6 January 2013

Supplement and errata for the report: "**Polarimetric Upgrades to Improve Rainfall Measurements**; NOAA/NSSL's WSR-88D Radar for Research and Enhancement of Operations; April 1998

The report "**Polarimetric Upgrades to Improve Rainfall Measurements"** has been a useful resource for transferring NSSL research results to the National Weather Service and its contractor. Because the dual polarimetric upgrades have been made to the network of WSR-88D radars at the time of this writing (January 2013), it seemed useful to update the supplements and errata in case users of the data have interest in reviewing the report to learn the underlying engineering results upon which the upgrades have been based. Furthermore, NSSL plans to make measurements of the copolar and cross-polar radiation patterns on KOUN after changes have been made by Barron Services, Inc. These changes to KOUN were to test the performance of the Polarimetric modifications planned for the network before changes were made to the fleet of WSR-88Ds. Thus this report could be useful for comparisons of measurements that were made on KOUN in the 1990s. The supplemental material and errata listed below, a result of the continuing collaboration and exchange between the Radar Operations Center and NSSL, should keep this report correct and current.

Page	para.	Line	
4	2	1	here and every else in the text, change 8.53 m to 8.534 m
		4	ditto, change 0.111 m to 0.1109 m
12	0	6	change to read: '….Thus the scan in Fig.II.4 represents the E plane radiation pattern 0.05^{o} above the principal plane.'
16	1	11	change "might" to "should", and at the end of this paragraph add: "This agreement also suggests that the ad hoc antenna range in Norman is likely suitable for pattern measurements to about the -20 dB level below the radiation peak.
Fig.II.6			change the label: "calculated aperture illumination" to "calculated illumination on the reflector". Although both labels are correct, this is not proven until p.26. At this point we have only calculated the illumination on the reflector's surface.
25-26	5-0		change to read: "In order to support…….near sidelobes for the 0^{o} cut (Fig.II.1a) are principally due to blockages and scatter from spars and imperfections in the reflector's parabolic shape, we calculated the sidelobe levels without feed support spars and assuming a perfectly made reflector.

This calculation gives the radiation pattern outside the ridges of sidelobes due to the feed support spars. We use diffraction theory to compute the ……….(Sherman 1970)"

26 1 1 change to read: "The dashed line in Fig.II.6 is the calculated illumination of the reflector's surface. This calculation used the feed's radiation pattern adjusted for the changing distance from the feed to points on the surface. The angle between……"

2 1-4 change to read: "The calculation of the actual radiation pattern requires numerical evaluation of a Hankel Transform. But, we can obtain an estimate of the radiation pattern by fitting the *aperture* illumination function with an equation for which a theoretical pattern is known. This equation for the...."

3 because θ in this paragraph is different than θ on p.27, change θ to β everywhere in this paragraph.

3 to clarify the derivation of Eq.(II.2), and to correct an error in computing the secondary radiation pattern, change this paragraph to read: "To relate the electric field incident on the surface of the reflector to the aperture illumination function we use the fact that the amplitude of the field at a point 'A' on the reflector's surface is the same as that in the aperture plane at the point which lies on a line passing through point 'A' and parallel to the axis of the reflector (Fradin 1961, p.381). Thus the following normalized power density $S_{\mathbf{n}}(\beta)$ across the reflector's surface is derived from (II.1) by relating ρ to the angle β.

(II.2)

where β is the angle subtended by the line connecting the reflector's vertex to the focus and the line drawn from the focus to a point on the reflector. But the reflector illumination $S_{\mathbf{n}}(\beta)$, calculated from the measured primary radiation pattern, is the same as the illumination across the aperture. Therefore the radiation intensity given by the dashed line in Fig.II.6, and the intensity given by (II.2), are both the aperture illumination function. The factor raised to the m^{th} power ……… ………and its diameter $2\,\rho_{\mathbf{o}} = 8534$ cm into (II.2), we have plotted in the revised Fig.II.6 (next page in this errata) the theoretical aperture distribution for m = 3 (the fitting was tested for m = 2, 2.5, and 3; m = 3 produced the best fit to the dashed curve in Fig.II.6 over the angular interval $\pm 45^{\circ}$. This angular interval is where the illumination is most intense. The curves for m = 2.5 and 2.0 fit the calculated aperture illumination better near the edge of the reflector, but there the illumination is weakest. It is most important to have the best fit of a theoretical aperture distribution at locations where the illumination is most intense."

