9.3 OPEN RADAR DATA ACQUISITION (ORDA) CALIBRATION CONSISTENCY

Alan D. Free*
SI International, Norman, Oklahoma

Nita K. Patel and Robert W. Macemon
RS Information Systems, Inc., Norman, Oklahoma

1. ABSTRACT

Radar calibration depends on the accurate measurement of several system-unique variables used in the radar equation. Accurate measurements of antenna gain, system noise, receiver gain and transmitted power are vital in computing reflectivity. This paper investigates Open Radar Data Acquisition (ORDA) automatic calibration techniques to consistently and accurately measure these changing variables in the WSR-88D. The paper also explores the variability added by the technician's measurement of calibration parameters. Finally, the paper shows how changes in particular system-specific parameters used to compute reflectivity affect accuracy.

2. INTRODUCTION

Several parameters determine the measured reflectivity for any given radar system. Some of these parameters vary daily while others shift only slightly over long periods of time. Nevertheless, any uncompensated shift adversely affects computed reflectivity accuracy. Calibration is the process of measuring these shifting parameters and applying measured offsets to obtain consistently accurate reflectivity measurements.

In the WSR-88D system, the calibration accuracy is specified to be within 1dB. That is, computed reflectivity values should be no more than 1dB different from absolute measurements. Achieving this level of accuracy requires consistent and fault tolerant calibration measurements using accurate and inherently stable test signals.

3. CALIBRATIONS

Calibration of the WSR-88D from transmitter to receiver consists of measuring transmitter power, measuring system noise floor, measuring gain/loss of all components in the receiver signal path, computing an error offset for reflectivity and measuring antenna system parameters, namely, antenna gain and pointing accuracy.

Parameters contributing to reflectivity accuracy, transmitter power, noise level and receiver gain linearity, are measured during the on-line calibration each Volume Coverage Pattern (VCP). Off-line System Test Software (STS) calibration functions provide additional detail, measurements of slowly varying parameters and assist in system verification, maintenance and troubleshooting.

3.1 ORDA Receiver Signal Path

The ORDA design is functionally similar to the Legacy receiver signal path; however, the ORDA receiver signal path has replaced Legacy matched filtering, A/D conversion and signal processing with a SIGMET Intermediate Frequency Digitizer (IFD) and signal processor (RVP), as shown in Figure 1. The ORDA design digitizes IF signal while maintaining all WSR-88D receiver specifications (such as dynamic range and sensitivity). Digitized IF and overall ORDA re-design of the Legacy receiver signal path reduces noise and improves receiver performance and reliability.

* *Corresponding author address:* Alan D. Free, SI International, 2227 W. Lindsey St., Suite 1500, Norman, OK 73069; e-mail: Alan.D.Free@noaa.gov

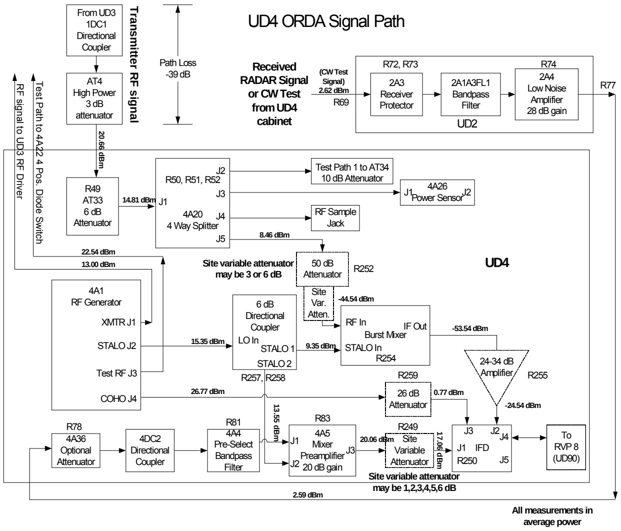

Figure 1: ORDA Receiver Signal Path

3.2 Test Path

The WSR-88D system has four built-in test signals used for calibration, diagnostics and system performance checks. Typical values for each test signal through the receiver path are provided in Figure 2.

