_v^* > +$$
$$< n_h n_h^* > + < n_v n_v^* >$$

where S_h and S_v are the powers of weather signal in the respective channels, the brackets define ensemble (or time) averages, the asterisk denotes complex conjugate, and we used the fact that the weather signal and noise voltages are zero mean and are uncorrelated. The latter equation can be written as:

$$P_{sum} = S_h + S_v + 2(S_h S_v)^{1/2} \rho_{hv} \cos(\varphi_{dp}) + N_h + N_v$$

$N_{h,v}$ are the noise powers in the H and V channels respectively and φ_{DP} is the differential phase, which is one of the measurable on the DP system. Due to high coherency between signals in H and V channels, we can set $\rho_{hv} = 1$. By digitally multiplying signal in H-channel by $\exp(j\,\varphi_{DP})$ before coherent summation, the SNR, for the coherently summed signal can be written as,

$$SNR_{sum} = \frac{S_h + S_v + 2(S_h S_v)^{1/2}}{N_h + N_v}.$$

For equal noise powers (i.e., $N_h = N_v = N$) and SNR in each channel defined in power units as $SNR_h = S_h/N_h$, $SNR_v = S_v/N_v$, SNR_{sum} can be written in terms of the scatterer's differential reflectivity, $Z_{dr} \equiv S_h / S_v$, as

$$SNR_{sum} = \frac{1}{2} SNR_h (1 + Z_{dr}^{-1/2})^2 . \qquad (1)$$

If $Z_{dr} \approx 1$, then $SNR_{sum} \approx 2\ SNR_{v,h}$. Thus the effective SNR can be increased by 3 dB. In other words, coherent summation can restore the loss of sensitivity caused by splitting the transmitted power into the H and V channels.

Fringes of radar echoes with very low SNR usually contain small droplets with $Z_{dr} \approx 1$ or ice crystals with Z_{DR} in the interval +0.5 to +2 dB, i.e., Z_{dr} in the interval 1.1 to 1.6 in power units. Using this Z_{dr} interval in (1) we obtain the increase of SNR_{sum} from 3 to 2 dB. This is the typical increase for the coherently summed signals.

An example of the spatial expansion of data fields, due to the SNR increase after coherent summation, is shown in Fig. 5 (a, b). This case shows Bragg scatter echo from optically clear air. Bragg scatter originates on fluctuations of refractivity and produces weak echoes with $Z_{DR} = 0$ due to reflection symmetry at scales about 5 cm, i.e., roughly half of the radar's wavelength. Panel (c) shows the ρ_{hv} field with values very close to unity in areas of Bragg scatter. Properties $Z_{DR} = 0$ dB (i.e., $Z_{dr} = 1$) and $\rho_{hv} \approx 1$ for Bragg scatterers are favorable for coherent summation. The two first panels in Fig. 5 show vertical cross sections of SNR in the horizontal channel (a) and SNR after coherent summation of signals in the channels (b). It is seen that echo coverage and signal intensity in panel (b) are larger than in panel (a).

Comparison of the vertical profiles of C_n^2 from KOUN and those obtained using a 66.8 cm wavelength profiler from NOAA's Profiler Network (NPN, panel e) shows good agreement between the height of KOUN's echo and the height of maximum reflection from the profiler, confirming that Bragg scatter is observed. The rawinsonde profiles shown in panel (d) exhibits a strong gradient of relative humidity at heights between 1.5 and 2.0 km which is an additional support for Bragg scatter (e.g., Gossard and Strauch 1983, Doviak and Zrnic 2006, chapter 11). Bragg scatter occurs in humid turbulent air with gradients in temperature and humidity. The main contribution to backscattered signal at S-band is the gradient of humidity (e,g., Wyngaard and LeMone 1980, Fairall 1991). Thus clear air observations can be used to monitor humid layers near the ground.

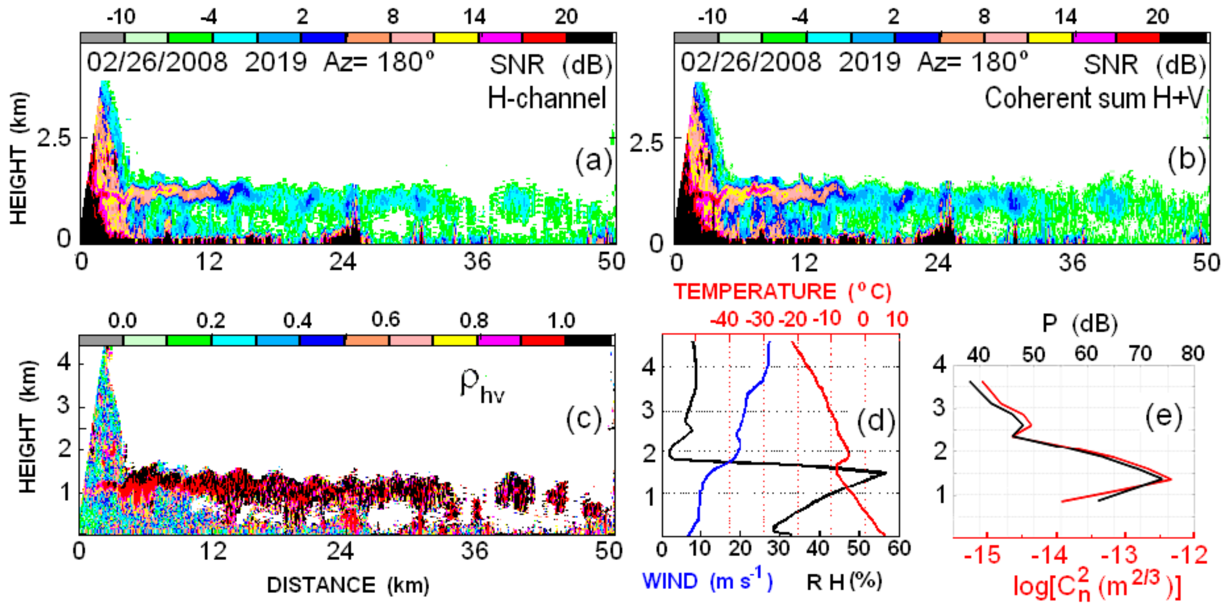

Fig. 5. Vertical cross-sections of (a) SNR_h, (b) SNR_{sum}, (c) ρ_{hv} fields. (d) Rawinsonde profiles of the temperature (red), wind velocity (blue), and relative humidity (black) above Norman, OK at 0Z February 27, 2008. (e) Echo power *P* (black) and estimated log(C_n^2) (red) from the NPN profiler at Vici, OK on 02/26/2008 at 2018 UT. All data are presented above the radar horizon.

5. Conclusions

- Two-dimensional processing of noise speckles allows for effective noise suppression. This results in a reduction in the SNR threshold of radar products by 5 dB relative to the threshold used in the "legacy" system. Such a SNR reduction is equal to an increase in radar sensitivity by 5 dB, which is larger than the loss of sensitivity due to power splitting in the SHV polarization configuration. This means the noise processing allows restoration of the signal loss due to the DP upgrade and an improvement in echo coverage with respect to the single polarization systems.

- Noise speckle processing is done in the RPG, i.e., it does not require any computing resources from RDA subsystem.

- The noise speckle remover can also be used to suppress contamination from interference signals.

- Coherent summation of signals in the horizontal and vertical channels increases radar sensitivity by 2-3 dB, which is substantial for radar observations of weak echoes, particularly from clear air returns. Clear air observations can be used to monitor humid layers near the ground.

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