27 1 5 change to read: "….pattern (for m = 3, and b = 0.16) and …."

Eq.II.3 this equation should be revised to:

$$S(u) = 20\ \text{Log}_{10}\left[5.405\left|1.68\frac{4!J_4(u)}{u^4} + 0.16\frac{J_1(u)}{u}\right|\right] \qquad \text{(II.3)}$$

where

$$u = \frac{2\pi\rho_o \sin\theta}{\lambda}, \quad 2\rho_o = 8.534, \quad \lambda(\text{KOUN}) = 0.1109\,\text{m}, \qquad \text{(II.4)}$$

and θ is the zenith angle measured from the axis of the reflector. This theoretical function ignores changes in sidelobe levels due to spar blockage and reflector surface departure from a parabolic shape. The first term in this equation is the secondary radiation pattern due to the tapered illumination [i.e., the first term in (II.1)], and the second term is due to the uniform illumination of the aperture [i.e., the second term in (II.1)].

27 2 1 change to read: "Eq.II.3 is plotted on the revised Fig.II.7 for $0 \le \theta \le 20^o$ and compared with the envelope of sidelobes (the dashed dotted line) deduced from patterns measured by Andrew Canada (Paramax Report, p. C-6) for the same polarization……"

28→29 1, 2→0 replace these two paragraphs with:

"Measurements of KOUN's main lobe (i.e., the dots in Fig.II.7) agree reasonably well with the theoretical pattern down to the -15 or -20 dB level; thereafter, antenna range artifacts (i.e., scatter from buildings, terrain, etc.) make pattern measurements unreliable. These data points are obtained from KOUN pattern measurements [i.e., Fig.II.8(c); a 0^o cut]. Thus these data can also be affected by spar blockage, reflector surface perturbations, and the radome. The KOUN side lobe level for the 0^o cut (i.e. the dashed line) is from Fig. II.8(b); this cut passes along the ridge of enhanced sidelobes due to spar blockage. Sidelobes measured for KOUN are less than a couple of dB larger than those 0^o cut measurements made at the Andrew Canada range for a reflector without a radome. The measured KOUN sidelobe level increase over that seen from Andrew Canada's data is partly due to the radome (Section II.1.2.4). The solid line is the worst case sidelobe levels specified for the WSR-88D and it is seen that the increase in sidelobes due to spars and radome falls below this specified value. The dashed dotted line is the eye-balled envelope of the sidelobes on the left side of the pattern (page C-6 of Paramax Services Corp., 1992) for the 30° cut. The 30° cut falls between the ridges of enhanced sidelobes due to spar blockage.

Fig.II.7 Due to an error in normalization this figure has been corrected.

