Sharp shortening the update time of phased array weather radar

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1. Introduction

Severe weather phenomena develop so fast that update time for radar remote sensing should be less than 1 min (e.g., Heinselman et al. 2008). The shortest update time for the current WSR-88D, an USA network radar with a mechanically scanned reflector antenna, is 4.5 min. The update time can be reduced with agile-beam phased array radar (PAR) that steers its beam electronically (e.g., Zrnić et al. 2007, Zrnić et al., 2013). To reduce the update time on a prototype 10-cm wavelength weather PAR, multiplexing of radar beams (Yu et al. 2007), oversampling and whitening in range (Torres and Zrnic 2003), and adaptive scanning (Reinoso-Rondinel et al. 2010) have been tested. Multiplexing of radar beams aims at reducing correlation between weather signal (i.e., echoes) samples, consequentially decreasing the number of samples required for spectral moment estimation and leading to more rapid sampling of weather. Oversampling and whitening in range de-correlates echoes from within the resolution volume, consequentially reducing the standard deviation of estimates (Torres and Zrnic, 2003). Adaptive scanning selects those regions of the atmosphere that have significant weather and the NWRT scans those regions more frequently than those atmospheric volumes without significant weather.

Frequency allocation at S band for weather radars is stringent. The frequency band allowed for each WSR-88D radar is 0.7 MHZ so no frequency agile technique is commonly implemented with the weather radars, but the frequency agile technique was used to shorten the update time for a 3 cm wavelength weather radar used for research (Pazmany and Bluestein, 2011). Given the demands on spectral usage, it is unlikely bandwidth allocation will be increased. Thus this technique is unlikely an option for the future weather PAR. So other alternatives should be explored, and one such alternative is described herein.

The update time can be also reduced with imaging PAR that transmits a wide beam and forms multiple receiving beams (e.g., Palmer et al. 1998, 2005, Li and Stoica 2007, Kidder et al. 2011, Isom 2012). The major pitfall of this approach for weather applications is a reduced radiation power density of the transmit beam and consequently reduced detection capability. Detection capability attained with the WSR-88D has become a standard for operational weather radars in the US.

The volume scan update times of a PAR is reduced by switching the beam directions for each of several pulses transmitted in rapid succession (e.g., pulse separations about a pulse width) so multiple beams in transmit can be formed, and echoes from scatterers are simultaneously and continuously received along synthesized multiple beams, a technique referred to as the Multiplexed Beam Technique (MBT, Lai et al. 2004). To retrieve mainlobe-to-mainlobe (m-m) coupled echoes, phase coding for every transmit pulse was employed (Lai et al., 2004). This technique is a particular implementation of the MIMO radars (Multiple In Multiple Out, e.g., Li and Stoica 2007). Coding of transmitted pulses using MBT have also been considered to reduce coupling; the Walsh coding (Urkowitz 1997) or 13-bit Barker code have been studied (Lai et al. 2004). Experiments using the Barker code showed a good spatial isolation for reflectivity fields having no strong gradients (Lai et al. 2004). This technique is attractive but its implementation in the weather PAR is a challenge because phase coding is used in the WSR-88D to resolve range ambiguities and most likely will be employed in future weather PAR.

In this communication, we derive a different approach, one that does not use coding, to retrieve m-m echoes using multiple beams. To demonstrate the approach we process echo data collected along two multiplexed beams and assume mainlobe-to-sidelobe (m-s) voltage coupling factors β are known either from radiation pattern measurements or from a unique collection of weather data.

2. Description of the method to retrieve m-m echo voltages

2.1. WSR-88D KOUN's antenna pattern

Consider a circular symmetric one-dimensional pattern function $F(\theta')$ of the transmitted electric field given by

$$F(\theta') = g^{1/2} f(\theta') \tag{1}$$

where g is the one-way power density gain along the beam (i.e., mainlobe) axis, and $f^2(\theta')$ is the normalized power density pattern (Doviak and Zrnic 2006, section 3.1.2). The polar angle θ' is measured from the beam axis (i.e., the polar axis). We focus on the transmitted electric field and received voltages because the voltages of sampled weather echoes are processed to suppress the ground clutter, resolve range-folded echoes, and determine spectral moments and polarimetric parameters of precipitation. Echoes received through sidelobes can corrupt wanted echoes received through each of the multiplexed mainlobes, especially if a sidelobe is in a region of high reflectivity and a mainlobe is in a region of low reflectivity. A technique is presented whereby m-m coupled echoes can be retrieved with negligible contamination from mainlobe-to-sidelobe (m-s) coupled echoes.