- Continuous Wave (CW) – constant level test signal at RF frequency
- RF Noise Source (NOISE) – broadband noise source
- Klystron Delayed (KD) - sample of the transmitter output, delayed by 10 μs
- RF Drive (RFD) – sample of the RF drive signal input to the Klystron

The CW signal is used during calibration to measure system linearity and dynamic dange. The RF NOISE test source is used to measure system noise temperature. The KD test signal is used for clutter suppression measurements. The RFD test signal is used in offline diagnostics.

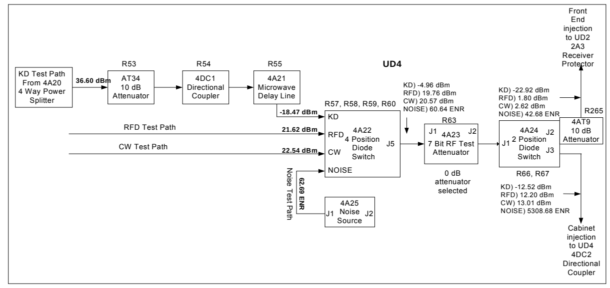

Figure 2: ORDA Test Path

3.3 On-Line & Off-Line Calibrations

On-Line Calibration is performed during system startup, periodically in standby and during each VCP retrace, i.e., transition from end of a particular VCP to the start of the next VCP. Table 1 details the procedures run during the on-line and off-line calibrations in the ORDA system. Off-line calibration is available through the off-line System Test Software (STS).

Off-Line STS is used to validate calibration standards and build-in test sources. STS uses externally calibrated test equipment when necessary to measure, compare and correct signal levels and signal path losses in site-unique adaptation data.

Table 1: On-line and Off-line Calibration

Test	On-line	Off-line
System Noise		
Short Pulse	☑	☑
Long Pulse	☑	☑
Noise Temperature	☑	☑
Reflectivity Correction (dBZ_0)	☑	☑
System linearity		
Linearity	☑	☑
Test Attenuator Calibration		☑
Velocity/Spectrum Width		
I/Q Processing	☑	☑
External Phase Shifter		☑
Power Meter Zero	☑	☑
Transmitter Power	☑	☑
Error estimates		
Short Pulse		☑
Long Pulse		☑
KD Check		
KD power		☑
Clutter Suppression		☑

CW Substitution		☑
Suncheck Az/El Offsets Antenna Gain		 ☑ ☑

4. REFLECTIVITY EQUATION

The generic weather reflectivity radar equation for Rayleigh scattering when converted to WSR-88D units is defined in Equation 1 with each parameter described in Table 2.

$$Z_e = S \times R^2 \times \frac{1}{L_P} \times \frac{2^{10} \times 180^2 \times \ln(2) \times 10^{20} \times \lambda^2}{\pi^5 \times P_T \times G^2 \times \theta^2 \times c \times \tau \times |K|^2 \times L}$$

Equation 1

Table 2: Reflectivity Equation Parameters

	Description	Units
λ	Wavelength	cm
π	Pi	none
K	Refractivity	none
S	Input Signal ($S = P_R - N$) where *P_R* is the Power received and *N* is System Noise.	mW
P_R	Receive Signal	mW
P_T	Transmit Power	kW
N	Noise	mW
R	Range	km
L	Losses ($L = L_t \times L_r \times L_d \times g$) L_t is transmitter waveguide loss L_r is receiver waveguide loss L_d is receiver detection loss g is receiver gain	dB
τ	Pulsewidth	μsec
G	Antenna Gain	none
c	Speed of Light	m/sec
K	Refractivity	none
L_P	2-way atmospheric propagation loss $L_P = R \times a$, where *R* is range and *a* is atmospheric attenuation	dB
a	Elevation dependent atmospheric loss per 2 km (round trip)	km^{-1}
g	Receiver Gain	none
θ	Beamwidth	degrees

Many of these parameters are constants or relatively time invariant. The ORDA system regularly monitors and adjusts the following critical performance parameters: Transmit Power (P_T), Noise (N), and Receiver Gain (g). Additionally, the wavelength (λ), Antenna Gain (G), and Losses (L & L_p) are measured periodically during system maintenance or when relevant system components are replaced

5. SYSTEM CALIBRATION COMPONENTS

The performance parameters determine system calibration and the system's ability to accurately measure reflectivity, velocity and spectrum width. The ORDA system outputs 1km reflectivity moment data computed using Equation 2.