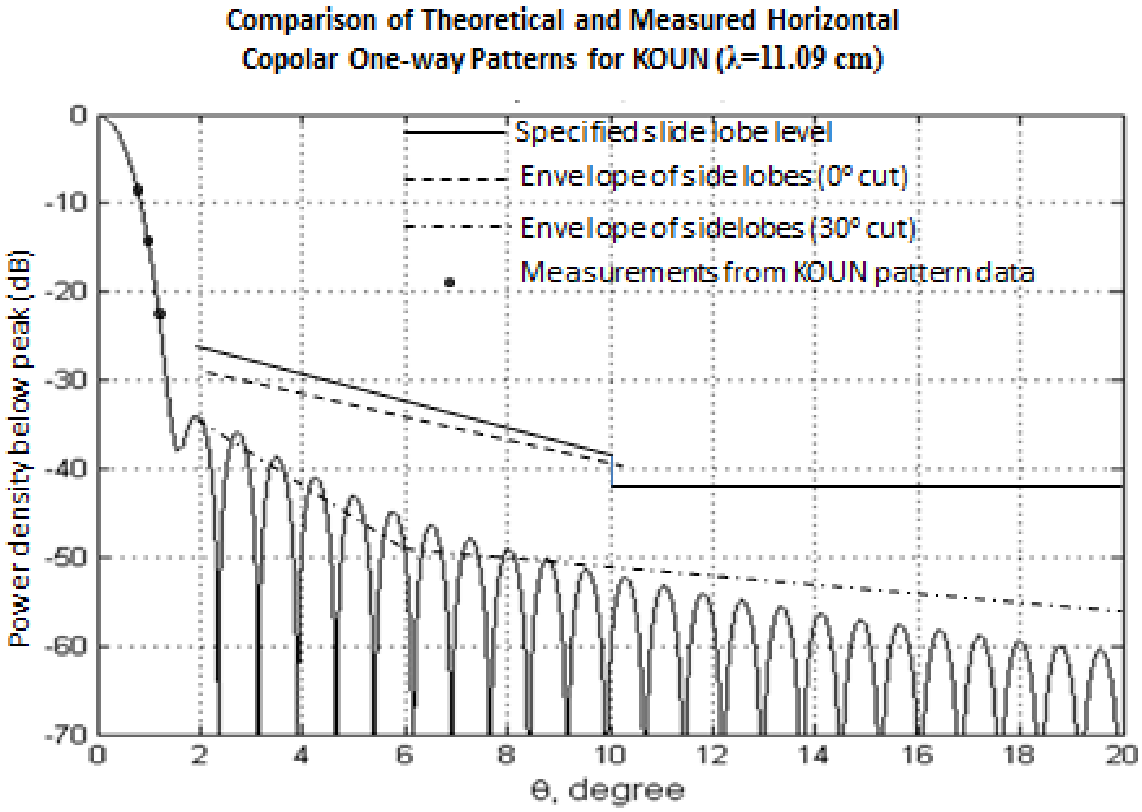

Fig.II.7 KOUN's theoretical copolar radiation pattern calculated from (II.3). Also shown is the approximate envelope (dashed dotted line) of the peak side lobes measured (without radome for the 30° cut) on Andrew Canada's antenna range[1]. The dashed line is the envelope of KOUN sidelobes that form a ridge of enhanced sidelobes (due to feed support blockage) along the 0° cut and is obtained from the right side of Fig.II.8(b). The solid line is the specified worst case

1 This envelope is obtained from the left side of the pattern plotted in Fig.C-6 of the Paramax Systems Co. Report (1992). The left side pattern shows a systematic decrease of sidelobe suggesting less influence from artifacts on the antenna range that appear to affect the pattern on the right side. Higher measured sidelobe levels beyond 8° are likely due to imperfections in the shape of the reflector and artifacts of the antenna range. The 30° cut sidelobe level of the center-fed WSR-88D reflector is practically the same as that obtained for an offset-fed reflector that has no blockage associated with feed support spars (compare Fig.II.7 with Fig.7 of Bringi, et al., JTECH. 2011) suggesting the illuminations of both reflectors are the similar. Thus the most significant advantage of the offset parabolic reflector is the lack of sidelobe ridges due to feed supports blocking secondary radiation. Although this ridge of sidelobes occupies a fraction of the entire radiation pattern, it is several dB larger than the levels outside the ridge as seen in this figure. These enhance sidelobes can cause meteorological measurement error if the ridge of sidelobes illuminates regions of significantly enhanced reflectivity. Theoretical sidelobe levels beyond 6° are principally due to the second term in (II.3).

acceptable WSR-88D side lobe levels. The main lobe measurements points are obtained from Fig.II.8(c) KOUN right side pattern data after change to a dual polarimetric feed.