The antenna patterns of radiation from NSSL's Research and Development WSR-88D (i.e., KOUN) made after NSSL engineers converted the single H polarization feed to a dual H, V polarimetric feed manufactured by Andrew Canada is summarized in Fig. 1 and compared with a theoretical pattern $F(\theta')$ for KOUN (Doviak et al., 1998).

Measured sidelobe levels (antenna without radome for the 30^o cut) are represented by the envelope (green line) of the peak side lobes measured by Andrew Canada (Paramax Report, 1992, p.C-6) on its antenna range. The 30^o cut avoids the three ridge of higher sidelobes due to blockage from three feed support spars and thus this pattern is representative of most of the volume illuminated by sidelobes. Thus the sidelobe pattern indicated by the green line is representative of the most of the sidelobes of the WSR-88D and should be the sidelobe levels of a PAR if it is to replace the WSR-88D. By precisely controlling the amplitude and phase of each element, and accounting for mutual coupling, PAR sidelobes can be within 1 or 2 dB of the theoretical to levels below -50 dB (e.g., Schrank, 1988). Thus the theoretical pattern given in Fig. 1 will be used to estimate the limits of performance of a PAR using time multiplexed transmit beams in conjunction with simultaneous receiving beams.

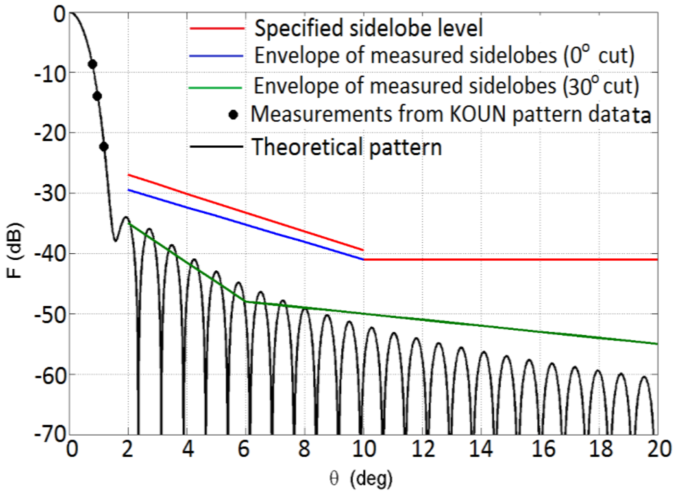

Fig.1. Theoretical one-way power density pattern, $10\log[f^2(\theta')]$, *as a function of polar angle* θ' *for KOUN's antenna (the black line), and comparison with measurements.*

2.2. Resolution volumes contributing to m-m and m-s coupled power

To concisely illustrate the technique using the relative gain pattern in Fig.1, we need to switch the spherical coordinate system to one used by radar meteorologists (e.g., Doviak and Zrnić, 2006, Fig.3.1). In this (r, θ, φ) spherical coordinate system the polar axis z is vertical at the antenna and the x axis is the direction broadside to the phased array antenna. The directions (θ, φ) are the zenith and azimuth angles. Assume two beam multiplexing in which $\theta_0 = 90^o$ is fixed. Consider a pair of transmitting beams, one directed at broadside $\varphi_0 = 0^o$ and the other at $\varphi_0 = \gamma = 11^o$ choosing a beam separation less than several degrees from broadside allows us to ignore the small changes in beamwidth and gain of the two beams of a planar PAR.