$$dBZ = 10\log\left(\frac{P_R - N}{N}\right) + 20\log(R) - A \times R + dBZ_0$$

Equation 2

Where P_R is the return signal power, N is the noise value corrected for elevation, R is range, A is the two-way atmospheric loss in dB and dBZ_0 is the system calibration constant, computed using Equation 3.

$$dBZ_0 = 10\log\left(\left(\frac{2^{10} \times \ln(2) \times 10^{20} \times 180^2}{\pi^5 \times c}\right) \times \left(\frac{\lambda^2}{G^2 \times \theta^2 \times \tau \times |K|^2 \times L_d}\right) \times \left(\frac{1}{P_T \times L_t}\right) \times \left(\frac{1}{L_r}\right) \times \frac{N}{g}\right)$$

Equation 3

dBZ_0 represents the reflectivity of a 0dB Signal-to-Noise target at a range of 1km, and includes all the constants in the radar equation (Rinehart, 1997 and SIGMET, 2005).

Equation 4 provides a concise equation for computing the system calibration constant with all inputs measured in dB.

$$dBZ_0 = C + A - P_a - L_{dBr} + I_0$$

Equation 4

Where C are the constants from the general radar equation, A is the sum of applicable adaptation data constants (i.e., wavelength, antenna gain, beamwidth, pulse- width, matched filter loss, and refractivity), P_a is transmit power radiated into space, L_{dBr} is the receiver loss from antenna to receiver input, and I_0 is the 0dB signal-to-noise value at the receiver input (i.e., the receiver Minimum Detectable Signal (MDS)).

C, A, and L_{dBr} are constants and relatively time invariant; therefore, these parameters are measured in Off-line STS functions. I_0 and P_a are the only variables in the dBZ_0 equation that frequently vary; therefore, these parameters are measured periodically. Accurate I_0 measurements are dependent on precise System Noise measurements.

5.1 Noise, N

Many types of noise contribute to the total noise within a receiver; however, for the WSR-88D, the predominant noise source is thermal noise (Free, 2005). Active components in the receiver, particularly the Low Noise Amplifier and the Mixer/Preamp, add phase noise, shot noise and non-linearities. Additionally, the IFD contributes quantization noise and sampling noise from the A/D converter and the input clock.

In the ORDA design, the IFD quantization noise affects are constant over the entire dynamic dange as opposed to the variable quantization noise induced by the AGC circuitry present in the Legacy receiver signal path. Nevertheless, these noise quantities are orders of magnitude less than the thermal noise contribution through the entire transfer range of the receiver. Therefore, the thermal noise is the dominant contributor to any variations in the measured System Noise floor. Depending on system waveguide configurations and other receiver path components, noise measurements from system to system typically vary from 1dB to 2dB.

5.1.1 Noise Measurement Technique

System Noise measurements provide a measure of the receiver path. Noise is measured with the transmitter off, i.e., non-radiating. When in standby, Noise is measured with the antenna in parked position (nominally 0° azimuth and 23° elevation). Operationally during VCP retrace, the measurement is made with the antenna above 3.5° in elevation to avoid bias due to ground noise. No test signals are injected during noise measurements. 5000 I/Q samples along a span of 10 radials are used in computing the WSR-88D System Noise floor.

The actual noise level measured by the signal processor is based on the thermal noise temperature at the front end, the system bandwidth, receiver gain and the thermal noise temperature contributed by the receiver components using Equation 5.

$$Noise_{dBm} = 10\log(kB(T_{ant} + T_{Rx})) + g + 30$$

Equation 5

Where k is Boltzman's Constant, B is the receiver noise bandwidth, T_{ant} is the thermal temperature at the front end, T_{Rx} is the noise contribution of the receiver and g is the receiver gain from the Receiver Protector to the IFD.

5.1.2 Elevation Dependence

Noise is dependent on the measurement elevation due to extra noise contributions from ground noise and antenna sidelobes. As a result, the WSR-88D only measures the System Noise floor at an elevation greater than 3.5° and then compensates this measured value for lower elevation angles. Test results from the Norman, OK radar (KCRI) shows noise measurement dependence on elevation (Figure 3).