29 1 1-9 change to read: “The following formula

$$\theta_1 \simeq 1.27\frac{\lambda}{D}(\text{rad.}) . \qquad \text{(II.5)}$$

fits well the measurements and the theoretical curve (i.e., 0.946° from (II.5) and 0.95° from the theoretical curve. Although this formula applies well for KOUN at the wavelength of 11.09 cm, this theoretical expression also applies well for the WSR-88Ds operating in the band 11.11 to 10 cm (i.e., 2.7 to 3.0 GHz). For example at λ = 10 cm (II.5) gives θ_1 = 0.853°; this compares reasonably well with 0.85° measured by Andrew Canada (Paramax, 1992 pp. C-55, C-57). The Andrew Canada reported measurements (i.e., for horizontally polarized waves; the feed used in the legacy radar transmitted only H polarized waves) at each of the selected wavelengths are an average of five measurements made at different cuts across the beam. Furthermore, measurements made by Seavey Engineering (Barron Radar, 2009, p.22), in 2009 on another WSR-88D reflector illuminated with 11.11 cm H radiation from another dual polarimetric feed gives a beam width of 0.95°, also in good agreement with that derived from the formula. However, Seavey measurements are subject to more error because they are widths obtained from one pattern cut. Moreover, because feed horns are different, there is no expectation that the beamwidths measured by Seavey Engineering should be in exact agreement with those measured by Andrew Canada. Nevertheless, based upon the few available data, the theoretical formula $\theta_1 = 1.27\lambda / D_a$ appears to provide, for the WSR-88D antennas, beamwidths with accuracy better than 0.1° over the entire operating band of frequencies.

The angular diameter θ_0 of the first null circle (the first null circle is a minimum not a zero) obtained from Fig.II.7 for KOUN is 3.1°. The good agreement of formula the half power beam width for operation in the entire band suggests that the angular diameter of other WSR-88D radars can be obtain from the formula

$$\theta_0 = 4.16\frac{\lambda}{D}(\text{rad})$$

(II.6)

The angular diameter of the first null circle defines the main lobe or beam of the antenna. Substituting into (II.6) gives $\theta_0 = 3.10^{\circ}$ for KOUN. Comparing with that 3.45° measured by Andrew Canada [i.e., Fig.II.2(b) right panel] and that measured by NSSL for KOUN [i.e., 3.56° from Fig.II.8(c)], it is seen both independent measurements agree to within 0.1 dB, but differ significantly from the 3.1° obtained from (II.6). The measured null location is subject to significant error because the antenna range is not ideal (i.e., measurements more than 20 dB below the main lobe peak are subject to significant errors induced by scatterers on the antenna range). However the null circle diameter obtained from II.6 is in excellent agreement with the theoretical value of 3.12° obtained by interpolating data in Table 2 of Sherman (1970).

2 — delete this paragraph because it no longer applies to the revised Eq.II.3.

32 1 6-8 — change 1.04° to 0.95° and deleted the last sentence.

34 3 2 — change to read: "…illustrates that the cross-polar radiation along the…"

6 — change to read: "….is expected for center-fed circularly symmetric…"

9 — add: (4) reflection of the copolar beam from the ground and conversion of H polarization to V polarization when the beam is at low elevation angles.

36 1 — at the end of this paragraph add:

For example, if the cross-polar and copolar fields are in or out of phase, a null in the on axis radiation would be achieved by rotating the source antenna by $\frac{\pi}{2} \pm \tan^{-1}(E_{\mathbf{xp}} / E_{\mathbf{cp}})$ where $E_{\mathbf{xp}}$ and $E_{\mathbf{cp}}$ are the cross-polar and copolar field amplitudes along the boresight. Thus a -32 dB on-axis cross-polar peak could be nulled by a 1.4° tilt of the source antenna, a sufficiently small angle that it might not be noticed by eye. If the cross-polar and copolar were in phase quadrature, a minimum in signal having the magnitude of the cross-polar radiation would be observed. Thus nulling the cross-polar radiation by rotating the source antenna requires measurements of its orientation to insure that purely H and V radiation is transmitted or received. This would verify whether the antenna under test transmitting purely H and V radiation.