Assume the reflectivity field is absent along the 0^o beam, but is present along the γ^o beam producing a 100 dB SNR from m-m coupled power along the γ^o beam. Imagine two radar pulses transmitted sequentially toward the two directions, 0^o and 11^o. In reception a pair of beams in directions 0^o and 11^o are synthesized to simultaneously receive echoes. The 0^o beam also has a one-way sidelobe of -53 dB at the 11^o direction (Fig. 1). This receive sidelobe intersects the transmit mainlobe at 11^o and also receive echoes. Ignoring echoes transmitted and received through sidelobes (i.e., sidelobe-to-sidelobe, s-s coupling), echoes from the 11^o sidelobe of the 0^o receive beam are about 100 – 53 = 47 dB above the noise level. So instead of noise from the 0^o direction the radar receives a strong signal of 47 dB SNR. This simplified example illustrates the significance of m-s coupling for the multiplexed beam technique. Therefore retrieval of m-m complex echo voltages when contaminated with m-s coupled power is the central problem for the multiplexed beam technique. In the next subsection we use two beams to describe the retrieval method.

Consider a phased array antenna consecutively transmitting RF pulses to two directions. The time delay between these pulses is of the order of a pulse width τ. In reception, the PAR can process echoes from the array elements to construct multiple receive beams simultaneously pointed in two directions, and echoes from each beam directions can be simultaneously sampled and processed.

In general a radar receiver gate is set to sample a weather signal voltage $V(r_n, \varphi_0)$ principally from a resolution volume $V_6(r_n, \varphi_0)$ centered at range r_n , along the receive beam's zenith $\theta_0 = 90^o$, and azimuth φ_0. To simplify notation and because θ_0 is fixed at 90^o, henceforth θ_0 is omitted in the arguments. The definition of resolution volume V_6 can be found in Doviak and

Zrnic (2006, section 4.4.4). Assume the first pulse is transmitted along the direction $\theta_0 = 0^o$ and the second pulse along the direction $\theta_0 = \gamma^o$. For pulses transmitted along the 0^o and γ^o beams, gates are set to simultaneously sample echoes from V_6s along the 0^o and γ^o receiver beams. Thus these gates also simultaneously sample voltages not only from V_6s associated with m-m coupling, but also those V_6s associated with m-s coupling and as well s-s coupling as will be shown next.

Assume the sample gate spacing is equal to the pulse width τ of a rectangular transmitted pulse so that resolution volumes V_6s are spaced $c\tau/2$ (c is speed of light) along range. For weather PARs having very low sidelobes (e.g., similar or lower than those of the WSR-88D) transmitting pulses to and receiving echoes from a single direction, s-s coupled power is negligible for most commonly observed circumstances. This is so because weather echoes received via sidelobes are attenuated by the two-way radiation/reception pattern, and if one-way sidelobes levels are 50 dB below the mainlobe the two-way radiation/reception pattern suppresses sidelobe coupled power by 100 dB. We shall ignore s-s coupling and focus attention on the more significant m-s coupling.

Associated with each m-m coupled echo there is one corresponding resolution volume V_6 containing the scatterers that principally contribute to the sampled echoes. However, if an additional pulse is sequentially transmitted along a second beam, there are two additional V_6 volumes contributing significant powers through sidelobes of the radiation and reception patterns; these typically cannot be ignored because they are from a region where sidelobes intersect with the mainlobe (i.e., where there is m-s coupled power).