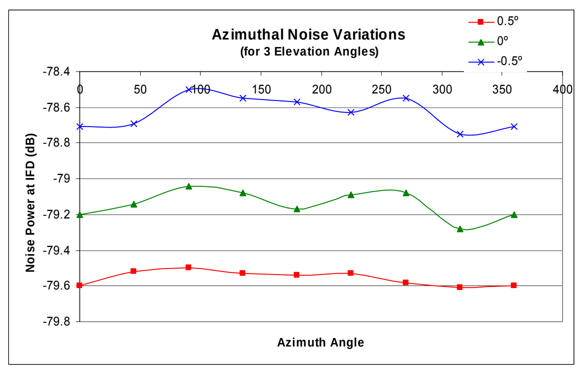

Figure 3: Azimuth and Elevation Noise Changes

For low elevations, the System Noise parameter is adjusted by an elevation scale factor representing the influence of ground noise on the measurement. Figure 4 shows the WSR-88D fleet-wide average of the elevation scale adaptation data values.

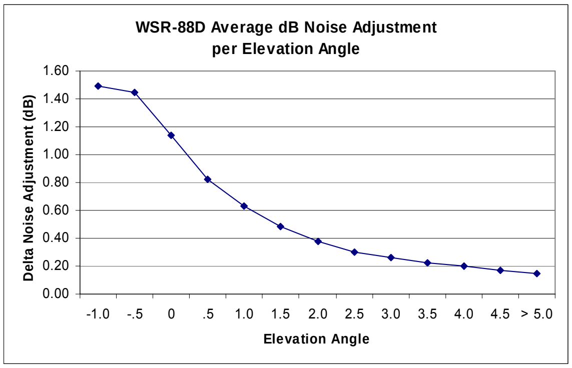

Figure 4: Noise Adjustment per Elevation Angle

5.1.3 Pulsewidth Dependence

In ORDA, the System Noise is measured in both short and long pulse to obtain accurate system calibration for both short and long pulse VCPs. ORDA uses digital matched filtering; therefore, the filter parameters are optimized for both short and long pulse independently. Since the matched filter loss is a contributor to the System Noise measurement, independent computations are made for the different pulse widths. This is different from the Legacy design, in which a single matched filter optimized for short pulse was used. In Legacy computations, an offset was added to the short pulse measurement to obtain the long pulse System Noise value.

With the 14-bit, 72MHz IFD, the noise level with the input terminated at 50Ω is nominally given as –85dBm/Mhz. With a 600KHz bandwidth for short pulse, this translates into a noise level of approximately –87dBm (N_{IFD}) at the IFD input. Terminated at the antenna, the System Noise floor in short pulse is adjusted to approximately –81dBm (N_{FE}). The long pulse noise floor is approximately –85dBm. The primary contributor to the difference in the noise floor between short pulse and long pulse is the differences in the matched filter bandwidth, 600KHz for short pulse and 200KHz for long pulse.

5.1.4 Beta Site Noise Data

An analysis of ORDA beta site logs indicates that ORDA System Noise is very stable. Results from ORDA Beta systems show noise variations around 0.1dB for consecutive noise measurements, and within 0.2dB for long-term measurements. Further, seasonal temperature differences will affect noise readings since ambient temperature noise is reflected in the sidelobes and backlobe of the antenna. Therefore, some variation in the System Noise measurements will be seen in long-duration analysis.