37 — at the top of this page insert the following paragraph:

In support of the contention that an on -axis peak of cross-polar radiation exists for the WSR-88D (and perhaps for the CSU antenna), we refer to the work of Potter (1963). Potter states that in order to obtain circularly symmetric beams for both the H and V polarized waves from a circularly symmetric feed, a TM_{11} mode should be excited within the throat of the feed. Potter presents radiation patterns of this feed showing excellent symmetry of the copolar radiation pattern. On the other hand, there also is a pronounced on-axis peak in the cross-polar radiation! This peak in cross-polar radiation is about 33 dB below the copolar peak, in remarkable agreement with the WSR-88D cross-polar peak observed in Fig. II.6. It is therefore suggested that the cross-polar peak is due to the purposely excited TM_{11} mode in the throat of the WSR-88D feed.

	1		delete the first sentence and change the second sentence to " Comparing the CSU and WSR-88D…"
	2		last line: Change II.6.4 to II.6.7.
39	1	1	change "Section II.3" to "Section II.6.2"
40	2		at the end of this paragraph add: On the other hand, because the antenna range is not ideal, achieving a null by rotating the standard gain horn does not necessarily imply that the null is a characteristic of the cross-polar pattern as discussed in the next paragraph,
41	0	6	change "less" to "more"
		7-8	change to: "…a few dB below this level (i.e., -33 dB) could also be in error as also mentioned in Sections II.6.5 and II.6.7. Thus it is also not surprising that KOUN's copolar sidelobes…."
	0		at the end of this paragraph add: "To obtain better measurements of the cross-polar fields, we made additional measurements described in Section II.6.7.
42	2	4	change "Section II.6.7" to "Section II.6.6"
44	0	5	Figs.II.13a, b should be Figs.II.11a, b.
46	1	5	insert after "…dB level.": The significant differences at azimuths larger than plus/minus 1^{o} could be due to scatter from artifacts (i.e., buildings, utility poles, tress, etc.) associated with the antenna range in Norman,. Also, bear in mind…"

		10	change to: "…scan for the 0^o elevation cut are more likely…
		11	delete this last line.
46			the equation should be placed after the second line of the third paragraph
49	2	1	change to read: "Cross-polar radiation (e.g., A_v) combines with copolar radiation (e.g., A_H) to form, in general, …."
		9	change to: "….(Fig.II.A.1 in which the ellipse collapses to a line for linear polarization). τ is positive…"
	3	1	change to: "..between the vertical (cross-polar) and the horizontal (copolar) fields is not 0…"
	Eq (II.8)		the equality symbol should be replaced by an approximation symbol.
		5	change to: "….Appendix (i.e., Section II.8)…"
		6	delete the parenthetical phrase.
		7	change "receiver" to "transmitter".
50	2	3	change to: "…The standard gain horn, transmitting H or V polarized waves, was rotated until a minimum was established in the KOUN's V or H receive channel. That a minimum was achieved and not a zero (i.e., not a sharp and deep null) suggests the cross-polar field is in phase quadrature to the on-axis copolar field. The amount of …."
Fig.II.A.1			replace E_{vo} and E_{Ho} respectively with A_v and A_H.
55	3	4	change to: ....which RHC (or LHC) was chosen for transmission and LHC (or RHC) was chosen for reception....
56	Eq.(III.1)		for modifications to this equation if the antenna transmits both copolar and cross-polar waves , see Supplements on pages 240-241 in the errata to the book "Doppler Radar and Weather Observations" Academic Press, 1993. These errata are periodically updated and posted on NSSL's website at www.nssl.noaa.gov. In the "Quick Links" box select "Publications" to open the page to select "Recent Books" to find the book and listed Errata for the 3rd and 4th printings.
57	0	5	change "polarizabilities" to "susceptibilities".

		11-12	modify these lines to read: ".... the wave.normal ***k***, the apparent canting angle ψ, the true canting angle ψ', and δ."
	1	12	change to read:....because $4\pi\langle|s_{hh}|^2\rangle \equiv \sigma_b$ (McCormick and Hendry, 1975), it is seen...."
58	0	1	change to read:......scatterer's properties ***X.***
61	4	5	last line change to: "….the incident field. Canting angles are…"
62	0	9	delete the phrase "(III.21) assumes that the phase difference at transmission is zero,"
	1	1	change to: "The transformation matrix $\boldsymbol{V}^{(\mathbf{T})}$, which relates…"
		2	change to: "….[E_h, E_v] as it leaves the antenna to the polarization state of the scattererd wave returned to the antenna, is,
	(III.22)		delete the first matrix.