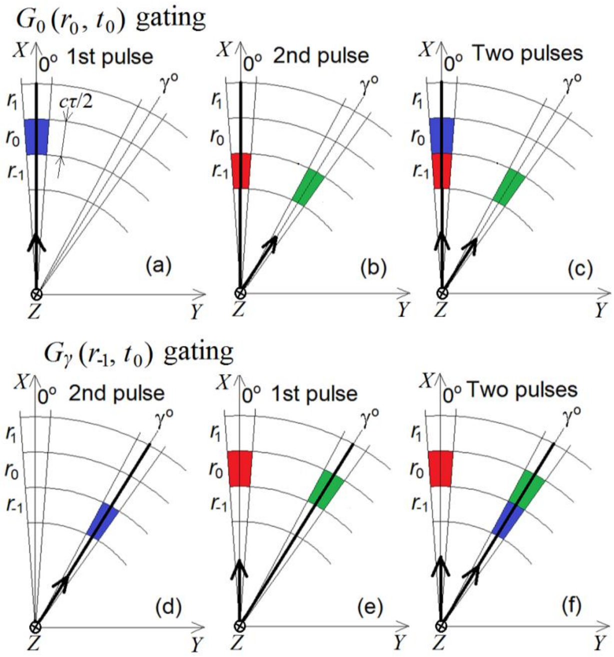

Fig.2. (a - c): Resolution volumes V_6's (colored sectors) having scatterers that simultaneously and principally contribute to weather echoes sampled with gate $G_0(r_0, t_0)$. The blue V_6 corresponds to the resolution volume from which echoes are due to m-m coupling, the green and red ones give echoes due to m-s coupling. (d-f): Same as (a-c) but for gate $G_\gamma(r_{-1}, t_0)$. Transmitting beams are shown with the thick black arrows, and receiving beams are shown with the long thick black lines.

To determine the V_6 volumes containing scatterers contributing m-s coupled power to sampled weather echoes, consider the gating function $G_0(r_n, t_0)$ (n =….-2,-1,0,+1,+2….) having a mainlobe at $\varphi_0 = 0^o$ —the subscript '0' defines the receive beam direction—applied at $t = t_0$ after a reference time. The gate $G_0(r_0, t_0)$ ($r_n = r_0$) samples m-m coupled weather echoes from V_6 (r_0, 0^o). Assume pulses are sequentially transmitted to two different azimuths, first along the azimuth 0^o, and then along the azimuth γ^o. The resolution volume V_6 (r_0, 0^o) is illuminated both by the 0^o transmit beam and as well the -γ^o sidelobe of the γ^o transmit beam. For weather echoes received through the mainlobe of the 0^o beam, the scatterers in V_6 (r_0, 0^o) return weather echoes due to usual m-m coupling (the blue sector in Fig. 2a). But there are two additional V_6s that contribute power to the voltages sampled with gate $G_0(r_0, t_0)$. For one, the γ^o transmit beam has a sidelobe at -γ^o and so it also illuminates resolution volumes in the 0^odirection. Because this sidelobe pulse is transmitted immediately after the 0^o beam pulse (i.e., with a delay τ) the sampling gate $G_0(r_0, t_0)$ also simultaneously samples echoes due to m-s coupling, but these echoes emanate from V_6 (0^o, r_{-1}) (the red sector in Fig. 2b). The second m-s coupled weather echoes sampled simultaneously by gate $G_0(r_0, t_0)$ emanates from $V_6(\gamma^o, r_{-1})$ (the green sector in Fig. 2b). This is the one received by the 0^o beam via its +γ^o sidelobe when scatterers in this volume are illuminated by the γ^o transmit beam. Thus the three resolution volumes shown in Fig.2c provide echoes simultaneously sampled with the $G_0(r_0, t_0)$ gate.

Likewise we can deduce that gate $G_\gamma(r_{-1}, t_0)$ simultaneously samples echoes from the three V_6s shown in panel (f) of Fig. 2. Because the reference time for gating locations is the same for all gates, $G_0(r_0, t_0)$ and $G_\gamma(r_{-1}, t_0)$ are simultaneously applied at t_0 ($t_0 = 2r_0/c$).

2.3. The procedure to retrieve m-m coupled voltages

Let $V_{mm}(r_0, 0, t_0)$ and $V_{mm}(r_{-1}, \gamma, t_0)$ — mm indexes the m-m coupled voltages—be the instantaneous complex voltages received from the mainlobes of the 0^o and γ^o directions if only the m-m coupled component is sampled respectively by gates $G_0(r_0, t_0)$ and $G_\gamma(r_{-1}, t_0)$. These voltages V (V only represents the m-m voltages; henceforth the subscript 'mm' will be dropped) would be measured in absence of m-s coupling. These are the wanted instantaneous voltages from the respective resolution volumes at $(r_0, 0^o)$ and (r_{-1}, γ^o) and would be measured without multiplexed beams. With multiplexed beams, these voltages are corrupted by m-s coupled complex voltages from other V_6s seen in Figs. (2c) and (2f).