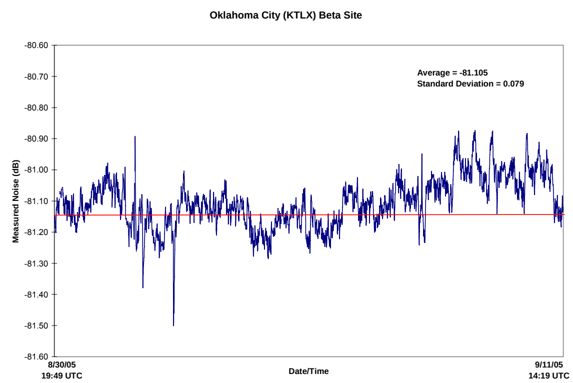

Figure 5: KTLX Noise Measurements

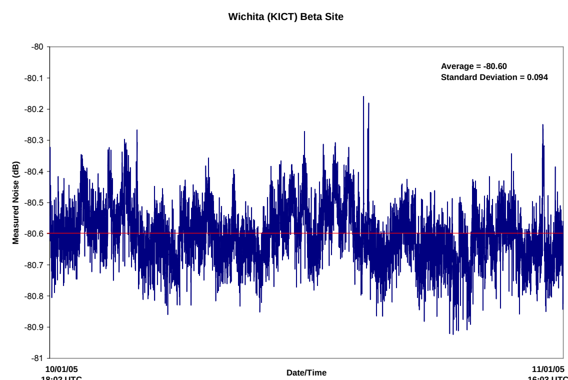

Figure 6: KICT Noise Measurements

5.2 Transmitter Power, P_t

In addition to the System Noise floor, the transmitted power directly affects system calibration. Along with Noise (N) and receiver gain (g), transmitted power can fluctuate during system operation; therefore, P_t is measured periodically.

P_t is measured during the surveillance cut of each VCP and also during the Performance Check. During a VCP cut, the system measures the average power of the transmitter once a second. The samples are averaged together and corrected for the duty cycle to obtain the transmitter peak power. During the Performance Check, a similar procedure is used; however, samples are obtained at one-second intervals with the antenna parked.

The transmitter design was not modified in the ORDA architecture; therefore, the design is the same as that available in the Legacy WSR-88D configuration. Nominal transmitter peak power is 700kW.

Because the WSR-88D system uses an average power meter to measure power, the zero level (i.e., bias) is important. The Power Meter Zero procedure is done during on-line calibration to verify a slight positive bias exists on the power meter thereby ensuring accuracy of power measurements when radiating.

5.2.1 Beta Site Transmitter Power Data

The transmitter shows excellent stability over time, generally within 0.1dB (approximately 15kW at 700kW) as shown in Figures 7 and 8.

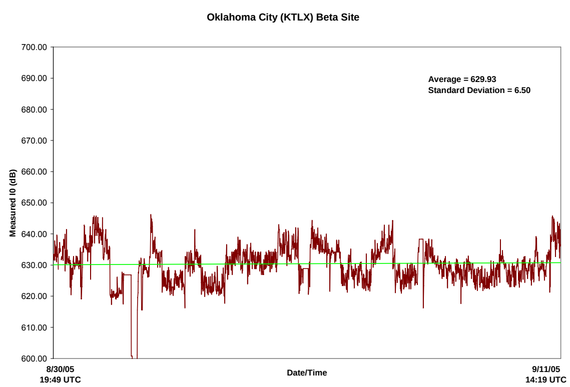

Figure 7: KTLX Transmitter Power

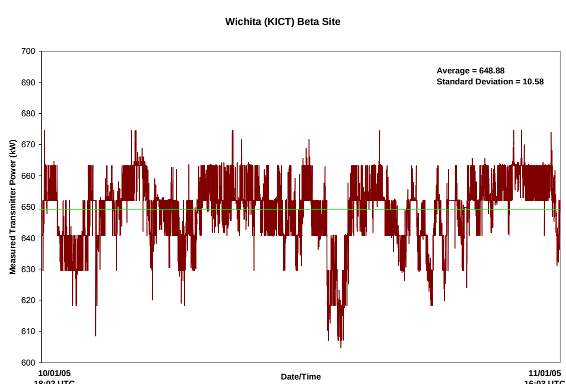

Figure 8: KICT Transmitter Power

5.3 Receiver Gain, g

The receiver gain is the overall gain of the signal path from the Receiver Protector input to the signal's digitization in the IFD. Nominal receiver signal gain for the WSR-88D in the ORDA configuration is 33dB. Therefore, a noise level of -81dBm measured at the IFD corresponds to a noise level of -114dBm at the input to the Receiver Protector.

Measuring receiver gain requires injecting a test signal with known amplitude into the receiver protector and measuring the resulting signal through the receiver path. In the ORDA design, CW Test signals are used and the CW test signal power is measured off-line by the technician. To reduce variance and detect problems, 10 different level test signals throughout the linear range are used for each on-line calibration.