After (III.22) insert:

In the balance of section III.1 it is assumed that H, V waves are alternately transmitted, but simultaneously received (i.e., the ATSR mode). Noting that there is no cross-coupling within the antenna, the signals received are:

$$\begin{bmatrix} V_{\mathbf{hh}} & V_{\mathbf{hv}} \\ V_{\mathbf{vh}} & V_{\mathbf{vv}} \end{bmatrix} = \boldsymbol{V}^{(\mathbf{T})} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ or } \boldsymbol{V}^{(\mathbf{T})} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

in which the transmitted E_h and E_v are assumed to have unit amplitudes and no phase difference.

		8	change to: "..resolution volume), and the diacritical tilde (~) denotes a measured parameter."
63	1	1	change $\tilde{L}DR_{\mathbf{vh}}$ to $\tilde{L}dr_{vh}$
64	0	1	change to read: ...a column vector $[E_r, E_l]^t$ of the ....
		2	change to read: ....is the column vector $[E_h, E_v]^t$ for linearly polarized waves, and....
	Eq.III.28		the first and last matrices of this equation should be

$$\begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix} \cdots\cdots\cdots \begin{bmatrix} 1 & 1 \\ -j & j \end{bmatrix}$$

	Eq.III.29		the signs of 'j' need to be changed
65	Eq.III.31		sign of 'j' needs to be changed (note the polarity of 'j' in Eqs.30 and 31 are opposite to that used by Torlaschi and Holt in order to be consistent with the convention chosen in our report)
	2	2	change III.3.0 to III.30
	Eq.III.32		sign of 'j' in the lower of the two equations needs to be changed
	2	5	delete "a solution valid even if drops are not equi-oriented"
	Eq.III.33		the 'j' sign multiplying φ_{DP} needs to be +, and $\langle s_{hh}s_{vv}^{*}\rangle$ should be $\langle s_{hh}^{*}s_{vv}\rangle$.
66	1	1	Change III.3.3 to III.33
	Eqs.III.34, 35		make the same changes as done for Eq.III.33
	1	13	change III.3.5 to III.35
	Eq.III.36		the sign multiplying the *Real part* in the numerator needs to be +
	3	5	change to read: ....., which is often the product of....
67	2	7	change copolar to cross-polar
70	1	8	delete "linear"
83	2	3	modify to read:......and that all drops are of the same size and shape, and that they do not vibrate nor are they canted within
84	0	9	change to read: Because all drops are identical, the $V_{h'}$......
94	Fig. IV.7		change caption to read: .....Z_{DR} varies from -1 to +3 dB in the ....
95	2	2	change Z_{DP} to K_{DP} at both places
98	Eq.IV.29		change $\lvert\rho_{hvm}\rvert$ to $\lvert\rho_{hvm}(0)\rvert$ and ρ_{hv} to $\lvert\rho_{hv}(0)\rvert$

	1	1	change $\lvert\rho_{hvm}\rvert$ to $\lvert\rho_{hvm}(0)\rvert$
		2	change ρ_{hv} to $\lvert\rho_{hv}(0)\rvert$; delete $\lvert\rho_{hv}(0)\rvert$ at the beginning of the sentence and change to read: This bias, obtained from (IV.29), is plotted.....
98-100 last line			change to read: ...the added change in K_{DP} would be about 0.03^{o} km^{-1}...
100	1	7-8	change to read:......the capability to simultaneously transmit H, V waves, but to alternately receive the reflected H, V waves in a single receiver through the use of a low power switch; this mode of operation......
101 Fig. IV.12			labels on some of these figures are incorrect. The dimension of K_{DP} is degree per km; ρ_{hv} has no dimension, and Z_{DR} has dimensions of dB.
List of References			Insert: Potter, P. D., 1963: A new horn antenna with suppressed sidelobes and equal beamwidths. *The Microwave Journal,* June, pp. 71-78.