Let's now determine the two m-s coupled voltages received through the mainlobe at the 0^o direction. These are due to the 2nd pulse transmitted in the γ^o direction. One contribution (shown in Fig. 2b with red color) comes from $V_6(r_{-1}, 0^o)$ being illuminated through the transmit beam's sidelobe at $-\gamma^o$ relative to the transmit direction γ^o. This contribution is $\beta(-\gamma)V(r_{-1}, 0, t_0)$, i.e. the m-m coupled voltage $V(r_{-1}, 0, t_0)$ suppressed by the voltage coupling factor $\beta(-\gamma)$. $V(r_{-1}, 0, t_0)$ is that voltage which would be associated with scatterers in $V_6(r_{-1}, 0^o)$ if both transmit and receive mainlobes weighted the scatterers. The m-s coupled echoes from the second V_6 (shown in Fig. 2b with green) which are also due to the 2nd transmitted pules, is received from $V_6(r_{-1}, \gamma)$ through the γ^o sidelobe of the 0^o beam. This contribution is $\beta(\gamma)V(r_{-1}, \gamma, t_0)$. Thus the measured voltage $U(r_0, 0, t_0)$ sampled by gate $G_0(r_0, t_0)$ is the sum

$$U(r_0, 0, t_0) = V(r_0, 0, t_0) + \beta(\gamma)V(r_{-1}, \gamma, t_0) + \beta(-\gamma)V(r_{-1}, 0, t_0), \tag{2}$$

all sampled simultaneously although they are from different resolution volumes at locations given by the arguments. The first term in (2) is the m-m coupled voltage, the wanted voltage, but the last two terms in (2) are unwanted voltages due to m-s coupling. Using similar considerations for the beam at direction γ^o we obtain the measured voltage $U(r_{-1}, \gamma, t_0)$ sampled by gate $G_\gamma(r_{-1}, t_0)$

$$U(r_{-1}, \gamma, t_0) = V(r_{-1}, \gamma, t_0) + \beta(-\gamma)V(r_0, 0, t_0) + \beta(\gamma)V(r_0, \gamma, t_0), \tag{3}$$

$V(r_{-1}, 0, t_0)$ on the right side of (2) is the m-m contributor to the measured voltage $U(r_{-1}, 0, t_{-1})$ which, following the procedure to obtain (2), can be written as

$$U(r_{-1}, 0, t_{-1}) = V(r_{-1}, 0, t_{-1}) + \beta(\gamma)V(r_{-2}, \gamma, t_{-1}) + \beta(-\gamma)V(r_{-2}, 0, t_{-1}), \tag{4}$$

Note $V(r_{-1}, 0, t_{-1})$ in (4) is for time t_{-1} whereas we need $V(r_{-1}, 0, t_0)$ to be used in (2). Because the time gap between t_0 and t_{-1} is τ, (i.e., of order of one μs) we can assume $V(r_{-1}, 0, t_0) = V(r_{-1}, 0, t_{-1})$. In other words, scatterers in the radar resolution volume can be considered "frozen" during time lags much shorter than the correlation time of weather echoes. From now on we will consider "frozen" scatterers and omit time arguments in voltages.

Substitute $V(r_{-1}, \gamma)$ from (3) and $V(r_{-1}, 0)$ from (4) into (2) and solve for $V(r_0, 0)$ to obtain:

$$V(r_0, 0) = U(r_0, 0) - \beta(\gamma)U(r_{-1}, \gamma) - \beta(-\gamma)U(r_{-1}, 0) + \beta^2(\gamma)V(r_0, \gamma) + \beta(\gamma)\,\beta(-\gamma)[V(r_{-2}, \gamma) + V(r_0, 0)] + \beta^2(-\gamma)V(r_{-2}, 0). \tag{5}$$

Eq. (5) is convenient because it represents the wanted voltage $V(r_0, 0)$ on the left side as a power series of β in which the unwanted m-s voltages are now to second order in β whereas in (2) they were to first order in β; that is, $\beta(\gamma)V(r_0, \gamma)$ in (3) is the m-s coupled voltage associated with scatter from $V_6(r_0, \gamma)$.