5.3.1 Sensitivity, I_0

For calibration, receiver gain is added to the System Noise level to determine system sensitivity, I_0. System sensitivity represents the power level of a 0dB Signal-to-Noise target measured at the receiver input. I_0 provides a measure of the linearity of the system as well as the Noise floor of the system. Nominal ORDA sensitivity is -114dBm, which correlates to Legacy sensitivity values of nominally -113dBm.

5.3.2 Linear Transfer Curve

Linear system response is vital to ensure system accuracy. The linear slope of the receiver over the IFD's Dynamic Range is expected to 1.00 (that is, measured power equals input power). The excellent linearity of the WSR-88D receiver is seen in Figure 9 in which the slope is 1.0003 and the variance is a negligible 0.0053. Further, all the data points in the linear region conform to the curve. The WSR-88D receiver displays excellent linearity until the signal level reaches within 1-2dB of the 1dB compression point. The low end, where the noise floor affects the signal, shows expected behavior with no anomalies.

5.3.3 Dynamic Range

The Dynamic Range is defined as the difference between MDS (S/N ratio is 0dB) and the IFD's 1dB compression point, where the signal deviates 1dB from linear. The Legacy WSR-88D AGC-based receiver's Dynamic Range was typically measured to be 91dB to 92dB (Sirmans, 2000).

The IFD's normal compression point is +6dBm resulting in a Dynamic Range of only 87dB. However, SIGMET's signal processing uses a statistical linearization technique for signals above compression; thereby recovering another 6dB of signal. This gives a Dynamic Range of 93dB to 94dB for the ORDA receiver signal path.

Figure 9 shows the ORDA off-line linearity and reflectivity test measurement display. This calibration test computes the System Noise floor, compression point, MDS, linearity and Dynamic Range and shows the results in a graphical window. This test was done in short pulse at the KCRI channel 2 test bed system in Norman, OK. As shown here, the Dynamic Range from 0dB S/N to the 1dB compression point is given as 95 dB.

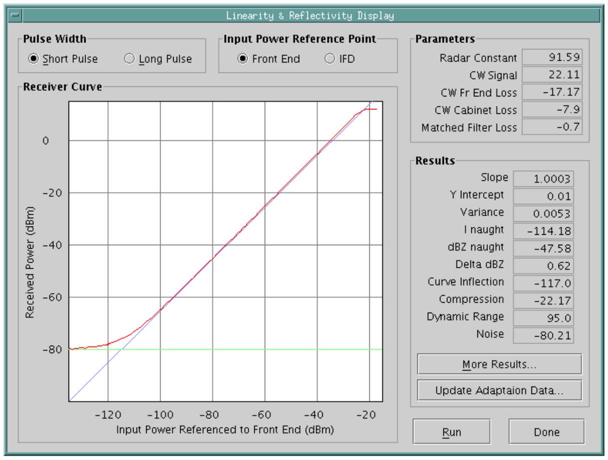

Figure 9: Receiver Transfer Curve

5.3.4 Beta Site Receiver Gain

Plots of log data from ORDA beta sites indicate that the ORDA system gain is very stable as shown in Ffigures 10-13. The main deviations in dBZ_0 track the changes in I_0 very well. Very rare spikes of approximately 1dB are seen, but generally the results are within 0.1dB.

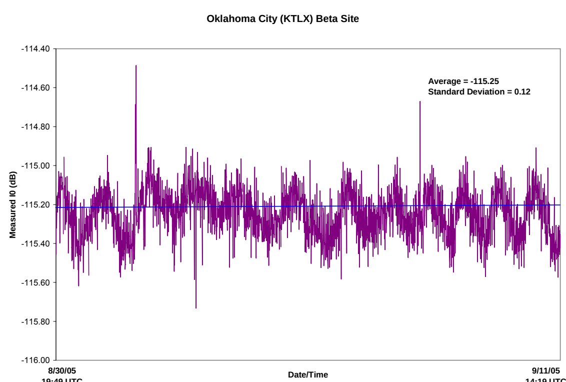

Figure 10: KTLX I_0

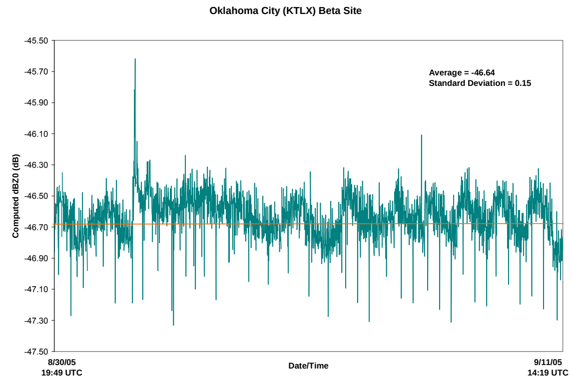

Figure 11: KTLX Calibration

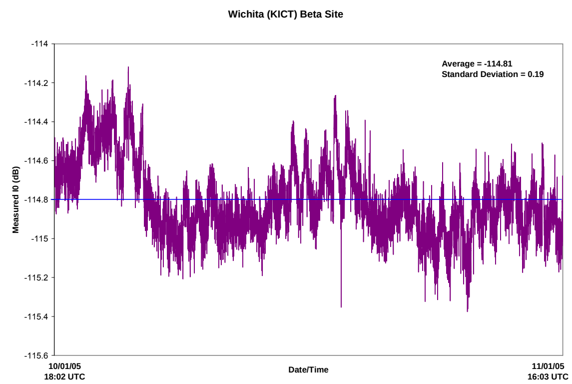

Figure 12: KICT I_0

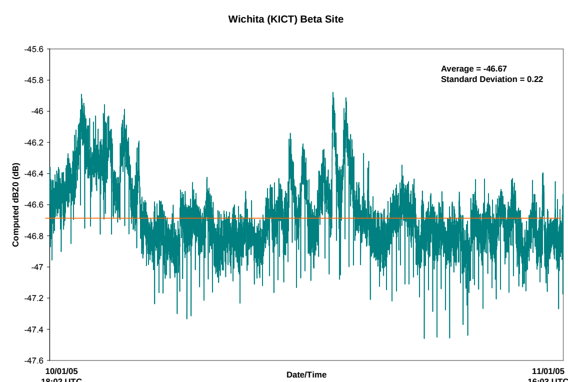

Figure 13: KICT Calibration

6. CALIBRATION PARAMETER MEASUREMENTS

Each calibration parameter is measured using Built-In-Test Equipment (BITE). The accuracy of this BITE is determined off-line by a technician, comparing the values to calibrated test equipment and updating the system to accurately reflect measured values.

Test signals are required to measure P_t and to determine I_0. Noise is a special case; the “test signal” used is no signal at all. A technician measuring a signal with an external average power meter typically achieves an accuracy of ±0.2dB for any given signal. Therefore it is important that the system use as few test signals as possible to accurately measure parameters, since variances in technician measurement could quickly exceed the desired accuracy of ±1.0dB.

If more than one signal is used to measure a single parameter, the signals should be independent and used independently to help identify problems. Otherwise, measurement and/or signal level variations cannot be easily identified. When multiple signals and multiple measurements are required to determine a parameter’s value, system accuracy suffers. As an example, the Legacy system uses 2 different receiver signals (CW and RFD) to determine SYSCAL, SYStem CALibration. The average RFD measurement is allowed to be within 1.5dB of the CW target before any alarms are raised even though these 2 signals are derived from the same source within the RF generator. This practice allows a possible error of up to 1.5dB in this critical parameter. Since the 2 signals have a common source, changes in the RF power from the RF Generator cannot be detected.

Accurate calibration requires all signals and measurements to be reliable and stable. It is not sufficient that measurements or signals are independent. For example, the Legacy system uses 2 average power meters to measure transmitter power, located at different points in the transmit path. They are independent, but unfortunately the one located at the antenna is not reliable (due to slip ring variances, temperature variances, and the long signal path).

Maintenance factors in calibration are difficult to isolate and create errors that are nearly impossible to discover. It is important to reduce them as much as possible. This means using a minimum set of signals and automating maintenance routines where possible to reduce human input. Automated calibration and diagnostic software tools to help localize problems in different ways help to reduce the human factor.