Power contributions from s-s coupling are neglected in radar weather observations. This coupling is of the 4th order of β. Thus, a solution for true voltages should be obtained to the 3rd order of β. To obtain such a solution, one more iteration of (5) is needed . Making the next step and expressing voltages V in (5) in terms of U using (2) and (3), we arrive at the following series:

$$V(r_0, 0^o) = U(r_0, 0) - \beta(\gamma)A_1 + \beta^2(\gamma)A_2 - \beta^3(\gamma)A_3 + O(\beta^4), \tag{6a}$$

with

$$A_1 = U(r_{-1}, \gamma) + U(r_{-1}, 0^o)\delta, \tag{6b}$$
$$A_2 = U(r_0, \gamma) + [U(r_{-2}, \gamma) + U(r_0, 0)]\delta + U(r_{-2}, 0)\delta^2 , \tag{6c}$$
$$A_3 = U(r_1, \gamma) + [U(r_1, 0) + 2U(r_{-1}, \gamma)]\delta + [U(r_{-3}, \gamma) + 2U(r_{-1}, 0)]\delta^2 + U(r_{-3}, 0)\delta^3 , \tag{6d}$$
$$\delta = \beta(-\gamma)\beta^{-1}(\gamma). \tag{6e}$$

True voltage $V(0^o,r_0)$ in (6a) is expressed in terms of measured voltages U and the unwanted m-s coupled voltages are multiplied by β^4. This is the solution for the problem with accuracy of β^3 for the beam in 0^o direction.

To obtain voltage from r_0 in the γ direction, measured voltages from r_{-3} to r_1 for the two beams are used. Similar calculations can be conducted for the beam in the γ direction to obtain:

$$V(r_{0,}\gamma) = U(r_{0,}\gamma) - \beta(\gamma)B_1 + \beta^2(\gamma)B_2 - \beta^3(\gamma)B_3 + O(\beta^4), \tag{7a}$$
$$B_1 = U(r_{1,}\gamma) + U(r_{1,}0^o)\delta, \tag{7b}$$
$$B_2 = U(r_{2,}\gamma) + [U(r_{0,}\gamma) + U(r_{2,}0^o)]\delta + U(r_{0,}0^o)\delta^2, \tag{7c}$$
$$B_3 = U(\gamma,r_3) + [U(r_{3,}0^o) + 2U(r_{1,}\gamma)]\delta + [U(r_{-1,}\gamma) + 2U(r_{1,}0^o)]\delta^2 + U(r_{-1,}0^o)\delta^3, \tag{7d}$$

By omitting terms of β^4 magnitude, we obtain the solution with this accuracy, which does not modify weather echoes at a noticeable level as will be shown in Section 3. Eqs. (6a) and (7a) allow obtaining m-m coupled voltages V from measured voltages U for the beams at 0^o and γ directions. Thus by injecting two pulses in two different directions and receiving echoes from those two directions simultaneously, we obtain acceptable estimates of the m-m coupled voltages. So radar can scan two directions over time devoted for one pulse which is equivalent to two times faster scanning. By transmitting three sequential pulses it is possible to triple the scanning rate. Corresponding equations can be derived in a way similar to one used to obtain (6a) and (7a).

3. Using radar data to demonstrate the m-m retrieval procedure

Because the radiation pattern of any future weather PAR should not be worse than what we have for the present WSR-88Ds, it is of interest to assess effects of m-s coupling for time multiplexed transmissions using real storm data and the theoretical WSR-88D radiation pattern shown in Fig.1. This will be accomplished by simulating multiplexed transmissions and simultaneous reception using two beams and actual storm data.

Consider contiguous transmission of two radar pulses in two directions: the first pulse is transmitted in the 0^o direction and the second one is transmitted in the 10^o direction. At $\theta' = 10^o$, the value of $10\log[f^2(\theta' = 10^o)]$ is less than -50 dB (Fig.1). To demonstrate effects of the m-s coupling, time-series voltage data collected with the WSR-88D KOUN were used. We take the KOUN SNR field (Fig.3a) as "ground truth". We then emulate dual-beam multiplexing using contiguous transmission of pulses in the 0^o and 10^o directions and Eq. (2) to calculate the receive echoes from one of the two synthesized received beams (i.e., the 0^o beam) noting for circularly symmetric patterns $\beta(-\gamma) = \beta(\gamma)$. Sidelobe-to-sidelobe coupling is neglected.