7. VARIANCE REDUCTION

On-line calibrations require each parameter to be measured as accurately as possible. Since the 3 main measurements (Transmitter Power, Noise, and Linearity) influence the parameters needed for dBZ_0 (Transmitted Power and I_0), accurately measuring these is critical. To do this, it is imperative to get as many samples as possible of each measurement. Unfortunately, variance depends on the square root of the number of samples, so there is a diminishing return on sample size.

For Transmitter Power, the Legacy components reused in ORDA constrain the system to obtaining average power meter readings to one sample per second. Also, the transmitter takes time to settle after changing PRF’s. This means only a subset of transmitter power readings are valid. ORDA software calculates Transmitter Power using samples from valid sampling periods, removes the highest and lowest, and averages the rest.

Noise is the easiest parameter to measure for many reasons. Samples do not depend on transmitter pulses, but merely on antenna position and avoidance of external noise sources (such as the sun). For ORDA, over 5000 noise samples are taken for each measurement, and the standard deviation is less than 0.1dB (measured with a dummy load over many calibrations).

Linearity is most difficult and problem-prone measurement. The Off-line STS Linearity function measures the receiver through its linear range and is used to determine receiver gain and MDS (MDS is translated to I_0 for calculation of dBZ_0). Using only CW signal sources, the ORDA system makes measurements at 10 different points on the linear curve and verifies that each is within 1dB of linear before using. Every calibration uses a new set of 10 points to reduce the possibility of a problem with the RF Test Attenuator. In addition, during the system Performance Check over 60 points are used to determine receiver gain and MDS.

Multiple points are used to reduce possibility of single failure points. Also, the maximum and minimum values are ignored in computations with multiple samples to reduce the affect of single, anomalous readings and to reduce variance.

8. CONCLUSION

Table 3 shows calibration results from both Legacy and ORDA. The numbers are compiled from over 3000 samples in each Legacy and ORDA and represent the standard deviation in dB of the appropriate Delta calibration numbers (Delta SYSCAL for Legacy, Delta dBZ_0 for ORDA). The lower standard deviation indicates a more stable ORDA calibration process.

Table 3: Calibration Standard Deviation

Site	LEGACY	ORDA
KTLX	0.527	0.204
KICT	0.287	0.232

Accurately determining reflectivity from the Radar Equation requires accurate and consistent measurement of several critical system parameters. The ORDA calibration schemes were designed to use the minimum amount of signals to determine these parameters to reduce variance and chances of systemic errors.

Automated calibrations reduce technician error and provide more consistent calibration across the WSR-88D fleet.

9. ACKNOWLEGEMENTS

The authors would like to acknowledge the ORDA software and systems engineers for their assistance in developing tools to assist in the calibration accuracy analysis.

Note: The views expressed are those of the author(s) and do not necessarily represent those of the National Weather Service.

10. REFERENCES

Free, A., Heck, A., and Patel, N., 2005: NEXRAD Open Radar Data Acquisition (ORDA) Receiver Calibration, 21st International AMS Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology

Free, A., Patel, N., and Heck, A., 2004: ORDA Internal Report – ORDA System Calibration

Free, A. and Patel, N, 2005: Clutter Censoring Theory and Application for the WSR-88D, 32nd International AMS Conference on Radar Meteorology

Ice, R., McGehee, T., Rhoton, R., Saxion, D., Warde, D., Guenther, R., Sirmans, D., and Rachel, D., 2005: Radar Operations Center (ROC) Evaluation of New Signal Processing Techniques for the WSR-88D, 21st International AMS Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology

Jim, G., and Free, A., 2004: ORDA Internal Report – ORDA Receiver Path

Nathanson, F., 1969: Radar Design Principles: Signal Processing and the Environment, McGraw-Hill Book Company, New York

Operational Support Facility, 1992: Internal Report – Calibration of the WSR-88D

Patel, N., Free, A., Jim, G., 2005: NEXRAD Open Radar Data Acquisition (ORDA) Receiver Characteristics, 21st International AMS Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology.

Rinehart, Ronald E., 1997: Radar for Meteorologists, 3rd edition, Rinehart Publications, Columbia, MO.

SIGMET, 2005: RVP8 User's Manual

Sirmans, D. and Urell, W., 2000: ROC Internal Report – Digital Receiver Test Results