To demonstrate the need for low sidelobe levels using beam multiplexing, let's first assume the sidelobe levels at $\theta' = 10^o$ is -30 dB below the mainlobe. Panel (b) presents a the SNR field with m-m coupling, and m-s coupling from two resolution volumes when the coupling factor β^2(dB) = 10log(β^2)= -30. One can see severe errors in the SNR field to the south due to m-s coupled echoes from the strong reflectivity cores with maximal SNR of 65-70 dBZ. These anomalous echoes are due to the m-s coupling caused by the 10^o sidelobes of the second pulse and received by $G_0(r_n)$. This exemplifies unacceptable m-s coupling without application of the m-m voltage retrieval procedure described in section 2c. If we use only the first two terms of the retrieval solution (6), (i.e., $V(0^o,r_0) = U(0^o,r_0) - \beta(\gamma)A_1$) to retrieve the m-m coupled voltages, we can approximately retrieve the true reflectivity field as is shown in panel (c). Although there is substantial improvement in the retrieved reflectivity field, one can see, by comparing panels (3a) and (3c), unwanted residual echoes. So the two-term procedure is not sufficient to accurately restore the field.

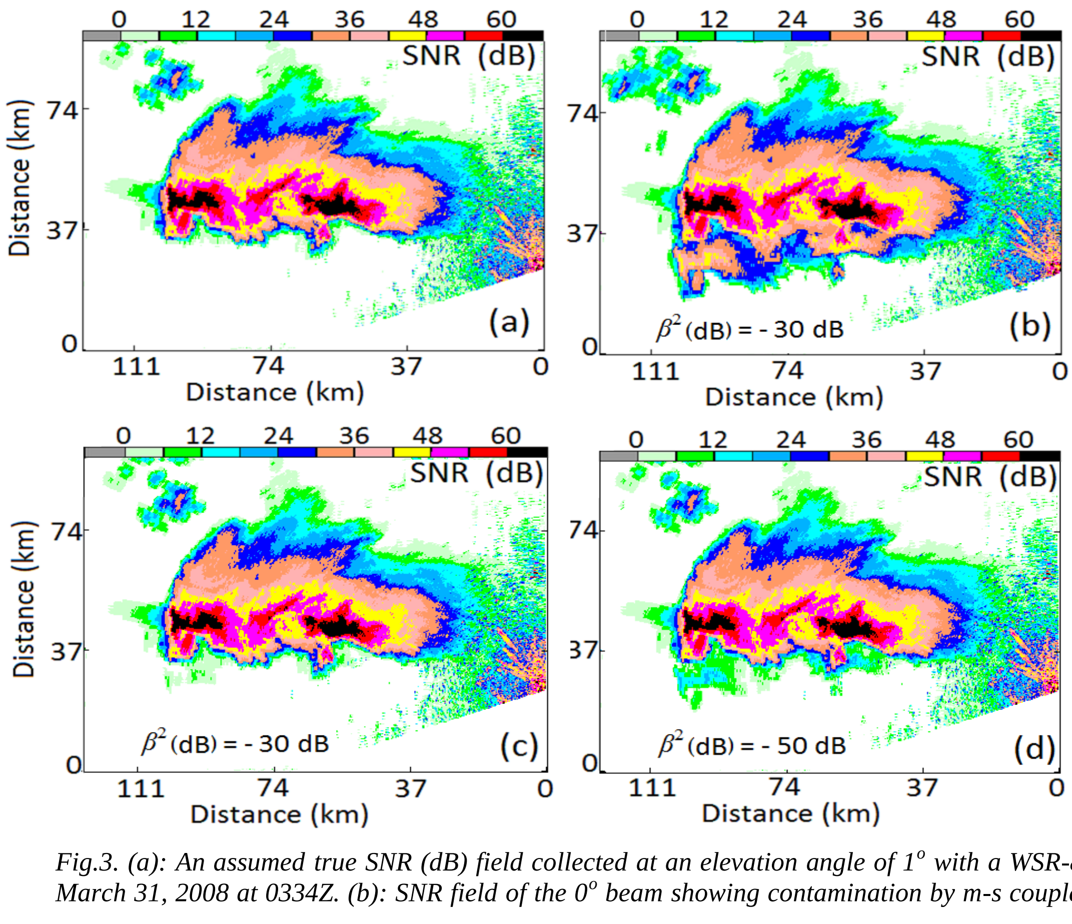

Fig.3. (a): An assumed true SNR (dB) field collected at an elevation angle of 1^o with a WSR-88D (i.e., KOUN) on March 31, 2008 at 0334Z. (b): SNR field of the 0^o beam showing contamination by m-s coupled power when using

dual-beam multiplexing and assuming β^2(dB) = -30. (c): Retrieved SNR field using 2-term procedure (6)-(7) for β^2(dB)= -30. (d): As in (b) but for β^2(dB)= -50.

However, if the first three terms of (6) are used, the retrieved SNR field (not shown here) is practically identical to the ground truth field in panel (a). As discussed earlier, the number of terms in (6) or (7) required to accurately retrieve the reflectivity field depends on maximal differences in the true reflectivity fields at the ranges where the (6) and (7) apply, and the smallness of the voltage coupling factor β. For a moderate sidelobe level of β^2(dB) = -40, the two-term solution is sufficient even if there are reflectivity differences of 100 dB in the two directions and at the ranges will (6) and (7) apply.

Panel (3d) presents the reflectivity field if the m-s coupling factor β^2(dB) = -50. This is approximately the power coupling factor of the WSR-88D for the stipulated beam separation. Although m-s coupled contamination is much less than encountered with -30 dB sidelobe levels, one can see weak ghost echoes to the south from the strong reflectivity cores. This shows that even if sidelobe levels are exceptionally low, m-s coupled echoes will still present a problem to beam multiplexing and corrections need to be applied. However, in this case only the first two terms of (6) are required to retrieve an acceptable SNR field (not shown because it looks identical to panel 3a).

Although this dual-beam multiplexing simulation is not a rigorous demonstration of the retrieval procedure, it shows that under ideal conditions the wanted reflectivity field can be retrieved. More importantly the wanted m-m coupled voltages can be retrieved so spectral moment estimates can be made with acceptable error.

4. Conclusions

The described multiplexed beam method can reduce the update time by a number equal to the number of beams. No frequency agile and phase coding techniques to separate returns from different directions are used in the technique. The method can be compared with the imaging radar concept where one wide transmit pulse is used to illuminate large portion of clouds and multiple beams in receive are synthesized. The difference between these approaches is as follows. a) The imaging radar cannot achieve sensitivity of a single beam radar because transmitted power is injected into a very wide angle. The approach described in this paper has no degradation of sensitivity because all beams have the same power as the power in the single beam radar. b) The imaging radar illuminates a large cloud area so effects of sidelobes from all angles should be taken into consideration. In our approach, few directions can be sampled simultaneously and effects of the sidelobes are eliminated by the restoration procedure eqs. (6-7).

If a sidelobe level of -50 dB is achievable for $\beta^2(\gamma)$ and $\beta^2(-\gamma)$ at angle γ of a PAR antenna, the two-term solutions (6) and (7) are sufficient to obtain true voltages with a power residues below noise. This is valid for the difference in powers at two directions as large as 100 dB. For sidelobe level of -30 dB, the 3-term solution (6) and (7) are needed to bring the power residues below noise.

The described technique allows retrieving the mainlobe-to-mainlobe echoes from their mixt with mainlobe-to-sidelobe returns. Thus all existing signal processing techniques in the WSR-88Ds to resolve range ambiguities and suppress clutter remain the same if this processing migrates into a weather PAR. The only limitation is the duty circle of the transmitter. The duty circle must allow transmitting few pulses with small delays (order of microseconds). In the surveillance scan, a PAR version of the WSR-88D would utilize a PRF of 320 Hz with a 1.57 μs pulse. The duty circle of the WSR-88D transmitter is 0.002, so four pulses can be transmitted in the surveillance scan during the major pulse repetition interval. Data from distances close to the radar is lost due to the successive transmission of multiple RF pulses. For instance, if four 1.57 μs pulses can be transmitted with time delay of 1 μs between them, then the time for transmission is 4x1.57 μs + 3x1 μs = 9.3 μs that equals to 3.1 km of lost distance, which is tolerable because first 5 km of distance are strongly contaminated by ground clutter and typically is not considered as reliable echoes. Transmitting 3 or 4 sequential pulses into different directions allows reducing the scanning rate by factors 3 and 4 correspondingly.

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